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# ECO-EFFICIENCY OF PELLET PRODUCTION - COMPARISON OF LOG WOOD AND SAWMILL BYPRODUCT SYSTEMS

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**Abstract:** *The study aims to investigate the environmental performance of two sawdust-based and two logwood chipped-based pellet supply systems. Based on a life cycle assessment approach (LCA), environmental inputs, emissions and wastes are compiled and analyzed for different indicators. The study resulted in four major findings: (1) chip-based supply systems outperform sawdust-based systems; (2) the pellet manufacturing process has a share of about 60 to 80% in the overall energy input of the whole supply system; (3) the drying process step causes about 60 to 80% of the energy requirement for the pellet manufacturing process; (4) superheated steam dryer technology offers a high potential for efficiency improvement. Pellet industry can improve competitiveness by using more advanced dryer technology and by taking advantage of the "economies of scale" effect.*

## 1. Introduction

The renewable energy debate triggered a number of bioenergy initiatives in many countries around the world. Cordwood, wood chips, wastepaper, wood pellets, along with other biomass-based products or byproducts are all examples of biomass fuels. However, many of them have one disadvantage, the high variability of fuel characteristics, such as moisture content, homogeneity, or irregular size, resulting in sub-optimal combustion (ASPLAN, 2000, VINTERBÄCK, 2004, WOLF et al., 2006). One approach to overcome this drawback is to refine the biomass by homogenizing and compacting it into compounds of regular density and shape, which results in easy handling and distribution and in a controlled combustion process. The so-called pellets have become an important biomass-fuel, and the demand for it has been continuously increasing. Sawdust has been the main primary material for pellet manufacturing, and there is only little knowledge about the efficiency of alternatives (HÄSSIG, 2007), such as chipped logwood, or switchgrass (JANNASCH et al., 2002).

The study aims at investigating the eco-efficiency of four pellet supply system alternatives, two of them being sawdust-based, and two being chip-based. We used a life cycle assessment (LCA) approach to compile environmental inputs, emissions and wastes of the pellet supply systems from a "cradle-to-grave" perspective. We will first present the quantitative modeling approach, then present some eco-efficiency indicators for the whole pellet supply system, and finally discuss the pellets manufacturing process in detail.

## 2. Methodology

### 2.1. Life Cycle Approach

There are several approaches to quantify environmental performance indicators, such as “cause and effect approach”, “ risk-based approach”, “life cycle approach” (ISO, 1997). The present analysis follows the “life cycle approach” by selecting and considering the inputs and outputs associated with supply of pellets, and the significant environmental aspects and impacts at any stage of the pellet’s life cycle before combustion. Inputs consist of materials and energy, which enters into the process network (source flow). Output covers materials and energy, which leaves the process network (sink flow). The life cycle approach therefore analyzes the flows of energy, materials, emissions, and wastes through the whole process network from sources to sinks. Table 1 provides examples of OPIs that may be appropriate to measure the environmental performance of an organization's operations.

**Tab. 1 : Selection of Possible Operational Performance Indicators OPIs, according to (ISO, 1997)**
**FU – functional unit (1 metric ton of pellets)**

| *OPI Type* | *OPI Class* | *Possible OPIs (selected from ISO 14031)* |
|---|---|---|
| **Input** | *Materials* | Quantity of raw materials reused in the production process; quantity of water per unit of product; quantity of hazardous materials used in the production process. **$[kg \cdot FU^{-1}]$** |
| | *Energy* | Quantity of energy used per unit of product or service; quantity of each type of energy used; quantity of energy generated with by-products or process streams. **$[MJ \cdot FU^{-1}]$** |
| | *Services* | amount of hazardous materials used by contracted service providers; amount of cleaning agents used by contracted service providers; amount of recyclable and reusable materials used by contracted service providers; amount or type of wastes generated by contracted service providers. **$[kg \cdot FU^{-1}]$** |
| | *Facilities and Equipment* | Total land area used for production purposes; number of emergency events or non-routine operations (e.g. shutdowns) per year. |
| **Output** | *Wastes* | Quantity of waste per year or per unit of product; quantity of waste stored on site; quantity of waste converted to reusable material per year. **$[kg \cdot FU^{-1}]$** |
| | *Emissions* | Quantity of specific emissions per unit of product; quantity of waste energy released to air; quantity of air emissions having ozone-depletion potential; quantity of air emissions having global climate-change potential. **$[kg \cdot FU^{-1}]$** |

Since the environmental performance evaluation concept has not yet been widely introduced into the forest operations community, some of the key definitions related to it will be given in the following paragraphs.

| | |
|---|---|
| ***Eco-Efficiency*** | Eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity (DESIMONE et al., 1997). |
| ***Life-Cycle-Assessment LCA*** | Compilation and evaluation of the inputs and the potential environmental impacts of a product system through its life cycle (ISO, 1997). |
| ***Life-Cycle-Inventory Analysis LCIA*** | Phase of life cycle assessment involving compilation and quantification of inputs and outputs, for a given product system through its life cycle (ISO, 1997). |

## 2.2. Product System Model

Figure 2 illustrates the functions of the pellet product system and the system boundaries. It consists of three subsystems, (1) the raw material supply system, (2) the pellet manufacturing system, and (3) the pellet distribution system (figure 1). The main purpose of the present study is to investigate the effects of four raw material supply alternatives on the eco-efficiency of pellet production, which are (a) log wood, chipped in the forest and then transported by truck to the plant; (b) log wood, transported by truck to the plant, and then chipped; (c) sawdust, conveyed by a belt-conveyer from a sawmill to an adjacent pellet plant, and (d) sawdust, transported by truck to the pellet plant.

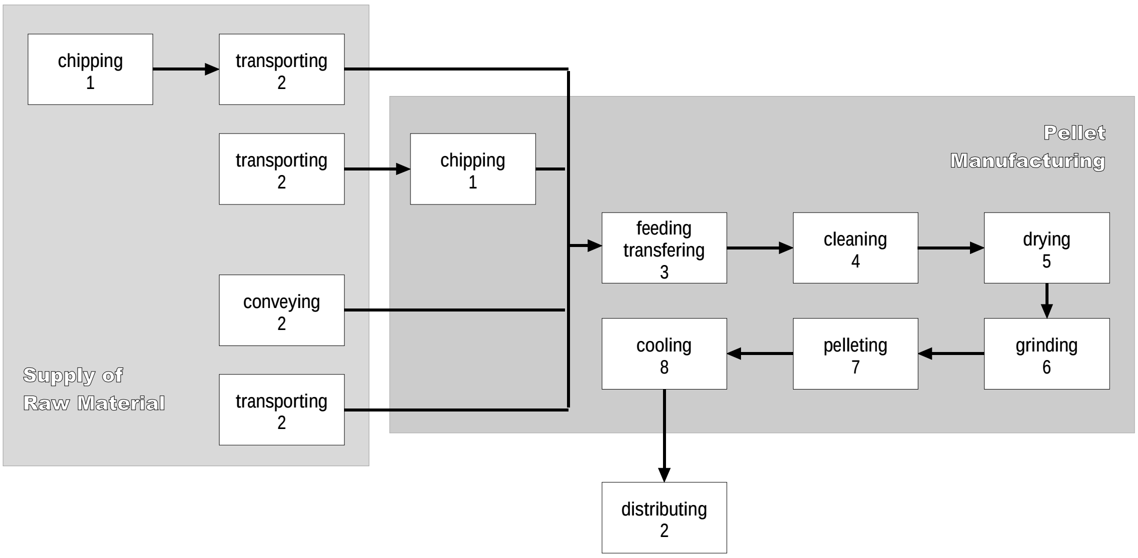

**Fig. 1 :** **Boundaries and functions of the pellet product system.** Three subsystems: (1) supply of raw material, (2) pellet manufacturing, and (3) pellet distribution. Transport functions (#2) occur at several locations, and the chipping function (#1) may be allocated to the forest or to the plant.

### 2.3. Life Cycle Inventory Analysis LCI

Life cycle inventory analysis involves the compilation and quantification of inputs and outputs for the pellet product system throughout its life cycle, covering (1) production of raw materials and energy carriers, (2) energy production, (3) machine manufacturing, (4) facility construction, and (5) pellet manufacturing. The first step of information gathering consists of choosing the right environmental performance indicators. Indicators should (1) concern with a global business value or environmental issue, (2) be relevant to virtually all businesses and (3) have an agreed measurement method and definition (VERFAILLIE et al., 2000, WBCSD, 2000). Additionally, they should foster continual improvement and make sectors and industries comparable across time. We chose the following indicators

- Energy consumption
- Materials consumption
- Greenhouse gas emissions ($CO_2$)
- Ozone depleting substance emissions (CFCs, Halons)
- Ecotoxicity
- Respiration effects (PM10, dust)

A second step involves the physical definition of the system by allocating machines, tools, and facilities to the functions of figure 1, which is shown in table 2. Each machine is then characterized by a material profile, consisting of the mass of [1] non-alloyed steel, [2] low-alloyed steel, [3] high-alloyed steel, [4] rubber, [5] synthetic materials, [6] aluminum, [7] glass, and [8] copper. An operational profile, consisting of the [9] life span, [10] fuel consumption, [11] repair factor, and [12] productivity of each machine/facility completes the inventory data gathering. 15 machine profiles had to be prepared by collecting data from manufacturers, operators, and statistical records.

**Tab. 2 : Physical components of the pellet product system.** Function # refers to figure 1

| *Function # (figure 1)* | *Function* | *Machine, facility* | *Mass [kg]* | *Power [kW]* |
|---|---|---|---|---|
| *1* | *Mobile chipping* | Mobile, truck-mounted chipper | 28’000 | 300 |
| | *Plant chipping* | Stationary chipper | 29’000 | 660 |
| *2* | *Truck transport, container* | 40 ton truck | 24’000 | 300 |
| | *Truck transport, stanchion* | 40 ton truck | 16’500 | 300 |
| | *Truck transport, silo* | 40 ton truck | 18’000 | 300 |
| | *conveyor transport* | Chain conveyor | 8’000 | 30 |
| *3* | *Feeding, transferring* | Moving floor conveyor | 18’000 | 55 |
| *4* | *Cleaning* | Reciprocating screen | 2’000 | 7.5 |
| *5* | *Drying* | Band dryer, sawdust | 70’000 | 150 |
| | | Band dryer, chips | 20’000 | 50 |
| *6* | *Grinding* | Hammer mill | 8’000 | 335 |
| *7* | *Pelleting* | Pelletizer | 14’000 | 165 |
| *8* | *Cooling* | Cooler | 8’000 | 65 |
| *9* | *Plant infrastructure* | Silo | 27’500 | |
| | | Buildings | 1’060’000 | |

Life Cycle Inventory Analysis aims to compile and to quantify all relevant inputs and outputs of the whole process network (ISO, 1997), which are needed to manufacture one unit (metric ton) of pellets (figure 1). A second step of life cycle inventory analysis consists of the aggregation of all inputs and outputs (table 1) on a product system level, which requires numerical analysis.

Production economics provides a formal approach to investigate process networks or even economic sectors, which relies on two fundamental concepts: (1) commodities, and (2) activities (KOOPMANS, 1951a, b). An activity, also called a process, consists of a specific technology, which transforms specific input-flows into output-flows according to well-defined procedures. The mapping of process networks as flows on a graph has become an important approach to analyze environmental impacts (KOOPMANS, 1951a, b). Activities are represented as nodes while arcs represent flows of goods, resources, emissions, and wastes. The resulting graph is non-cyclic, directed, and finite. Additionally, several source nodes and sink nodes may exist, being located outside of the system's boundaries. This type of graph has also become known as GOZINTO-graph, following “the part that goes into”.

Flows on a graph may be represented by a system of linear equations. Each row describes the flow of one commodity. There is a convention to map source flows with positive, and sink flows with negative figures. Using matrix notation (1) results in a flow matrix with n rows, representing n commodities, and with m columns, representing m activities. Such a matrix that is unique for a specific process network is called technology matrix A. Activities (columns) are assumed linearly scalable. The set of scaling factors is represented by a scaling vector X with length m. A unique solution requires (1) a quadratic technology matrix a (m equals n), and (2) a known balance of inflows and outflows for all commodities. The balance boundary conditions are represented by a vector Y with length n.

$$A \cdot X = Y \qquad (1)$$

Model analysis is complete, if we know the vector X. It can be found by solving matrix equation (1) for X (2).

$$X = A^{-1} \cdot Y \qquad (2)$$

Equation (2) completely describes the flow of commodities for a given process network. For life cycle inventory analysis, the model has to be enhanced to analyze the flow of environmental burdens. There is a well-documented approach (KOOPMANS, 1951a, b) which assumes the flow of commodities to be proportional to the flow of environmental burdens. A single type of environmental burden may be represented by a vector B, which has the same length as the scaling vector X. If p types of environmental burdens have to be considered, activity specific environmental burdens may be mapped on a matrix B that has p rows and m columns.

$$b = B \cdot X \qquad (3)$$

Multiplying the burden matrix B by the scaling vector X results in the burden vector b of the total system (3).

### 2.4. Data Analysis

The specification of the flow parameters for the physical units (functions of figure 1 + allocated machines of table 2) was done as follows (VERFAILLIE et al., 2000):

- Commodity inflow, measured in mass (kg) per machine for each type of raw material, was estimated according to manufacturer’s information,
- Inflow of environmental burdens for each type of material was taken from a standard life cycle inventory (ECOINVENT, online),
- Commodity outflow was measured in productive machine hours (PMHs),
- Outflow of environmental burdens was calculated according to (3).

The specification of the flow parameters for the “pellet product” system was done as follows:

- Commodity inflow into the system layer, measured in (PMHs) for each type of machine, was taken from operational profiles of the machines,
- Emissions of combustion processes were taken from literature.

## 3. Results and Discussion

There are several possibilities how to combine alternatives of raw materials supply with the pellet manufacturing process (figure 1). The present analysis considers four alternatives, consisting of two types of raw materials, sawdust and logwood. The inbound supply of sawdust consists of two alternatives, (1) transport by a chain conveyor from an adjacent sawmill, and (2) container transport by a truck. Logwood has to be chipped, what can be done either with a mobile chipper in the forest or with a stationary chipper at the pellet plant site. The analysis is based on the following assumptions:

- Sawdust moisture content: initial 50%, post-drying 10%.
- Chip moisture content: initial 35%, post-drying 14%.

Analysis clearly demonstrated that the initial moisture content of the raw materials is the main factor to control eco-efficiency of the pellet product system. Initial moisture contents of 50% for sawdust and of 35% for chips are assumptions that represent real-world conditions.

### 3.1. Characteristics of the Pellet Product System

Figure 2 illustrates the energy consumption per ton of pellets for the four production system alternatives. The sawdust-based systems require a total energy input of about 6000 MJ per ton, whereas the log wood systems demand about 3500 MJ per ton. The energy input covers both the process energy and the gray energy spent to extract raw materials and energy carriers, to produce materials, to manufacture machines, and to build plants. The pellet manufacturing process has a share in the total energy demand of about 90% for the sawdust-based and of about 80% for the chip-based systems, whereas raw materials supply has a share of 6 to 15% and pellet distribution of 2 to 4%.

The overall efficiency of supply (eq. 4) is a figure of merit for energy-efficiency.

$$\eta_{sys} = \left[ 1 - \frac{E_{input}}{E_{cal}} \right] \tag{4}$$

| whereas | | |
|---|---|---|
| | $\eta_{sys}$ | overall system efficiency |
| | $E_{input}$ | cumulative process and grey energy input |
| | $E_{cal}$ | higher heating value (calorific value) |

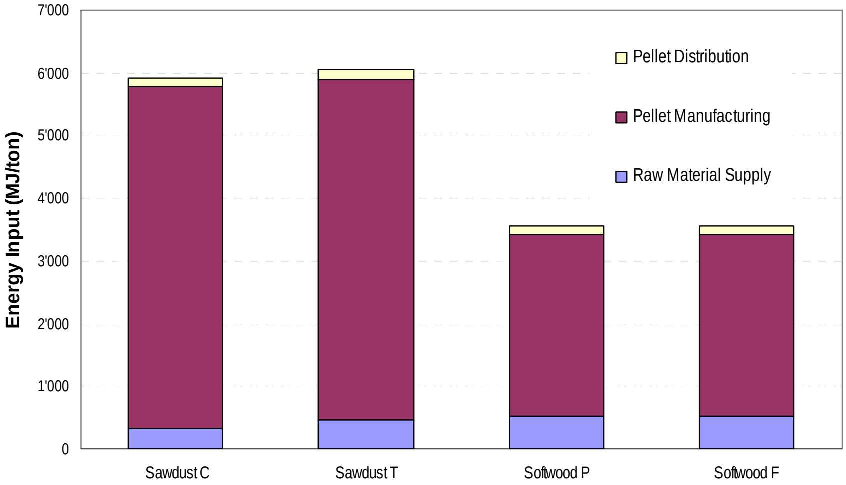

**Fig. 2 : Energy input for pellet production system alternatives, consisting of raw material supply, pelleting, and pellet distribution.** C conveyor transport, T truck transport, P plant chipping, F forest chipping

The chip-based systems have an efficiency of about 80%, compared to the sawdust-based systems with about 67%. The heating or calorific value of pellets is the amount of heat release during the combustion of a specified amount of it. The higher heating value for pellets is about 18 MJ per kilogram and refers to the total heat released without the energy required to vaporize the moisture fixed in the pellets.

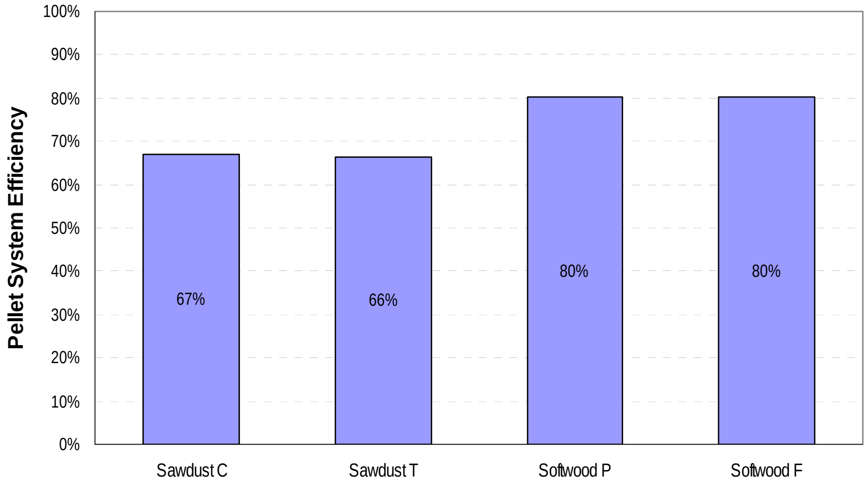

**Fig. 3 : Pellet energy-efficiency for different production system alternatives.** C conveyor transport, T truck transport, P plant chipping, F forest chipping.

Figure 4 illustrates the carbon dioxide emissions for the pellet production alternatives. The sawdust-based system emits about 400 kg per ton of pellets, whereas the chip-based system emits only about 170 kg per ton.

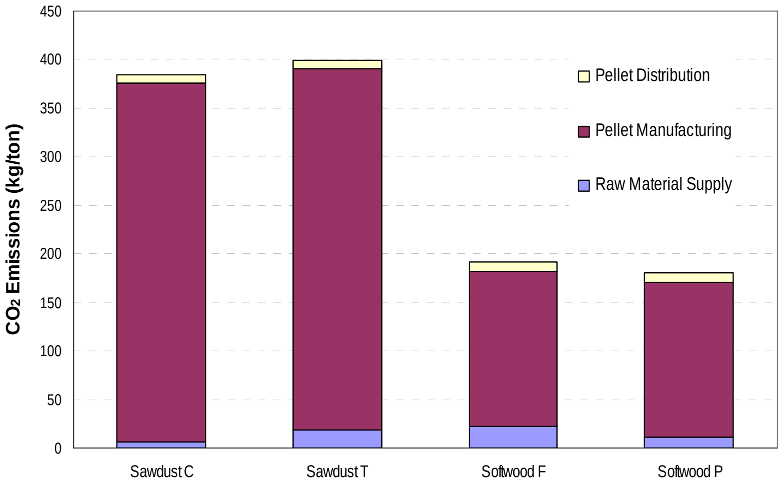

**Fig. 4 :** **CO2 emissions for pellet production system alternatives, consisting of raw material supply, pelleting, and pellet distribution.**

In analogy to the energy efficiency (eq. 4), we can define carbon dioxide efficiency (eq. 5).

$$\eta_{CO2} = \left[1 - \frac{CO_{2[out]}}{CO_{2[seq]}}\right] \tag{5}$$

| whereas | $\eta_{CO2}$ | overall system efficiency |
|---|---|---|
| | $CO_{2[out]}$ | $CO_2$ emissions of the supply system |
| | $CO_{2[seq]}$ | $CO_2$ sequestrated by growth of wood |

The amount of carbon dioxide sequestrated by the growth of one ton of wood is assumed to be about 1850 kg. This results in a carbon dioxide efficiency of about 78% for the sawdust-based system and of about 90% for the chip-based system.

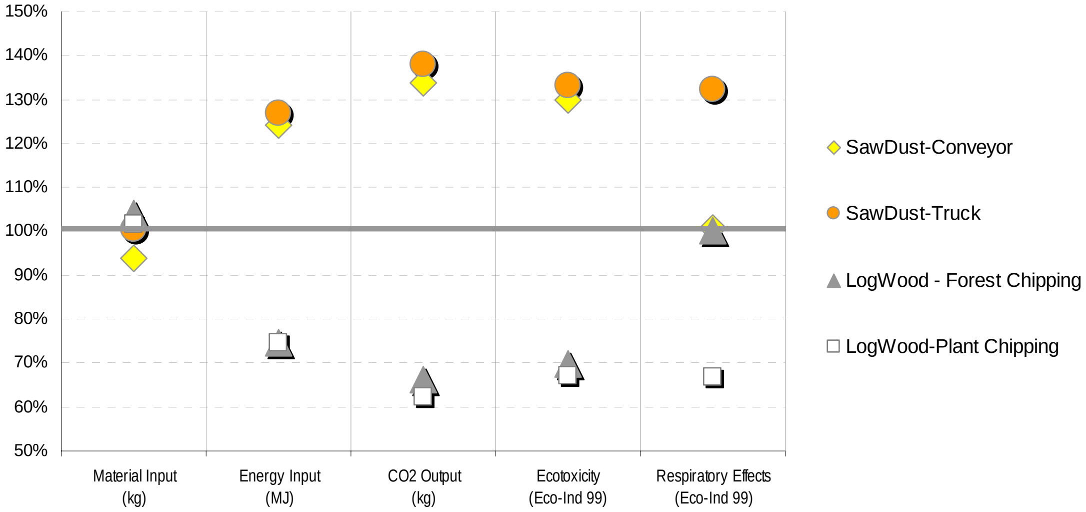

**Fig. 5 :** **Eco-Profile of the relative environmental impact of pellet production system alternatives.**

Figure 5 summarizes the relative impact of environmental stressors: (1) resource depletion or material input, (2) energy input, (3) carbon dioxide emissions, (4) eco-toxicity, and (5) respiratory effects.

While all the alternatives have a similar material input, they differ considerably regarding the other stressors. The sawdust-based system has a significantly higher environmental impact compared to the chip-based systems. However, there is a major difference related to the respiratory effects. The use of diesel engines for chipping in the forest and sawdust transportation by container truck causes higher emissions of particles (PM10) and of dust. Therefore, the chip-based system with chipping at the plant site is the most favorable one, whereas the sawdust-based system based on truck transportation performs worst.

### 3.2. Characteristics of the Pellet Manufacturing Subsystem

The results presented above clearly indicate, that the pellet manufacturing process accounts for about 80 to 90% of the overall environmental impacts (see e.g. Figure 2). this finding requires this process to be investigated in more detail.

Figure 6 illustrates the energy input for three pelleting process alternatives. Three out of seven process steps require about 95% of the energy input, drying as the most important (60 to 80%), pelleting as the second important (12 to about 22%), and grinding as the third important ( 4 to 9%). This clearly indicates, that the drying process is the "bottleneck" for any improvement.

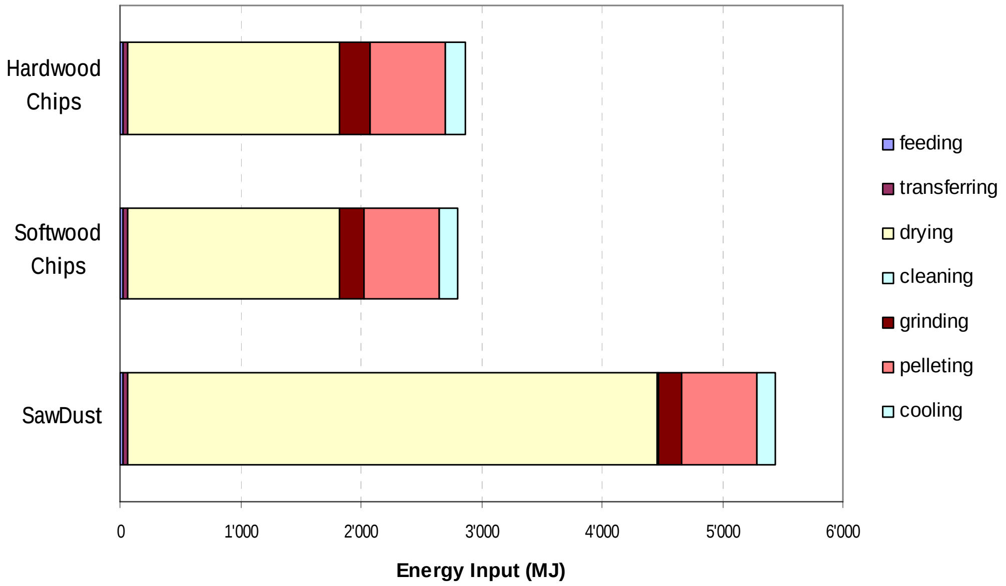

**Fig. 6** **Energy Input for pelleting process alternatives.**

The present analysis is based on band dryer technology. There are two other alternatives, the tube bundle dryer, and superheated steam dryer technologies (THEK and OBERNBERGER, 2004). Previous studies indicated, that the superheated steam drying technology has a high potential to improve energy efficiency. The main advantage of such a dryer is its high potential of heat recovery by extracting surplus steam from the system and by using it for another process as a heating source, such as hot water supply in district heating networks.  a maximum of about 80 to 90% of the heat input into the dryer may be recovered and reused.  However, investment costs of a superheated steam dryer are significantly higher compared to tube bundle dryers or to belt dryers.

## 4. Conclusions

The study aimed at investigating the effects of four raw material supply alternatives on the eco-efficiency of pellet supply systems. The study resulted in four major findings.  (1) Chip-based supply systems clearly outperform sawdust-based systems in terms of energy efficiency, carbon dioxide emission, eco-toxicity, and particle emissions (PM10). (2) The pellet manufacturing process causes about 60 to 80% of the total energy input, consisting of raw materials supply, pellet manufacturing, and pellet distribution. (3) Three out of seven process steps of the pelleting manufacturing process cause about 95% of the overall energy input, of which the drying process is the most important with a share of 60 to 80%. (4) Previous studies indicate that superheated steam dryer technology offers a high potential for the efficiency improvement of the pelleting process.

The results have implications for the pellet-fuel industry, for which chipped logwood is an interesting raw material alternative.  However, competitiveness of pellets compared to other energy carriers has to be improved. There are two promising paths of improvement, (1) the use of superheated steam dryer technology to make the drying process more efficient, and (2) to make use of the "the economies of scale" effect by building plants with an annual capacity of about 70'000 tons or more (THEK and OBERNBERGER, 2004).

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