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Profitability of supplying wood chips dried at small or medium scale heating plants

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Abstract— **Moisture is the most important quality factor of fuel wood. It affects both the profitability of supplying wood chips and the economy of running a heating plant. Most fuel wood is seasoned outdoors, so drying depends on the weather and the desired moisture level of wood cannot always be reached. To avoid weather dependency, wood chips can easily be dried in driers connected to a heating plant. Most of the year small-and medium-sized heating plants have significant excess heating capacity that could be used to dry fuel wood. The investment and running costs of a dryer determine how feasible such a drying method is as part of the wood fuel supply chain. The profitability of drying increases considerably if the heating enterprise can increase its sales because of a higher boiler output. Thus, warm air drying of fuel wood can quite easily be made profitable if there is a potential to enlarge the heat clientele.**

***Index Terms*— Moisture, fuel wood, drying, profitability, heating**

I. INTRODUCTION

The most important quality factor in fuel wood is moisture [1]. In order to increase the calorific value of fuel wood, no matter what its form, the wood has to be dried. Besides, most boilers and combustion devices cannot combust wet wood efficiently. Traditionally, fuel wood is seasoned in outdoor stores until the desired moisture level has been reached. These stores, often simple stockpiles at a landing, also serve as a buffer for high fuel demand in winter.

Most fuel wood supply chains follow the same principles. First trees are felled, delimbed and forwarded to a landing where they are stacked for storage or transported to a specific storage site such as a wood yard or terminal. Then they are seasoned long enough to ensure that moisture has decreased to the desired level. Finally, after a six to twelve months long storage, wood stacks are chipped and wood chips are transported to a heating or power plant for energy generation. Some suppliers may chip semi-dried logs and store these chips at the plant. Naturally, variations of these supply chains and methods occur depending on harvesting circumstances such as the terrain and machines used as well as the types of fuel wood to be harvested. For example, in Nordic countries, logging residues and whole trees are used much more extensively than in Central and Southern Europe. [2]

Although the most common contemporary supply methods of fuel wood originate from experience and good practice, they all have some significant weaknesses with regard to quality management. Outdoor seasoning is always very weather-dependent and only estimates can, therefore, be provided for moisture. Because of constantly changing drying conditions, the moisture of delivered wood chips inevitably fluctuates. In a rainy year, wood fuel may never reach the desired moisture level and the end-user therefore has to combust wet wood. If wood is used that is too wet, the efficiency of a boiler decreases, malfunctions increase and maximum output cannot be reached. Besides, much more wood is needed to produce the desired amount of energy [3]. Another challenge of seasoning wood outdoors is related to general storage management and costs. The larger the end-user, the more wood has to be stored in advance in order to meet high demand in winter. This may make storage management complicated if wood stacks are distributed at many landings around the end-user. In any case, keeping large amounts of wood in storage for a long time is costly and involves a risk of losing some of the value of the stored wood because of a decreased quality or material losses for example by natural biodegrading [4].

One possibility of drying wood chips is to do it in a warm air dryer built next to a heating plant. Small- and medium-sized heating plants have significant excess heating capacity most of the year. Their utilization rate is less than 50% on average [5]. Only during a couple of winter months do they work close to their full capacity. Therefore, fuel wood dryers could use this excess capacity to dry wood chips to be used in these heating plants. The benefits of combusting dry wood chips (20–30%) are indisputable: boilers would work more efficiently; there would be fewer malfunctions of the system; boiler output would be higher; fewer additional fuels are required and fewer wood chips are needed [6].

This study aims to show the opportunities and analyze the profitability of drying wood chips in warm air dryers as part of a fuel supply chain. It also aimed to provide calculation tools and practical examples for entrepreneurs and other fuel wood suppliers for understanding the basics of warm air drying. This understanding is needed for either building or buying such a dryer.

II. MATERIALS AND METHODS

In order to evaluate benefits of drying wood chips for the whole supply chain of fuel wood, the costs of wood supply for chosen cases and possible drying costs were calculated. In addition, an Excel-based calculation model was created to help dimension fuel wood dryers that can be used at small- and medium-sized heating plants. Finally, drying of wood

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chips was demonstrated in such a dryer and drying results were compared with the model.

2.1 Studied supply chains

Pricing of different phases of supply chains can be done in many ways, depending on contracts. Often the first parts of the chain such as logging, forwarding, chipping and transportation are priced based on volumes or weight. On the other hand, sometimes the end user may only wish to pay for delivered wood chips based on their heating value. In practice, there are many more supply and pricing combinations, depending on each case [7].

To make comparison easier, the supply costs of wood chip per produced energy (€/MWh) were calculated based predominantly on volumes or the calorific value of delivered wood chips. Costs used in this exercise are from recent studies and from entrepreneur interviews [8]. Two virtual supply chain models typically used in rural areas in Finland were chosen in order to provide wood chips for two heating plants producing either 1,500 MWh (5,400 GJ) or 5,000 MWh (18,000 GJ) heating energy annually. Fuel wood consisted of whole trees in both cases.

In the first supply model, a *contractor model*, the wood supplier or the end-user buys fuel wood directly at road side stores. Subcontractors are used for chipping and transportation. Harvesting costs are included in the roadside price of stacked fuel wood because drying takes place after harvesting and therefore harvesting costs do not change. In the other supply model, *one supplier* takes care of the whole supply chain and delivers wood chips directly to the plant. No matter what the model, a truck-mounted mobile chipper for chipping and a chip truck with a 120 m^3 load space are used to supply to the bigger plant. Correspondingly, a tractor-powered chipper and an agricultural tractor with a 20 m^3 trailer were used to supply the smaller plant.

2.2 Drying

In order to understand some of the physics of drying and how to size a fuel wood dryer, an Excel-based calculator was created. This calculator was also used to help analyze the costs of drying wood chips in a warm air dryer.

In addition, drying was tested and demonstrated in a robust movable fuel wood dryer built in a freight container drying wood chips made from stem wood and whole trees. If wood chips or firewood is dried in this dryer, batches can be 25 loose-m^3 at the largest. In the container, warm air is led into the chamber through a heat exchanger placed on top of the container. Drying heat is produced using a wood chip-fired boiler with an output of 80 kW placed in another container. Warm air is blown through wood chips with one 2.5 kW blower and it is led out into a discharge tunnel from the bottom through a perforated floor. Before being released, warm wet air is circulated through the walls of the dryer to warm the container. It is also possible to circulate some of this warm air back into the chamber if so desired, for example when air is not fully saturated with water and still has drying capacity left.

Several data loggers were installed in the dryer in order to measure the temperature and relative humidity of incoming and outgoing air, speed of drying air and air pressure before and after wood chips. For a short drying demonstration, the drying chamber was divided into two boxes, 3.2 m^3 each, into which wood chips made from pine whole trees and stem wood were put. In this way it was possible to compare whether whole tree chips would dry differently from stem wood chips. For the drying model, two different chip layer depths, 0.5 and 1 m, were tested.

The calculation model was used to calculate the drying costs of the wood chips. Then the profitability of drying wood chips as part of the supply studied chains was analyzed by comparing the net present values of drying costs and benefits to the whole wood heat supply chain.

Figure 1. The drying chamber was divided in two to enable the simultaneous drying of two different wood chip types. (Photo: Jyrki Raitila)

III. RESULTS

3.1 Effect of moisture content on the supply costs of wood chips in wood heat production

As explained earlier, two different wood chip supply models commonly used in Finland and other Nordic countries were studied. They supply two heating plants, Plant 1 and Plant 2, with wood chips.

Plant 1 (energy production 5,000 MWh/a)

The following assumptions and costs were used in supply chain calculations for the *contractor model*:

- Road side price of whole trees; 12 €/MWh (3.3 €/GJ)
- Chipping costs; 3.6 €/loose-m^3
- Transportation costs; 3.6 €/km
- Combustion efficiency of boiler; 78–88% depending on wood chip moisture (55–20%)
- Costs caused by heating system malfunction; 120 € each maintenance visit
- Costs caused by extra heating oil used for heating; 14,000–0 €/a depending on wood chip moisture (55–20%)

Bigger plants usually pay for the heating value of wood chips which is measured at the plant. Therefore euros per heating value (€/MWh) was used for the costs of wood chip raw materials. The moisture of wood chips directly affects combustion efficiency and wood chip volumes required for energy production through chipping and transportation costs. It should also be noticed that when wet chips (>47%) are transported the full capacity of a chip truck cannot be used if the total weight of the vehicle is limited to 60 tons [9].

In the *one supplier model* cost calculation is simpler because the supplier is paid for delivered wood chips for their heating value (€/MWh). Therefore the following costs were used:

- Delivered wood chips; 20 €/MWh (5.6 €/GJ)
- Combustion efficiency of boiler; 78–88% depending on wood chip moisture (55–20%)
- Costs caused by heating system malfunction; 120 € each maintenance visit
- Costs caused by extra heating oil used for heating; 14,000–0 €/a depending on wood chip moisture (55–20%)

Figure 2 illustrates costs of both wood chip supply chains for produced heating energy in relation to the moisture of the delivered wood chips.

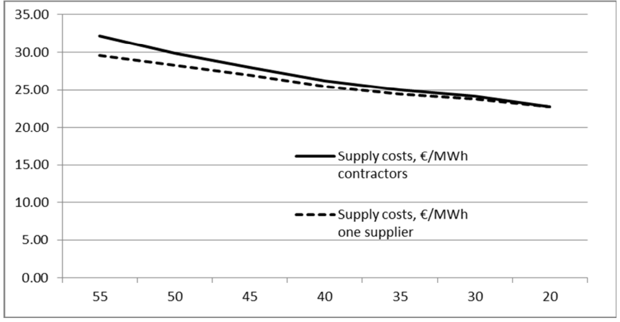

Figure 2. Supply costs of wood chips for 5,000 MWh energy production in the one supplier and contractor models.

Plant 2 (energy production 1,500 MWh/a)

The following assumptions and costs were used in the supply chain calculations for the contractor model:

- Road side price of whole trees; 25 €/solid-m^3
- Chipping costs; 4.5 €/ loose-m^3
- Transportation costs; 2 €/loose-m^3
- Combustion efficiency of boiler; 78–88% depending on wood chip moisture (55–20%)
- Costs caused by heating system malfunction; 120 € each maintenance visit
- Costs caused by extra heating oil used for heating; 5,200–0 €/a depending on wood chip moisture (55–20%)

In the one supplier model the corresponding costs were:

- Delivered wood chips; 20 €/MWh (5.6 €/GJ)
- Combustion efficiency of boiler; 78–88% depending on wood chip moisture (55–20%)
- Costs caused by heating system malfunction; 120 € each maintenance visit
- Costs caused by extra heating oil used for heating; 5,200–0 €/a depending on wood chip moisture (55–20%)

It is important to notice that, in this supply chain, the costs for wood, chipping and transportation are purposely based on volumes, because smaller plants find it easier to have just one way to measure and pay for different costs. If different phases of the supply chain are paid for in volumes, the cost difference for delivered wood chips between contractor and one supplier models becomes significantly higher, the wetter the raw material is (Figure 3). This is natural because for the same amount of wood less heating energy is delivered.

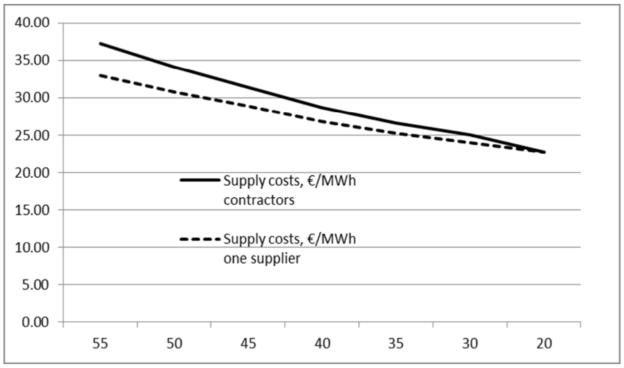

Figure 3. Supply costs of wood chips for 1,500 MWh energy production in the one supplier and contractor models.

These calculation examples show how moisture affects the cost of supplying heating plants with wood chips. The cost difference is the bigger the more supply costs are based on volumes. The total cost difference also shows how much more the end user could pay for dryer wood chips for the same amount of heating energy produced. In other words, the cost difference could be used for drying, either natural or artificial.

3.2 Drying model

A drying calculation model was created so as to provide some basic parameters for designing or testing a warm air dryer. Among other things, the following basic values are needed for the calculation: fuel amount, bulk density of fuel wood, initial moisture and temperature of wood, target moisture of wood, temperature of incoming air, relative humidity of drying air before heating, dimensions of the dryer, overall heat transfer coefficient of the dryer building, flow rate of drying air, efficiency of the drier, and drying time. When these values are inserted the calculator renders how much heat is required for heating ice in wood to 0^0C (1), melting ice in wood (2), heating water in wood (3), heating dry wood to the final temperature (4), evaporation of water in wood (5), and heat losses (6). Then the amount of heat required (7) and heat input (8) will be calculated according to the following procedure:

(1) heating ice in wood = $-m_f u_f t_{ice} c_{ice}$
(2) melting ice in wood = $m_f u_f L_{ice}$
(3) heating water in wood = $m_f u_f (t_{w1} - t_{w0}) c_w$
(4) heating dry wood = $m_f (100-u_f)(t_f - t_{f0}) c_f$
(5) evaporation of water in wood = $m_f u_f L_w$
(6) heat losses = $k_b A_b (t_{in} - t_{out})/1000$
(7) amount of heat required = (1)+(2)+(3)+(4)+(5)+(6)
(8) heat input = (7)/t_{drying}

Where

m_f	mass of fuel, kg
u_f	moisture content of fuel, dimensionless (0 – <1)
c_{ice}	specific heat of ice, kJ/(^{0}C kg)
t_{ice}	initial temperature of ice (and fuel), ^{0}C
L_{ice}	specific latent heat of melting ice, kJ/kg
t_{w1}	final water temperature, ^{0}C

t_{w0} initial water temperature, ^{0}C (0^{0}C if the initial temperature of fuel is 0^{0}C or less)
c_w specific heat of water, kJ/(^{0}C kg)
t_f final fuel temperature, ^{0}C
t_{f0} initial fuel temperature, ^{0}C
c_f specific heat of fuel, kJ/(^{0}C kg)
L_w specific latent heat of water, kJ/kg
k_b overall heat transfer coefficient of the dryer building, W/(^{0}C m^2)
A_b wall surface of the dryer building, m^2
t_{in} average temperature inside the dryer chamber, ^{0}C
t_{out} average temperature outside the dryer chamber, ^{0}C
t_{drying} drying time in seconds

In addition to primary results, amount of required heat and heat input, secondary results such as mass flow rate of water vapor in drying air, temperature of drying air after heating and drying will be calculated and used in the course of the calculation.

3.3 Dryer demonstration and model testing

In order to test the drying model, warm air drying was demonstrated in a rather simple dryer built in a freight container. The dryer did not contain any heat recovery or air circulation systems, but warm air was simply blown through the drying chamber. Because both chip batches were relatively small (3.2 m^3) compared to the capacity of the dryer (25 m^3), all wood chips dried very fast and evenly. The main measurements and model results are summarized in Table 1. Usually wood chips made from whole trees contain more fines and therefore require more output from the air blower in order to ensure sufficient air flow through the whole layer. In this demonstration, however, particle sizes of both wood chip types did not differ very much from each other, and therefore air flow through both chip layers was very similar (see air pressure differences). In general, this demonstration showed that this kind of inexpensive freight container dryer is suitable for drying both types of wood chips. It has also proved to work nicely for log wood in previous tests [10].

Table 1. Main measurements and model calculations of the drying demo in which 3.2 m^3 of both whole tree and stem wood chips were dried. The wood chip layer was 1 m thick.

	Whole tree chips		**Stem wood chips**	
Initial moisture, %	38.2		43.5	
Moisture after drying, top, %	1.9		2.4	
Moisture after drying, bottom, %	5.5		7.7	
Avg. air flow, m^3/h	450		450	
Demonstration time, h	100		100	
Time when final moisture was reached, h	48		70	
Air pressure difference between top and bottom, Pa	28		30	
	Measured	**Model**	**Measured**	**Model**
Avg. temperature of drying air, in, °C	57*	55	57*	61
Avg. temperature of drying air, out, °C	27	25	30	28
Avg. water content in drying air, out, g/kg of air	4.8	5.0	5.1	5.6

*There was only one source for warm drying air. Thus the measured temperature of drying air was the same for both batches.

Drying was monitored with several data loggers measuring the temperature of incoming and outgoing air, the water content in incoming and outgoing air and the relative humidity of drying air. As seen in the relative air humidity curves (Figure 4 & 5), whole tree chips dried faster because their initial moisture was lower than that of stem wood chips. In this demonstration wood chip were dried "too dry" in order to get enough data from the whole drying period. In fact, most wood chips were bone dry already half way the demo period. Because of the simple structure of the dryer, the average efficiency of the dryer was as low as 50%. For more energy-efficient drying, a proportion of the drying air should be circulated back into the drying chamber or the process should be stopped when the humidity of the outgoing air begins to decrease rapidly (Figure 6). The temperature curve of incoming drying air indicates that it might be more efficient to slow down the drying process at night because then the temperature of incoming fresh air can be significantly lower and therefore requires more heating energy (Figure 6). In practice, there is no need to dry fuel wood below 20% for combustion or storage reasons.

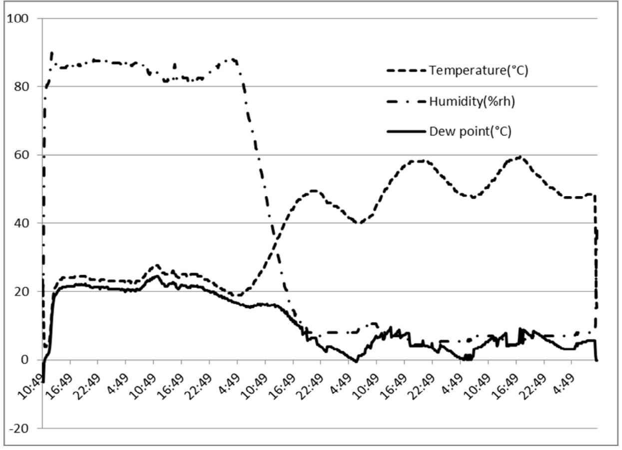

Figure 4. Temperature and air humidity of outgoing air measured for whole tree chips.

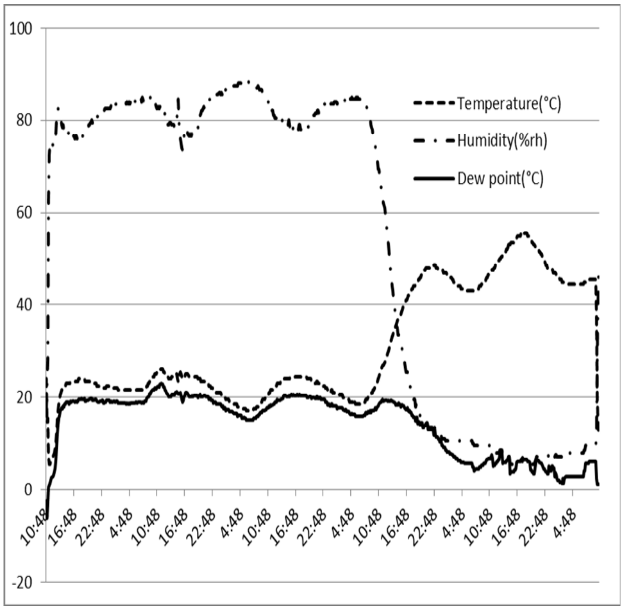

Figure 5. Temperature and air humidity of outgoing air measured for stem wood chips.

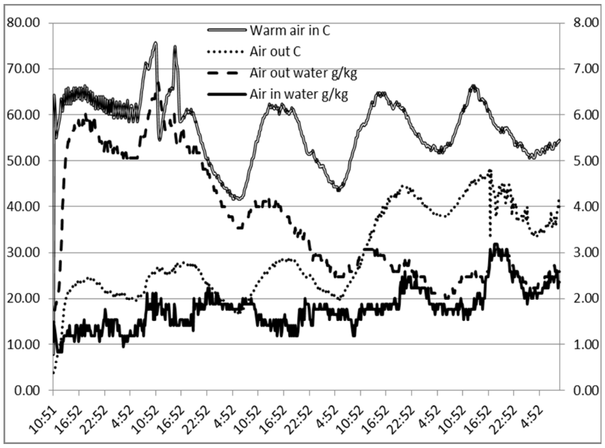

Figure 6. Temperatures and water content (vapor) of incoming and outgoing air when drying stem wood chips. No more drying takes place when air in and out curves cross.

These trying tests showed the calculation model can be used to dimension and help optimize wood fuel dryers, to calculate the drying energy needed, and to help evaluate total drying costs. Therefore it was used to help evaluate the drying costs of drying wood chips as explained in the following section.

3.3 Profitability of drying wood chips at a heating plant

Plant 2 was chosen for a case study of evaluating profitability of drying wood chips at a heating plant, because the tested and demonstrated freight container dryer has enough drying capacity to dry all the wood chips used annually at that plant. For the annual amount of wood chips combusted at Plant 2 a much bigger dryer would be needed. Profitability was evaluated by calculating the costs of drying and comparing them with the benefits from more economical heat production with drier wood chips containing water only 20%. A drying example was calculated for a 25 m^3 fuel wood dryer for 55% and 45% wood chips with the following parameters:

- Annual volume of dried wood chips; 2,100 loose-m^3
- Annual heating energy used for drying, calculated with the drying model; 374 MWh (55% moisture) and 225 MWh (45% moisture)
- Heating costs for drying; 40 €/MWh including capital and running costs of the heating plant or 24 €/MWh without any other but fuel costs
- Investment costs of dryer; 35,000 € according to a Finnish manufacturer [11]
- Electricity and maintenance costs; 1,300 €/a
- Pay-off period; 10 a
- Interest rate; 5%

With these parameters, the drying costs were 9.3 €/loose-m^3 for 55% wood chips if drying heat costs 40 €/MWh and 6.5 €/loose-m^3 if drying heat costs 24 €/MWh. The corresponding costs for 45% wood chips were 7.0 €/loose-m^3 and 4.8 €/loose-m^3. Two different costs for drying heat were chosen, depending on whether capital and running costs of the heating plant should be included. There is a basis for both arguments. If drying heat is bought from a heat enterprise, even if this enterprise owns both the plant and the dryer, it is natural to include all real costs of heat production in the heat price unless capital and running costs are covered in some other way. Profit, however, is not included. On the other hand, the heat enterprise may consider capital and running costs to be covered by heat supply contracts. Therefore, drying wood chips only increases annual fuel costs. In practice, the higher drying heat price should be applied when both investments, the plant and dryer, are made at the same time and considered as one unit. The lower price can be considered when the heat enterprise already has enough customers for normal heating business but still has boiler capacity for drying.

When drying costs were compared with lower heating energy production costs, the following benefits were taken into consideration: fewer wood chips are needed, transportation and chipping costs are lower, boiler efficiency increases, fewer malfunctions occur, and less additional fuels are needed.

Profitability of drying and drying investment was evaluated by using the net present value method [12]. Net present values of costs and benefits for a ten year pay-off period were calculated for both *contractor* and *one supplier* supply chains, using Plant 2 as the end user. Because dry wood chips cannot be stored outdoors, an additional storage investment (35,000 €) was also included in the calculations.

Table 2. Profitability of the dryer investment in selected supply cases. Figures indicate the difference between costs and benefits in net present values (NPV) in the ten-year investment period.

	Drying heat 40 €/MWh		**Drying heat 24 €/MWh**		**Drying heat 40 €/MWh + storage**		**Drying heat 24 €/MWh + storage**	
Initial moisture of wood chips	Contractor model	One supplier	Contractor model	One supplier	Contractor model	One supplier	Contractor model	One supplier
55	14,79	-36,	60,19	9,2	-775	-51,	46,68	-6,3

%	2	170	6	34		738	3	34
45 %	-8,159	-37,222	19,407	-9,655	-23,727	-52,789	5,894	-25,223

In the one supplier model, investments would only be profitable if drying heat is lower (24 €/MWh) and fresh wood is dried without any pre-seasoning. On the other hand, drying investments would be profitable in most contractor cases. This is natural because in the contractor model most of the supply costs of wood chips were based on volumes, and therefore drying reduces the supply costs of fuel wood more than in supply chains that charge for work units mainly based on the heating value of wood.

In the previous comparisons it is assumed that the annual heat sales remain unchanged despite increased heat production capacity due to better fuel. Profitability of drying increases considerably if the heating enterprise can increase its sales because of a higher boiler output.

Let us assume that Plant 2 annually dries the drier's maximum capacity of 2,500 loose-m^3 of wood chips instead of the 2,100 loose-m^3 needed in order to provide energy for annual heat sales of 1,500 MWh. Then the plant could sell 300 MWh more heating energy. This would increase annual gross revenues by 18,000 € if customers pay 60 €/MWh for heat. This annual increase in revenues makes the drying investment profitable in all options (Table 3).

Table 3. Profitability of the dryer investment in chosen supply cases if 300 MWh extra energy can be sold. Figures indicate the difference between costs and benefits in net present values (NPV) in the ten year investment period.

	Drying heat 40 €/MWh		**Drying heat 24 €/MWh**		**Drying heat 40 €/MWh + storage**		**Drying heat 24 €/MWh + storage**	
Initial moisture of wood chips	Contractor model	One supplier	Contractor model	One supplier	Contractor model	One supplier	Contractor model	One supplier
55 %	162,462	101,792	216,514	155,845	146,894	63,779	203,001	140,277
45 %	135,139	100,541	167,956	133,358	119,571	61,724	154,443	117,790

In the least profitable option (one supplier, 40 €/MWh for drying heat and storage) gross revenues should increase by 9,000 € annually in order to make the drying investment profitable. In practice, this requires drying 200 loose-m^3 more wood chips and using half of the increased boiler output. Correspondingly, in the contractor model, drying only 50 loose-m^3 of chips, and thus increasing revenues by 3,000 € would guarantee the profitability of the investment.

The calculated examples show that drying wood chips in a warm air dryer can very well be a feasible option for small- and medium-scale heating enterprises, particularly, if such a heating plant can increase annual heat sales because of the increased heating output of the system.

DISCUSSION

Moisture is the most important quality factor in fuel wood. It affects both the profitability of supplying wood chips and the economy of running a heating plant. Most fuel wood is seasoned outdoors. Although this method is cheap, it depends on the weather and therefore the desired moisture level of wood cannot always be reached. If wood that is too wet is combusted, the efficiency of a boiler decreases, malfunctions increase and the highest output cannot be reached. Besides, much more wood is needed to produce the required amount of energy.

To get rid of weather dependency, wood chips can easily be dried in driers connected to a heating plant. Small- and medium-sized heating plants have significant excess heating capacity most of the year because they are sized to meet high output needs in winter. However, the maximum capacity is usually required only for three to six weeks a year [13]. Therefore, these plants could be used to dry their own wood chips. According to a recent questionnaire study, more than half of the heat entrepreneurs in Central Finland are interested in drying wood chips or log wood at their heating plants [14].

The investment and running costs of a dryer determine how feasible such a drying method is as part of the wood fuel supply chain. Compared to the heating plant investment, suitable dryers can be acquired only at less than 10% of the plant investment. Because dry wood chips cannot be stored in the open, a storage shelter should be provided, however.

As total investments can be quite modest, the running costs of the dryer play the biggest part in the profitability of drying fuel wood. The most crucial cost factor is the cost of heating drying air. If the heating plant is built as a separate project, and capital, maintenance and running costs are covered by normal heating business, extra heat for drying can be obtained at the cost of the fuel required for drying. On the other hand, if both the plant and dryer are constructed in the same project, it might be necessary to include at least some of the capital costs of the plant in the drying cost as well.

Pricing of different phases of supply chains can be carried out in many ways, depending on contracts. Often the first parts of the chain such as logging, forwarding, chipping and transportation are priced for volumes or weight [15]. On the other hand, sometimes the end user may only wish to pay for delivered wood chips based on their heating value. In reality, many more trade and pricing practices exist, depending on countries, companies and volumes of business. In any case, the moisture of delivered fuel wood affects the profitability of the whole heating energy supply the greater the more work phases are priced for volumes.

Warm air drying was studied in connection with two common Finnish supply chains models*, contractor and one supplier models*. In the one supplier model, investments would only be profitable if drying heat is 24 €/MWh and fresh wood is dried without any pre-seasoning. On the other hand, with the same heat cost, drying investments would be profitable in most contractor cases. This is natural because, in the contractor model, most supply costs of wood chips were based on volumes.

The profitability of drying increases remarkably if the heating enterprise can increase its sales because of a higher boiler output. If half of the increased boiler output due to better fuel can be used for heat sales, all the investment options studied would be profitable, even if a 40 €/MWh heat cost for drying is applied. Thus warm air drying of fuel wood can quite easily be made profitable if there is potential to enlarge the heat clientele.

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