



Faculty of Technology and Science
Environmental and Energy Systems

Magnus Ståhl

Improving Wood Fuel Pellets for Household Use

Perspectives on Quality, Efficiency and Environment

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Magnus Ståhl. *Improving Wood Fuel Pellets for Household Use - Perspectives on Quality, Efficiency and Environment*

DISSERTATION

Karlstad University Studies 2008:49

ISSN 1403-8099

ISBN 978-91-7063-209-9

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Distribution:

Faculty of Technology and Science
Environmental and Energy Systems
SE-651 88 Karlstad
SWEDEN
+46 54 700 10 00

www.kau.se

Printed at: Universitetstryckeriet, Karlstad 2008

Abstract

Ståhl, M. 2008. Improving Wood Fuel Pellets for Household Use – Perspectives on Quality, Efficiency and Environment. Doctoral Thesis. ISSN 1403-8099.

Globally, the awareness of the climate change problems has increased in recent years and presently governments aim at reducing the use of fossil fuels to mitigate the emissions of greenhouse gases. A decrease of the emissions could be achieved by using CO₂-neutral biofuels, such as wood fuel pellets. The primary raw material for wood fuel pellets is sawdust, which is dried and compressed to attain improved fuel and transportation properties. The use of wood fuel pellets for heating has increased dramatically during the last decade and it is expected to keep doing so henceforth. This will lead to the use of new raw materials, which will affect the quality of the product, the energy efficiency and the costs for the production system and the environment.

A new raw material mixture was investigated (Paper **IV**) as was the energy efficiency of the production system (Papers **II** and **IV**). Furthermore, the quality of the product was investigated (Papers **I**, **III**, **IV** and **V**) as were selected environmental aspects of the wood fuel pellet system (Papers **I** and **V**).

Almost all of the monoterpenes are emitted during the drying and pelletising steps, causing environmental and health related problems. Drying of sawdust can be used to control the moisture content and emissions of Volatile Organic Compounds (Paper **I**).

The amount of recovered energy over a condenser increases, as does rotary dryer efficiency, with increased recirculation within the test range, implying an energy efficient operation. It should be possible to use the model industrially (validation is being performed) to predict capacity and recovered energy changes when changes to the drying gas recirculation are made (Paper **II**).

Crumbled pellets or a high amount of fines and unsuitable equipment set-ups cause most of the problems for the household user. The present Swedish pellet standard is not adequate enough to provide a sufficient pellet quality to the end-user with the present variations in transport and storage/feeding systems. We suggest that some of the parameters in the standards should be expressed using intervals (Paper **III**).

In Paper **IV** we conclude that: (1) the energy consumption decreases with an increased amount of rapeseed cake in wood fuel pellets; (2) the mechanical durability could decrease with an increase in the amount of rapeseed cake in wood fuel pellets; (3) the bulk density of pellets seems to decrease with an increased amount of rapeseed cake in pellets; and (4) tests performed with a reconditioned die and a clean pellet machine seem to be preferable.

The survey of Paper **V** concludes that scientific research on the wood fuel pellet chain is fragmented. In addition, it concludes that the end-user perspectives and experiences should be investigated in order to identify the key areas that should be improved upstream the pellet chain. Furthermore, there are almost no system studies made that cover the entire wood fuel pellet chain. In the long run, more knowledge is needed about the physical and chemical processes that form pellets out of wood fibres. This knowledge could be used both to improve the present industrial processes and to develop new technological solutions.

Keywords: wood fuel pellets, sawdust, raw material, drying, pellet production, energy efficiency, recirculation, quality, system integration, environment.

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Preface

I received my Bachelor of Science degree in Environmental and Energy Sciences in 1998. After taking additional environmental courses and after a journey to Kenya/Tanzania for the purposes of study, I worked as a lecturer at the Department of Energy, Environmental and Building Technology at Karlstad University from 1999 to mid-2001.

I began my PhD studies in Environmental and Energy Systems at Karlstad University in mid 2001. I focused on the production of pellets in general, and on the drying of raw material and pellet quality in particular. The research within this area fascinates me as its applications and products represent further steps on the way to CO₂-mitigation by substituting fossil fuels, such as coal and oil.

At the Department of Energy, Environmental and Building Technology at Karlstad University, we have a long tradition of research in the area of wood products. Drying research, focusing mainly on sawdust drying, has been done here since 1989. Dissertations concerning drying has been carried out by Berghel, Improved Fluidized Bed Drying Technology for Wood Fuels (2004); Renström, Energy Efficient Wood Fuel Drying (2004); and Granström, Emissions of Volatile Organic Compounds from Wood (2005). In addition, Brunzell¹ presented her licentiate thesis Energy Efficient Textile Drying in 2005. In the wake of sawdust drying, I presented my licentiate thesis Wood Fuel Pellets: Sawdust Drying in the Energy System in 2005. Widening the scope, two licentiate theses were presented on the pulp and paper industry: Technical Alternatives and Energy in LCA, Rehnström (2004) and Studies to Avoid Decreased Efficiency in Multiple Stage Biological Wastewater Treatment Plants – Concerning Forest Industry Effluents, Sandberg (2008).

The research group focusing on bio-energy issues, while having its main focus set on Heat and Drying Systems (HDS), have had considerable and positive influence on my work. The HDS group study heat and mass transfer in the drying of biofuels and clothes. It was a very stimulating experience to take part in forming this group.

¹ Previous surname of Lena Stawreberg.

At Karlstad University, there is a Forum for Energy and Sustainable Development aiming at integrating energy and sustainable development issues into different research areas in cooperation with the industry. The essential questions at issue concern energy supply and energy use. Within Karlstad University, the energy supply research concerns renewable energy fuels, industrial by-products and solar energy (for electricity, heat and fuel production), while the energy use research concerns energy efficiency, thermodynamics and optimisation methods. My work covers renewable energy fuels (wood fuel pellets), industrial by-products (sawdust and rapeseed cake) and energy efficiency as regards the drying and pelletising of sawdust. In addition, my work concerns environmental and quality issues of wood fuel pellet production and use.

In all scientific work, it is important to make contact with other researchers within your own field of research. Therefore, since mid 2005, I am member of the steering group that manages both the active Swedish Pellet Researchers Network (NäPfo – *Nätverket för Pelletsforskare*), as well as the European Pellet Researchers Network (EuPRN). NäPfo and EuPRN have about 50 and 65 active researcher members, respectively. During 2006, I was the editor of the newsletter concerning Swedish pellet research, and, since mid 2006, I am the editor of the newsletter concerning European pellet research. The newsletters of these networks reach more than 500 people (200 researchers) interested in pellet research. In May 2006 and May 2008, I hosted the network meetings within the EuPRN on the World Bioenergy Conference in Jönköping, Sweden.

In my work, within my field of research, I hope to contribute to the development regarding the implementation of energy efficient use of renewable national energy resources as well as to a climate improvement.

List of Publications

This thesis is based on the following papers, referred to in the text by their Roman numerals:

- I. Ståhl, M., Granström, K., Berghel, J. & Renström, R. (2004). Industrial Processes for Biomass Drying and their Effects on the Quality Properties of Wood Pellets. *Biomass and Bioenergy*, Vol. 27, pp. 621-628.
- II. Ståhl, M. & Berghel, J. (2008). Validation of a Mathematical Model by Studying the Effects of Recirculation of Drying Gases. *Drying Technology*, Vol. 26, No. 6, pp. 786-792.
- III. Ståhl, M. & Wikström, F. Swedish Perspective on Wood Fuel Pellets for Household Heating – A Modified Standard for Pellets Could Reduce End–User Problems. *Accepted pending revision for publication in Biomass and Bioenergy. Revised version submitted 27 October 2008.*
- IV. Ståhl, M. & Berghel, J. Energy Efficient Pilot-Scale Production of Wood Fuel Pellets made from a Raw Material Mix Including Sawdust and Rapeseed Cake. *Submitted May 2008 to Biomass and Bioenergy.*
- V. Ståhl, M. & Wikström, F. Wood Fuel Pellet Technology Research: Quality and Environmental Aspects. *Manuscript.*

Results relating to this thesis have been reported at the following conferences:

Ståhl, M., Granström, K., Berghel, J. & Renström, R. Industrial Processes for Biomass Drying and their Effects on the Quality Properties of Wood Pellets. Proceedings of the first World Conference on Pellets, Stockholm, Sweden, 2-4 September 2002, pp 87-91

Berghel, J. & Ståhl, M. The Possibility to Control the Pellet Production Chain from Wet Raw Material to Pellet in Laboratory Scale. Poster presentation at the European Pellets Conference, World Sustainable Energy Days, Wels, Austria 2-3 March 2005.

Berghel, J. & Ståhl, M. The Possibility to Control the Pellet Production Chain from Wet Raw Material to Pellet in Laboratory Scale. Poster presentation at the SVEBIO annual meeting and conference, Stockholm, Sweden, 24-25 May 2005.

Ståhl, M. Theoretical Effects of Recirculation of Drying Gases in a Co-current Rotary Dryer. Proceedings of the 3rd Nordic Drying Conference, Karlstad, Sweden, 15-17 June 2005.

Ståhl, M. Wood Fuel Pellets: Sawdust Drying in the Energy System. Licentiate Thesis. Karlstad University Press 2005:47. ISBN 91-7063-018-6.

Ståhl, M. Wood Fuel Pellets: Sawdust Drying in the Energy System. Oral presentation at Pellets 06, Helsingborg, Sweden, 7-8 February 2006.

Ståhl, M. Drying Parameter Variations and Wood Fuel Pellets Quality—Pilot Study with a new Pelletising Equipment Set-up. Poster. Proceedings of Pellets 2006, the 2nd World Conference on Pellets, Jönköping, Sweden, 30 May-1 June 2006, pp. 171-172.

Ståhl, M. & Berghel, J. Validation of a Developed Mathematical Model Studying the Effects of Recirculation of Drying Gases. Poster. Proceedings of the 15th International Drying Symposium, Budapest, Hungary, 20-23 August 2006.

Ståhl, M. Energieffektiv pelletspressning med rapsrester. (“*Energy Efficient Pelletising Using Rapeseed Cake*”). Oral presentation at Pellets 08, Sundsvall, Sweden, 29-30 January 2008.

The Author's Contributions

- Paper I Equal parts of planning with me serving as project leader. I performed the experiments relating to moisture content and Karin Granström performed the experiments relating to VOC emissions. The paper was co-written by the authors.
- Paper II Equal parts of planning with me serving as project leader. Both authors performed the modelling. The paper was co-written by the authors.
- Paper III Equal parts of planning with me serving as project leader. The paper was co-written by the authors.
- Paper IV Equal parts of planning with me serving as project leader. Both authors performed the experimental tests. All writings performed by me.
- Paper V Equal parts of planning with me serving as project leader. The paper was co-written by the authors.

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Introduction

Background

The global awareness of the climate change problems has increased in recent years and presently governments aim at reducing the use of fossil fuels to mitigate the emissions of greenhouse gases. Hillring (1997 and 1999) calls for an international harmonisation of the energy policies, including the level of taxes, both within the European countries and worldwide. Global initiatives are taken within the United Nations Climate Change Conferences towards improved climate regulations. The greenhouse gas CO₂ affects the climate (an increased concentration of greenhouse gases is the primary source of global warming), and a decrease in the emissions could be achieved by, e.g., implementing carbon trading, legislation, taxes on carbon dioxide and/or using CO₂-neutral renewable energy sources, such as biofuels. During the 1990s and the first decade of the 21st century the main argument for renewable energy sources is our concern for the environment.

The oil crisis in 1973-74 made clear that the Western European countries were dependent on energy imports, mainly oil. They are no longer considered self-sufficient in terms of energy. The interest shown in alternative energy sources has therefore increased. For the European Union, the White Paper concerning biomass (European Commission, 1997) aimed at doubling the share of renewable energies with respect to the total energy demand, going from 6% to 12% by 2010². In addition, the European Union published their Green Paper “A European Strategy for a Sustainable, Competitive and Secure Energy Supply” in 2006, in which they stated that all 25 member states have to cooperate to achieve a secure energy supply. Furthermore, it aims at decreasing the energy use and attaining energy efficient processes.

Since the beginning of the early 1980s, with the Swedish governmental energy policy of the 1990s accelerating the process (favouring renewable energy sources in order to phase out fossil fuels), the use of biofuels have increased significantly. The increase is also partly due to the high price of fuel oil and the

² The EurObservER shows, in the “Wood Energy Barometer”, that the present trend in bioenergy use will not reach this goal.
(http://europa.eu.int/comm/energy/res/sectors/bioenergy_publications_en.htm).

tax reduction on the installation of biofuel heating systems (Miljörot 2004; SFS 2003:1204). The policy instruments used were: legislation for emission control; investment support for combined heat and power plants; and energy taxation including the introduction of a CO₂ tax on fossil fuels³ (Hillring, 1999). There are also taxes on SO_x and NO_x emissions in Sweden. The growth of the Swedish biofuel market, however, is due to several successful strategies. According to Hillring (2002), examples of successful strategies were to increase the information content of products and services and to make size rationalisation, i.e., small biofuel production units have become large biofuel production plants.

The reduction of the use of fossil fuels will in all probability imply that the amount of energy coming from biomass will increase. An increase in the use of biofuels is possible, several studies have tried to estimate the possible contribution of biofuels to the global energy supply. However, large uncertainties are involved, such as price development of raw materials, new legislation and policies concerning renewable energy sources, etc. According to Parikka (2004) about 40 EJ yr⁻¹ comes from woody biomass. However, Berndes et al. (2003) reviewed 17 studies concerning biomass and concluded that in 2050 up to about 115 EJ yr⁻¹ could come from forest wood biofuels. Today, the world's primary energy supplies amount to approximately 480 EJ yr⁻¹ (IEA, 2007).

In Sweden, the share of primary energy supplies that originates from bioenergy has increased from 10% in the 1980s to 19% (124 TWh) of the total energy use (625 TWh [114 000 TWh globally]) in 2006 (Swedish Energy Agency, 2007). The Swedish Bioenergy Association has stated that the bioenergy use in Sweden could expand by an additional 50 TWh by 2020 (Svebio, 2008). Wood fuel pellets is a biofuel that has increased rapidly in production and use. The wood fuel pellet is a processed renewable energy fuel and transport product that is defined by national and international standards and described in several information sheets (SS 187120, 1998; CEN/TS 14961, 2005; Svebio, 2004). Wood fuel pellets are compressed biofuels, cylindrical in shape and with a length of 4 or 5 times the diameter (usually 6–12 mm⁴) used for heating, both in

³ For the industry, the total tax is 61 and 89 SEK/MWh for oil (Eo 1) and coal respectively (Swedish Energy Agency, 2008).

⁴ The 8 mm pellet is the most common on the Swedish market probably since large-scale consumers used to dominate the Swedish pellet market. In Austria, the 6 mm pellets dominate the market, probably since small-scale users predominate on the Austrian pellet market. The 6 mm pellet is

small-scale combustion units and in large-scale heating plants. In 2007, the main users in the world were Sweden, the Netherlands, the United States of America and Denmark, whereas Sweden, Germany, Canada and the United States of America were the main producers, in this specific order. In 2006, the amount of produced fuel pellets worldwide equalled 6 733 000 tons (Vinterbäck, 2008). In 2007, there were 442 pellet plants in the world with a potential production capacity of 14 million tons of fuel pellets a year (Ljungblom, 2007). If the market continues to increase, a continued development on a large and small scale is implied, encompassing wood and agricultural fuel pellets and pellets derived from new pellet countries in Africa, South America and South East Asia. An increased internationalisation of the biofuel market will also result in increased competition and force down the prices among local producers (Hillring, 2002). According to Vinterbäck (2008), it is predicted that the global annual production will amount to 15 000 000 tons a year in 2010.

In Sweden, the total share of primary energy that originated from wood fuel pellets was more than 1% or 8 TWh⁵ in 2007. Altogether, in 2007, 1 715 000 tons were delivered to the Swedish pellet market. This includes the domestic production of wood fuel pellets of 1 411 020 tons and the importation of 358 435 tons of pellets (PiR, 2008)⁶. The wood fuel pellets import has doubled in the last 5 years. Recently, the imported pellets came from the Baltic region (Ericsson & Nilsson, 2004), but with large pellet plants being established in the USA and Canada more pellets will probably be imported from there. The international biofuel market, however, is still at an early and dynamic stage of development (Ericsson & Nilsson, 2004). The Swedish Association of Pellet Producers (PiR) predicts that in 2008 more than 2 000 000 tons of pellets will be used in Sweden. The total amount of pellets delivered to the Swedish market has a sales value of more than 2 billion Swedish crowns (about 230 million euros). Between 2006 and 2007, the total amount of pellets delivered to the Swedish market increased by 2%, and it has increased by 90% over the past five years (PiR, 2008). In Sweden, about half of the quantity of pellets was used in large-scale heating plants and about 37% (635 000 tons) was used for single

easier to use in fully automatic heating systems in small units used in family houses, due to better flow qualities.

⁵ Wood fuel pellets has a heating value of approximately 4,7 kWh/kg.

⁶ In addition, 54 455 tons of pellets were exported in 2007.

house heating purposes⁷ (Figure 1). The latter are more sensitive to changes in pellet quality and require pellets that do not only fulfil the standard but also meet the requirements of the user's heating system.

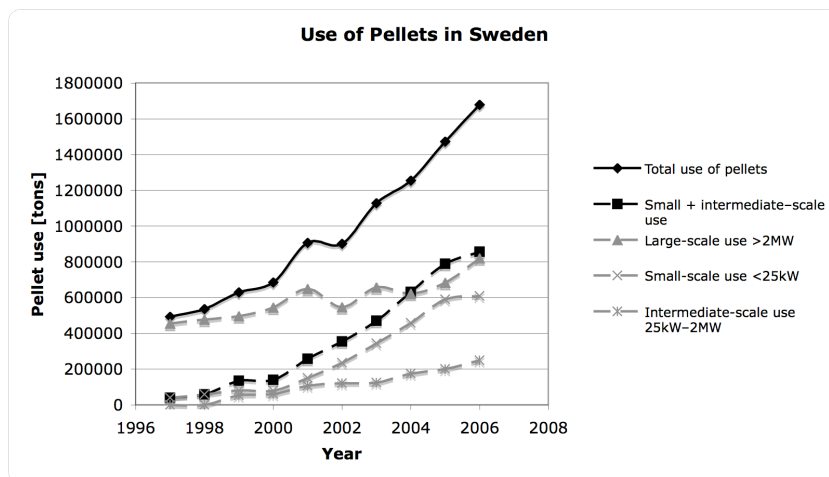


Figure 1. The use of wood fuel pellets in Sweden from 1997–2006 divided into user groups (Adapted from PiR, 2008).

The pellets are produced in both large-scale and small-scale production plants. The first pellet plant in Sweden (using woody biomass) was established in Mora and the production began in 1982. In 1986, however, it was closed down due to an undeveloped combustion technology (Vinterbäck, 2000). In the mid-1980s, other pellet plants were built, like the ones in Vårgårda and Kil. At the same time, SBE (Svensk BrikettEnergi AB) began producing briquettes. In Sweden, there are currently 46 pellet plants that produce more than 5 000 tons a year and 51 pellet plants that produce less than 5 000 tons a year (Höglund, 2008). The largest plant, SCA BioNorr AB in Härnösand, has a capacity of 160 000 tons a year. In comparison, the world's largest pellet plant in Florida, USA, is planned to produce 560 000 tons of wood fuel a year, the raw material coming mostly from round timber (Ljungblom, 2007).

⁷ In Sweden, there are 2 007 097 single-family houses with an average useful floor space of 122 m² (SCB, 2005). The typical Swedish family comprises 4 individuals that on average use 140 kWh/m² for heating and hot water consumption (SCB, 2005). They use electricity, oil, district heating, heat pumps, firewood and pellets as sources of heat. In 2005, about 6% used oil (1998, 15%), 31% used electricity, 8% used district heating, 7% used heat pumps and 11% used biofuels (1998, 4%) (SCB, 2005).

Focus and scope

In this work, the focus has been on wood fuel pellets. For a researcher active in Sweden, this involves studying pellets made from sawdust from Norway spruce (*Picea abies*) and/or Scots pine (*Pinus sylvestris*), since these raw materials predominate in the domestic fuel pellet production. Other woody raw materials or alternative raw materials are included when necessary.

The wood fuel pellets system has a number of vital system components and interacting subsystems (see Figure 2). My papers deal with: **(I)** the moisture content of raw material and pellets and the emissions during drying and pelletising; **(II)** the energy recovery and usefulness of the waste energy from a dryer; **(III)** the cause of common end-user problems and possible solutions; **(IV)** the mixture of raw materials and how it affects the energy use of the dryer and the mechanical durability of the fuel pellets; and **(V)** the state of knowledge about the links in the wood fuel pellet chain.

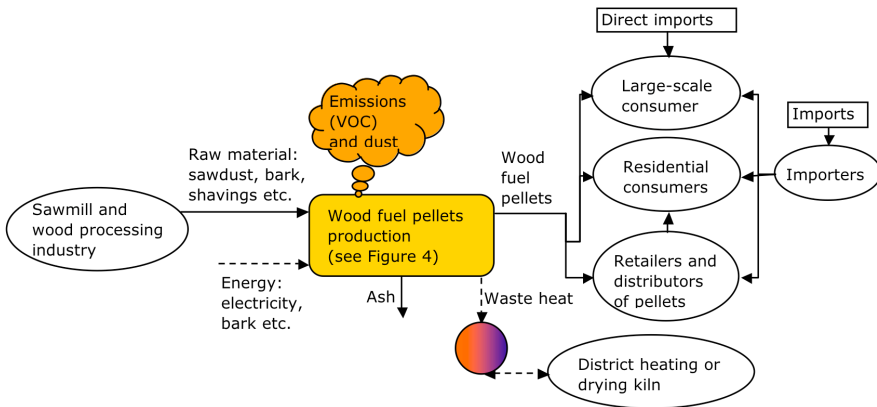


Figure 2. The wood fuel pellets system and surrounding interacting subsystems (modified from Vinterbäck 2000).

The energy efficiency studies are concentrated on the drying and pelletising processes, even though integrated systems (such as district-heating) are considered. Economic analyses of the systems are outside the scope of this thesis, although some factors of importance to the production costs are discussed.

In this study, I have examined the concept of fuel pellet quality from a consumer/household perspective. Households are, with respect to quality, the most demanding users of pellets. I have worked with two quality definitions.

The first definition concerns the quantitative quality parameters used in the Swedish standard for pellets (SS 187120, 1998) and the second definition concerns the consumers' needs and expectations of the pellets and surrounding services'.

Objectives

The purpose of this thesis is to contribute to knowledge that can be used to improve existing wood fuel pellets for household use as well as improve the pellet production technology.

For the residential consumer knowledge about wood fuel pellet quality is particularly important. For the pellet producer knowledge about the energy efficiency is important, e.g., in relation to production costs and the efforts to reduce energy losses. For the society knowledge about the environmental effects is important in relation to health issues, as well as natural and working environment issues.

Quality

One of the aims of Paper **I** was to investigate how the quality parameter of *moisture content* is related to the emissions of monoterpenes in wood fuel pellet production.

The aim of Paper **III** was to analyse the causes of the problems encountered by household end-users and investigate whether an improved pellet quality standard could reduce these problems.

One of the aims of Paper **IV** was to analyse chosen quality parameters for pellets (such as *durability*, *length* and *bulk density*) made from sawdust mixed with rapeseed cake, all in accordance with the Swedish standard (SS 187120, 1998) for pellets.

In the survey made for Paper **V**, one aim was to identify gaps of knowledge with regard to wood fuel pellet technology. This is used to establish the needs for further research on quality aspects throughout the wood fuel pellet chain.

Efficiency

The efficiency aim of Paper **II** was to investigate how the recirculation of drying gases affects the energy efficiency of rotary dryers and how the energy

efficiency is related to the capacity of the dryer. Another aim was to develop a mathematical model that could be implemented in the pellet industry.

The efficiency aim of Paper **IV** was to investigate how the energy consumption of the pelletising machine changes when increased amounts of rapeseed cake is mixed with sawdust in producing pellets.

Environment

The environmental aim of Paper **I** was to quantify the emissions of monoterpenes to the environment for the drying and pelletising processes, independently as well as combined. Furthermore, the aim was to contribute to a discussion about whether it is preferable that the monoterpenes should be emitted during production or left within the pellets.

In the survey made for Paper **V**, one aim was to identify gaps of knowledge with regard to environmental and health aspects. This is used to establish the needs for further research on environmental and health issues throughout the wood fuel pellet chain.

Wood Fuel Pellet Production Technology

The technology used for the production of pellets has its origin in the animal feed-stock industry. However, wood fuel pellet production makes harder demands on the equipment and is more energy demanding. The production of wood fuel pellets most often takes place in stand-alone pellet plants, but also at the producers of suitable raw materials, like sawmills. System integration is also possible (i.e., when a dryer is integrated with a lumber kiln or with a bioenergy combine system). The processing of the chosen raw material (from wet sawdust to pellets⁸, see Figure 3) is performed to achieve advantages as compared with the unprocessed materials, such as wet sawdust. The pellets have higher density and lower moisture content. They also have a higher effective heating value, they are more convenient (and more economic) to transport, they have improved storage characteristics, and they are homogeneous in shape.



Figure 3. Stacks of wet sawdust (to the left), dry sawdust (in the middle) and wood fuel pellets (to the right).

The production of pellets embraces pre-treatment, the actual compression of wood, after-treatment, and combustion. During the production of wood fuel pellets, the following steps are included (see Figure 4):

- Storage of a buffer stock of the raw material (delivered or produced on site).
- Screening of raw material, reducing gravel contents, and metal detector treatment. If other coarse raw materials than sawdust are used, decomposition

⁸ It is not only pellets that can be produced from sawdust for industrial heating purposes, but also briquettes and wood powder.

is needed.

- Drying of the raw material (when needed).
- Grinding of dry raw material.
- Storage of a buffer stock of dry raw material.
- Pelletising, i.e., shaping and compression of dry raw material into fuel pellets.
- Cooling of wood fuel pellets.
- Screening of wood fuel pellets (fine fractions are returned to the process).
- Storage of pellets in stacks, in small or large bags, or loading on a bulk transportation vehicle.

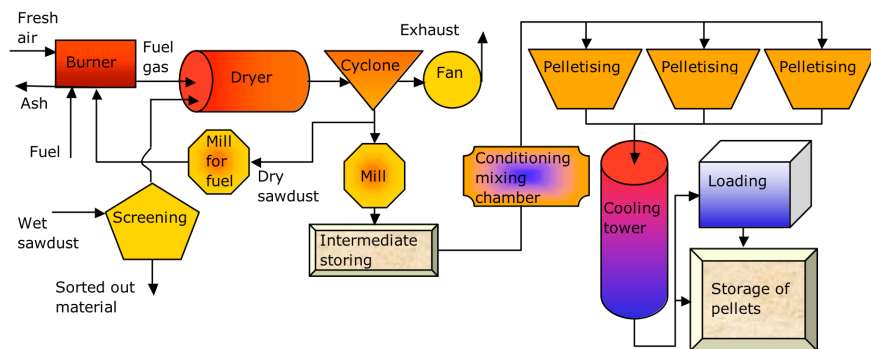


Figure 4. Schematic sketch of the production of wood fuel pellets, the main components and the material flow through the production chain.

The Raw Material

In Sweden, the typical raw material for pellets is sawdust from Norway spruce (*Picea abies*) and/or Scots pine (*Pinus sylvestris*). Other raw materials, such as hardwood, bark, light thinning material, cull tree, logging residues, energy forest fuel (like *Salix*), peat or straw could be utilised or mixed with softwood. The raw material cost is one of the main cost factors for pellet producers (Thek & Obernberger, 2004; Zakrisson, 2002; Näslund, 2003), and choosing the right raw material is therefore an important issue for the producers. In addition, the handling and storage of the raw material is important for the quality of the pellets. Granö (2007) lists the following factors as necessary to obtain high end product quality: good sanitary quality (keep the raw material free from dirt, dust and mould); removal of nutritious parts at harvest (cleaner flue gases); avoiding wet raw material (low and homogenous moisture content ensures higher durability of pellets); and a low amount of bark (ensures a lower ash content). A good pellet energy quality implies a high usable energy content (Granö, 2007).

Avoidance of contamination by, e.g., sand particles (SiO_2 , Al) minimises the risk of slagging in the burners (Öhman et al., 2002).

At the Swedish sawmills, the total volume of by-products used as wood fuel is approximately 50% of the production of sawn wood (Staland et al., 2000). On the average, 10% of the incoming wood at a sawmill is turned into sawdust and 4% into shavings (the rest being slabs and bark). This means that, even if they are small, the sawmills produce large quantities of by-products suitable for processing into pellets. In 2000, the amount of sawdust produced at the Swedish sawmills were 3.6 million m^3 (solid) (Staland et al., 2000), which equals about 0.7 million tons of pellets⁹. All of the sawdust is not turned into fuel. In 2000, 72% was used as fuel (for combustion) and 26% was used mainly by the particleboard industry.

The increased use of wood fuel pellets during the last decade has resulted in a shortage of the preferred materials for production of wood fuel pellets in Sweden, i.e., dry cutter shavings and dry and wet sawdust. If the present trend in the sawmill industry lasts and the processing continues to increase, it will pose a problem as only a small increase in the supply of present raw material is available.

In Sweden, the biofuel energy price for the district heating plants (excluding taxes) is tabulated by the Swedish Energy Agency (2008). In 2007, the price was 244 SEK/MWh for pellets, 158 SEK/MWh for wood chips and 134 SEK/MWh for by-products, such as sawdust. The price for wood chips has been at a constant level of slightly over 100 SEK/MWh for more than 10 years. This is due to the following factors: (1) the governments energy policy, i.e., the energy taxation system; (2) good know-how regarding the handling of the raw material; (3) most of the raw materials are by-products; and (4) there is a stable supply of raw material. However, the price for wood chips increased in 2007 (see above). This could be due to increased international price settings or to the wood chips being more exposed to competition than earlier.

Alternative Raw Materials

If we are looking at a more extensive increase in the use of pellets, other raw materials or mixes of raw materials have to be used (or the import of pellets has

⁹ With a bulk density of 350kg/m^3 for fresh (wet) sawdust and the drying of sawdust going from a moisture content of 50% to one of 10% (wb).

to increase). Consequently, research that investigates the pellet characteristics of these new raw materials and mixes of raw materials is necessary (see Paper **IV**), since these new materials could have characteristics that differ from the characteristics of pellets made from pure stemwood.

As an example, cull tree and short-term thinning material may come into use. The characteristics of pellets made from these materials would be similar to those of the present pellets, although the ash content is twice that of stem wood pellets (Martinsson & Österberg, 2004). Such pellets should be used for small-scale combustion as they fulfil the demands of residential users for fuel pellets with high and even quality. Large-scale combustion plants could use bark (Bradfield & Levi (1984) report that pellets can be produced with various amounts of bark), peat (Öhman et al., 2006A), energy forest fuels and logging residues, since these plants can handle raw materials with high ash and nitrogen contents. *Salix* and logging residues produce pellets with ash and nitrogen contents that are 10 and 6-9 times that of stem wood pellets, respectively (Martinsson & Österberg, 2004). In the future, energy crops and lignin could also come into use, particularly if the ethanol production increases during the coming years, lignin being one of its by-products (Martinsson, 2003).

In addition to using wood products as raw material there is a wide range of agricultural products that could be used for pellet production, alone or by mixing them with sawdust. Martinsson (2003) estimates that both energy crops and lignin could come into use for pellet production in the future. Bhattacharya (1993) points out that large amounts of agricultural (and forestry) residue are annually generated in developing countries. Larsson (2003) on the other hand has modelled the potential for energy crop (reed canary grass) utilisation in northern Sweden. For the whole of Sweden, however, an expert opinion from The Swedish Bioenergy Association (Svebio) states in the Swedish Government Official Report (SOU 2007:36) that Swedish agriculture has a considerable bioenergy potential. Since the European Union will raise a demand for a renewable energy supply, Svebio believe there will be an increased supply of bioenergy coming from the agricultural sector. The SOU (2007:36) estimates (from an “economically feasible biofuels production” point of view) that about 34 TWh will come from agriculture in 2020. However, Svebio estimates that it will be about 60 TWh at best, which is equal to 15% of the total energy use in Sweden at present. The Swedish commission against dependence on oil predicts that as much as 228 TWh could come from bioenergy, i.e., if all kinds of bioenergy sources are included (SOU 2007:36). Berg et al. (2007) made a

compilation and a synthesis of knowledge about energy crops going from cultivation to energy conversion. They state that a functional chain is necessary to fully use the potential of energy crops (straw, grain, Salix, reed canary grass and hemp) as a fuel and the cultivation and harvesting has to be coordinated with transportation, storage and combustion of the crops. This is important in an economic perspective and when to market the new products.

Several authors have studied the use of alternative/crop raw materials for pellet production. As an example, reed canary grass has been studied in Sweden. Paulrud and Nilsson (2001) report that differences in ash content do not affect the briquetting of reed canary grass and they state that fuel containing only stem fraction show the highest durability. Örberg et al. (2006) investigated the pelletising and combustion of reed canary grass in order to make it more movable through the die. Fasina (2008) studied the physical properties at the production of peanut hull pellets.

There have also been studies made in which lignin was used as the raw material for pellet production. Öhman et al. (2006B) report that pelletised hydrolysis residue from lignocellulosic ethanol production could be interesting to use as a fuel for residential purposes. These pellets showed lower slagging tendencies, had a higher heating value (also discussed by White, 1987) and a lower ash content compared with stemwood pellets. In addition, low particle emissions were attained.

Heschel et al. (1999) show that the ignition behaviour and the combustion rate improve and that good self de-ashing is obtained when blended pellets (made from lignite and wood, as well as from Xylite) are used instead of conventional lignite briquettes.

Storage of Raw Materials

Storing is necessary since there is a difference in the supply and demand of the raw material. Seeing that there are divergences between the production and consumption of pellets, the storage capacity has to be at least 45% of the yearly production capacity (Nyström, 1995). Storage at the manufacturer's often means indoor or outdoor stack solutions. The storing treatment of both raw material and wood pellets is important. Jirjis (1995) suggests that the raw material should be stored uncomminuted to maintain the quality of the fuel. During the storage of woody biomass there are activities within the stacks, e.g.,

dry matter losses due to rotting (Jirjis, 1995), moisture content changes (Jirjis, 1995; Nurmi, 1999) and heat development. The latter could initially be due to microbiological activities and it could even evolve into self-ignition (Jirjis, 1995). The dry matter losses should be minimised in order to maintain the energy content. Furthermore, incorrect storage could involve health risks due to dust and mould exposure. Stored raw materials also provide higher quality pellets compared with pellets made from fresh wood (Lehtikangas, 2000). Dyrke et al. (1999) report on similar issues and other problems, but also on solutions concerning storage of wood fuels.

Pre-treatment

The pre-treatment is performed to improve the material properties before densification since the current densification machines only can process raw materials within a certain range of particle size and moisture content (Bhattacharya, 1989). The pre-treatment includes screening for the removal of unwanted materials (gravel, metals), decomposition of coarse material, drying to reach optimum moisture content, grinding to get the wanted size distribution (finer grinding increases the durability of the pellet [Näslund, 2003]) and, finally, conditioning by hot steam to soften and heat the dry raw material (Näslund, 2003; Bhattacharya, 1989; Alakangas & Paju, 2001; Resch, 1989). The densification technology will be further discussed in the section on pelletising of sawdust below.

Drying of Sawdust

If the raw material is wet, drying must be performed. The wet raw material used for pellet production typically contains about 50–55% water (wb). For the production of pellets, the Swedish manufacturers normally dry the raw material to reach a water content of 6–12% (wb) before pelletising (Olsson, 2002; Bhattacharya et al., 1989).

In a pellet manufacturing process, the total energy demand for drying is about 10–12% of the heating value of wood fuel pellets. Drying is also one of the main cost factors for pellet production. A correct design and an optimisation of the energy use in the drying process itself are therefore important, for both producer and environment, as is the use of heat recovery (Wimmerstedt, 1995; Wimmerstedt, 1999; Obernberger & Thek, 2004).

Drying is important as wet wood, when it is burned, not only has lower energy content but also low combustion temperatures and high emissions of hydrocarbons and particles as compared to dry biofuels, such as pellets (Strumillo et al., 1995; Wimmerstedt, 1999). If biofuels are dried, and subsequently compressed into pellets, the fuels will have a controlled moisture content and a higher energy density, and they will be easier and cheaper to transport.

Industrial Drying

Dryers can be classified according to the medium used in the drying process (air, flue gases or steam). In Sweden, flue gas dryers and superheated steam dryers (mostly pressurised and, e.g., used in bioenergy combines) are used for commercial drying of sawdust. However, the most common technology used by pellet manufacturers in Sweden for the drying of sawdust is a rotary drum dryer with a co-current or counter-current flow of drying gases. The dryers investigated in this thesis work as convection dryers in which a gas both supplies the necessary energy and transports the emitted steam away. Rotary dryers represent the most commonly used technique because of their flexibility to handle small and large capacities, their reversibility (both the material and medium could be recirculated) and their ability to handle a wide assortment of feeds (Berghel, 2004; Renström, 2004; Ståhl & Berghel, 2008 (Paper II); Bhattacharya, 1989). Flue gases from a burner, burning for instance bark or oil, are used as a heating medium, and recirculation of the emitted drying gases can be utilised. Furthermore, if a condenser is utilised, there is a potential for energy recovery from the gases leaving the dryer. In Paper II, for example, it is shown that the increased recirculation of drying gases implies a more energy efficient operation of the rotary dryers.

According to Mujumdar (1995) and Odilio & Mujumdar (2005), the superheated steam dryers have some key advantages over air dryers. No oxidation or combustion reactions are possible. Steam dryers have higher drying rates than do air and gas dryers. Steam drying also avoids the dangers of fire or explosions and allows toxic or valuable liquids to be separated in condensers. However, the systems (when pressurised) are more complex and even a small steam leakage is devastating to the energy efficiency of the steam dryer (Berghel & Renström, 2000). The flue gas rotary dryers have advantages as they are relatively cheap and easy to install and run. They can also dry a variety of materials of different sizes. However, the flue gas rotary dryers

combine high inlet temperatures with long residence times. According to Wimmerstedt et al. (1984), this may result in pyrolysis and partial gasification, i.e., energy losses.

Drying Theory

Wood is a hygroscopic material, which means that it can absorb and emit steam so that equilibrium is reached with the surrounding medium (NE, 2008-06-12). Wood strives to reach moisture equilibrium with its surroundings and during drying it may pass through several different stages of drying before the chosen moisture content of the dried material is reached. According to Mujumdar & Menon (1995), there are three stages: the first drying stage, during which the drying rate is constant, is such that the surface of the material is wet and the inside contains free water. The critical moisture content¹⁰ is reached when dry spots appear on the sawdust surface. Here, the second drying stage begins. This ends when all surface water is evaporated. Further drying, the third stage, could be performed until the sawdust is completely dry. When it comes to wood fuel pellet production, however, the raw material is dried until a moisture content of 6–12% (wb) is reached. Drying of sawdust implies a removal of free water (in the hollows of the sawdust) and bound water (in the cell walls). The drying rate is highest as long as the sawdust has wet spots on the surface (the second stage), subsequently it decreases (the third stage). In a flue gas dryer, the material that is to be dried is heated to the wet bulb temperature¹¹ until the moisture content reaches the critical moisture content. Further drying, i.e., drying below the critical moisture content, implies that the material temperature will approach the gas temperature.

According to Kelly (1995), several processes occur simultaneously during drying: (1) the pneumatic transport of the drying medium through the dryer; (2) the transport of the sawdust through the dryer; (3) the heat transfer from the

¹⁰ The point at which the constant-rate stage ends and the falling-rate stage begins is termed the critical moisture content.
(http://www.wenger.com/English/Systems/Drying/TrueTemp/em_dry_tt3.asp)

¹¹ Wet-bulb temperature is measured using a standard mercury-in-glass thermometer, with the thermometer bulb wrapped in muslin that is kept wet. The evaporation of water from the thermometer has a cooling effect, so the temperature indicated by the wet bulb thermometer is less than the temperature indicated by a dry-bulb (normal, unmodified) thermometer. The rate of evaporation from the wet-bulb thermometer depends on the humidity of the air. Evaporation is slower when the air is already saturated with water vapour. For this reason, the difference in temperatures indicated by the two thermometers gives a measure of atmospheric humidity
(<http://www.bom.gov.au/climate/glossary/wetbulb.shtml>).

drying gases to the surface of the sawdust (the temperature difference being the driving force); (4) the heat transfer from the surface to the inner parts of the sawdust (due to heat conductivity); (5) the mass transfer of moisture from within the material to the surface of the sawdust (the pressure difference being a driving force); and (6) the transport of moisture from the surface of the sawdust to the drying medium (the pressure difference being the driving force).

Since Paper **II** treats the capacity change due to increased recirculation of the drying medium, this section will focus on the mass transfer processes. If recirculation of the emitted drying medium is applied, the driving forces will be affected. Due to changes in the difference in partial pressure, the driving forces change for the mass transfer process. A decrease in the difference in partial pressure between the drying medium and the sawdust means that the capacity to remove water from the sawdust decreases. Further studies are needed to establish to what extent the capacity is decreased (see further work).

Grinding of Sawdust

The dried material is brought to the grinding process by feed control. Grinding of sawdust is often necessary, as a finer and homogeneous material is needed to produce pellets with high durability (Li & Liu, 2000). The most common grinding equipment is the hammer mill, but roller mills are also used. Grinding is performed either with already dried raw material or with the drying simultaneously performed within the mill. In the latter case, hot gases are supplied to the mill. The grinded material is transported through a cyclone where the air/hot gas is separated from the sawdust.

Pelletising of Sawdust

After the grinding, the dried and uniformed raw material is transported to the pelletising machine, usually by means of a screw feeder¹². The feeder is adjustable in speed so that an appropriate and even raw material flow is achieved. The flow rate affects the press capacity. Raw material in lumps affects pellet durability negatively. Before the material enters the dies, it is conditioned with superheated steam in a mixing chamber to heat and soften the material. This could lead to an increase in the pellet moisture content (in comparison to

¹² Vacuum feeder systems are also available.

the dried raw material moisture content). The conditioning has a positive effect on pellet durability and reduces the wear of the die, as there is less friction (Resch, 1989; Näslund, 2003).

The densification, i.e., compressing of the dry raw material into pellets is done to obtain a homogeneous fuel with improved uniformity, moisture content, transportation and storage properties, etc. The most common technology for densification of wood fuels uses high pressures and temperatures (no additives) in ring dies, either fixed or rotating, with two internal rolls (Näslund, 2003; Alakangas & Paju, 2001). The Danish Sprout-Matador pellet press, which is the most common machine used by Swedish pellet manufacturers, uses this technique (Näslund, 2003). The pellet presses come in the capacity range of 150 kg/h to several tons/h. The dried and grinded raw material is fed to the die, and the rolls, which work under high pressure, compress the material through the die holes. Knives then cut off the compressed material.

In addition to the most common technology, presses with 1 or 3 rolls, instead of two, could be used. Furthermore, flat dies, with 2–6 rolls on top of it, could be used. There are also smaller machines using briquette technology, such as hydraulic or eccentric piston presses (MiniPell and Träpressen [Näslund, 2003]). Moreover, there are machines operating with lower pressures and temperatures. Näslund (2003) has tested a press operating with low temperatures. However, the results were not fully satisfactory (Kemyx [Näslund, 2003]). In Norway, there is a manufacturer using steam explosion¹³ in the production of pellets. The raw material is exposed to high pressure and high temperature steam in order to disrupt all the fibres and set free the lignin. The pellets produced have high bulk density and strength combined with high resistance towards moisture absorption.

The die in the press can be stationary or rotating. The conflicting goals of obtaining a high output of pellets and an even wear of the die have to be balanced, since changing a die is costly. The design of the die holes is important. The type of raw material and the proportions between diameter and length decide the pressure within the holes; the longer the holes, the higher the pressure. When the pellet diameter is decided – in Sweden it is usually set at 8 mm – the length of the holes has to be adapted. If surface conditioning with

¹³ The steam explosion process is used in Masonite manufacturing. Cambi is the company that developed the process.

chromium steel is used on the die holes, the proportions between diameter and length could increase. As the die wears down, the compression length of the holes decreases until it becomes too short. The die must then be replaced. Typically, this has to be done every 2000 hours (Näslund, 2003).

The rolls press the raw material through the die holes. Most often, the rolls are situated inside the ring dies pressing the material outwards. The bigger the rolls, the slower the pressure increase on the material. The position of the rolls has to be adjusted frequently due to irregularities in the material flow that affect the pressurised position system of the rolls. Furthermore, the process eventually wears them down.

Pressing the sawdust through the holes causes friction, which results in a temperature rise. The temperature in the die during pelletising can reach over 100°C. This is considered crucial for the bonding process of pellets, as the lignin softening temperature has to be reached (Back, 1987). Increased amounts of lignin and extractive substances could increase the durability (Lehtikangas, 2001; Jirjis et al., 2006), but should the contents be too high the amount of fines could increase (Bradfield & Levi, 1984). However, lignin softening is not the only bonding mechanism. Mobarak et al. (1982) state that self-bonding during pelletising is partly due to adhesive degradation products of hemicelluloses but they also open up to several interacting processes being included, something Back (1991) also states. Bhattacharya et al. (1989), Jirjis et al. (2006) and Bradfield and Levi (1984) give examples of such processes: the stickiness/interlocking of wood fibres, and adhesion due to heat-softened lignin and other chemicals produced by the action of pressure and temperature. Rhén et al. (2005) also point out some advantages of using higher temperatures during pelletising. High temperatures and a low initial moisture content of the raw material increase the compression strength and the dry density of the pellets. However, if the temperature were lower, more monoterpenes would stay within the pellet, which implies increased durability (Lehtikangas, 1999).

Additives

Additives, i.e., substances such as starch, lignin and others with advantageous characteristics could be used to improve the quality of the pellets. However, they are not necessarily being used with stemwood raw material as they often provide the pellets with unwanted substances that could lead to a higher ash content for the product, as well as higher production costs. Presently, the most common wood fuel densification technologies in Sweden use no additives.

However, if product improvements are wanted or sawdust pellets are to be used in a new range of applications, the use of additives (or new mixes of different raw materials) could come to the fore. Furthermore, since the stemwood sawdust raw material has run short at the Swedish manufacturers', other raw materials have to be used if the use of pellets increases further, i.e., if the Swedish wood fuel pellet plants henceforth will provide the Swedish market with more pellets (increased wood fuel pellet import is, of course, also possible). These new raw materials may need the additives to reach the quality criteria set in the standard. Research shows that improved quality characteristics for pellets could be reached with the use of additives. Slagging tendencies could be totally eliminated by using limestone suspension and kaolin both in stemwood pellets and in bark and logging residue pellets (Öhman et al., 2004 and Öhman et al., 2006A). Öhman et al. (2006A) also show that the technique is ready for implementation in the industry and that the use of kaolin reduces the emission of fine particles. The use of lime could also reduce the SO₂-emissions considerably (Heschel et al., 1999). Pichler et al. (2006) show that corn starch (0.2-3%) increases the durability of the pellets significantly. However, the use of pelletising aids containing oil (rapeseed cake, sunflower seeds etc.) lead to decreased durability and decreased bulk density (Paper IV and Pichler et al., 2006). In Paper IV, however, it is shown that the energy consumption decreases with an increased amount of rapeseed cake mixed in with wood fuel pellets.

Cooling of Wood Fuel Pellets

If dried raw material and conditioning are used, the pellets can reach temperatures of nearly 150°C after pelletising (but they often stay around 60–90°C) due to conditioning and friction, and they must therefore be cooled. A common technique is to use a counter current airflow through the pellet flow cooling the pellets down to a few degrees over the ambient temperature (Näslund, 2003). The air also transports moisture emitted during the densification step and from the hot pellets. Cooling makes the lignin re-solidify and enhances pellet durability and storage stability (Lehtikangas, 1999). A quick cooling procedure is important for getting as hard a pellet as possible (Martinsson & Österberg, 2004). However, a cooling process that is too quick could prevent the pellets from being sufficiently cooled, especially on the inside (Näslund, 2003). After the cooling process, the pellets are screened to minimise the amount of fine particles, and fines are brought back to the process. The

high amount of fines causes problems for household users (see subsequent chapter). The fines also have a higher moisture absorption capacity than pellets, which could increase fungal susceptibility and, consequently, the temperature development (Lehtikangas, 2000).

Storage of Wood Fuel Pellets

At the producer's, the pellets may be stored in stacks before being packed into bags or filled into a bulk transport vehicle. The storage of the final product, i.e., the pellets, differs substantially from the storage of unprocessed raw materials. The most obvious difference is the low moisture content, which according to Lehtikangas (2000) limits the growth of microorganisms. If the wood pellets are sufficiently cooled before storage, the earlier mentioned temperature increase in the stacks can be avoided. The microbial activity can also be avoided if high quality pellets, in terms of durability, are produced. This implies that pellets with high durability are preferred, as fines have been observed to cause cake formations as they agglomerate (Lehtikangas, 2000). The capacity of fines to absorb water is higher than that of pellets, which may cause fungal growth and consequently higher temperatures. An increased amount of fines also leads to increased emissions of nitrogen oxides from combustion, which is probably due to increased combustion temperatures (Bachs, 1998). If proper preventive measures are not taken, the storage of materials with high moisture contents can cause microbial activities in the stacks. Fungal mycelia have been observed by Lehtikangas (2000) in bark pellets with a relatively high moisture content (about 20% wb). All fungi need oxygen, water, nutrients, an environment that is not too acid, and relatively high temperatures (compared with the ambient outdoor temperature). Rhén et al. (2005) report that the lower the initial moisture contents of the raw material, the higher the moisture uptake during storage of pellets. This could speak in favour of producing pellets with relatively high moisture contents, but the final total moisture content in pellets has to be taken into consideration. Pier & Kelly (1997) have also observed anaerobic decomposition with methane (CH₄) emissions during storage.

Delivery and Storage at the Consumer's

In Sweden, the wood fuel pellets are transported to the small-scale end-user in bags of 16 kg on a loading pallet, in big bags of 600–1000 kg or by a bulk transport vehicle. The pellets can also be collected at the manufacturer's. In

Paper III it is concluded that delivery in small bags is preferable when it comes to getting as small amounts of fines as possible with the delivered pellets (see summary below). The end consumers in Sweden, such as the households, pay about 2000–2600 SEK/ton of pellets (ÄFAB, 2008). The price development of pellets, oil and electricity in Sweden is shown in Figure 5. Among these energy sources, wood fuel pellets are the cheapest.

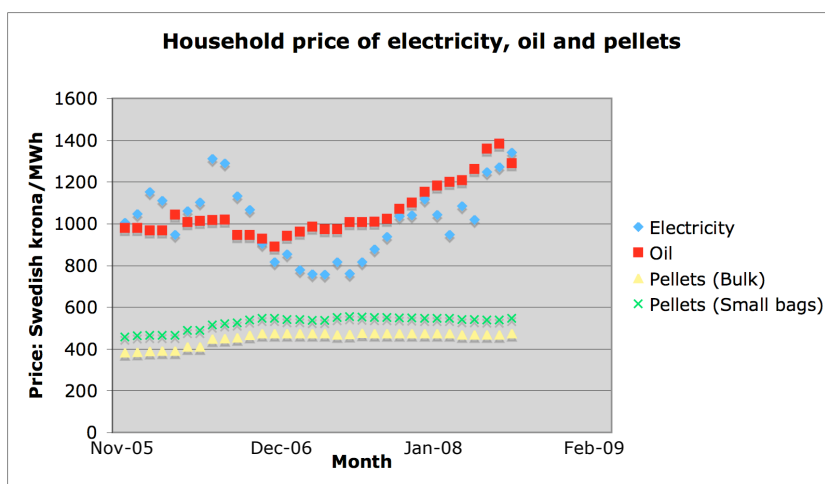


Figure 5: The households' expenditures on electricity (including energy tax, certificate fee and Grid Service Cost), oil and wood fuel pellets in Sweden, VAT included (ÄFAB, 2008-03-25). Cf. the prices for district heating plants on page 22.

Storage at the end-user's could imply bulk storage or storage in big/small bags. Research concerning end-user storage is rare. In Paper III, a problem inventory was made and it was concluded that crumbled pellets or high amounts of fines cause most of the problems the household users have concerning wood fuel pellets. Hence, mechanical durability is a critical factor. Even though the amount of fines can be small at the factory's storage, the problem for the end-user is that the amount of fines increases during transport from the manufacturer to the burner. According to Löfgren and Arkelöv (2004), the amount of fines in the delivered pellets increased with up to 10% of the total weight going from storage at the manufacturer's to storage at the household. Since pellets are sensitive to transport, in terms of getting as little fines as possible, there are norms about the delivery. These norms, General Regulations for Selling Pellets to the Consumer and Suggestions and Advice when Supplying Pellets, unique to Sweden, are issued by the PIR (The Swedish Association of Pellet Producers), and they are checked by the Swedish Heating

Boilers and Burners Association (SBBA). The norms consist of conditions regarding price setting, the consumer's and the supplier's obligations regarding the delivery of pellets, the design of the storage and the amount of fines with each delivery of pellets (PiR, 2005). The suppliers are responsible for delivering the pellets to the end user in accordance with the Swedish standard SS 187120 (1998). The amount of fines should not exceed 4% of the total weight for bulk or 1,5% for small bags. The use of these criteria, however, is optional. These norms are a good complement to the Swedish Consumer Purchases Act (SFS 1990:932). In addition, the consumer can get information about storage from the Swedish Consumer Ombudsman¹⁴.

Combustion

A number of authors have written State of the Art articles concerning combustion¹⁵ of biofuels, such as Battacharya (1998), Obernberger (1998) and Fiedler (2004). They all conclude that it is a mature technology (further discussed in Paper V).



Figure 6. Infra-red photo of a pile of wood fuel pellets burning in my right hand.

The combustion of pellets (see Figure 6) can be done in large-scale heating plants as well as in household heating appliances. Swedish household heating systems are often half automatic and often consist of a two component device (a pellet burner combined with an oil boiler). In contrast, the Austrian systems are often fully automated allowing a modulated operation, and they have

¹⁴ The Swedish Consumer Ombudsman at the Swedish Consumer Agency is a public authority that looks after the consumers' interests.

¹⁵ Combustion means thermal conversion of a substance in the presence of oxygen during which different processes occur, such as drying, pyrolysis and char combustion.

automatic ash removal (Fiedler, 2004). The introduction of fully automatic systems in Sweden could attract new groups of consumers that search for a compact, designed heating system with longer service intervals.

Compared with the large-scale users, the household users are more quality demanding. They have relatively simple conversion installations, mostly without advanced controls or professional management, i.e., they do not have trained personnel supervision nor fully automated equipment (Langheinrich & Kaltschmitt, 2006). Hence, the household user cannot be as tolerant of differences in pellet quality as can the large-scale user (this is further discussed in Paper III). However, the household user can get information from the Swedish Consumer Agency who gives information about what to consider when choosing your pellet heating system. Information can also be retrieved from installers who have pellet certification. Increased knowledge is an important factor since heating with pellets includes increased demands on supervision and maintenance compared with, e.g., oil heating. Insufficient knowledge and lack of time are among the reasons for not choosing pellets for single-house heating (Olin & Helby, 2002). In addition, the household pellet heating systems of today have security systems to prevent, e.g., backfiring from happening (pellet burners that are “P-marked” should have three independent security applications, such as security glass, smoke detector and a plastic feeding tube that can burn off to prevent a fire from reaching the pellet storage).

Co-firing of fuels is one opportunity to introduce biofuels such as stemwood pellets and pellets from alternative raw materials into large-scale combustion. Lignin pellets from Lignoboost are co-fired with coal at Värtaverken in Stockholm, Sweden. Hillring (2003) states that the access to cheap fuels, sensitivity to energy taxation and strategic decisions concerning the production of green energy are the main incentives for co-firing. It is believed that co-firing will expand since new environmental legislation for recycling systems and landfill fees will increase the amount of possible waste fuels to burn (Hillring, 2003).

The combustion of wood fuel pellets involves emissions of flue gases that affect the environment. This topic is described in the section on environment and health effects below.

Production Cost

The production cost can be calculated in various ways. If the Full Costing Method VDI 2067 (VDI, 1983) is used, the production costs are divided into four main areas: investment and maintenance costs (such as machinery investment); manufacturing costs (such as electricity costs); management costs (such as personnel cost) and other costs (such as insurances, taxes).

The production of wood fuel pellets mostly implies that sawdust is dried before pelletising. The drying of biofuel, however, is the main cost factor in pellet production followed by the cost of raw material (Thek and Obernberger, 2004). Zakrisson (2002), however, claims the opposite, which could be due to a difference in price setting between Austria and Sweden. Nevertheless, these two costs combined could amount to as much as one third of the total production cost¹⁶ (Thek and Obernberger, 2004). It is therefore important with correct design and optimisation of the energy use in the drying process, as is the use of heat recovery (Wimmerstedt, 1995). Pelletisation in and of itself and personnel are also costly (Thek and Obernberger, 2004). Thek and Obernberger (2004) recommend that small pellet plants (less than 10 000 tons a year) should not dry their own raw material due to the high cost.

In a comparison made between Swedish and Austrian pellet production costs, the Swedish production costs proved to be considerably lower (Thek and Obernberger, 2004). The main reasons are a larger plant capacity, an efficient heat recovery system from the dryers and a much lower electricity cost (Thek and Obernberger, 2004; Zakrisson, 2002).

¹⁶ In Thek and Obernberger (2004) the text says "...one third of the production cost...", the chart in that paper, however, show that it is more likely to equal two thirds of the production cost.

Environmental and Health Effects

A literature survey was made for this thesis to elucidate environmental and health effects associated with wood fuel pellet production. Health related problems in the wood fuel pellet business are strongly related to the worker environment and in some extent to the emissions during usage. The biggest challenge for the pellet plants is to protect their workers from dust exposure. The exposure to VOC seems to be less of a problem.

Workers at plants that produce wood fuel pellets can be exposed to a poor physical working environment. The workers at the pellet plants are highly exposed to wood dust (Edman et al., 2003; Alvarez de Davila, 2002; Ager, 1998), which has been reported to cause respiratory difficulties and irritation to the upper airways (Ruppe, 1929). The exposure limits for inhalable wood dust are 2 mg/m³ according to the Swedish OEL (The Swedish Occupational Exposure Level, AFS, 2005). Hagström (2008) shows that the workers' personal exposure to wood dust is high (mean 2.4 mg/m³) with almost half of the measurements showing values above the Swedish OEL. Hagström classifies it as being unacceptable due to the risk for overexposure. It is also noteworthy that some alternative raw materials, e.g., straw, are even dustier than chips and pellets (Madsen et al., 2004).

During the production of pellets, almost all of the monoterpenes are emitted during drying and densification (see Paper I); the remaining terpenes are emitted from the smoke stacks gases (Svedberg & Galle, 2001). In pine and spruce the main constituents are α -pinene, β -pinene and Δ^3 -carene (Fengel & Wegener, 1983). Exposure to terpenes has been shown to cause health problems, such as irritation of the skin and eyes and allergic reactions (Eriksson & Levin, 1990). The worker exposure to monoterpenes, however, is low, i.e., lower than the exposure limits (150 mg/m³) for monoterpenes (AFS, 2005), as is the exposure to Carbon Monoxide, Nitrogen Dioxide and VOC (Hagström 2008). In addition, Hagström (2008) has observed dermal exposure to resin acids.

Terpene emissions also cause environmental damage. In the presence of nitrogen oxides and sunlight, the VOC's emitted to air during pellet production contribute to the formation of harmful photo-oxidants. Elevated levels of photo-oxidants are an important cause of widespread forest and crop damage

in Europe. Photo-oxidants are also harmful to humans, as they cause irritation to the respiratory tract and to sensitive parts of the lungs.

Granström (2003) shows that if the raw material is dried to moisture content below 12% (wb), the emissions of terpenes increase rapidly. Furthermore, the emissions increase with increasing temperatures. For a decrease in air pollution to take place, i.e., lower emissions of VOC, the sawdust should be kept at a moisture content above 10%, and the drying medium should not exceed 170°C (Granström, 2003). In order to determine whether it is better to emit most of the terpenes during pellet production or to leave them in the pellets, further research needs to be done. If the terpenes, on the one hand, were emitted during controlled processes in the pellet factory, a minimum of terpenes would be emitted during storage at the residential end-user's, preventing health risks. Furthermore, the terpene emissions could be utilised as fuel in the pellet plant. On the other hand, the terpene content is believed to affect the durability of pellets. According to Lehtikangas (2001), bark pellets had higher durability because of their high extractive content. In addition, the energy content of the terpenes increases the pellet calorific heating value if they remain in the pellets – albeit to a small extent (Paper I). Furthermore, the monoterpene content varies between different tree species, within the same species, between different tree stands and within individual trees (Granström, 2005). Therefore, it is difficult to determine whether the loss of heating value is significant or not.

Another health issue discussed in the literature is the workers' exposure to noise at a higher level than the daily exposure limit (Alvarez de Davila, 2002; Ager, 1998). On the other hand, the levels of microorganisms (bacteria and mould) do not seem to be a problem (Alvarez de Davila, 2002), although the amounts in straw and in wood chips are higher than the recommended value (Madsen et al., 2004).

Oxidation or fire in the pellet plant, storage or burning equipment could cause direct or indirect health problems. At the plants, the cause of fire are due to technical defects along the production chain (for example during drying, dust explosions, etc.) or to heat development in the stacks. At the household, the causes are often backfiring (see Paper III), smoke formation or gas explosion (Persson et al., 2001; Persson et al., 2004).

Working in a cargo-ship storage could be lethal due to the lack of oxygen and a high gas exposure (Svedberg, 2008). Therefore, the present safety regulations have to be updated. During storage there could also be high levels of CO and

Hexanal (Svedberg et al., 2004; Svedberg & Galle, 2001). The health effects concerning CO and Hexanal need to be investigated, which also seems to be the case concerning dioxin.

Several authors have studied the emissions from domestic pellet heating systems (Olsson, 2006; Kjällstrand, 2002; Johansson, 2002; Boman et al., 2004; and Wiinikka & Gebart, 2004). Johansson (2002) shows that there are large particle emissions from, e.g., pellet burners and that the emissions are largest in the start-up phase. Boman et al. (2004) point out that it is important to characterise the inorganic particulate matter from residential combustion from a health effect point of view. The total emissions of particles can be decreased by adjusting the burning temperatures (Wiinikka & Gebart, 2004). Olsson (2006) has studied the incomplete burning of different organic materials and found that antioxidants could form during initial smouldering and flaming burning and that carcinogenic benzene and polycyclic aromatic hydrocarbons in low concentrations can form during glowing burning. Olsson (2006) has also studied residential emissions from pellet combustion and found that it was generally low. It is, however, very important that the best appliances are installed, and that they are used and maintained correctly. The conversion from electrical heating to pellets does give a contribution of pollutants to the air but it does not exceed recommended levels (Jonsson & Hillring 2006). Conversion from wood logs to pellets even improves the ambient air quality (Boman et al., 2003; Jonsson & Hillring, 2006).

Environmental and Energy System Aspects

As compared to using fossil fuels, the use of biofuels, such as pellets, decreases the environmental impact such as climate change problems. However, even if biofuels are used, there are more actions still to be taken for a better environment, such as improved emission controls and more energy efficient technology to prevent health risks and decrease the use of natural resources. This chapter will concentrate on the use of energy within the wood fuel pellet system (the pellet chain) in general and on energy efficiency within the wood fuel pellets production system in particular.

In activities interacting with the producer, energy savings can be made, such as diminishing the transportation of raw material and pellets, i.e., improving the logistics regarding pellet deliveries and making more efficient use of burner equipment, etc. The latter implies running the burner/boiler as efficiently as

possible and in good running conditions. Large-scale heating plants can adjust their equipment to the fuel used for best performance. The logistics might be improved by better coordination of the delivery between the producer, the large-scale consumer and the small-scale consumer by using bulk transport vehicles. If the deliveries to an area with small-scale consumers could be integrated with the delivery to one or more large-scale consumers, the distribution would be more efficient, i.e., fewer transports would be needed. All of the suggestions made above would save both money and environment.

A decrease in the energy used in the production chain will not only be of gain to the pellets producer (cheaper production) but, of course, also to the environment (less emissions etc.). Within the production chain, a number of actions can be taken to decrease the amount of energy used. As the drying of sawdust is the most energy-demanding process within the production of wood fuel pellets, most of the actions should concentrate on this (unless an optimal drying process is already being used). Hence, the largest theoretical energy saving potential could be found within the drying process. Savings could also be made concerning heat, material, personnel and equipment.

System Integration

In convective drying, some form of heat exchange between the exhaust and inlet gas streams is often used, because most of the heat used in drying follows the exhaust gas stream (Strumillo et al., 1995). If a condenser is used, the energy in the drying gases can be utilised by integrating it with a district-heating grid or a lumber kiln, which implies energy gains (see Figure 7). The lower the return flow temperature of the condenser (from the district-heating grid), the more energy can be recovered (and consequently transferred back to the district-heating grid) at a constant flow temperature.

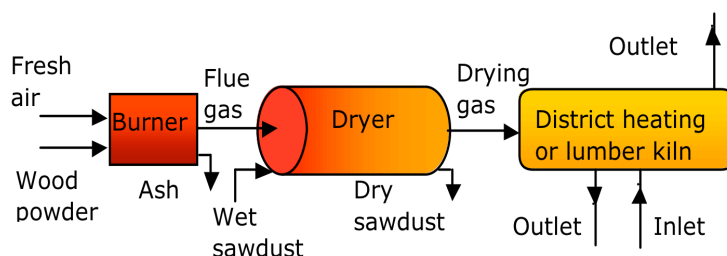


Figure 7. A schematic sketch of how a district-heating grid or a lumber kiln could be integrated into a biofuel production plant.

Using recirculation of the drying gases also means energy savings as the energy in the not fully saturated exhaust steam otherwise leaves the dryer. This is why recirculation is one of the most applied techniques for energy savings in dryers (Iguaz et al., 2002). Also, the higher the dew point, the more useful the recovered energy (Johansson & Wimmerstedt, 2001; Johansson, 2002). According to Wimmerstedt (1999), a dew point of 80°C is reported from the industry, which means potentials for increased energy recovery. The effects of the recirculation of drying gases in a co-current rotary dryer are studied in Paper II.

As regards energy, the optimal integration between the lumber kiln and the sawdust dryer at a sawmill demands that all the energy needed has to come from the sawdust dryer waste heat or vice versa. Vidlund et al. (2003) show different ways of integrating a lumber kiln with a sawdust dryer, using direct or indirect drying. Apart from the conclusion that pressurised dryers have to be used (Vidlund et al., 2003), they see several reasons for integration, such as less CO₂ emissions¹⁷ (due to the more efficient use of the biofuel resource), fewer transports of raw material, and a high degree of recovered heat utilisation. Considerable energy savings, up to 90% of the heat demand of the drying process, are possible due to integration (Vidlund et al., 2003). The most effective integration is to connect in series the biofuel dryer and the drying kiln (Andersson et al., 2006).

Pellets are produced either in stand-alone plants or in integrated pellet production units (at a sawmill, pulp and/or paper plant). Increased integration could reduce the need of transportation and increase the use of waste energy. Such system thinking could therefore result in synergy effects concerning saved energy and reduced emissions of greenhouse gases, such as CO₂. However, there are things to consider concerning system integration. The raw material supply has to be secured if a specific solution that requires a special kind of raw material is chosen. Furthermore, if the integration is made in order to make the process more energy efficient, the possible changes in the pellet characteristics/quality have to be taken into consideration (further discussed in Paper II). Compromises between energy efficiency (decreased costs) and pellet quality may be necessary.

¹⁷ Biofuels are CO₂ neutral. Less CO₂ is released to the environment if biofuels are used instead of fossil fuels. Also, fewer transports are needed with a more effective use of biofuels.

Efforts to reduce the energy use in the Swedish pulp and paper industry could increase the biofuel use. Due to environmental requirements, the pulp and paper industry is also closing its water loops, which could lead to a higher heat content in effluent water to be used elsewhere. Andersson et al. (2006) show that all studied dryers (drying raw material for pellet production) use less energy in an integrated system (pellet plant and pulp industry) and that the CO₂ emissions decrease with as much as 31-36 kg/MWh of pellets produced. The integration works best if the pellet plant uses the flue gases from a black liquor recovery boiler (Andersson et al., 2006).

In a bioenergy combine studied by Wahlund et al. (2002), the integration implies that part of a CHP plant's heat is used for drying the raw material for pellet production. The integration increases the operational hours and the biomass utilisation in regions with surplus biomass. Large CO₂ mitigation is possible if coal is replaced by biofuels in the CHP plant.

There are many other integration options to consider, such as new bioenergy combines (biorefineries) that produce paper, pellets, RME, etc., and further work is needed to show the energy savings that can be reached and the synergetic effects that could arise.

Quality and Standardisation of Wood Fuel Pellets

Quality

There are several ways of defining “quality”. It could be defined as the products’ or services’ ability to fulfil the customers’ needs and expectations (Bergman & Klevsjö, 2001). It could also be defined as “the degree to which a set of inherent characteristics fulfils requirements” (SIS-CEN/TS 15234, 2006). It is important to distinguish between quality discussed in the customer context, and quality as a measure of pellet properties in relation to a standard. While professional end-users at a heating plant may analyse pellet properties, end-users that use pellets in small scale for domestic use probably have needs and expectations on the performance of the heating system, and not on the pellet itself (this matter is further discussed in Paper V). They also have a relatively simple conversion installation that most often do not have advanced controls or professional management (Langheinrich & Kaltschmitt, 2006). The small-scale users’ awareness of pellets being a well functioning fuel also increases as the fuel accessibility increases and information is spread by other users (by word of mouth, pellet blogs, etc.), the energy advisory service, retailers, researchers, etc. As mentioned earlier, quality assurance provided through a standardisation is crucial, especially for the small-scale consumers as they demand a high and even quality of the pellets. Good quality increases the customer’s confidence in the product (Alakangas et al., 2001). This is particularly important dealing with single house-heating consumers, as they are not as tolerant of differences in the pellet quality as large-scale users would be.

The quality of fuel pellets can be described using quantitative properties, such as chemical, physical and mechanical properties (see subsequent sections). It might be in order, however, to introduce qualitative properties to solve earlier mentioned problems (see section on Other Properties below).

Chemical Properties

The chemical composition of biomass, i.e., wood, is cellulose and hemicelluloses, lignin, extractives, and minor and major elements. In fresh wood, the approximate shares of water (total weight), carbon (dry weight), oxygen (dw) and hydrogen (dw) are 50%, 50%, 42% and 6%, respectively. The remaining share mostly consists of ash (inorganic material).

The extractives, such as waxes, terpenes and phenols, are produced as defence mechanisms against destructive activities. The wax on the needle controls the evaporation of water from the coniferous trees. Apart from this, the extractives have high energy contents, about 35 MJ/kg (dw), which influences the heating value of wooden pellets. In comparison, lignin has an energy content of about 25–27 MJ/kg (dw), cellulose 17 MJ/kg (dw) and wood, on the average, 19.2 MJ/kg (dw) (Jirjis, personal communication). Knowledge of how the extractives affect mechanical properties, such as mechanical strength, is incomplete. However, the extractives might act as plasticisers or inert bulking agents or become part of the matrix (Jirjis, personal communication).

The lignin is probably working as a binding agent within the pellet together with other bonding mechanisms (see section on Pelletising of Sawdust above). To get the lignin to work as a binding agent, the glass transition point (melting point) has to be reached. For native lignin (when dry) this temperature is 200°C. If the lignin absorbs more than 2% of water, the temperature is reduced to 115°C (Back, 1987).

According to Granström (2005), the monoterpenes, such as α - and β -pinene and Δ^3 -carene, are the most volatile group of compounds present in wood. They are found in the resin. In Norway spruce 0.1–0.15% of the tree's dry substance consists of monoterpenes, for Scots pine the numbers are 0.2–0.6%. Apart from having several protective functions in trees, monoterpenes have a energy value of about 40 MJ/kg. In the discussion above, the latter has been elucidated in the context of pellet production technology.

Neither the major elements (Na, Ca, K, S, Mg, P, Si...) nor the minor elements (Fe, B, Zn, Cu, Mn, Mo, Cl...) are significant energy carriers. The elements also have different effects on combustion – chlorine (Cl), sulphur (S) and potassium (K) contribute to corrosion problems with burner equipment and chimneys (Lehtikangas, 1999); magnesium (Mg), calcium (Ca) and phosphorus (P) have effects on pollutant retention in ashes (Hahn, 2004).

Physical Properties

The physical quality properties of wood fuel pellets are moisture content, calorific value, volatile matter content, ash content, ash melting behaviour and content of impurities.

Among the quality properties, moisture content (the ratio of water content to total weight) is among the most important, as several authors have stated (Pichler et al., 2006; Jirjis et al., 2006; Lehtikangas, 2001; Obernberger & Thek, 2004; Fasina, 2008; Rhén et al., 2005; Greinöcker et al., 2006). The moisture content of the pellets affects the energy content and causes dry matter loss (microorganisms eat the substance). Hence, it affects the combustion process, i.e., the combustion efficiency and the fuel gas emissions. It also affects storage on account of an increased microbial activity and the self-ignition risks, and it implies health effects. In addition, it affects the mechanical properties, e.g., durability and the bulk density as well as the energy consumption during drying and pelletising. This was discussed in the chapter headed “Wood Pellet Production Technology” above. According to the Swedish standard 187170 (1997), measuring the moisture content involves weighing of the sample before and after drying it in an heating oven for 24 hours in $105 \pm 2^\circ\text{C}$. The difference in weight that is obtained is used for determining the moisture content. It is to be noted that dry matter losses occur during drying. According to Jirjis (personal communication), the actual value of the moisture content is 1–3 percentage point lower than that one would get without the dry matter losses. If the moisture content is only 1 lower than the seller claims it is, it could cost a large biofuel user tens of thousands of euros a year. The moisture content is discussed further in the chapter on drying.

The calorific heating value (CHV) is of great importance to the trade of biofuels. The buyer of the fuel wants to get as much energy out of the fuel as possible. According to the Swedish standard SS-ISO 1928, the determination of the gross CHV must be made using a bomb calorimeter. Subsequently, the net CHV can be calculated. Each test costs about 50 euros (Burvall, personal communication). Therefore, the samples are often a mix of several fuel deliveries.

Volatile matter is mostly VOC. Most of these substances are emitted during production. Some may remain, however, and be emitted later in the fuel pellet chain.

For Scots pine and Norway spruce, the ash contents, containing both inorganic compounds from the wood itself and materials added due to contamination during the processing of the raw material, are low in pure stem wood (about 0.3% (dw)) but higher in needles and bark (about 3-5% (dw)) (Martinsson & Österberg, 2004; Savolainen et al., 2000; Eid Hohle, 2001). Lehtikangas (2001)

reports that pellets had a higher ash content and a lower calorific heating value than did the raw material, probably owing to loss of volatiles during drying. This has been studied in Paper I. It is crucial to produce pellets with low ash contents. Martinsson & Österberg (2004) shows that a lower ash content implies less frequent ash clearing, which is important for the automatic operation of a burner/stove. The ash contains most of the elements and could therefore be spread in the forest to avoid nutrient depletion and increased acidification (Lundborg, 1998; Vesterinen, 2003; Wikström, 2007). The ash, however, often needs pre-treatment before it is returned to the forest.

Ash melting behaviour is important for the user of wood pellets. A high ash melting point is wanted since agglomerated ash causes burner problems. This implies that burning the fuel at the recommended initial temperature means operational safety for the user. It also means less pollutant emissions (Hahn, 2004).

Impurities within the pellets, such as sand particles (measured as silicon (Si) content) and other kinds of contamination, could lead to wear of pelletising equipment and sintering/slagging tendencies during burning (Öhman et al., 2004).

Mechanical Properties

The mechanical quality properties of pellets are bulk density, size distribution, bridging propensity, durability and strength.

The bulk density (the density of a load of pellets) is used when the fuel is traded by volume. It has to be $\geq 600 \text{ kg/m}^3$ according to the Swedish standard. The bulk density affects the amount of energy supplied and, of course, transport and storage demands. A Swedish pellet manufacturer has pointed out a packing problem (volume change) that occurs when newly produced and stored pellets are to be packed in small bags (16 kg/bag), i.e., the volumes of the 16 kg bags are not the same for these different assortments.

An even and homogeneous size distribution is important for fuels such as wood pellets since this implies undisturbed and continuous material flows. This is particularly important when using small-scale burner equipment. Unfavourable particle size distribution can also cause clogging during conveying, dust formation during transport, and bridging during storage. The

bridging is not only the result of an unwanted size distribution, it is also the result of a large share of fines.

When the quality of pellets is to be determined, tests of its durability is performed. The durability – the amount of fines (percentage of fines in total weight) from pellets exposed to movements – is determined according to Swedish standard SS 187180 (1999). After a tumbler test, the amount of fines, i.e., particles smaller than 3 mm, has to be $\leq 0.8\%$ (wt) for group 1 pellets (SS 187120). The durability is crucial for not getting fines when storing, which could cause mould growth and feed interruptions, due to bridging. It could also lead to uncontrolled burning, e.g., dust explosions. Lehtikangas (2001) reports that durability was influenced by the lignin content, and that the bark pellets had good durability (also reported by Martinsson, 2003), which was perhaps due to a higher content of extractives. Obernberger & Thek (2004) conclude that several parameters, such as compression technology and used raw material, affect the abrasion of pellets.

Other Properties

The chemical, physical and mechanical properties described above are all quantitative properties. Consequently, in the Swedish standard for pellets they are expressed in quantitative terms (see subsequent section). In order to take the consumers needs into account I think that it might also be in order to introduce non quantative properties (quality aspects). These properties could concern the manageability of the product with respect to the user, such as package size or colour encoding of different assortments for different users. In addition, properties that concern the maintenance of the heating equipment for optimal use could, e.g., be introduced in the standard.

Standardisation

Several problems can be avoided or mitigated by the use of a standard. For example, operational disturbances such as stoppage in the feeding system and backfiring. Also, inconvenient handling issues such as ash emptying problems. A standard could also increase the quality of the product. A high quality product in the sense that the wood fuel pellet remains a pellet (i.e., it should have good durability, a low moisture content, produce a low amount of ash, not contain hidden unwanted substances [sand particles, heavy metals such as Mercury etc.] and have the specified dimensions) will increase consumer

confidence, and a standard will work as a facilitator for transactions between buyers and sellers (Langheinrich & Kaltschmitt, 2006). Therefore, quality assurance provided through standardisation is crucial. In Sweden, the producers of wood fuel pellets for the household market strive to fulfil the criteria of the Swedish standard for pellets (SS 187120). Selling pellets that abide by the Swedish standard guarantees an official national quality of fuel pellets. It provides guidelines to the producer and informs the final consumer about quality characteristics (Hahn, 2004). The standardisation is also advantageous for fuel pellets equipment industry, since it simplifies construction and operation of burners.

The Swedish standardisation (see Table 1 below) from 1998 was one of the first standardisations for fuel pellets in Europe, and it is still a legally valid regulation. Today 54% of the Swedish fuel pellet producers use the standard, which amounts to 75% of the total production of wood fuel pellets (Höglund, 2008).

Table 1. Group classification of wood fuel pellets according to the Swedish standard.

Characteristics	Testing method	Unit	Group 1	Group 2	Group 3
Dimensions: diameter and length in manufacturer's storage	Measured from 10 random batches	mm	Is declared, $< 4 * D$	Is declared, $< 5 * D$	Is declared, $< 5 * D$
Bulk density	SS 187178	kg/m ³	≥ 600	≥ 500	≥ 500
Durability in manufacturer's storage	SS 187180	% of weight of fines <3mm	≤ 0.8	≤ 1.5	> 1.5
Net calorific heating value as received	SS-ISO 1928	MJ/kg kWh/kg	≥ 16.9 ≥ 4.7	≥ 16.9 ≥ 4.7	≥ 15.1 ≥ 4.2
Ash content	SS 187171	% of dry weight	≤ 0.7	≤ 1.5	≤ 1.5
Moisture content as received	SS 187170	% wet basis	≤ 10	≤ 10	≤ 12
Sulphur content	SS 187777	% of dry weight	≤ 0.08	≤ 0.08	To be noted
Additive content		% of dry weight	Content and kind of additive to be noted		
Chlorine content	SS 187185	% of dry weight	≤ 0.03	≤ 0.03	To be noted
Ash melting point	SS-ISO 540	°C	Initial temperature to be noted		

Most European countries do not have national standards for fuel pellets due to a non-existing or small market, or because they waited for a common European standard. There are standards containing pellet quality properties regulations in, among other countries, Austria (ÖNORM M 7135), Germany (DIN 51731), Italy (CTI-R 04/5), Sweden (SS 187120), the UK (British BioGen, Code of good practice) and the USA (PFI). Since 2005, there is a common European standardisation called CEN /TS 14961 (2005). The CEN/TS 14961 is presently a pure classification standard but general quality standards are on their way. The CEN/TS 14961 is described by Alakangas et al. (2006). The quality parameters for wood fuel pellets (when leaving the producer) are defined in CEN/TS 14961 (2005) in threshold levels in two categories, normative and informative (see Appendix I). The Swedish Standard Institute has also submitted an application to ISO for the development of a global standard of solid biofuels. This project (ISO/TC 238 Solid Biofuels) may begin during 2008 (Norrby, 2007).

The Swedish standard for pellets SS 187120 defines quality parameters for wood fuel pellets. The characteristics specified are: dimension; bulk density; durability; heating value; contents of ash, moisture, Sulphur, Chlorine and additives; and the ash melting point. All parameters emanate from pellets as a product leaving the producer. In the standard, there is one example of a high quality class of solid biofuel recommended for household usage, i.e., pellets classified in Group 1 (see Table 1 above).

The Swedish standard (187120) does not include transportation requirements as does the Austrian standard (ÖNORM M 7135). In Sweden, the Swedish Association of Pellet Producers (PiR) has issued optional norms concerning the selling of pellets to consumers and advice on how to be best prepared on the day of pellets delivery. In addition, there is a system of marked pellets in Germany called the PVD-norm. This includes a way of tracing the pellets back to the day of production.

In addition to the standardisations (with regulations within the European Union and Sweden), there is in Sweden also a Nordic environmental eco-labelling on pellets, called “Svanen” (“The Swan”). Pellet manufacturers that fulfil the criteria for the “Svanen” eco-labelling are, with each delivery, required to specify the pellet dimension, heating value, ash content, density, information about the raw material used, and whether there are any additives (Nordic eco-labelling 2007, see Appendix II).

According to a test performed by Löfgren and Arkelöv (2004), all Swedish manufacturers of pellets seem to fulfil the criteria of the Swedish standard for pellets. However, a new delivery (or change of distributor) of pellets can cause or solve the problems encountered implying significant variations in the quality of delivered pellets (Löfgren & Arkelöv, 2004; Norberg, 2006). This indicates that improvements to the standard are necessary.

In a problem inventory (Paper III), it is concluded that crumbled pellets, a high amount of fines and unsuitable equipment set-ups (e.g., when a new burner is placed in an old boiler that is not matched to it) cause most of the problems. Furthermore, the present pellet standard is not stringent enough to provide a sufficient pellet quality to the customer with the present variations of transport and storage/feeding systems. Improving the transport systems or equipment/heating systems could solve the shutdown problems at the household level. In order to reduce the problems with quality variations in the wood fuel pellets, some of the parameters in the standards should be expressed using intervals. Also, the new European classification standard, CEN/TS 14961, does not reduce the problems analysed and it even contributes to a change for the worse with regard to some parameters. According to Alakangas (2007), the feedback on the new European standard concerns, among other things, the need for a minimum as well as a maximum length of pellet (too long pellets cause problems, e.g., in the feeding system), and standard properties that might need to be interrelated for household user pellets.

Langheinrich & Kaltschmitt (2006) study the implementation of a quality assurance system, which is currently being standardised according to CEN/TS 15234 (2006). The new European standard for solid biofuels (CEN/TS 15234) is a fuel quality assurance that could serve as a tool for efficient trading with biofuels. According to CEN/TS 15234 “the Fuel Quality Assurance of the supply chain and the information to be used in the quality control of the biofuel ... ensures traceability and gives confidence by demonstrating that all processes along the supply chain (of solid biofuels) up to the point of delivery to the end-user are under control”. All steps of the supply chain, from the raw material to the sold product at the end-user’s site shall be documented according to this standard. If a bag of pellets is the traded package, it shall include a fuel quality declaration that, as a minimum, shall include information about: the supplier; a reference to the standard; origin and source; country of harvest or first trade; traded form; normative properties; chemical treatment; signature, name, date and place (see appendix C4 in CEN/TS 15234 for an example concerning

pellets delivered in small bags). If this assurance is used and documented it provides confidence that a stable quality is achieved but it does not necessarily mean that all user problems are solved.

Another way of solving some of the problems would be to provide the installation contractor with proper education. In Sweden, there are now a number of installation contractors that are certified by PellSam (the Swedish wood pellet trade body) so that the end-user can be sure that the right pellet heating equipment is installed in the right way. PellSam also offers their consumers an insurance scheme with six years of full cover for unexpected breakdowns or damages to the pellet equipment (Hahn, 2004).

The standardisation sets limits for quality parameters of pellets, and all manufacturers fulfil the criteria, one should not be content with that. There could still be large variations between various pellet producers and pellet deliveries, in terms of amount of fines, etc. This means that the single-house heating end-user has to adjust the burner for each new delivery (for optimal combustion). The solutions to these problems could be to raise the demands in the standardisation or to introduce parameter settings using intervals.

Summary of Paper I

The work described in this paper examines the emission of monoterpenes from pellet production focusing on the choice of drying technique and the pelletising process. In the discussion of drying techniques, the key parameters – the drying medium, the temperature and the residence time – are considered. The environmental effects and the quality properties of pellets are the main discussion issues.

Samples were collected from six different suppliers using six different dryers. The raw material was sawdust and cutter shavings from Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). When possible, the samples from each supplier were wet sawdust, dry sawdust and pellets. The dryers in the study work under different conditions regarding temperature, residence time and drying medium (Table 2).

Table 2. Production technologies used in the comparison made in Paper I and their key parameters.

Producer	A	B	C	D	E	F
Drying technique	Flash dryer	Spouted bed	Rotary dryer	Rotary dryer	Lumber kiln	Lumber kiln rotary dryer
Drying media	Superheated steam	Superheated steam	Flue gas from forest residues	Flue gas from sawdust (powder)	Air	Air
Raw material	Wet sawdust	Wet sawdust	Wet sawdust	Wet sawdust	Dry sawdust and cutter shavings	Wet sawdust and cutter shavings
Temperature	>140°C	Inlet temp 240°C, outlet temp 130°C.	temp 90-100°C.	utlet temp 115°C.	6082°C	6082°C
Residence time	Short	Short, 2.5 minutes	Medium	Medium	Long pine 110h spruce 80h	Long pine 110h spruce 80h
Additives	No	No	Lignin	No	No	Wafolin S

More than 70% of the terpene losses occurred during drying (see Figure 8 below). Sawdust dried in rotary dryers lost about 80% of the initial terpene content (see C and D in Figure 9 below), whereas sawdust dried in steam dryers lost 48 and 71%, respectively (see A and B in Figure 9 below).

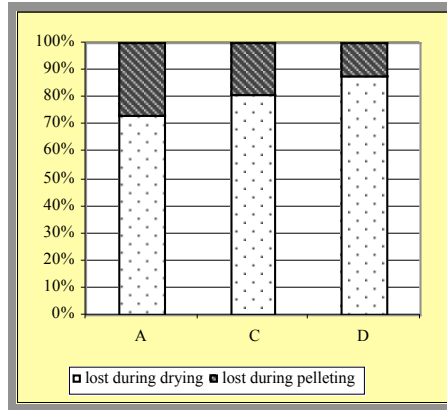


Figure 8. The relative importance of drying vs. pelletising for the emissions of terpenes.

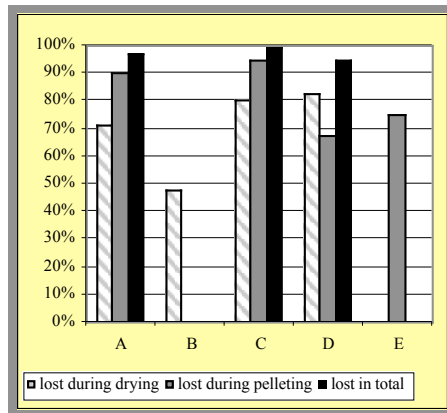


Figure 9. Terpene losses during drying and pelletising. The striped bars show the difference in terpene content between wet sawdust before drying and dried sawdust. The grey bars show the difference between dried sawdust before pelletising and pellets. The black bars show the difference between wet sawdust and pellets.

During pellet production, 68–95% of the terpenes in the dry wood were released. A correlation between the dried sawdust moisture content and the terpene loss during pelletising was found: the higher the moisture content, the higher the losses. Also, more water evaporated in the presses might indicate that the material spent more time in the press. It should also be noted that dried sawdust with higher terpene content emits more terpenes during pelletising. On the whole, however, almost all the volatile terpenes leave the sawdust during drying and pelletising.

According to the Swedish standard for wood pellets, heating value is a quality property. Dry matter, such as extractives (monoterpenes), has a high energy content and losses should be avoided (Jirjis, 1995). The sawdust with the highest content of terpenes in this study had 3.86g/kg oven dried weight (odw) before drying and 0.112g/kg odw as pellets. The difference is 3.75g/kg odw, which gives a loss of 150kJ with a heating value of 40 MJ for terpenes and 19.6MJ/kg odw for biomass, or 0.76% of the original energy content in the wood fuel. Low VOC emissions during drying would improve the energy content of the sawdust and also decrease air pollution in the surroundings of the dryer.

Moisture content is an important physical parameter that affects pellet quality in several ways. It can be controlled in the drying process.

Annotation 2008

In Paper I it was concluded that “low VOC emissions during drying would improve the energy content of the sawdust and also decrease air pollution in the surroundings of the dryer”. This is true, but not applicable with present pellet production technology. During production (drying and pelletising), all or almost all of the monoterpenes leave the sawdust. However, in a closed drying process the monoterpenes could be taken care of to be used in other applications.

Summary of Paper II

The work described in this paper studies the effects of the recirculation of discharged drying gases in a directly fired co-current three-pass rotary dryer that uses flue gases as a heating medium (typically placed in a pellet plant like the one in Figure 10 below¹⁸). Furthermore, energy is recovered over a condenser (connected to a district-heating grid) from the gases that leave the dryer. A conceptual model is set up and validated using data from an industrial rotary dryer. A possible energy recovery is examined and a discussion of how the dryer capacity could be affected is carried out. The studied key parameters are: the amount of recirculation of drying gases; the dew point of the discharged drying gases; the energy recovered in the condenser after the dryer; and the efficiency of the dryer.



Figure 10. SBE's (Svensk BrikettEnergi AB¹⁹) pellet plant in Ulricehamn, Sweden, 2002.

The system studied includes four parts based on equipment used at a biofuel factory using recirculation of drying gases and energy recovery over a condenser: (1) a burner; (2) a direct heated rotary dryer; (3) a condenser; (4) a

¹⁸ The theoretical model is a simplification that could have its origin in this drying system.

¹⁹ Lantmännen Agroenergi, since 2003.

district heating model (see Figure 11). The developed and validated model used for this study, which includes part (1) and (2), was made to calculate, e.g., the dew point of the drying gases after the dryer, the recovered energy over the condenser and the efficiency of the dryer.

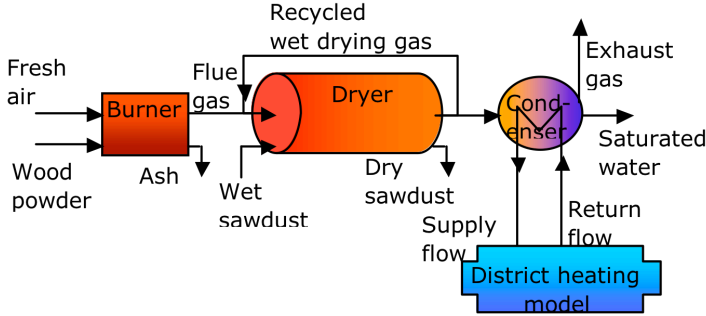


Figure 11. A schematic sketch of drying equipment used at a fuel factory that uses recirculation of drying gases.

See Table 3 for the base conditions for the calculations of mass and energy flows when drying sawdust in a rotary dryer, such as the burner specifications, the dimensions of the dryer, its operating conditions and the condenser specifications.

The ability to estimate the drying rate is an important parameter when modelling a rotary dryer. The drying rate is strongly dependent on the average volumetric heat transfer coefficient (U_a). In a rotary dryer, several parameters influence U_a , such as the dryer diameter (D) and the gas flow rate (G). Based on equations from Kamke and Wilson (1985), Alvarez and Shene (1994) and Song et al. (2003), an expression for U_a is developed, including a correction factor (f) validated from field data from a local industrial pellet plant:

$$U_a = 271 \cdot f \cdot G^{0.719} \cdot D^{-1} \quad (1)$$

In addition, mass and heat balances were used for the burner, the dryer and the condenser to calculate the possible amount of energy recovery and changes in dryer capacity. The validation of the dryer model with industrial data results in a benchmark scenario with no recirculation of drying gases. In addition, five scenarios are elucidated (S1–S5), all using recirculation of drying gases. Scenarios 1–3 are carried out with a constant drying gas flow rate, i.e., the same gas flow rate as in the benchmark scenario. S1, S2 and S3 have 30, 50 and 65% recirculation, respectively. Compared with scenario 2 and using 50%

recirculation, scenarios 4 and 5 have increased and decreased the drying gas flow rate with +10% and -10%, respectively.

Table 3. Base conditions for the calculations of mass and energy flows when drying sawdust in a rotary dryer.

Ambient air	
Temperature	5.9°C
RH	80%
Burner	
Power rating (\dot{Q}_F)	6.2 MW
Fuel	Wood powder
Fuel moisture content	2% (wb)
Fuel consumption	1188 ton·h ⁻¹
Efficiency	90%
Excess air	3.0–5.8 (non-dimensional)
Dryer	
Type	Three-pass
Length (L)	9 m
Diameter (D)	2,7 m
Volume (V)	51,5 m ³
Speed of rotation	4.6 rpm
Flow directions	Co-current
Drying temperature ($T_{g,in}$)	423–800 °C (inlet)
Drying gas mass flow	8.56-12.41 kg·s ⁻¹
Losses (\dot{Q}_{ID})	2,4%
Product (Sawdust)	
Composition	Scots pine (sawdust)
Inlet moisture content	55% (wb)
Outlet moisture content	9% (wb)
Inlet temperature ($T_{s,in}$)	5,9°C (invariable)
Outlet temperature ($T_{s,out}$)	70°C (invariable)
Condenser	
Inlet gas temperature	77.6–83.8°C
Outlet temperature (DH)	57.5–73.7°C ^a
Losses (\dot{Q}_{IC})	Neglected

^a See Figure 11 and Figure 12.

A district heating demand model was used to estimate the useful amount of energy that could be recovered over the condenser. Calculations of the delivered amount of heat from the condenser to the grid were made at given supply and return flow temperatures of the water on the district-heating side and at a given heat demand of the district-heating grid. From data on the temperature fluctuations over a year, using time steps of 100 hours, a duration graph is constructed, simulating the energy demand of a small town in the middle of Sweden (Karlstad). The graph is used for the calculation of the usefulness of the energy that could be utilised by the district heating system.

With a correction of $f = 5$, the field data and the data from the model correspond satisfactorily. The results show that the dew point of the gases leaving the dryer increases significantly when the recirculation ratio increases (Figure 12) and when the gas flow rate decreases (Figure 13).

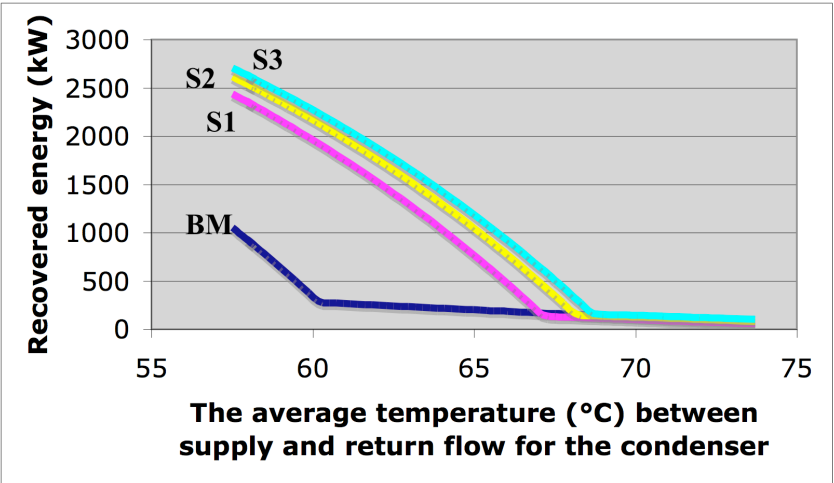


Figure 12. Recovered energy as a function of the average temperature between supply and return flow over a condenser due to increasing drying gas recirculation.

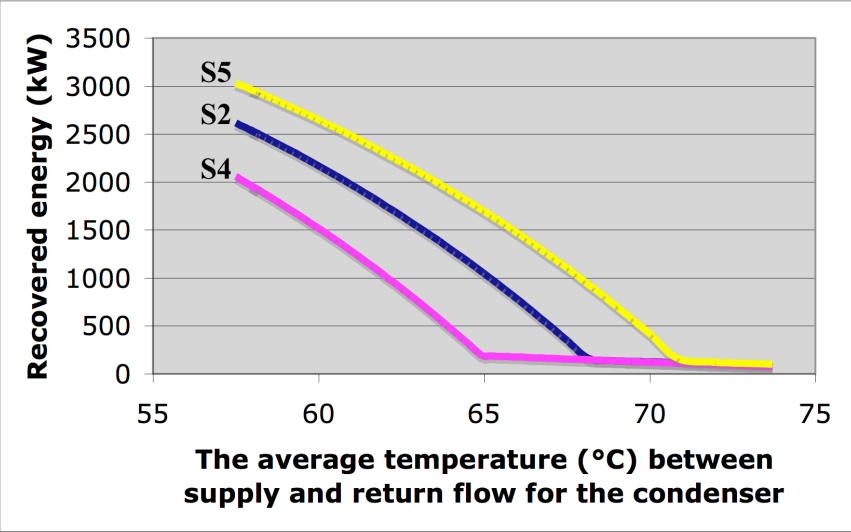


Figure 13. Recovered energy as a function of the average temperature between supply and return flow over a condenser due to changes in the gas flow rate.

The increased recirculation of drying gases improves the dryer efficiency (Figure 14), as does the decrease in gas flow rate (Figure 15).

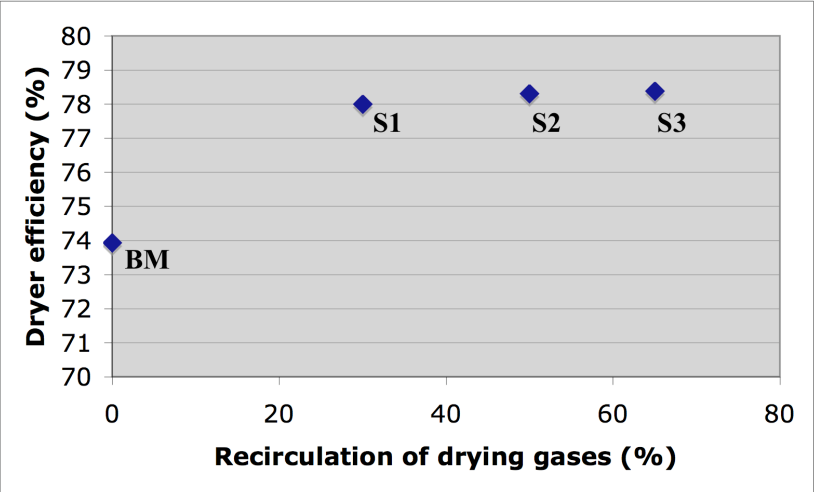


Figure 14. The change in dryer efficiency as a function of the recirculation of drying gases.

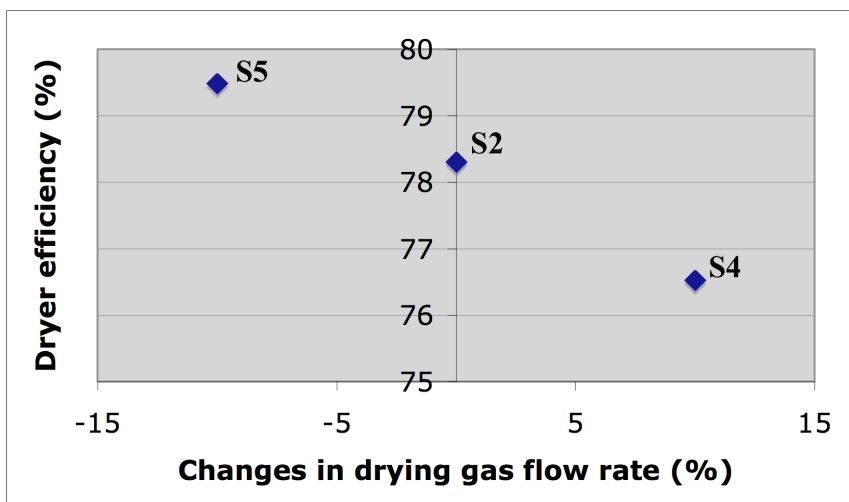


Figure 15. The change in dryer efficiency as a function of changes in the drying gas flow rate, at 50% recirculation of the drying gases.

In this work it is concluded that increased recirculation of drying gases implies a more energy efficient operation of rotary dryers as well as a significantly higher dew point. The latter means that more energy can be recovered in the condenser, which in turn implies that more energy can be delivered to district heating grids. Furthermore, since the validation shows that the model correlates well with industrial data it should be possible to use the model industrially to predict capacity changes and recovered energy when changes in drying gas recirculation are made.

Summary of Paper III

The work performed in this paper is based on a literature study. End-user problems are analysed with regards to their origin, and the question of whether an improved Swedish pellet standard could reduce the problems is posed. In addition to scientific publications, which are scarce in this area, grey literature (mostly concerning Swedish conditions) was used as a source.

The most commonly reported problems in the studied literature were chosen for further analysis. The first analysis attends to the origins of the problems and were based on the studied literature and personal communication in order to make a survey of the cause (or causes) of each specific problem. The second analysis aims at identifying the problems/causes that could be reduced if changes to the Swedish standard for pellets SS 187120 were to be made. The identified and classified problems encountered are evaluated regarding the regulated parameters in the standard. An attempt to link a specific problem/cause to the existing parameter regulation in the standard is made and improvements are discussed.

From the survey, we came to the following conclusions: (1) wood fuel pellets in Sweden fulfil the requirements of the Swedish standard; (2) there are few problems reported where the storage, burner and boiler is integrated in a system designed for pellet use; (3) when the technical parts (storage, burner and boiler) are not integrated, e.g., using equipment from different producers, the risk of encountering problems increases; (4) most problems are encountered when bulk transports are used, and few problems are reported when using small pellets bags; (5) some problems depend on the variation of pellet properties, e.g., energy content; (6) most of the serious problems are due to the crumbling of pellets and/or to a high amount of fines.

Despite significant improvements of pellet quality and storage and burner equipment, there are still some problems that the household pellets user encounters. The Swedish pellet standard is not sufficient to meet the demands of end-users that use equipment that is not sufficiently integrated. Therefore, we suggested some changes in the standard in order to increase quality for the end-users: (1) a classification in intervals for some parameters rather than thresholds (this would provide the end-user with a more homogeneous quality product); (2) a class with higher demands on mechanical durability; and (3) a threshold for maximum pellet length (as discussed in Paper **III**). In addition,

since the performance of the transport system for bulk transports is critical, suitable transportation regulations concerning pellets, such as those described in the European standard for solid biofuels (CEN /TS 15234, 2006), should be compiled.

Summary of Paper IV

In this work, wood fuel pellets are produced from sawdust mixed with various percentages of rapeseed cake in a pilot-scale pelletising machine. The aim was to investigate how the energy consumption changes when an increased amount of rapeseed cake was used. Furthermore, analysis concerning the pellet quality was made, which investigated how the physical parameters, such as mechanical durability, bulk density and length of pellets, are affected by the use of rapeseed cake, in accordance with the Swedish Standard (187120) for pellets. In addition, a method to be used for pellets produced in a pilot-scale pelletising machine was developed and improvements were presented.

The pellets were produced in a complete pilot-scale pellet production unit (Figure 16) located at the Department of Energy, Environmental and Building Technology at Karlstad University, Sweden.

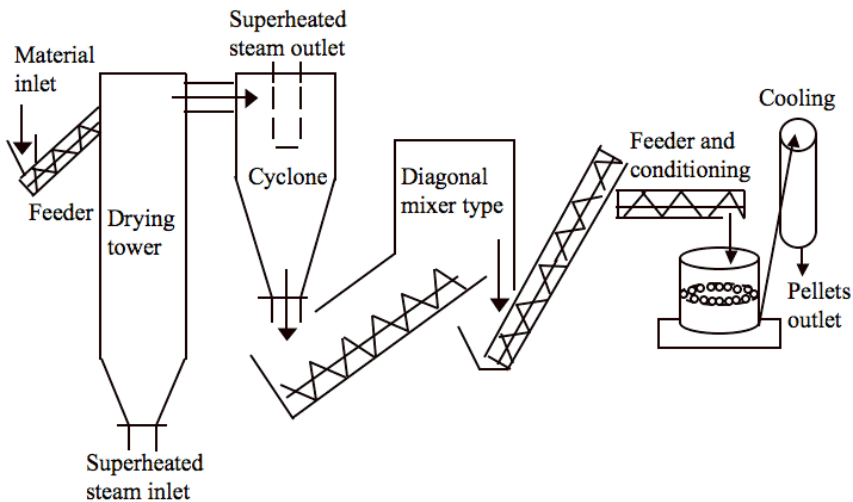


Figure 16. The pellet production line at Karlstad University.

The raw materials used were sawdust, Scots Pine (*Pinus Sylvestris*) and rapeseed cake (amount of rape oil was 18% [wb]). The latter is a residual product from the production of a chemically unchanged oil that is refined from cold-pressed rape oil. The tests were performed under similar steady conditions concerning die pressure, die temperature, screw frequency and moisture content of the raw material for reliable results. Before running the last series of tests, the pellet machine, especially the die, was reconditioned in order to investigate effects of

clogging of the die. A reference test was made with 0% rapeseed cake at a screw frequency of 3.5 Hz. During the pellet production, the die pressure, the die temperature, the screw frequency and the load current of the pelletising machine were measured.

The conclusions drawn from this work were: (1) the energy consumption decreases with an increase in the amount of rapeseed cake in wood fuel pellets (Figure 17); (2) the mechanical durability could decrease with an increase in the amount of rapeseed cake in wood fuel pellets (Figure 18); (3) the bulk density of pellets seems to decrease (and the length to increase) with an increased amount of rapeseed cake in pellets; and (4) tests performed with a reconditioned die and a clean pellet machine yield test results with smaller standard deviation.

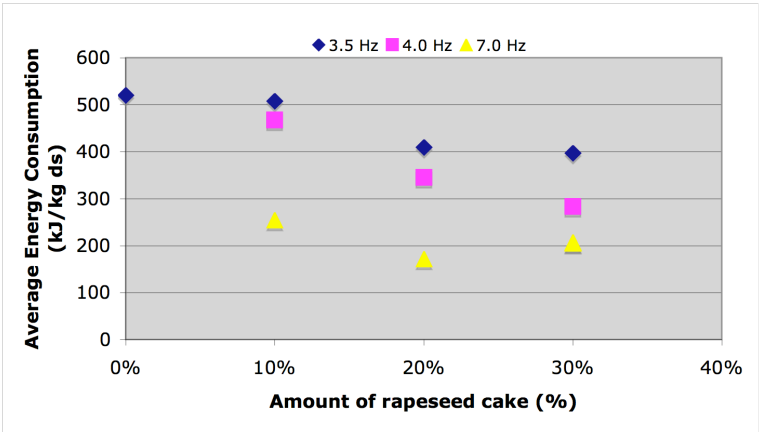


Figure 17. Average energy consumption of the pelletising machine vs. amount of rapeseed cake in the pellets at three different screw frequencies (Hz).

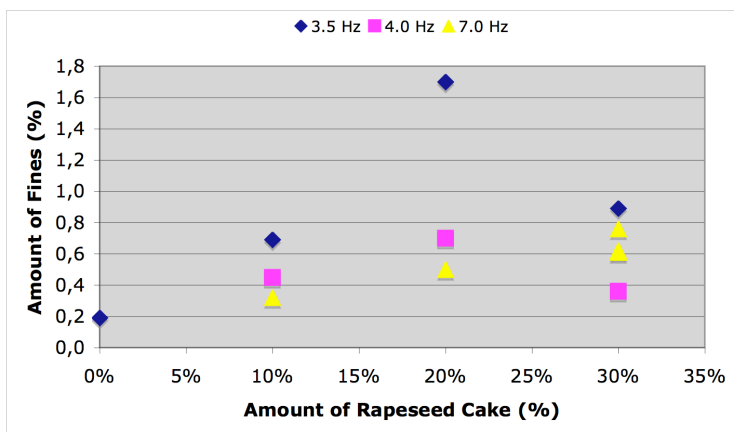


Figure 18. Amount of fines in the cooled pellets vs. amount of rapeseed cake in the pellets at three different screw frequencies (Hz).

The results presented above indicate that a compromise between a decreased use of energy and a decreased durability has to be made.

Summary of Paper V

The use of wood fuel pellets increases rapidly. Since the technology and the market are young and in rapid progress, there is an urgent need for communication of knowledge and experiences. Therefore, the aim of this paper is to present a survey of research on wood fuel pellets technology, focusing on quality and environmental aspects. The system boundary for the study is set to contain the wood fuel pellet chain from where the raw material arrives at the pellet factory to where the ashes leave the combustion unit (see Figure 19).

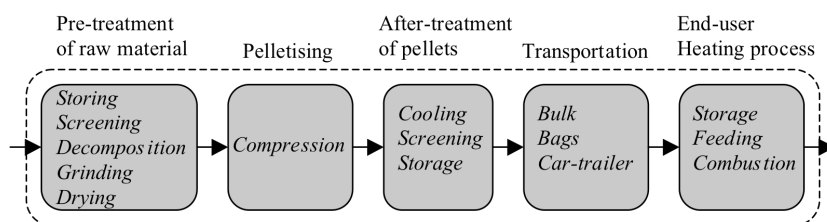


Figure 19. The studied wood fuel pellet technology.

This study is based on a literature survey made of the scientific literature, i.e., articles in scientific journals, and a survey of grey literature, such as conference papers and reports (from independent research laboratories, The Swedish Energy Agency, etc.). The scientific articles were found using databases, such as Compendex (2007) and ScienceDirect (2007).

In this study the technology of the wood fuel pellet chain is described and divided into the following areas: pre-treatment; pelletising and after-treatment (i.e., the production process); transportation; and the end-user heating process. The quality and environmental aspects of wood fuel pellet technology are presented for each area. We conclude that the concept of quality should be used with greater care in the scientific literature. The concept of quality needs to be given more stringent, precise and general definitions.

We conclude that scientific research on the wood fuel pellet chain is fragmented. A few areas, such as combustion processes, are well understood. Most areas, however, including several technically or economically important ones, have scarcely been investigated. We call for more research in these areas.

In the short run, the end-user perspectives and experiences should be investigated in order to identify the key areas that should be improved upstream

the pellet chain. Here, it is important to distinguish between quality that is end-user oriented and quality that is based on pellet characteristics, implying that a pellet that fulfils the quality standard may not be sufficient to ensure a proper function at the end-user site.

Furthermore, there are almost no system studies that cover the entire wood fuel pellet chain. Such studies could be important for the pellet producers and for creating sustainable systems that avoid sub-optimisations. Energy efficient bioenergy combines could be the solution that reduces the overall use of both energy and costs. In addition, we think that more knowledge is needed about the environmental and health effects along the pellet chain, especially at the household level.

In the long run, more knowledge is needed about the physical and chemical processes that form pellets out of wood fibres and other materials. This knowledge could be used both to improve the present industrial processes and to develop new technological solutions.

Discussion

Through my research, I hope to contribute to the knowledge base regarding how to improve the wood fuel pellet as a product and how to improve the wood fuel pellet technology with respect to pellet quality, energy efficiency and environmental aspects. Since the use of wood fuel pellets has increased rapidly during the last decade, and is expected to do so henceforth, the importance of these issues will be even greater in the future. An increase in pellet use means that new raw materials will be used, and this will affect: (1) the quality of the product as new raw materials have other chemical and physical properties; (2) the energy efficiency depending on how the new materials behave in the production and heating systems; and (3) the environment due to more complicated transport and handling systems.

Quality

Clearly, drying technology is important for fuel pellet quality. During drying of raw material for pellet production, it is possible to control important wood fuel pellet properties, including the moisture content. For example, Berghel & Renström (2004) show that the temperature of emitted drying gases can be used to control the moisture content of dried material. The moisture content of the pellets, which was studied in Paper I represents an important physical parameter that affects pellet quality in several ways.

The standardisation of wood fuel pellets in Sweden is crucial for the market development. The standardisation is also crucial for the small-scale consumers' need for good and even quality pellets. Still there is some work to be done concerning the standardisations, since quality variations between different pellet deliveries occur. This is also stated by the Swedish Energy Agency concerning amount of fines, bulk density and ash (Swedish Energy Agency, 2007b). In addition, other quality parameters might be added (Paper III). Also, the introduction of parameter settings using intervals could imply a more even quality of the pellets delivered to the end-user.

The use of additives and mixes of raw materials could improve the quality of wood fuel pellets. This might prove to be even more important during the coming years if the market for pellets continues to increase or demands for new types of pellets (a 2nd generation of pellets) are raised due to new applications that call for other product qualities than the qualities associated with pure

stemwood pellets (discussed in Paper V). Paper IV showed that the amount of fines increased when using rapeseed cake mixed with sawdust. To increase the durability there are other additives (e.g., extractives in wood) that could be used.

In an overview of activities in pellets R&D in Europe (Olsson & Vinterbäck, 2005), it is reported that there were over 110 active research groups involving over 200 researchers in Europe in 2005. Accordingly, there is a lot of technical research, whereas only a few specific links of the pellets chain are being examined (Paper V). However, the technical development of the fuel pellet and the pellet system need more attention. The pending transition into a 2nd generation of fuel pellets requires that researchers give priority to the end-users' requirements regarding the quality of fuel pellets. Different pellet assortments (qualities) could be sold to different users.

Efficiency

The energy efficiency of the drying process may be increased through the recirculation of drying gases, if integration with, e.g., a condenser connected to a district-heating grid is used (Paper II). Further, the dew point of the gases leaving the dryer can increase under certain circumstances, which implies that more energy could be recovered. Due to changes in the mass transfer driving forces, there is a conflict, however, between an increase in recovered energy (increased recirculation) and the capacity of the dryer. In economic terms, this is a conflict between reduction of energy costs and reduction of capital costs. Running the dryer as efficiently as possible is important, but the capacity of the dryer, the effect it has on the quality properties of wood fuel pellets and the environmental effects must be considered.

Rising prices of fossil fuels and environmental aims to replace fossil fuels with renewable resources speak in favour of wood fuel pellets. The wood fuel pellet is a national fuel that supplies a substantial amount of energy in Sweden, both as heat and electricity. The increase in pellet production can continue if new raw materials are used. Using new raw materials or mixes of raw materials could improve the efficiency (Paper IV). There may, however, be negative effect on the quality of the pellets.

Environment

The environmental problems related to the increase of fuel pellet production needs to be counteracted, e.g., by preventing emissions. During pellet

production almost all of the monoterpenes are emitted and most of them are emitted during the drying step (Paper I). If the dryer is run under controlled conditions with regard to temperature and residence time, it is possible to control the emissions of monoterpenes. Furthermore, the choice of drying technology, the residence time of the dried material and the initial drying medium temperature all affect the amount of emitted monoterpenes (see Paper I). Controlling the emissions of monoterpenes could reduce health problems of workers at the pellet plants and reduce the formation of photo-oxidants.

The expanding production implies that more people will work in the industry. The literature survey of Paper V shows that the biggest challenge for the pellet industry, concerning health is to protect their workers from dust exposure.

Further Work

There are very few publications that combine the drying of the raw materials with the quality properties of wood fuel pellets. Often the focus is set on the pelletising process without paying attention to how the choice of dryer technology and dryer parameter settings affect wood pellet quality. The result could be that the interaction/interrelation between drying and pelletising is overlooked and that sub-optimisations in the system could occur. Therefore, research that aims at investigating dryer performance and its effects on chosen pellet quality parameters should be performed, as well as system studies of the whole pellet chain. Issues such as how drying gas temperatures and raw material residence times in the dryer affect pellet quality could be studied. The ultimate goal is an energy efficient dryer, used in a wood fuel pellets production chain that produces high quality pellets that fulfil the end-users' need for and expectations on the pellets.

Paper II raised several questions that should be studied further, such as: How does the increased recirculation affect the dryer capacity? How and to what extent is the mass and heat transfer coefficients affected by the increasingly humid drying gases? Further, in the model presented in Paper II, the flue gases are led directly to the dryer, which means that a lot of substances are mixed within the dryer. This could be environmentally hazardous and it could pose a fire hazard. A heat exchanger or other solutions to this problem would be interesting issues to examine in order to make environmental improvements and create a less inflammable system.

The importance of the wood fuel pellet quality, in terms of being a transport and fuel product and in terms of how the product and surrounding services fulfil the customers' needs and expectations, is discussed above. As a natural continuation of the study in Paper **III**, it would be interesting to do a survey based on, e.g., interviews and questionnaires. Not only the end-user view on quality would be of interest but also the view of the seller, the distributor, the installer, the producer and the insurance companies. In addition, a comparison between users in Sweden, who often use half automatic two component device household heating systems (a pellet burner combined with an oil boiler), and users in Austria, where the systems are often fully automated allowing a modulated operation and automatic ash removal, should be interesting.

With an increased use of pellets in the world, new raw materials (other than sawdust from stemwood) are most likely to be introduced industrially. Bark, peat, logging residues, lignin, and agricultural energy crops could come into use for pellet production (Paper **IV**). The new raw materials could be used instead of stemwood sawdust, be mixed in with sawdust or be used as an additive in sawdust pellets. Lignin, for example, could be used as an additive, i.e., as an admixture in sawdust pellets with the purpose of improving, e.g., the durability of the product. Furthermore, it could be mixed in to a greater extent to gain other advantages, or it could be pelletised and used as a fuel in a district heating plant. The latter is performed in Bäckhammar (Sweden) where the company Lignoboost has a new process at the paper mill that produces lignin and converts it into pellets that are used at the plant of Värtaverken in Stockholm (Sweden). This could shake the pellets market in the coming years when the technology and market is ready for it. Further work should therefore concentrate on investigating how the quality of the pellets changes due to new material or mixes of raw materials in the pellets. Furthermore, it is necessary to investigate the environmental impact of new raw materials. When new raw materials are used, additives may be needed to provide high quality pellets. In future work, it would be interesting to investigate how chemical and thermal activation of additives before pelletising affect the pellet quality parameters. In the development of the 2nd generation of pellets, I think it is important to prioritise the end-users' requirements on the fuel pellets (discussion in Paper **V**). Therefore, additional studies with a focus on the consumer are needed concerning pellet quality, but also concerning environmental and health effects.

Acknowledgements

Work like this requires support in various ways and I would therefore like to give my gratitude to the people that made this thesis possible.

Firstly, I wish to express my gratitude to my supervisor, Professor Bengt Månsson, for all his support and encouragement. Thank you for our many fruitful discussions.

My gratitude also goes to Dr Jonas Berghel, Dr Roger Renström, Dr Fredrik Wikström and Dr Karin Granström for all the support they have given me and for being there when I needed them, professionally, as good colleagues/friends and co-writers of my papers.

I also wish to thank all my colleagues at the Department of Environmental and Energy Systems at Karlstad University for making it an interesting, inspiring and fun place to work at.

Karolina Schultz Danielsson, thank you for correcting my written English.

To my most supportive and caring fans, my wife Lisa, my son Hugo and the rest of my family, I give all my love. Thank you for always being there when I need you the most.

“My friends, you bow to no one”²⁰

²⁰ From the movie “The Lord of the Rings - The Return of the King”. Directed by Peter Jackson. Original story from the book “The Lord of the Rings” by J.R.R. Tolkien.

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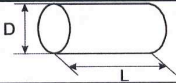
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Appendix I. The European Standard for Pellets CEN/TS 14961

CEN/TS 14961:2005 (E)

Table 5 —Specification of properties for pellets

Normative	Master table	
	Origin: According to 6.1 and Table 1	Woody biomass (1), Herbaceous biomass (2), Fruit biomass (3), Blends and mixtures (4)
	Traded Form (see Table 2)	Pellets
	Dimensions (mm)	
	Diameter (D) and Length (L)^a	
	D06	≤ 6 mm ± 0,5 mm and L ≤ 5 x Diameter
	D08	≤ 8 mm ± 0,5 mm, and L ≤ 4 x Diameter
	D10	≤ 10 mm ± 0,5 mm, and L ≤ 4 x Diameter
	D12	≤ 12 mm ± 1,0 mm, and L ≤ 4 x Diameter
	D25	≤ 25 mm ± 1,0 mm, and L ≤ 4 x Diameter
	Moisture (w-% as received)	
	M10	≤ 10 %
	M15	≤ 15 %
	M20	≤ 20 %
	Ash (w-% of dry basis)	
	A0.7	≤ 0,7 %
	A1.5	≤ 1,5 %
	A3.0	≤ 3,0 %
	A6.0	≤ 6,0 %
	A6.0+	> 6,0 % (actual value to be stated)
	Sulphur (w-% of dry basis)	
	S0.05	≤ 0,05 %
	S0.08	≤ 0,08 %
	S0.10	≤ 0,10 %
	S0.20+	> 0,20 % (actual value to be stated)
	Mechanical durability^a (w-% of pellets after testing)	
	DU97.5	≥ 97,5 %
	DU95.0	≥ 95,0 %
	DU90.0	≥ 90,0 %
	Amount of fines (w-%, < 3,15 mm) after production at factory gate	
	F1.0	≤ 1,0 %
	F2.0	≤ 2,0 %
	F2.0+	> 2,0 % (actual value to be stated)
	Additives (w-% of pressing mass)	
	Type and content of pressing aids, slugging inhibitors or any other additives have to be stated	
	Nitrogen, N (w-% of dry basis)	
	N0.3	≤ 0,3 %
	N0.5	≤ 0,5 %
	N1.0	≤ 1,0 %
	N3.0	≤ 3,0 %
	N3.0+	> 3,0 % (actual value to be stated)
Informative	Net calorific value, $q_{p,net,ar}$ (MJ/kg as received) or energy density, E_m (kWh/m ³ loose)	
	Recommended to be informed by retailer.	
	Bulk density as received (kg/m ³ loose)	
	Recommended to be stated if traded by volume basis	
	Chlorine, Cl (weight of dry basis, w-%)	
	Recommended to be stated as a category Cl 0.03, Cl 0.07, Cl 0.10 and Cl 0.10+ (if Cl > 0,10 % the actual value to be stated)	

^a Maximum 20 w-% of the pellets may have a length of 7,5 x Diameter.

Appendix II. The “Svanen” Quality Specification for Pellets

Grade specification: The following parameters must be tested and fulfilled. Samples shall be taken from the manufacturer’s stocks.

Physical properties/dimensions	Unit	Limit value	Test method
Size class I (CEN D06)			
Length in manufacturer’s stock*	mm	max 5 x Ø	
Diameter Ø	mm	$\leq 6 \pm 0.5$	
Size class II (CEN D08)			
Length in manufacturer’s stock*	mm	max 5 x Ø	
Diameter Ø	mm	$\leq 8 \pm 0.5$	
Bulk density	kg/m ³	a) $630 < x \leq 700$ b) $700 < x \leq 780$	CEN/TS 15 103
Fines content < 3.15 mm	% by weight	≤ 1	CEN/TS 15 149-1
Mechanical durability	% by weight	≥ 97.5	CEN/TS 15 210-1
Energy density	MJ/kg kWh/kg	≥ 17.1 ≥ 4.75	CEN/TS 14 918
Moisture content	% by weight	≤ 10.0	CEN/TS 14 774-1,2
Ash content of dry matter	% by weight	≤ 0.5	CEN/TS 14 775
Ash melting behaviour	°C	IT ≥ 1300 HT ≥ 1400	CEN/TS 15 370-1

*A maximum 20% (w/w) of pellets may have a length of 7.5 x Ø

Chemical composition	Unit	Limit value	Test method
Total sulphur content	% by weight	≤ 0.04	CEN/TS 15 289
Chlorine	% by weight	≤ 0.02	CEN/TS 15 289
Nitrogen	% by weight	≤ 0.3	CEN/TS 15 104

Improving Wood Fuel Pellets for Household Use

This work concerns wood fuel pellets for household use. The primary raw material for wood fuel pellets is sawdust, which is dried and compressed to attain improved fuel and transportation properties. Altogether, in 2007, 1 715 000 tons, which is equivalent to a sales value of more than 2 billion Swedish crowns, were delivered to the Swedish pellet market. Of this, almost 40% were delivered to the Swedish households.

The overall aims of this work are to improve wood fuel pellet quality, increase the energy efficiency of the production and lessen the environmental impact. The specific aims of this work are: to examine changes in key quality parameters and potential environmental effects during the drying and pelletising steps of the pellets production (Paper I); to find out how to improve the energy efficiency of rotary dryers and how the energy efficiency is related to the capacity of the dryer (Paper II); to identify the causes of the problems encountered by household end-users of pellets and suggest modifications of the pellet quality standard in order to reduce these problems (Paper III); to determine how the energy consumption of the pelletising machine and chosen pellet quality parameters were affected using an increased amount of rapeseed cake in wood fuel pellets (Paper IV); and to identify gaps of knowledge about wood fuel pellet technology and needs for further research on quality, environmental and health aspects throughout the wood fuel pellet chain, from sawdust to heat (Paper V).