Geir Skjevrak

Wood Pellets Utilized in the Commercial and Residential Sectors

- an in-depth study of selected barriers for increased use

Thesis for the partial fulfillment of the degree of doctor philosophiae

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Norwegian University of Science and Technology
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Preface

This thesis is submitted as partial fulfillment of the degree Doctor of philosophy at the Norway University of Science and Technology (NTNU).

This work was carried out at the Department of Energy and Process Engineering, NTNU.

Professor Johan Einar Hustad has been the main supervisor of this Ph.D. study.

Statoil ASA has financed parts of my work. I gratefully appreciate them for that giving me this opportunity to increase my skills, and understanding of biomass fuels and biomass systems.

Geir Skjevrak

Acknowledgement

The author has worked for several years to build up a business among wood pellets manufacturing and marketing in Scandinavia. This experience has given interest for R&D efforts in selected topics which can develop this immature industry. This Ph.D. work is a selection of a few certain R&D needs in the renewable energy pellets market. The author hopes that this work and the events around it will be a contribution towards more use of renewable energy.

I also would like to offer my gratitude to:

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This Ph.D. work has not been part of any project. All the ideas, planning, financing and performing is the author main responsible for.

Abstract

Biomass is an important energy carrier since it is a renewable source and the energy content in the fuel can be stored over time and also generate high temperatures. Bioenergy can be in liquid form, gas-phase or solid. The most common-phase is as a solid. Before use, the biomass needs harvesting and refining. Pelletization is one of the most promising solid fuel qualities with a wide range of benefits which are needed before the product can enter the market and compete with more traditional sources of energy like heating oil and electricity.

Despite its benefits, the pellet market still requires development. Several barriers need to be lifted such as understanding the market behavior, finding how bioenergy systems are adapted and what the level of technology is. Pellet feedstock is normally bi-products from sawmills, but increasing demand makes other feedstock alternatives interesting. Pulpwood from pine, straw and husk from agriculture and residue from the furniture industry are examples of new types of feedstock for pellet production. Different feedstocks can bring challenges due to the mechanical properties of the pellet fuel. Also chemical properties can be demanding if the inorganic content in the feedstock is high.

The main objectives of the present work are divided into three selected areas; small scale pellets users in Norway, pretreatment of pure feedstock from pine and manufacturing of low-grade feedstock pellets with additives.

The following research questions were settled for the work: 1) Which factors lead single household owners to choose wood pellet stoves compared to heat pump solutions and direct electrically heated systems? 2) How will existing users of wood pellets stoves choose if they should have any new system? 3) What is the practical experience of existing wood pellet stove users with aspects like the technical properties of fuel, stove or stakeholders? 4) How does extended storage of pine feedstock affect the mechanical pellet quality? 5) How does high and low temperature drying of pine feedstock affect the mechanical pellet quality? 6) How is the mechanical quality properties of pellets affected by the use of different selected additives? 7) Is the low-grade feedstock pellets

made with additives combustible in ordinary grate furnaces/boilers? 8) How are the ash melting properties of difficult fuels affected by the use of selected additives?

The research questions are aimed to solve by investigation of market penetration of wood pellet stoves through a survey. Further new pellet feedstocks like pulpwood, agricultural and furniture residues have been produced and tested. Also mixtures with different additives have been produced. The purpose of additives is mechanical fuel quality improvement and increasing the melting point of the ash in the fuel. Finally the new pellet fuel assortments were combusted and tested.

All experiments and data collections performed this work is done in an industrial context. Chipping, grinding and pelletization were performed in ordinary industrial plants. Feedstock samples are collected from ordinary harvesting or side-product processes. Combustion is performed in ordinary furnaces/boilers. All processes mentioned above were set up with necessary measurement equipment. This way of experiment approaches have given good validity of the results from the experiments.

The market investigation work was performed by a questionnaire among 188 random non-wood pellet users and 461 wood pellet users in Norway. The survey reached a response rate of 45 % from the existing wood pellet users. Factors that influence the decision of purchasing a heating system were identified like the age of the consumer, regional constraints in the availability of pellets and also that economic competitiveness is also weak compared to electrical heating. It was also found that pellet stoves need technical improvements to meet the end-user expectations. The ignition, control system, noise and imperfect combustion are examples of technical factors which need improvement.

New pellet feedstocks need treatment prior to the pelletization process. Such process steps are chipping, grinding, storage, drying and possibly the use of additives. In this thesis, several feedstock assortments were manufactured. Pine pulp was stored outside for a year and dried at both high and low temperatures. The high temperature dried material and also stored material resulted in higher energy use for pelletization. There

was lower energy consumption for fresh, low temperature dried material. Fresh material was found to have higher durability.

Barley straw, barley husk and residue from furniture contain a larger amount of ash and a higher concentration of problematic ash-forming elements compared to conventional woody biomasses. This causes normally severe ash sintering and slagging which were observed in this study.

Different raw feedstock were pelletized and combusted together with different additives. These additives might have multifunction such as: 1) improve the properties of fuel pellets from the mechanical point of view and 2) abate fuel ash slagging to achieve an efficient and smooth combustion process.

In this work, each raw feedstock was pelletized with different additives in various additive-to-fuel ratios. The influence of additive addition on the pellet production process (i.e., power consumption) and pellet properties (i.e., bulk density, durability and particle density) were investigated. For furniture residue, both sewage sludge and marble sludge improved the durability of the pellets. But when there was a high content of marble, the durability was reduced and the levels of fines increased. Barley straw and barley husk durability were also improved with the lignosulfonate additive. With the marble sludge additive the barley husk durability was increased. Opposite barley straw durability was lowered with marble sludge additive. With combinations of both additives, the positive effect of marble sludge additive for both the barley straw and barley husk was to some extent eliminated.

There are significant differences between the composition and ash chemistry of the formed slags. The slag from wood wastes was dominated by K, Na, Si and Ca, which were completely melted and fused into large blocks. The results from the chemical composition analyses of slag samples suggest intensive formation and fusion of low temperature melting alkali silicates. For the barley straw and barley husk that are rich in Si, K, P and Ca, most of the K reacts with both P and Si in ash residues and forms ash melts containing low temperature melting potassium silicates and phosphates. The ash

melts were not transported from the grate area in the furnace and gives thereby initiated and enhanced ash slagging which reduces the operation stability of the furnace.

Lignosulfonate, marble sludge and sewage sludge are proposed as additives to mitigate ash slagging during the combustion of the studied fuels. Marble sludge served as the most efficient additive to eliminate ash slagging during the combustion of pelletized barley straw, barley husk and wood wastes, respectively. The addition of marble sludge led to the formation of high temperature melting calcium-rich alkali silicates and/or phosphates. This process was accompanied by a significant reduction in ash melts and slag formation.

A less pronounced anti-slagging effect was observed from the combustion of lignosulfonate added to barley straw and barley husk pellets. However, the addition of lignosulfonate altered the ash chemistry and promoted the formation of high temperature melting potassium calcium phosphates in ash residues. As result of this, the fraction of ingoing fuel ash that forms slag decreased, and the slags had smaller size and a lower degree of sintering. The addition of sewage sludge slightly reduced the slag formation during the combustion of wood waste pellets. This occurred because sewage sludge contributed to the formation of high temperature melting alkali aluminum silicates.

List of Publications

The thesis is based on work presented in the following papers, referred to in the text by Roman numerals:

I. Filbakk, Tore; **Skjevrak, Geir**; Høibø, Olav Albert; Dibdiakova, Janka; Jirjis, Raida.
The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters. *Fuel Processing Technology*; Volume 92. (5). 871-878, **(2011)**.

II. **Skjevrak, Geir**; Sopha, Bertha Maya. Wood-Pellet Heating in Norway: Early Adopters' Satisfaction and Problems That Have Been Experienced. *Sustainability*, Volume **4**.(6) s. 1089-1103, **(2012)**.

III. Sopha, Bertha Maya; Klöckner, Christian; **Skjevrak, Geir**; Hertwich, Edgar G.
Norwegian households' perception of wood pellet stove compared to air-to-air heat pump and electric heating.
Energy Policy, Volume **38**.(7). 3744-3754. **(2010)**.

IV. **Geir Skjevrak**, Liang Wang, Filbakk, Tore, Henrik Kofoed Nielsen, Johan E. Hustad.
Effects of lignosulfonate and marble sludge additives on the mechanical properties of pellets of barley husk and straw fuel pellets.
Submitted to Fuel Processing Technology, under review.

V. **Geir Skjevrak**, Liang Wang, Johan E. Hustad.
Slagging Characteristics during Combustion of Biomass Pellets and Effect of Additives. *To be published.*

VI. G**eir Skjevrak**, Liang Wang, Michael Becidan. Øyvind Skreiberg.
Pelletizing and Combustion Behaviours of Wood Waste with Additives Mixing
Proceedings of 2012 Asia-Pacific Power and Energy Engineering Conference.
ISBN: 978-1-4577-0546-5

VII. Liang Wang, **Geir Skjevrak**, Johan E. Hustad, Morten Grønli.
Effects of Sewage Sludge and Marble Sludge Addition on Slag Characteristics during Wood Waste Pellets Combustion
Energy & Fuels, **25**, 5775-5785, **(2011**).

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Abbreviations

SS	Sewage Sludge
SSA	Sewage Sludge Ash
SEM	Scanning Electron Microscopy
EDX	Energy Dispersive X-ray Spectroscopy
XRF	X-ray Fluorescence
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectroscopy
XRD	X-ray Diffraction
IDT	Initial Deformation Temperature (°C)
ST	Soften Temperature (°C)
HT	Hemisphere Temperature (°C)
FT	Flow Temperature (°C)
AI	Alkali Index (GJ/kg)
$R_{a/b}$	Ratio of Basic to Acidic Constituents in Ash
$R_{a/b(+p)}$	Ratio of Basic to Acidic Constituents in Ash Considering Phosphorus

1 Introduction

This chapter gives an introduction to biomass as an energy carrier and why it is important. The background for the selection for research topics and objectives of the work are also stated. The organization of the thesis is explained at the end of the chapter.

1.1 Biomass and bioenergy

Biomass is one of the most important energy carriers in the world. This statement is maybe unexpected but true if you consider the number of people who have this energy source as their primary source. The biomass is used as firewood for cooking and charcoal manufacturing in developing countries. Almost half of the wood harvesting is used to energy purposes and more than 34 developing countries have covered more than 70 % of their total energy need from wood fuels [1].

Biomass has to some extent been forgotten. Cheap oil and coal have provided sufficient cheap energy to give economic growth. But increasing price levels of fossil energy and focus on greenhouse gas emissions have given renewed attention to biomass as an energy source. The intergovernmental Panel on Climate Change (IPCC) points out that biomass has the potential of a reduction of about 80-90 % of greenhouse gas emissions compared with fossil energy [2].

Biomass represents today about 10.2 % (50.3 EJ) of the totally primary energy supplied in the world [3]. With further development, bioenergy could play a more crucial role to change energy consumption into more renewable and environmentally friendly energy use. But the biomass resources cover many needs in addition to being a part of CO_2 system in the atmosphere; living place for flora and fauna, soil households, erosion controls, food production and more. Where and how to increase the use of biomass to energy is an important discussion, it should not be utilized if is not sustainable. The potential for increased use of biomass is high even before such considerations. It is suggested that the potential for increased use is in the range of 100 to 300 EJ. Figure 1 shows how the potential is distributed.

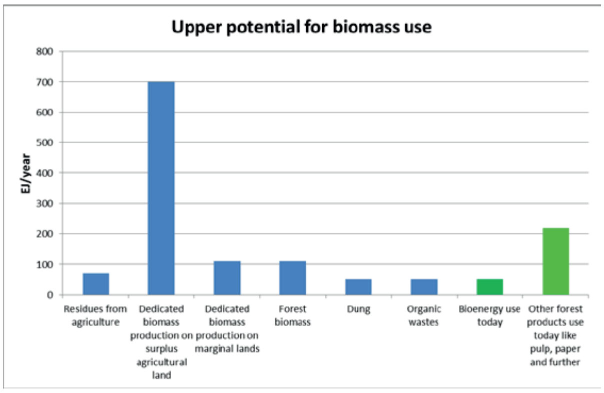


Figure 1 Upper potential for biomass use according to [2].

1.2 Biomass conversion pathways

Biomass exists in solid, gaseous and liquid forms. Biomass can also be processed and refined from solid to gas or liquids. Such processing depends on both the mass conversion and energy efficiency of the process. Figure 2 gives a schematic overview of the main pathways of bioenergy utilization.

Often energy with a high energy quality level i.e. oil and electricity is utilized for low grade energy purposes i.e. heat and steam production. Solid biomass to heat can also provide a high efficiency factor compared to liquid-based systems when the utilizing purpose is heat [4]. In that perspective, exchanging electricity, oil and gas with solid biomass in heat production would be a better utilization of the beneficial fuel properties of oil, gas and electricity to more high-grade energy use purposes. Thereby overall fuel efficiency might increase. Compared with other renewable energy sources, bioenergy is the only renewable that provides both capacity for long time storage and also can generate high temperature levels without conversion to electricity.

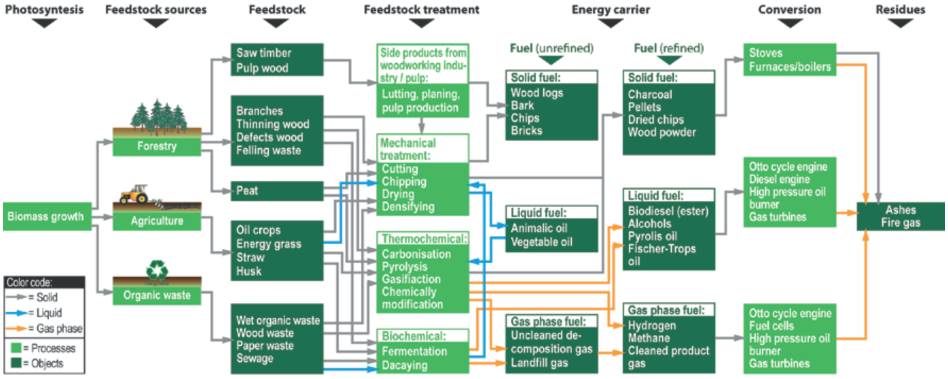


Figure 2 Biomass pathway to energy purposes (author’s figure).

1.3 Biomass as a fuel for energy production

Biomass properties

The biomass covers a wide range of biological materials derived from living or recently living organisms. The understanding and knowledge of biomass fuels properties and differences between them are important when creating energy systems. This chapter discusses important properties for high efficiency utilization biomass systems and advises pellets as a fuel quality with high potential. To understand utilization of different biomasses, it is crucial to characterize the different fuel properties. Figure 3 gives an overview of the main components in wood.

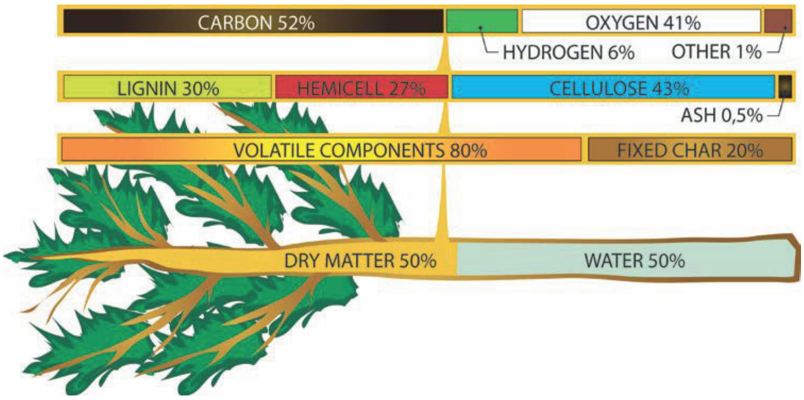


Figure 3 Physical structure of biomass with typical levels (author's figure).

Moisture

All kinds of biomass grown by photosynthesis have almost similar amounts of energy. This is due to the similar composition of the content. The energy content is determined by the share of carbon and hydrogen in the fuel. Other components like oxygen, nitrogen and ash do not make any contribution to the energy [5]. The moisture content of most of raw biomass materials varies significantly and spans a wide range from 10-70 % [6]. Biomass contains both intrinsic and extrinsic moisture. The extrinsic moisture of one biomass fuel is heavily affected by the prevailing weather conditions during the harvesting, transport and storage processes. High moisture content in biomass fuel is unwanted, since the heating value of the biomass fuel decreases with increasing moisture content. In addition, different problems may occur during combustion of biomass fuels with high moisture content. First, the ignition of fuel particles with be delayed, since extra time is needed to make the fuel particles dry enough to burn. With high moisture content, part of heat from the biomass fuel combustion will be used for drying raw feedstock, which in turn reduces the combustion temperature and efficiency. Second, larger amounts of flue gas will be generated during combustion of biomass fuels with high moisture content, and equipment with larger will be dimensions required [6].

Energy content and heating value

The energy content in the fuel is defined as:

Gross Heating Value (GHV): Heat released from combustion without any withdrawal for evaporation of the water created from the H-content in the fuel.

Net Heating Value (NHV): GHV deducted energy needed for evaporating water from H-content in the fuel.

Heating values are normally treated on a dry basis (d.b.) or dry ash free basis (d.a.f.).

Free water in the biomass fuel has to be removed; either as natural or forced drying before combustion or during combustion by using heat from the fuel to evaporate the water.

Effective Heating Value (EHV): NHV deducted energy needed for evaporating free water in fuel during combustion.

EHV can be calculated by following formula:

$$\boxed{EHV = 19 - 0.06 \cdot Mc \quad [MJ/kg]}$$

Mc: Moisture content (in % of raw weight) [%/kg]

The GHV might vary between levels from 10-22 MJ/kg for different biomasses. The EHV is closely related to the free water in the fuel.

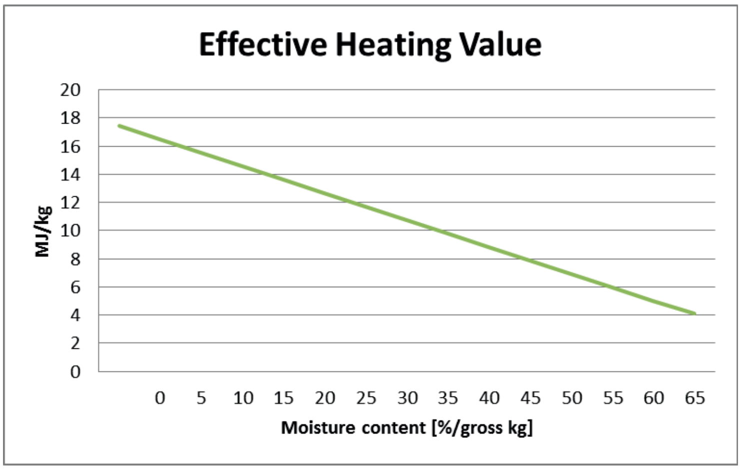


Figure 4 Effective Heating Value (EHV) as a function of the water content in fuel [7]

Density

Another parameter who limits the utilization of biomass to energy is the density of the fuel. Biomasses have a wide range of densities; differences can be as wide as 6 times from 100 to 600 kg m^{-3}. This is affecting strongly the potential for practical use since biomass bound for energy should needs normally to be stored, both at production sites, during transport and finally storage by the end user site.

Figure 5 illustrate different fuels and the need for space for a similar amount of energy:

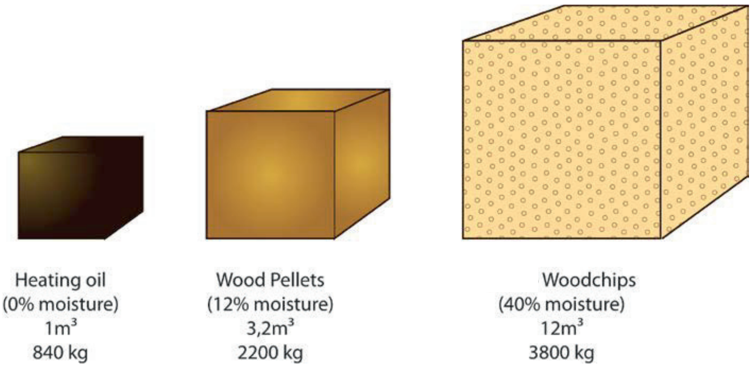


Figure 5 Volumetric comparison for different fuels with same amount of energy

Ash

Biomass fuels contain a wide range of ash forming matters containing the bulk of inorganic fraction of the original biomass. Ash forming matters in biomass can be inherent in the fuel or contaminations to the fuel during the processing steps. There are large variations for different biomass fuels in terms of ash content and concentrations of certain elements. The variations are related to many factors such as type of plants, growing conditions, utilization of fertilizer and harvesting time and methods. In general, the woody biomasses contain small amounts of ash that are normally dominated by elements Si and Ca. The agricultural crops and residues usually have high ash content, which are rich in K, Si, Ca and Cl. In addition, the P content of some cereal crops and grains is considerably high. The ash forming matters may transform and interact via complicated processes, ending up as bottom ash, fly ash and aerosol. Some of the intermediates and final products from the ash transformation process can cause operational problems such as ash sintering, slagging, fouling deposition and corrosion.

Particle size distribution

Considering the size of fuel, heterogeneity in fuels creates difficulty. The size of each particle and the distribution of such particles is very important for combustion. The surface / weight is important for the speed of drying, devolatilization and oxidation of the char. The different types of combustion technology are normally designed to handle a defined fuel type. But when a) large differences between particles with different ratios and b) large particles with low surface / weight ratios, this will complicate the practical combustion of the fuel particles. The ability to handle such differences is often weaker with small sized combustion equipment where cost savings are also is performed in design phase. Figure 6 shows the particle size distribution of a random sample of wood chips compared to pellets.

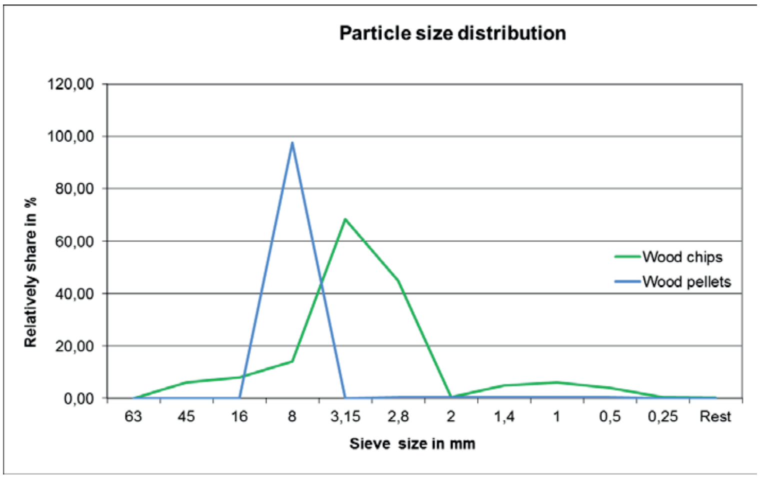


Figure 6 Particle size distribution differences between wood chips and wood pellets according to NS-EN 14961.

1.4 Size of combustion technology

Biomass combustion technology differs from thermal output from a couple of kW to the giants with outputs at about 750 MW_{th}. The feeding of fuel can be done continuously or in batches. Combustion technology providers have to offer cost-effective solutions. Small-scale solutions are vulnerable for regulation solutions handling differences in fuel properties. Therefore, in the range of economic feasibility, smaller equipment needs to be improved and have narrowed fuel properties.

The conversion technology which is to be selected to produce heat depends on several parameters; i.e:

- Available space for boiler, fuel storage, transportation of fuel and auxiliaries
- Availability of operating personnel
- Fuel availability; near bound or long distance?
- Output regulation profile

The technology for conversion of chemical energy in fuel can be divided into following principles in Table 1.

Table 1 Overview of the principles of common solid biomass combustion technologies (author's table).

Working principle	Area of application	Output	Fuel type
Wood stove/boiler	Single households	< 30 kW	Wood logs
Integrated	Single households	< 30 kW	Wood pellets
Pellets burner	Single households – retrofit of oil burner	< 20 kW	Wood pellets
Stoker/retort	Heating centrals	0.1-2 MW	Wood pellets/chips
Horizontal grate	Heating centrals	0.1-2 MW	Wood pellets/chips
Sloping grate	Heating centrals	0.1-20 MW	Wood pellets/chips
Wandering grate	Heating centrals	3-12 MW	Wood pellets/chips
Rotating burner	Heating centrals	0.1-0.6 MW	Wood pellets
Fluidized bed	Heating centrals	30 MW-600	Wood chips
Dust burner	Heating centrals	10 MW-200	Pulverized fuel

In a similar way, the type of fuel has to be considered and fit together with the fuel storage system, the fuel transport system, space available, boiler size and boiler technology. The demand for fuel quality normally increases when reducing the size of boilers.

1.5 Pellet production

Densification of biomass products have been performed for decades. Extrusion of biomass to animal feed pellets has been practiced for almost a century. But extrusion of wood to pellets for energy purposes and a specially designed fireplace for the utilization of it is only recently reported. In 1984, the inventor Jerry Whitfield, Oregon, USA demonstrated his stove fired with wood pellets and corresponding results like continuous operation and really low emissions compared to wood log stoves. Currently, in Nordic countries, woody biomass pellets are widely burned in different residential combustion appliances for producing heat. In addition, woody pellets are being combusted directly in large-scale boilers for producing heat and electricity as well.

The growth is driven by CO_2 reduction efforts and also that the oil prices have increased relatively more in the past decade.

The beneficial properties of wood pellets compared to other biomass fuels, makes them into an attractive fuel compared to more unrefined biomass fuels. Wood pellets have also properties that are similar to coal. This has made it possible to avoid large boiler / furnace investments in conversion technology in existing CHP production.

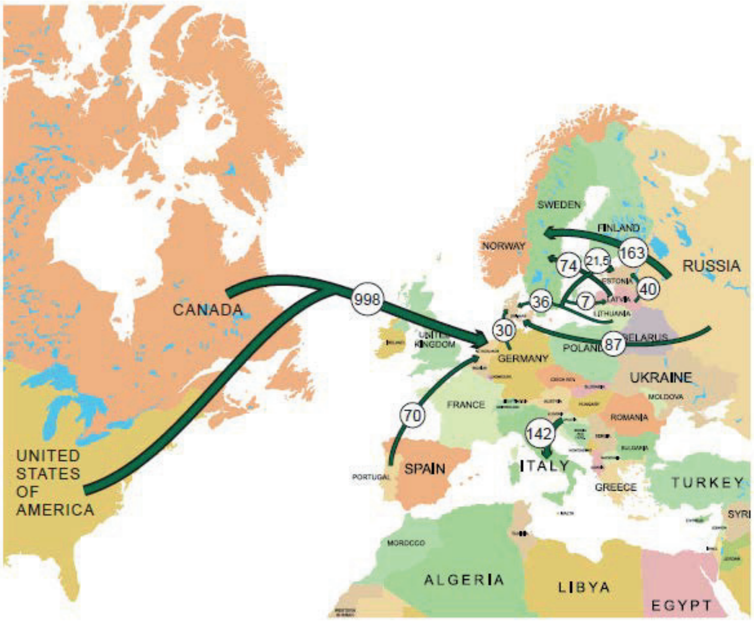


Figure 7 Indication of the flow of pellets worldwide in 2009. Figure made by data from [8]. Numbers in figure are the estimated annual flow of pellets in ktonnes.

The trade to Europe is caused by stronger environmental legislation, taxes on fossil fuels or subsidies of renewable fuels. The USA and Canada have high feedstock potential and low domestic demand [9]. Figure 7 illustrates the estimated main oversea flows of pellets in 2009.

The main advantages of pelletization are:

Bulk density Compared to raw woody biomass, produced pellets have significantly higher bulk density in the level from 550 kg/m^3 to 850 kg/m^3. Single pellet density is larger than 1 kg/dm^3. Work performed in this thesis has revealed levels of 1.2 kg/dm^3. The reason for the high particle density is caused by compressed lumen. Figure 8, a picture from work performed in paper I, shows the compressed lumen in the single pellets surface.

Moisture control In order to pelletize biomass fuel, its moisture content should be in a certain range to allow pelletization. Prior to pelletization, feedstock is normally dried artificially. For ordinary wood like the pine species, the highest durability achievable is for raw moisture levels like 7-13 % [10]. A low moisture level also improves the EHV value of the fuel, storage ability, reduces health impacts and self-ignition threats.

Granulate properties Woody pellets are also cylindrical granulate with certain bulk densities and sizes. The particle size is homogeneous over a narrow area. Therefore, woody pellets behave as solid single-shaped granulates that can easily be mechanically transported by small-sized conveyors, small screws or by a pneumatic conveying system.

Simpler combustion systems Since pellets are easier to handle and dry, the transport, storage and combustion systems can be manufactured more simplified and cheaper than other biomass fuels.

Low emission possibilities Due to its homogeneity and small particles, pellets furnaces can be operated continuously with fuel feed regulated by heat demand. Further the air addition can be made with corresponding levels. Emissions from a well-controlled wood pellets combustor are considerably lower than, those from wood-log based systems [11].

Cofiring with conventional fossil fuels The easy storage, the dryness of the fuel and also the homogeneity and small particles, all make the fuel possible to retrofit to both oil and coal fired furnaces, from large-scale CHP plants to small-scale household boiler burners [11].

Transport and storage ability The removal of water makes the fuel more possible to store over time if certain principles for storage are considered [12]. Also the high bulk density means that there are large benefits in terms of the space needed for storage and transport.

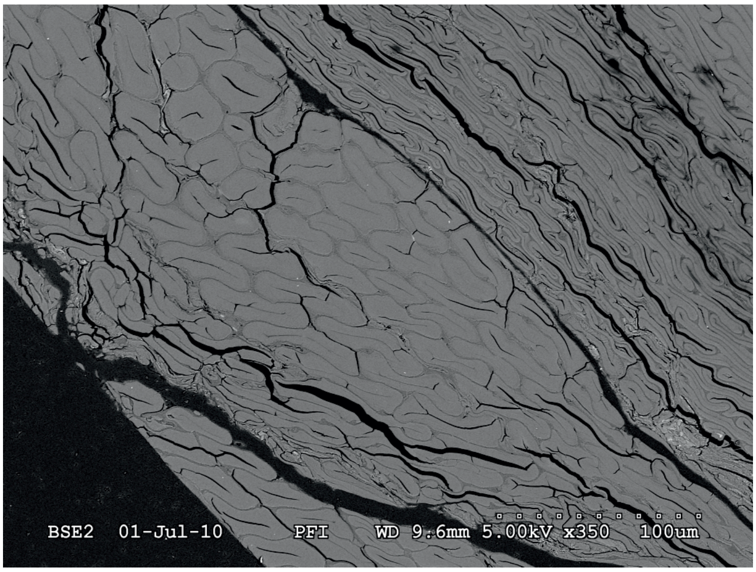


Figure 8 SEM picture with 350x magnification showing macro structure of a single pellets radial surface from work performed in paper I.

Tradability Compared to raw or original biomass fuels, wood pellets are a rather homogeneous fuel. This makes this product easier to be standardized in terms of quality parameters. High energy density, low degradation during storage are among the other advantages mentioned in this chapter. The standardization work is developing around the world and there is also a certain merging of standards. This is especially valid in Europe where EN 14961 is increasing being used [13].

1.6 Research motivation

The development of objectives is influenced strongly by the author's experience in the market with the production, marketing, logistics and heating plant constructions for wood pellets in Norway. The approach to develop the research objectives was to work with topics experienced as difficult and difficult for business development. Since the author had access to physical materials like fuel, manufacturing and test equipment, complete customer lists and more, it was considered to utilize this access beneficially.

The beneficial properties of wood pellets have considered their degree of refining compared with other solid biofuels worldwide. Benefits like high bulk density, homogeneity and the ability to store the product makes the fuel attractive when it competes with other energy carriers. In addition, a lot of attention is given due to it being a renewable source, locally supplied and often in a local market. Workplaces are created and the forestry and wood industry see a new market. Innovators see that here they can develop new businesses in all parts of the value chain. But the growth is fast and necessary knowledge is not often achieved. Or such knowledge does not exist.

In the end, the customers too often become disappointed when the new system does not meet their expectations. Capital owners do not get return on their investment. The government does not achieve their political expectations. This fact can also be seen in several parts of the market where Norway is an example.

In Norway such system failures have only been briefly studied so far. Since the first startup of the Cambi Bioenergi AS factory in Vestmarka in 1993 and the trials of the consultant company Silvinova in Elverum in the years ahead, there have been several major problems which can be grouped in following way:

Factory challenges

Establishing of pellets production in Norway has been driven by ambitious founders with a strong believe of the future of such industry. Accomplished by funding subsidies from the government, the establishment of such is mainly characterized by failures. The following pellets factories were established in Norway and then shut down:

Vaksdal Biobrensel at Dalekvam, Hordaland.
Cambi bioenergy at Vestmarka, Hedmark.
Rendalen biobrensel at Øvre Rendal, Hedmark.
Norpellets at Andebu, Vestfold
Frya bioenergi at Ringebu, Oppland.

Production facilities which are still operating have different levels of success, Table 2 shows the financial results in the period 2010-2012 for companies which are assumed to only have wood pellets production in its accounting system:

Table 2 Financial results for the wood pellets industry in Norway.

	Hallingdal Trepellets			**Pemco Trepellets**			**Vi-Tre**		
	2010	**2011**	**2012**	**2010**	**2011**	**2012**	**2010**	**2011**	**2012**
Estimated prod.level in tonne/year	14 000			21 000			7000		
Turnover kNOK	25 460	22 801	24 558	53 000	38 103	51 571	7 635	7 146	7 305
Profit/loss after tax kNOK	-5 531	-11 220	-4 107	4 077	1 433	2 844	-1 182	-1 786	-2 751

The table is derived from the companies annual official accounts and [14]. The major explanations of shut-downs is lack of feedstock, no possibility to achieve the necessary volume and a gap between the cost of feedstock and product prices in the market.
But there are also some technical and operating behavior issues which, from the author's view, explain the lack of growth in Norway. In Figure 9, a respondent written comment in a survey done in Papers II and III is shown. This response from a wood pellets stove user illustrates one of the experienced main challenges from the introductory work on wood pellets in Norway

Fuel quality challenges

Energy pellets have both mechanical and chemical parameters which affect the utilization of the product. The quality is normally regulated by certain standards where NS-EN 14961 seems to be main standard in Europe for the biomass trade. This standard is replacing national standards like the Norwegian standard NS 3165 and the Sweden standard SS 18 61 50.

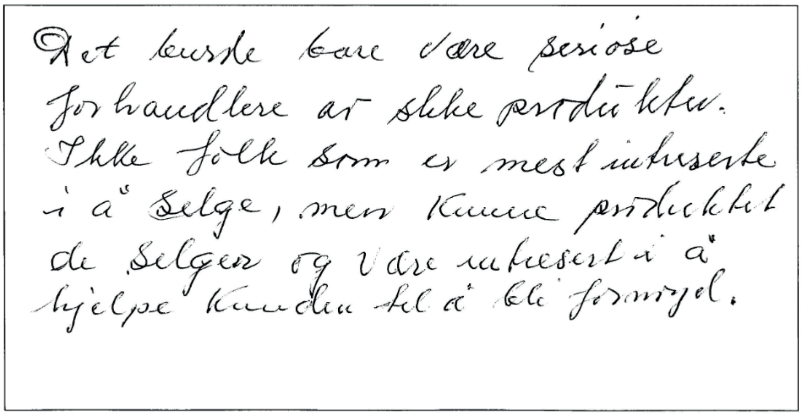
Despite tough standards, how they are established, interpreted and used, there are a couple of parameters where the author considers are more important to trade in the wood pellets value chain.

Ash is the inorganic component of the fuel. If the melting temperature of the ash component is below the combustion temperature, the ash component would start a sintering process on the combustion grate. This would soon cause difficult operational problems for the combustion unit and the ash handling system.

Wood pellets contain always a certain amount of dust. These are feedstock particles that is not a part of the pellets and are represented in its origin form. The treatment of wood pellets during transport and handling of the fuel will normally create a certain addition of fines. This is the reason why durability is an important factor for the quality measurement of wood pellets. Too large amounts of fines create dust in storages and in the surroundings if the system is not proper secured against air leakages. This might be a comfort problem and in too large amounts, it can be and health and safety issue. Further in the combustion of wood pellets, a too large amount of fines is in conflict with residence time in the combustion chamber. If the combustion air speed is too high, the particles would leave the combustion chamber unburned into the convection part of the boiler.

Market challenges

Wood pellets can be used in small fireplaces correctly designed for wood pellets use with fans and a continuously operated feeding system. These fireplaces can distribute the heat by air and are then called pellet stoves. If the heat produced is done by water-based furnaces/boilers, the reliability of the equipment seems higher. But Norway has a lack of water-based heat distribution systems, direct electricity heating and stoves utilizing wood or kerosene are most common. This gives relatively a larger need for pellet stove based systems, see Figure 11.



Det burde bare være seriøse
forhandlere av slike produkter.
Ikke folk som er mest interserte
i å selge, men kunne produktet
de selger og være interesert i å
hjelpe kunden til å bli fornøyd.

Figure 9 A respondent is written comment in a survey done in Papers II and III.

Pellets can retrofit coal in large coal fired plants. Since electricity production in Norway is almost based on hydropower, no pellets are used for large-scale electricity generation. The development of wood pellets market in Norway is shown in Figure 10.

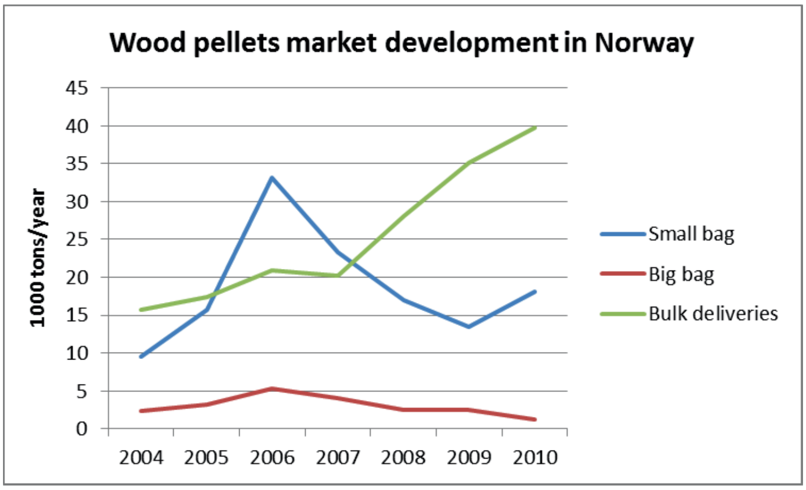


Figure 10 Wood pellets sales Norway 2004-2010. Source: [14]

The combination of increased electricity prices and subsidies from government gave a large increase of pellets use in households in the period 2005-2006. Households normally use only small bags. This increase can be seen clearly in Figure 10. The increase was reduced the following years, probably caused by increase of price level of pellets and lack of skilled vendors [15]. Big bags is containing approximately 1 tonnes and is too large for ordinary households, but are used in a certain degree for larger households. Bulk handling of pellets is normally used for heating plants.

If further growth is to occur with the relatively low economic incentive for wood pellets utilization, the disadvantages with the wood pellets system, in all scales, should be reduced.

The Norwegian heating sector is somewhat different than in other countries. This is due to low electricity prices, the lack of water-based heating systems and more distributed housing sizes where single households are relatively larger compared with other countries. This fact makes the Norwegian small-scale user heating market some extent different than other countries with a high share of wood stoves and kerosene stoves, see Figure 11.

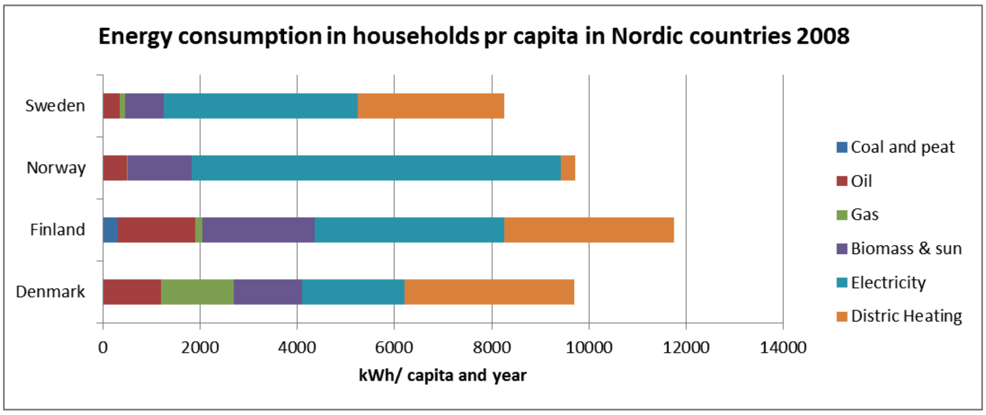


Figure 11 Use of energy carriers in households in the Nordic countries [16]

This work aims to make some of these barriers smaller by improving knowledge about some selected important barriers.

1.7 Selection of research topics

The title of this Ph.D. work is: "Wood pellets utilized in the commercial and residential sectors, - an in-depth study of selected barriers for increased use". Previous sections have described areas of development of wood pellets which are problematic. Based on the author's experience, the following parts are selected as tasks which are important to work further with and where increased knowledge would be beneficial for the development of the market generally and the Norwegian market in particular.

Small-scale pellets users in Norway

The Norwegian household heating market is characterized by a high use of direct electricity for heating and a low distribution of water-based heating systems. Further the use of wood stoves and oil compared to kerosene stoves is relatively high. When wood-pellets entered the market in Norway in the mid-90s, the expectations for growth were high. These expectations were not fulfilled. Even though price mechanisms and subsidies from the government are obvious explanation factors, there are other parameters which might explain the lack of growth of pellets.

Norway is in an early stage of promoting wood energy. The current status is that a small amount of wood pellets exist although the producers of wood pellets and subsidies for wood pellet are available. Knowledge about the mechanism of wood pellet adoption is probably lacking among decision makers.

What kind of factors? Are there any systematic patterns? What part of the value chain is most problematic? The potential research area could be wide, but method and how to collect data are essential for a scientific approach to the topic. The author has had access to customer registers of pellets sold, in small bags, big bags and bulk in major parts of Norway. These sales are both directly from manufacturer of pellets and also through major retailers. This source of primary information is valuable and has affected the selection of research topics.

Pretreatment of pure feedstocks from pine

Traditionally pellets manufacturing has been performed with side products from the wood working industry. Small factories utilize dry feedstock. When larger feedstock is established it is normally the wet side products which are utilized.

It is well known that the extractives from fresh wood evaporate fast when they are exposed to air. This natural process occurs in the wood working industry where wood often is chipped into small particles, stored and handled as a result of the main production.

When the area of feedstocks is increased and difficult feedstocks which are polluted should be avoided, round wood from pine would be a major feedstock. This segment can also contribute with large volumes. Especially from species and locations where the pulp industry has low paying willingness.

By its nature, pellets production represents the handling and storage of large volumes. Considerations about seasonal harvesting conditions and logistics means that the supply of feedstock might differ from a continuously operated manufacturing line. Should the feedstock be stored in chipped form or as round wood? Should it be debarked? How long storage is preferable? How do the moisture conditions develop during storage? What kind of drying equipment is favorable and how will it affect pellets quality?

Manufacturing of low-grade feedstock pellets with additives

Products from agriculture have a low content of lignin. Normally also a high content of ash constituents can be expected from these feedstocks. This means that both the mechanical properties and combustion properties can be more difficult compared with wood-based feedstocks.

Agricultural feedstocks in form of side products like straw and milling residues are available in large volumes in certain areas. What are the mechanical properties of such fuels when pelletized? Can additives improve the pellet quality? It is known that ash properties from difficult fuels can be improved with certain additives. Is additive possible to distribute additives in the fuel instead of the separate feeding of additives in combustion units? What consequences have the ash improving additive for the mechanical pellet quality? Can both mechanical quality improving additives and ash improving additives be utilized together? How do they influence each other?

Combustion of low-grade feedstock pellets with and without additives

Low-grade feedstocks as described above with additives should be valuable in smaller combustion units as an ordinary fuel like wood pellets. Is it possible to combust difficult fuels without melted ash? Will the ordinary ash handling system of the boiler transport the ash residue out from the furnace? Or will it be partly melted ash residues? Does the combustion have any consequences for flue gas properties? Or the boiler operation in general?

The research questions that are developed from the above considerations are now listed.

1.8 Thesis objective

The overall objective for the work performed in this thesis is to understand and improve selected barriers for the biomass pellets to energy system. From the purpose to utilize low-cost feedstocks and results from the market investigation performed in Paper II and III, following areas for research was prioritized:

Small scale pellet users in Norway (Papers II and III).

The research questions are: a) which factors lead single household owners to choose wood pellet stoves compared to heat pump solutions and direct electrically heated systems, b) how will existing users of wood pellets stoves choose if they should have any new system and c) what is the practical experience of existing wood pellet stove users with aspects like the technical properties of fuel, stove or stakeholders.

Pretreatment of pure feedstocks from pine (Paper I).

The research questions are: a) how does extended storage of pine feedstock affect the mechanical pellet quality? b) How does high and low temperature drying of pine feedstock affect the mechanical pellet quality?

Manufacturing of low-grade feedstock pellets with additives (Papers IV and VI).
The research question is: a) how is the mechanical quality properties of pellets affected by the use of different selected additives? Can it be improved?

Combustion of low-grade feedstock pellets with and without additives (Papers V, VI and VII).
The research questions are: a) is the low-grade feedstock pellets made with additives combustible in ordinary grate furnaces/boilers? b) how are the combustion results affected? c) how are the ash melting properties of difficult fuels affected by the use of selected additives?

1.9 Why the research is important

The increase in CO_2 emissions has to be reduced [13]. Population control, energy efficiency and renewable energy are among the main answers. Among the renewables, bioenergy is among the most important. Further bioenergy also gives workplaces, often in rural areas and supports activities in traditional forestry workplaces.

Among all the different biomass to energy pathways, solid biomass conversion to heat is most important. This is due to the high energy- and material efficiency factors and the large potential for production and use [4].

The author suggests the following major limitations to increased biomass energy use in Norway are addressed. This is based on a decade with experience in biomass market build up and trade:

- The relative difference between biomass cost for heating and electricity is too low, i.e. the biomass cost normally also contains the investment cost and the running/maintenance cost, this is opposite to electricity with low investment cost.
- Low taxation of electricity.
- Rebate of grid hire for electricity used for heating purposes.

- Low distribution rate of water-based heating systems.
- Rural and distributed population, i.e. low potential for district heating systems.
- Low level of knowledge about water-based heating systems among engineers and plumbers.
- There is a higher price level for components to biomass heating and water-based heat distribution systems compared to other countries.
- Customer and janitor personnel are not used to water-based systems.
- The plumber retailing system does not prioritize biomass- and water-based systems.
- General lifestyle makes manual work unattractive; such work is often required in biomass systems.

Should biomass use increase, all efforts which can increase the competiveness would be important. But the following areas are seen as crucial R&D work from the author's point of view:

Solid feedstocks, both with forestry and agricultural origin, have different price levels. Some of the cheapest feedstocks are bi-products derived from the production of lumber or grain. Some of the relatively cheap feedstocks can have difficulties during handling and combustion which is related to mechanical fuel properties or ash properties. Solutions which can reduce such disadvantages are important to increase the use of biomass for heating.

Since Norway has a low degree of water-based systems and lot of direct electricity heating, pellets-based stoves could seem to be a major contributor when a change is wished. The government has raised subsidies, but the growth had failed to come. What factors can explain this except economic feasibility? Increased understanding is important when further efforts are to be made for increased penetration of the market.

The research work which is performed in this thesis, is mainly done on a large scale and with real life conditions. It is expected that the results thereby have validity even though some manufacturing parameters are more difficult to preset.

1.10 Thesis organization

This thesis consists of five chapters. Chapter 1 gives an introduction to biomass for energy utilization and why pelletization of certain feedstocks is beneficial. The motivation for and the objectives of the research work are also presented. Pelletization of different types of biomass for energy purposes is a rather virgin research area, even though the research efforts have increased substantially in the last decade. Chapter 2 gives an introduction to the boundaries of the research in the selected objectives of this thesis. Chapters 3 – 5 present the research work sorted by the three different research areas. The conclusion of the work is given in Chapter 6 and recommendations for further work is given in Chapter 7.

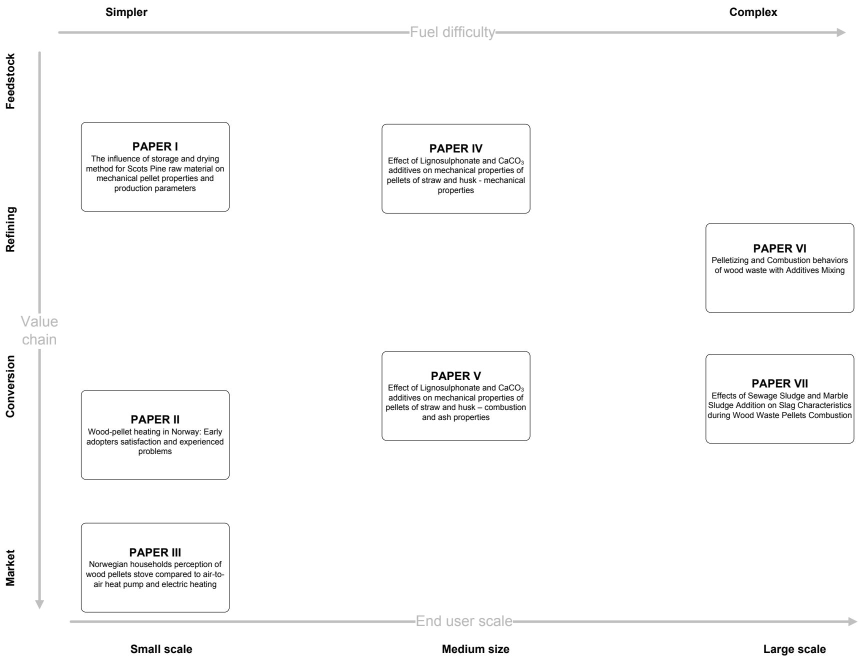


Figure 12 Structure of the papers in the thesis

How to read the thesis

Figure 12 shows how the papers are related to each other from different aspects. The axes are explained as follows:

Fuel purity – upper x-axis

Pure wood from hardwoods and softwoods without bark represents is the purest fuel with low implications regarding mechanical properties and ash related issues. The opposite are contaminated feedstocks from the furniture industry and agricultural feedstocks. In this figure the papers/research questions are organized with the fuel difficulty along the upper horizontal axis.

End user scale - lower x-axis

The smaller the size of the end user, the higher the demand for quality in wood pellets. Conversion equipment obviously needs to be cheaper when the production of energy is low. At the same time, smaller equipment is more vulnerable for the operating costs and unplanned maintenance. This means that more difficult fuels with problematic properties should not be put into smaller equipment. In this figure it is proposed to some extent that more difficult fuels also need increased size of boilers to handle the difficulties, at least in an economical matter.

Value Chain – y-axis

Pellets from biomass; from the origin of feedstocks to the conversion to heat represents a long value chain with several fuel conversion steps, other processes and stakeholders. The vertical axis in the figure shows where in the value chain each paper can be placed.

In the following the papers are presented in groups when the papers have topics which are closely related.

1.11 Scientific contribution of the work

- Models established for the prediction of wood pellets behavior in the Norwegian household market
- Identifying technical and system barriers in use of the wood pellets stove system in Norway

- Consequences identified and models established for drying techniques and pretreatment of pine stemwood to wood pellets.
- Pelletability and mechanical effects of ash improving additives identified for difficult feedstocks like furniture residue and barley straw.
- Identification of needed addition levels and type of possible additives to use.

2 Literature Review

Pelletization of biomass to fuels has had considerable attention in Europe with Sweden, Denmark and Austria as the main contributors in the field. This is naturally explained by the volume of pellets to energy used in each country and also the efforts each country makes to increase the use of new renewables. In the USA and Canada, which are large exporters of pellets to Europe, other perspectives are prioritized like research on the storage and handling of large volumes of pellet fuel, mostly in health and fire topics. Also system perspectives for handling feedstock systems into pellets are given attention. Regional availability of feedstocks influence research efforts where price level reasons and/or bi-products create interest in new kinds of feedstocks.

2.1 Small-scale pellet users in Norway

Is it shown in the introduction chapter that the Norwegian domestic heating sector to a large extent is different from other countries. The main difference is the large amount of electricity used for heating and lack of water-based systems for the distribution of heat, both for single buildings and also district heating systems. Wood pellets stoves are seen as an important contributor to change from heating oil, kerosene stoves and electricity but the development in the market has stagnated.

In addition to work done in this thesis, some work is performed on specific wood pellet utilization for the Norwegian market. One contribution is the articles published that have utilized other parts of the market survey that were performed in Papers I and II in this thesis [17-21]. These papers focus on Agent Based Modeling (ABM) as method, identifying and establishing models to predict end customer behavior and decision making for heating systems.

Bjørnstad, E. investigated the government subsidy programme [15]. A survey was performed to investigate the success of Norwegian government subsidy programme for wood pellets stoves and heat pump systems. This work found that heat pumps were more economically competitive, but this did not influence customer satisfaction. Only the electricity price influenced the satisfaction. Bjørnstad found further that technical quality, indoor climate, heat comfort and the availability of the suppliers of heating equipment were the most important explanatory variables.

Lillemo, S et al. has performed a survey on what is done in the market [22]. Also she conducted a survey using addresses provided by Enova, the official body which assigns investment subsidies to end users. The purpose was to detect factors influencing heating investment decision and choices of heating equipment. Four types of heating equipment were investigated; electric oven, firewood stove, pellet stove and air-to-air heat pump. Some of the findings were that pellets stove owners are more environmentally concerned and that wood pellets are difficult to obtain. Further that the investment cost and annual heating cost must be more competitive with other heating sources. Finally, the pellets stove design must be improved.

These surveys were performed later than the survey included in this thesis.

2.2 Pretreatment of pure feedstock from pine

Feedstock storage in wood-pellets production is demanding for space. The volumetric weight of feedstock is low and properties of feedstock can differ in a wide range. Access to feedstock varies over the year due to forest logging season, weather conditions in the forest and lumber industry activity. When producing wood pellets this is a more continuous process. Feedstock storage near the factory is necessary and is normally established to secure reliable supply.

Most of available feedstock is raw and the moisture content needs to be reduced. Drying is normally done with direct high temperature dryers or low temperature dryers. With high temperature dryers, short residence time can be achieved which again leads to less space demand. Thus a high exergy level is needed when high temperature flue gases are used as a drying medium. Low temperature dryers can use lower energy qualities like surplus heat, but need dryers that demand large space demanding dryers with long residence time in the drying phase.

In the Nordic countries rotary drum dryers using flue gas as the drying medium are most common for drying saw dust [23, 24]. These are relatively cheap and demand less space. Thus energy drying costs focus more on low temperature dryers and it is expected that this segment would increase. If dry material from saw mills is used, it has normally been dried by high temperature in the pellets industry. The different dryers can be classified according to the drying medium used [23]. Drum dryers using flue gas normally have an inlet temperature of the flue gas of around 400 ^{o}C . The outlet temperature of the drum dryers normally is around 130 ^{o}C. This drying method demands fast heat transfer, and thereby small particles.

During high temperature drying, volatile components (VOC) will be emitted from the material [24]. This is mainly extractives from the material. Therefore the extractive content will be lower in high temperature dried material. The volatile components have higher calorific value than the other tree substances due to higher H-C ratio. These emissions can cause harmful substances in the nearby surroundings [25, 26]. Loss of volatile components during the drying process will result in mass loss and lower calorific value [23]. If the drying process is performed at low temperature, the composition of the material will not be substantially altered during the drying process. This drying can be performed with temperatures less than 100 ^{o}C. Low temperature drying of chips can be performed by a band with a perforated bottom leading the drying medium up through the chips. Low temperature drying can be performed with chips of considerably larger size than possible in drum dryers. This can be an advantage if the raw material is log wood. The dryer is not suitable with very small particle sizes due to low gravity.

In stored raw material the composition of the material will change during the storage period [27]. The most substantial changes in the material occur if large piles of chips or saw dust with high moisture content are stored [28]. In the center of the pile the material will decay from fungal and bacteriological activity. This will result in heat development and mass loss. In the outer layer and in smaller piles these processes will not occur to the same extent. Today if material is stored it is often as large piles of wet raw saw dust from the saw milling industry. If the stored material has lower moisture content, fewer changes will occur in the material. Material stored as whole logs will also decay less because of a larger exposed area per weight unit to the surroundings than for wood chips.

As a consequence mass losses up to around 5 % per month are reported during chip storage. This results in a change of material composition by lower percentage of extractives and other volatiles. With storage of the unchipped material for reduction of the moisture content, earlier experiments have shown that the moisture can be reduced to about 30 %, and the chemical changes will be minor [29].

2.3 Manufacturing of pellets with additives

Pellets manufactured for feed purposes have often used additives since the recipes are decided by nutrient optimization and similar [30]. Pellets bound for energy, the feedstock ability to pelletize is influenced with a the composition of the feedstock, mainly the relationship between cellulose, hemicellulose, lignin, extractives and moisture. Additives might improve mechanical properties of the fuel i.e.: density, durability, moisture resistance [31]. Or additives might improve chemical properties like ash melting point and related problems. The value of the additive is of major importance, whether it is an energy contributor or if it only contributes with ash.

In the production of pellets for energy, several additives are reported. Most common is lignosulfonate-based additives [32]. Depending on the refining degree of the additive, the additive has different value and can be both in dry or liquid form. Also a common additive is starch which has similar property as lignin-based additives [33]. Obernberger and Thek [31] also report paraffin, molasses, stearin and cellulose fibres as additives for energy pellets.

Use of additives to improve melting properties of the fuel is not seen reported as an additive mixed in pellets where objective is to investigate mechanical pellets properties. However some work is performed with lab scale pellets production without focus on mechanical pellets properties [34-36].

2.4 Combustion and ash properties of difficult fuels

The demand of bioenergy has increased rapidly in the past decade. Biofuel assortments other than conventional woody biomass are entering the market for energy production purpose. Examples of these biofuel assortments are wood from wastes sources, agricultural wastes and forest residues.[37, 38] However, compared to the conventional woody biomass, there are a number of distinct differences related to ash content and concentrations of critical ash forming elements for these biofuel assortments. Normally, the concentration of ash forming elements in these biofuel assortments is higher and much more heterogeneous in terms of categories and existing forms.[38, 39] This is more evident for wastes and residues from agricultural sector, which are of rich in potassium, chlorine, sulfur and phosphorus.[39] During combustion, ash forming elements in biomass fuels undergo complex chemical and physical reactions, forming different ash intermediates and products in gas, liquid and solid phases.[38, 40] There is a certain fraction of ash forming elements will release as gases and vapors such as HCl(g), KCl(g) and KOH(g) and K2SO4(g).[41] As the vaporized species arrive cold regions in a biomass combustion boiler, they will condense and converge into aerosols and fine particles, which will accumulate and aggregate into coarse particles.[38] Formation and presence of these vapors, fine and coarse particles lead to fouling deposits on heat transfer tube surfaces, which induce corrosion of tube materials as well.[42] Besides the volatilized species, large amount ash forming matters in biomass fuels are retained in char and ash residues as bottom ash. The bottom ash may partially or completely melt during combustion, resulting adhesion and agglomeration of ash and char grains.[35] With continuous formation of ash melts, more ash and char grains will be attached and bond together, which typically accompanied by a net shrinkage and an overall densification of aggregated ash and char grains. After a long time accumulation time, ash slag with a large size and dense structure will form and can not be transported out of the boiler or burner.[43] The ash slagging is especially problematic for small scale and residential boilers burning biomass pellets as the fuel, since residence time of mixtures of raw fuel pellets, char and ash residues is rather long due slow mixing and moving of them on the grate. The amounts and characteristics of formed aggregates/slag depend on many factors. It has been reported that fuel ash content, relative concentration of certain elements and association of them have decisive effects on ash transformation and slagging behavior consequently.[34, 38, 43] A number of studies have been carried out to investigate formation and properties of ash slag during combustion of different biomass fuel pellets.[34, 35, 43-46] The slagging problems are more often occur during combustion of biomass fuels rich Si, K and P, and with relatively low amounts alkali earth metals.[38] The slag formation is closely related to formation and melting different potassium rich silicates for phosphorous poor fuel pellets. Enrichment of silicon in fuel pellets, due to contamination of sand/soil during transport and storage process, can considerably promote slag formation and enhance sintering degree of the formed slag.[45] On the other hand, for phosphorous rich fuels, such as cereal gains and crops, potassium rich phosphates readily to form and fuse during combustion process.[35] Therefore, the slags from combustion these phosphorous rich fuels contain potassium and phosphorous rich melts. However, due to the large heterogeneity of non-conventional biomass fuels, such as agricultural wastes and residues, the new and detail knowledge are still fragmentary, with respect to combustion properties and ash and slag formation.

Utilization of additive is a promising way to mitigate ash sintering and slagging during combustion of biomass pellets. Additives such as kaolin, lime and limestone have tested and showed ability to reduce ash slag formation in different studies.[34, 35, 46-49] Addition of additives altered biomass ash chemistry and promote formation of high temperature melting Ca rich silicates and phosphates.[38, 43] As results of these, amounts of formed ash melts were considerably reduced and the same for ash slagging tendency. However, the additives tested in previous studies relate to certain financial costs. It is interesting to search some additives from waste streams, which are efficient to abate biomass ash slagging and are cheap or even free to obtain and use.

3 Experimental Section

3.1 The fuels

Pure pine stemwood – (Paper I)
The first paper in this thesis investigates pretreatment of pine stemwood. The material used in the experiment was from a pine stand (Pinus Sylvestris) located in Bygland in Setesdal in southern Norway (EUREF North 6533862, East 82480) at 220 m altitude. The stand was classified as F14 in the Norwegian site class system. The material used was stem wood that was not debarked. The newly felled material was harvested in March 2009 and was chipped on the 16th and 17th of April 2009. The chipper used was an Erjo902 drum chipper with two knives and an integrated sieve. The material used for high temperature drying was stored in a chip pile for two weeks before being transported to the high temperature drying location. During the chipping 8 samples of the material were taken at random.

Barley straw and husk – (Paper IV and V)
Straw from barley from areas around Nes, Hedmark in Norway were collected after the harvest season in the autumn of 2010 (EUREF North 6746058.09, East 0278993.66). Barley husk was collected from the Felleskjøpets mill in Stange, Hedmark, Norway. Husk is the residue from the milling and refining process of barley grain.

Furniture industry residue – (Paper VI and VII)
Manufacturing of wood-furniture implies a high degree of mechanical treatment i.e: use of sawing, sanding and cutting machines. These residues are further handled to storage,

either pneumatically or by wheel loader. Storage is done normally in bins of concrete. This means that feedstock is normally a bit polluted by inorganic components from concrete dust and sanding paper and is seen as a problematic with respect to the ash content. Further this residue has low bulk density and a low particle size homogeneity. The feedstock used in this test is achieved from the largest furniture factory in Norway, the Ekornes plant in Sykkylven.

3.2 The additives

Several additives are used and proposed to improve energy pellet quality. But the value of the additive must be relatively of the right value compared to the fuel. The following additives are selected and used in this thesis with this background:

Sewage sludge – (Paper VII)
Waste water treatment plants produce normally solid waste. This waste is rich in organic content and is a product with low demand in the market and corresponding low price. This additive can be both an energy contributor to the fuel but also an additive which influences the ash melting profile of difficult fuels. Waste-water often utilizes a precipitator agent to recover phosphorous from the solid waste, this precipitator agent can enrich the fuel with certain inorganic components.

The work performed in this thesis was performed with sewage sludge from Saulekilen waste-water treatment plant in Arendal Norway. The sludge was mechanically dried, further drying was performed at ambient temperature distributed on a hot floor. When dried and before pelletization, the sludge was milled in a Champion mill with sieve size 5 mm. The sludge then becomes dusty.

Marble sludge (Paper V, VI and VII)
Marble in the form of almost pure $CaCO_3$ is normally a valuable product used for a very wide range of purposes. In Norway there are large marble resources. One of the main usage is refining of marble to a filler for paper production. From this refining process, too small particles are seen as a residue and are disposed into landfill or sea water. A sample from this fraction was received from Hustadmarmor factory in Fræna, Norway. This was received as a sludge and was dried on a hot floor to about 10 % moisture

content. After drying the solid sludge was manually crushed into small particles and manually sieved.

Lignosulfonate (Paper IV and V)

Lignosulfonate is a side product from the sulfite process. This feedstock is refined several purposes but a main one is as a binder. In the animal feed industry this is common. The additive is selected because it is expected to be a future surplus from hydrolysis residue from ethanol production [50]. Such residue is not available and lignosulfonate was therefore achieved from Borregaard ASA as the product Lignobond DD. This product was ready dried and needed no further treatment before use.

3.3 Characterization of fuels and additives

The pine chip, barley straw, barley husk and waste wood samples received were first air dried for 48 hours. Afterwards, they were grinded and milled with a cutting mill mounted with sieve with size less than 1 mm for further characterization. Sewage sludge, marble sludge and clay sludge were received in granular or slurry forms with high water content, which were air dried first and crushed into powder.

Both fuels and additives were further characterized by performing proximate and ultimate analyses. The moisture content, volatile content and ash content of each fuel or additive was measured by following procedures described in the American Society for Testing and Materials (ASTM) standards E 871, E 872 and D 1102. Finally, the fixed carbon content is calculated by the difference between 100 % and the sum of the measured volatile matter and ash content. Elemental compositions of the samples were measured by running an elemental analyzer (Vario MACRO Elementar) according to standard ASTM E 777 (carbon and hydrogen), ASTM E 778 (nitrogen), and ASTM E 775 (sulfur). The oxygen content was determined by difference of 100 % and the sum of the C, H, N, and S content. For each sample, proximate and ultimate analyses were repeated five times in order to get reproducible results. The properties of fuels and additives used in this work are shown in Table 3.

Table 3 Properties of fuels and additives used in the present work

Papers							
Fuel and additives	**Pine chip**	**Barley straw**	**Barley husk**	**Wood waste**	**Sewage sludge**	**Marble sludge**	**Lignosulfonate**
Proximate analysis							
HHV (MJ/kg.daf)		19.36	18.92	15.21	11.20	b	15.42
Moisture (wt%.raw)				5.94	9.50	b	
Volatiles (wt%.dry)		79.20	81.50	84.08	52.01	b	
Fixed carbon (wt%.dry)		17.60	14.40	15.21	5.79	b	76.80
Ash (wt%.dry)		3.20	4.10	0.71	42.20	98	23.20
C		48.40	46.40	50.20	47.00	b	42.50
H		5.80	6.00	6.47	6.40	b	4.50
N		0.72	2.0	0.80	7.91	b	0.13
S		0.07	0.14	0.14	1.19	b	6.46
O[a]		45.009	45.46	42.38	37.50	b	46.41
Cl		0.28	2.26	0.21	0.11	0.10	0.05
K_2O		28.64	32.13	14.47	0.69	0.02	0.99
Na_2O		0.38	0.01	11.37	0.47	0.22	0.07
SiO_2		41.50	30.95	22.75	26.71	0.20	0.12
Al_2O_3		0.18	1.43	6.26	31.74	0.80	0.03
P_2O_5		8.07	23.09	2.33	16.96	0.02	0.51
Fe_2O_3		1.73	1.12	4.52	4.52	0.57	0.12
CaO		13.43	6.89	26.13	13.08	95.12	55.32
MgO		0.04	< 0.001	5.77	1.08	2.99	0.01
IDT		984	870	1058	1126		
ST		1014	972	1142	1180		
HT		1195	1080	1175	1320		
FT		1256	1164	1195	1460		

a: by difference, daf: dry and ash free, raw: as received, d.b: dry basis

b: not relevant

3.4 Preparation of feedstocks

Preparation of pure pine stemwood (Paper I)

The feedstock properties largely influence the pellet quality. Feedstock directly from forest in form of stemwood needs chipping and drying before entering the pellets production process. The pine stemwood feedstock was chipped and dried and stored to following assortments:

- Newly felled material dried with low temperature
- Newly felled material dried with high temperature
- Material stored for 11 months dried with low temperature
- Material stored for 11 months dried with high temperature

The material to be stored was harvested in May 2008, and the chip pile for storing the material was constructed in late June 2008. The material was stored as chips for a period of 11 months. The chip pile had a height of 5.5 m and a diameter of 10 m at the bottom, see Figure 13. The storage experiment was ended in April 2009.

Inside the pile 8 temperature sensors and 16 netting bags each containing exactly 2.5 kg of wood chips were placed according to Figure 13. Beside the material used for the netting bags, a sample was taken and analyzed for the start value of the material. At the end of the experiment dry matter loss of each bag is calculated. The chip size distribution was measured according to NS-EN 15 492:2

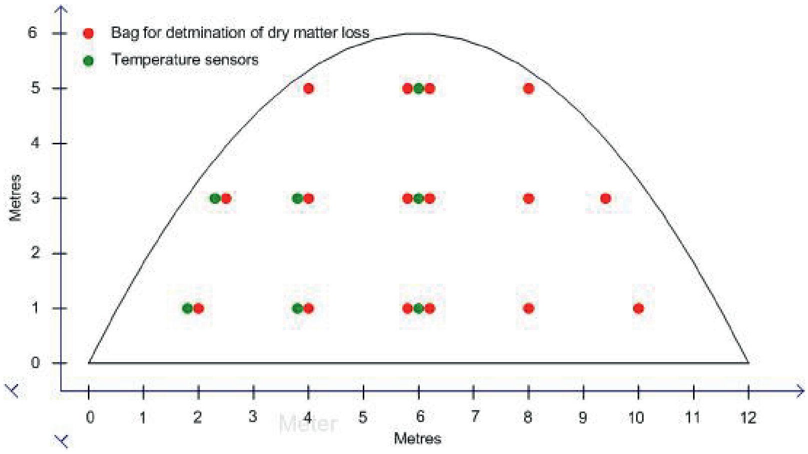


Figure 13 The chip pile used in the experiment

The chips had a relatively small particle size distribution with the majority of the particles around 10 mm and relatively low amount of fines (Table 4).

Table 4 Particle size distribution of material used

Sive size in mm	**Low temp drying Stored and fresh material**	**High temp drying Stored material**	**High temp drying Fresh material**
> 63	0.1	0	0
45-63	0.6	0	0
16-45	34.1	1.8	1.4
8-16	48	19.4	16.5
3.15-8	15.5	55.7	61.6
2.8-3.15	0.3	0.02	0.08
2-2.8	0.3	2.3	2.8
1.4-2	0.4	6.0	6.4
1-1.4	0.2	4.9	4.0
0.5-1	0	6.0	4.4
0.25-0.5	0.1	2.7	1.9
Bottom	0.1	1.2	0.9

At the end of storage time, netting bags were weighed and dried at 103 ^{o}C. Dry weight was taken. From this the dry matter loss in the different parts of the pile were calculated. Besides each of the netting bags an additional sample were taken for further analysis of the material. The rest of the materials were mixed as well as possible with an excavator, before 8 additional samples were taken from the mixed material. The rest of this material was used in the next part of the experiment.

To avoid long residence time or high moisture content after drying, particle size has to be small. Before high temperature drying the material was milled in a Jenz crusher with 60 mm integrated sieve to secure small enough particles (Table 4). The material for the experiment was kept separate from other material at the factory to avoid contamination.

The high temperature drying was performed in an industrial dryer at Statoil's pellet factory in Säffle, Sweden. The drum dryer has a capacity of 8 tonnes evaporation per hour, uses flue gas from a wood dust burner. The manufacturer of the drier is Saxlund. The inlet temperature of the flue gas is approximately 450 ^{o}C. The inert flue gas flows through the dryer in the same direction as the material. The drying time is a few minutes depending on inlet moisture and particle size. The dryer is controlled by regulating the outlet temperature of the drum dryer chamber. At the start of the drying period moisture sample was taken continuously and the dryer adjusted until the desired moisture content was obtained. The material was collected after desired moisture was achieved.

The dried material was collected through a hatch after the cyclone and collected directly into big bags of 1,5 m^3. All areas before treatment/handling were cleaned. After the drying process 5 samples of the stored and 5 of the fresh material were taken for chemical analysis.

The low temperature drying was performed in a trailer with a perforated bottom. The material used in the experiment was dried in batches of about 500 kg for each repetition of the pellet production experiment. Air with a temperature of 80 ^{o}C was blown through the material from underneath. The drying time was about 5 days, and samples were taken during the drying period to achieve the desired moisture content. The material layer was 0.6 m thick.

At the start of the storage in June 2008 the average moisture content of the chips was 40.9 % (raw weight) with a standard deviation of 2.9 %.. The driest sample had a moisture content of 35 % and the sample with the highest moisture 45 %.

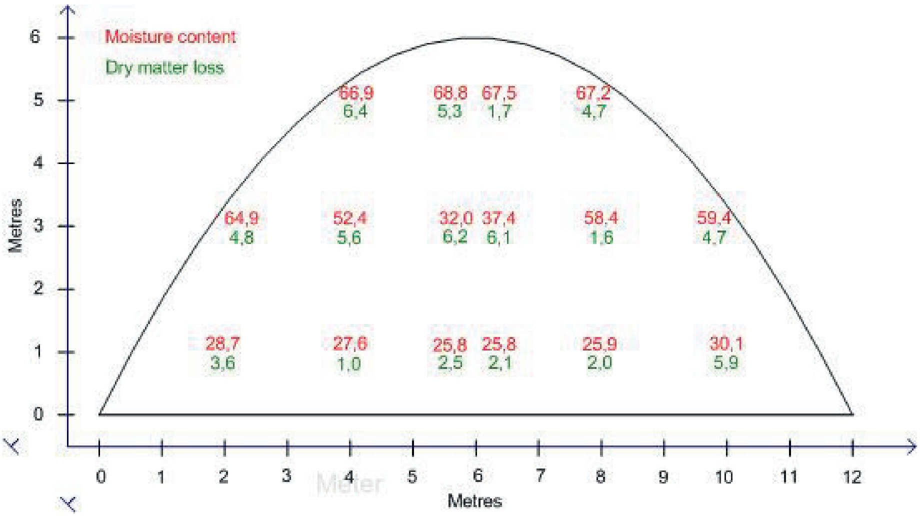


Figure 14 Moisture content and dry matter loss of the samples in the chip pile.

At the end of the storage period the moisture content in the pile was uneven, see Figure 14. In the bottom layer and the center of the pile the chips were dry, with a moisture content of 25 % to 30 %. The top and outer layer of the pile had in contrast a moisture content of about 65 %, and the moisture in these areas had increased considerably from the start of the storage period. For the samples taken at specific places in the chip pile the standard deviation of the moisture content was 19.1 %. The newly felled material is thereby in average more dry than the material stored in the chip pile. The outside layer is wetter than the middle of the pile.

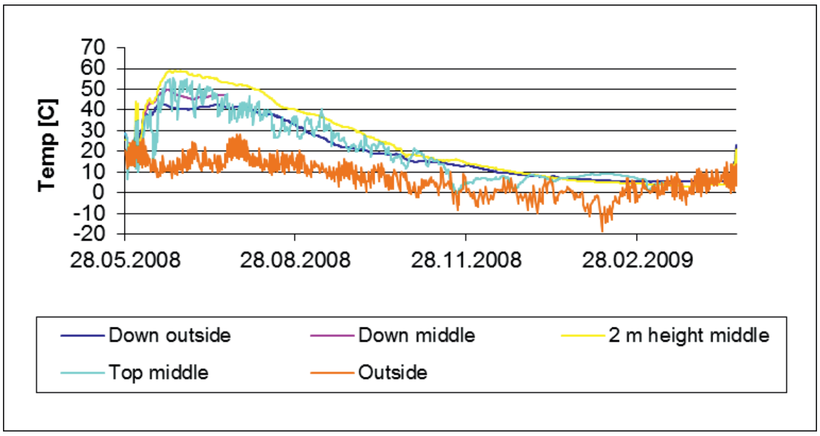


Figure 15 The temperature in different parts of the pile, and the outside temperature

The temperature inside the chip pile increased to about 60 °C in a few days after the start of the storage period, Figure 15. During the storage period the temperature in the chip pile slowly decreased, before stabilizing at approximately the same as the outside temperature towards the end of the storage period. The temperature was highest in the center of the pile. At the bottom of the pile the temperature was lower, around 45 °C at the highest. In the top layer the temperature was influenced by the surroundings and was more unstable compared to the other measuring points. Wetter material has a higher specific heat transfer ability which led to a larger influence from the outside temperature.

The substance loss was on average highest in the wettest areas of the pile, but was also considerable in the center of the pile. In these regions of the pile the substance loss was about 5 % during the 11 month period. In the center of the bottom region, the driest area of the pile, the substance loss was lower, around 2 %.

After the pile was mixed 8 additional samples were taken. This sample had an average moisture content of 60.2 % with a standard deviation of 2.4 %. At the start of the storage period the moisture content of the chip pile was 40.9 % with a standard deviation of 2.9 %.

The moisture content of the chip pile thereby increased considerably during the storage period.

Barley straw and husk preparation (Paper IV, V, VI and VII)

The barley straw was dried on field naturally. After harvesting, the straw was transported in loose form to the pellets factory and milled with a JF high grade cutter FCT 900 to particle size below 100 mm. The barley husk was dried artificially in the grain mill and received as is. There was no further treatment of the furniture feedstock residue.

Furniture industry residue preparation (Paper V)

There was no further treatment of the furniture feedstock residue. Sample taken randomly direct from storage at Ekornes furniture plant in Sykkylven.

3.5 Pellet production experiments

Pellet production experiments

After the preparation of pine feedstock and furniture residue, the pellet production experiments were performed in a Sprout Matador M30 pellet press with a nominal production capacity of 3.5 tonnes wood pellets per hour. The pellet press has a common construction; a rotating matrix and fixed but adjustable press rolls inside. For the experiment, a matrix with 8 mm whole diameter and 60 mm pressure length was used. Before the pellet press, the feedstock was sieved by a champion hammer mill with 5 mm sieve. After the pelleting process, the pellets need to be cooled down to ambient temperature and ventilated to get away moisture. For the samples from pure pine feedstock and furniture residue, the pellets were cooled down on the factory floor on plastics. The factory design is common for wood pellets factories which utilize dry feedstock.

The barley straw and husk pellets were processed in a similar factory line adapted to processing feedstock from agricultural activity to pellets. The tests were performed in an ordinary mode with hot equipment. The drier (Atlas 2.5 tonnes h^{-1} evaporator) was operated in cold mode without heat because the feedstock was pre-dried. Figure 16 shows a simplified setup of the manufacturing line. The pellet press (Kahl Akamat Herba-A/5K) is equipped with a cascade mixer. Additives were added continuously to the cascade mixer and blended with raw feedstock. More details on biomass pellet production with additives can be found in a previous work. After pelletization, the temperature in the pellets was lowered in an updraft cooler (Maskinbyg AS) with ambient air. The layout and capacities of the factory are common for smaller (< 6000 tonnes year^{-1}) pellet feed production plants, see Figure 16.

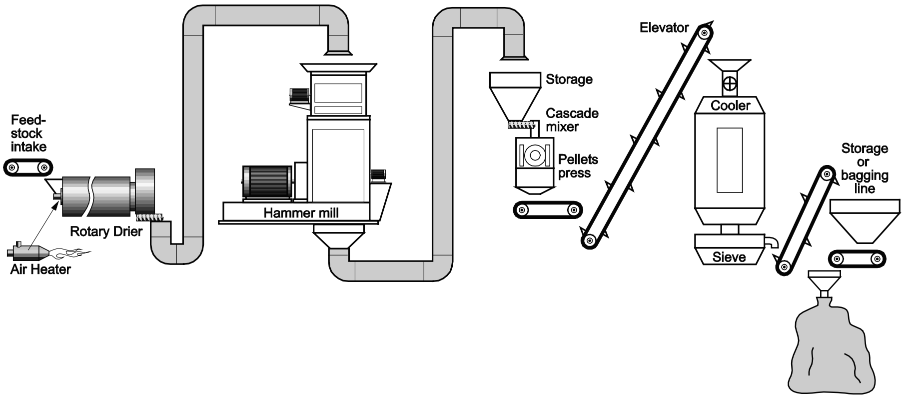


Figure 16 Simplified flow diagram of the straw/husk pellet manufacturing plant.

All the pellets were manufactured in large batches with levels of 300 kg to 1.6 tonnes. All additives were added continuously during production before the cascade mixer. This secured a good mixture between feedstock and additive.

3.6 Biomass combustion experiments

Barley straw combustion

The purpose with combustion trials was to detect whether the ash melting profile was improved by the additives and if the distribution of pellets additives was sufficient.

The barley straw experiments were performed in a Danish manufactured small-scale boiler and furnace (CN Stoker, 25 kW), see Fig. 17. This boiler unit has a separately furnace unit where the furnace is entering the boiler. Drying and pyrolysis of the fuel is occurring in the furnace while the combustion of pyrolysis gases is more likely to be performed in the boiler part. There is no automatic collection of ashes, they are to be collected manually in the bottom of the boiler. The boiler has a simplified regulating principle only low load and full load. No igniting unit. When the boiler operates on full load, the fuel feeding sequences is controlled by the O_2 level in flue gases.

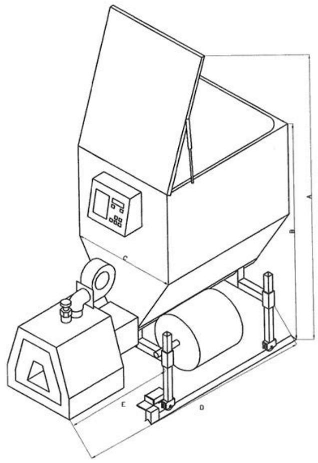


Fig. 17 Principle sketch of the furnace used for barley straw combustion.

In each tests, 60 kg of prepared samples was combusted. The boiler was operated only with full load until fuel was ended or the output of the boiler stagnated at zero when the grate was filled with ash.

The boiler was equipped with thermoelements which measured the temperature 60 mm above the grate (LabView). The flue gas composition was measured with a mobile flue gas analyzator (Testo 354/450 XL) during the combustion trials. All ash residues were collected from different parts of the convection parts and combustion chamber for further analysis.

Furniture residue combustion

The combustion experiments of furniture residue were performed in a TPS Stepfire boiler, see Figure 18.

The boiler/furnace is a horizontal grate with nominal output 1.2 MW_{th}. The boiler is well regulated with three different primary air zones and similar with secondary air zones. The primary air is controlled by amount of fuel fed into the boiler, secondary air is controlled by the O_2 level in the flue gases.

The experiments were decided to last for six hours, to be able to obtain stable conditions in the boiler and possibly produce enough sintered ash to be able to compare the fuel with and without additives. A total of five rounds were performed; one round of pure wood pellet as a reference round, and four rounds of wood pellet with the addition of sewage and marble sludge each containing two different concentrations of the additives. All runs were with full load except when melted ash reduced the effective grate area during trials. The boiler and furnace were cleaned between each run. All ashes were collected and storted by degree of melting.

A lance with eight thermoelements was installed 20 cm above the grate to record the temperature profile. Four of the thermoelements were of type K, and four others of type S.

The distance between each thermoelement was 25 cm, and none of them where placed over the primary air nozzles as this would disturb the temperature measurements. The lance was inserted through a hole for the ignition mechanism, and welded on the other side of the boiler. Four other thermocouples were installed around the boiler, just above the grate and before, during and after the heat exchanging system. The temperature data were logged with a LabView system. An illustration of the placement of the lance and other thermoelements in the boiler can be seen in Figure 18.

A flue gas analyzer, Testo 350 XL, was used to measure the CO, O_2, H_2, NO and NO_2 levels in the flue gas. This was done in order to evaluate the influence of the additives on the burning conditions.

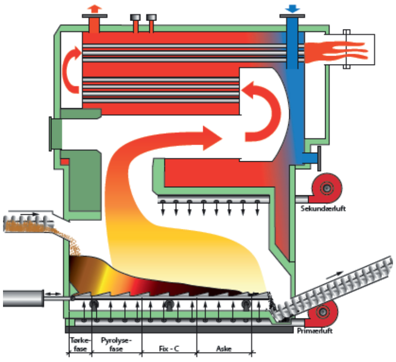


Figure 18 Principle sketch of the furnace used for furniture residue combustion.

3.7 Analytical methods

Characterization of pellets

The pellets manufactured in the different papers were tested according to widely used standards. Table 5 describes what tests were performed and what standards were followed.

Table 5 Standards that were followed for the test procedures of the produced pellets and feedstocks.

Test performed	Standard
Feedstock moisture	NS-EN 14774-2
Pellet moisture	NS-EN 14774-2
Durability	NS-EN 15210-1:2009
Pellet particle density	CEN/TS 15405:2006
Bulk density	NS-EN 15103
Ash content	NS-EN 14775
Particle size distribution	NS-EN 15149-2
Calorific value	NS-EN 14918/ASTM
Sulfur and chlorine content	NS-EN 15289
Carbon, nitrogen and hydrogen content	NS-EN 15104:2011/ASTM 5373
Oxygen (calculated)	ASTM D 5373
Ash deformation temperatures	ISO 540:1995

Analysis of ash and slag from combustion tests

The main ash chemical compositions of ash residues obtained from combustion tests were analyzed by an X-ray fluorescence spectrometer (XRF) (Bruker, S8 Tiger). Before XRF analysis, all samples were first grinded into powder and then molded into a capsule at high pressure for analysis. The instrument was calibrated by running standard samples, and the results were compared with the certificate (United States Certificates of Analysis, Syenite STM 1).

The collected ash residues were examined by a combination of X-ray diffractometry (XRD) and scanning electron microscopy equipped with an X-ray spectrometer (SEM-EDX) for identifying, and studying ash chemistry and the effects of additives.

Ash samples were first grinded into fine powders and then analyzed by XRD to identify occurrence and degree of crystalline mineral phases. A computer controlled Bruker D8 X-ray powder diffractometer was used in this work, which was equipped with a Cu characteristic and a scintillation detector. The collected X-ray spectrums were processed by TOPAS software for identifying the mineral phases in a sample, by matching experimental data to the reference patterns in the International Center Diffraction Database. In addition to the crystalline phases, a biomass sample may also contain a considerable amount of amorphous phases that are normally related to the melted fraction of the ash. Due to the limits of the XRD technique, the amorphous phases not can be directly observed, but presented as a broad halo on the baseline of the diffraction pattern.

One ash/slag sample was also examined by a scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (SEM-EDX), in order to obtain more microstructure and microchemistry information. Representative slag samples were first embedded into epoxy and cross-sectioned. The cross sections were then grinded and coated with carbon before they were examined by SEM-EDX. Backscattered electrons (BSE) images were taken for interesting areas from a cross-sectioned sample. The distribution of each element in the imaged area can be distinguished in the BSE images. The chemical compositions of selected spots and/or areas on a sample can be measured by an energy-dispersive X-ray spectrometer. In addition, elemental composition maps can be obtained, showing the spatial distribution of specific elements over the scanned area. Analytic results from SEM-EDX reveal correlations of interesting elements and indicate the presence/formation of certain chemical/mineral phases.

4 Summary of papers

Paper I

This study investigated how storage and drying methods for wood (Pinus sylvestris L.) used as a raw material for pellet production influenced pellet durability, bulk density and energy consumption. The pelletization experiments were performed using a Sprout Matador M30 press (nominal production capacity 3.5 tonnes/h). Results showed that pelletization of 11 month old stored wood compared to fresh material and high drying temperature (450 °C) compared to 75 °C resulted in higher energy consumption, probably due to increased friction in the matrix caused by the loss of extractives. However, the pellets produced were of higher density than those made from fresh material dried at a low temperature. The latter had the highest durability. Increased energy consumption showed no correlation with pellet durability.

Paper II

This study explored the factors that explain the overall satisfaction among the early adopters of wood pellet heating as well as the problems experienced with wood pellet heating in Norway. A mail survey was conducted to 466 existing wood pellets users. Findings show that both economic factor (i.e., cost) and technical factors (i.e., pellet stove performance) have played a significant role in early adopters' overall satisfaction with wood pellet heating. The most common problems experienced are igniter failure in the pellet stove, lack of committed and competent suppliers/vendors, more time and effort than expected during maintenance, and fines from pellets both during handling and combustion.

Paper III

The paper studies determinants of heating system adoption as well as financial incentives required to change to a wood pellet heating system based on Norwegian households' perception. Three types of heating systems, wood pellet, heat pump and electric resistance, are examined and compared. This study was conducted through as a questionnaire survey of 960 Norwegian households. Multinomial Logistics Regression (MLR) was applied to test the relationships between hypothesized variables and the anticipated future choice of heating system. Different choices of heating system are predicted by different predictors. Results also reveal that individual innovativeness is a driver for heat pump diffusion while social support is a driver for wood pellet diffusion. The incentives required to change to wood pellet heating are found significantly different among households with respect to their future choice of a heating system.

Paper IV

High amounts of fines and high ash content reduce the quality of the pellet fuel. Lignosulfonate and $CaCO_3$ are two additives that might improve straw and husk fuel quality. The objective of this experimental work was to determine the effects of additives on the mechanical quality of pellets. In an ordinary feed pellets factory, 17 samples of both feedstocks were produced with different ratios of additives. It was found that both lignosulfonate and $CaCO_3$ improve the durability of the pellets from Barley husk. Barley straw durability was improved with the addition of lignosulfonate but opposite results were found for $CaCO_3$.

Paper VI

It was found that the wood waste pellets have a considerable potential for slag formation during combustion and can cause operational problems. With the addition of additives, no significant changes were observed regarding mechanical properties of the wood waste pellets. Sewage sludge addition was found to have positive effects on NOx and CO emissions during combustion. Both sewage sludge and marble sludge addition have evident influence on slag formation during combustion. Sewage sludge addition reduced the slag formed and its size, and therefore improved the boiler operation. Marble sludge eliminated the slag formation during the wood waste pellets combustion.

Papers V and VII give results from the combustion of biomass pellets and the effects of additives. The main focus of the two studies are investigating slagging behavior during the combustion of biomass pellets produced from wood wastes, barley straw and barley husk. The influence of the addition of additives (sewage sludge, marble sludge and lignosulfates) on the slagging tendency of the biomass pellets was also investigated. Papers V and VII show that difficultslagging during combustion of the studied pellets is mainly due to the formation of low temperature melting of alkali rich silicates and/or alkali phosphates. Marble sludge serves as an efficient additive to significantly reduce or eliminate slag formation during combustion of studied biomass pellets. Adding marble sludge promoted the formation of high temperature melting calcium-rich alkali silicates and phosphates. This process was accompanied by an evident decrease of ash melt formation and the slagging tendency as well. The addition of either lignosulfates or sewage sludge has a minor effect on the slag formation during biomass pellets combustion. Interesting synergies between the biomass pellets ashes and the two additives have been observed in both papers.

5 Conclusions

The objective of the work presented in this thesis was to investigate selected wood pellet development problems that have strong relevance for Norwegian conditions and short-term market development. Targets were selected in three different areas based on the author’s experiences:

- Wood pellets market with emphasis on customer satisfaction and technical problems.
- Feedstock pretreatment, drying and storage.
- The impact of additives on pellet production and combustion.

The wood pellet market investigation work has been performed by investigation of existing customers and a reference selection of customers. The access to existing customers of wood pellets has been of major importance to get good quality data. This questionnaire response rate was high with level of 43 %, this also indicates high validity in the results. The physical trials with pre-treatment of feedstock, difficult feedstocks and the use of additives were performed in industrial applications. This also gives high validity of results, even though there are fewer possibilities to create planned parameters like different moisture levels since each batch has a large volume. The access to market data and industrial equipment for manufacturing of and combustion of pellets has been valuable for this research project.

Market development objectives were to identify factors that influence the purchase of heating systems in Norwegian households. This objective has been met and the knowledge can be utilized by the government in planning programmes for the increase in wood pellet use. It is especially worth mentioning the detection of regional constraints and the age of the end customer. Also the reliability of wood pellet providers is found to be important and that the operational cost of wood pellet applications is too high seen from the end user's viewpoint. The knowledge of possible strategies and government interventions to improve the process in order to understand the long-term development of wood pellet system can be increased.

The objective of detecting technical pellet stove performance among existing wood pellet users has also been mapped. This research work shows that technical improvements are significantly needed to satisfy expectations from the customer and further the operation costs. Ignite module function, inappropriate combustion, difficult control system, fuel feeding system and noise are the main technical parameters which need to be improved. Further vendor attention and knowledge of technology are indicated by the low customer satisfaction rate.

Summarized the market study indicates areas of improvement that are needed for certain parts of the value chain. Improvements of certain parameters, components and stakeholders in the value chain are needed.

This scientific work was performed as large scale trials in real life conditions. Since wood pellet manufacturing and drying is space and temperature, the results are more into empirical conditions than if similar objectives should be investigated through lab models. This gives benefits regarding the validity for results and the creation of enough amounts of test fuel for mechanical tests of fuel.

The first trial with pretreatment samples was performed in a lab scale press. It was rather difficult to achieve steady state conditions. Therefore we decided not to utilize these results, even though it implied a lot of handling and transportation, to utilize an ordinary pellets factory. During this manufacturing, the pellets produced for tests were steady.

Also the combustion trials needed enough fuel. It is difficult to control such large amounts of fuel in advance. This is especially valid for the moisture content of the feedstock. It was also not practical to perform several batches with different moisture levels when enough repetitions of trials should be performed. This consideration is discussed in the next chapter.

It was found that the different types of pretreatment of pure pine feedstock affected the quality and production parameters significantly. Both long time storage and high drying temperature resulted in higher energy use. It is known that extractives in wood are released when wood is exposed to heat and air as a function of time, and thereby higher friction as a result. When greater amounts of energy are used, the density of each pellet might increase. This result was also found during this experiment. However, the best durability results were found for the fresh and low temperature dried feedstock, even the pellet density was lower.

This negative correlation between the durability and density of the produced pellets indicates that the extractive content affects the mechanical pellet quality.

The barley straw and husk pellet trials showed that lignosulfonate additive has a significant and positive effect on the pellet durability when marble sludge is not used at the same time. Barley husk, which has the lowest durability with no additives, benefits more from the use of additive. This positive effect disappears when marble sludge was also added to increase ash melting point.

All trials in this test showed no significant changes in energy consumption, of any mixtures of additives. Obviously the particle density of pellets was affected by the addition of marble sludge since specific weight of marble is higher. The results from this work indicate that marble sludge is a preferable additive for husk-based pelletized fuels because it improves the mechanical pellet quality and can also improve the ash melting point. Furthermore, lignosulfonate improves the mechanical quality and can reduce the negative mechanical quality impact of marble sludge addition on straw feedstock.

The manufacturing of furniture residue pellets with sewage sludge and marble sludge additives showed increased particle density in a similar way when marble sludge was used as additive, but bulk densities were not affected in the same manner. All addition for sewage sludge and 4 % marble sludge increased the durability of the pellets. However, with 8 % marble sludge, there was too high content of particle bonding additive.

6 Further work and application of the results

This thesis work has results which can be utilized in industry. Further development, both in project form and as R&D work is needed.

With aspect of development and increased growth of the single household pellet market, the author recommends tasks which increase the reliability of pellet heating systems and reduce the need for operator skills. The recommended tasks are:

- Improved reliability and lifetime of ignition systems in pellet stoves.
- Improved pellet quality with aspects of fines/dust content. A reduced amount of dust/fines increases end user comfort and reduces maintenance needs.

The feedstock in pellets production will change between bi-products and main products or a combination of this. Since for the time being, demand is low for pulpwood within pulp/paper industry also more round wood can be expected as feedstock for pellets industry. This is especially valid for pine species which are less valuable as paper feedstock. The author recommends following R&D tasks:

- Repetition of trials with different moisture levels to create greater understanding and connections between moisture levels in feedstock, energy consumption and durability of the pellets.
- Different drying temperatures between the levels performed in this thesis (80 and 430 ºC) to detect fuel quality consequences of a more high speed drying process.

Relatively low-cost and difficult feedstocks like barley straw and bi-products from furniture production with high ash contents would be economic feasible since alternative use is limited. Further there often is a lack of large size utilization units which can handle difficult ash properties better during combustion. It has been shown that the use of selected additives can improve both mechanical properties and also properties during combustion. Tests were taken from a large batch of wood chips and each experiments were thus run at a constant moisture level. A follow up project could have more diversified moisture levels. The author recommends the following further R&D tasks in this topic:

- Repetition of trials, both barley straw and furniture production bi-products at other moisture levels evaluate effects of the feedstock and mechanical quality of the pellets.
- Establish models with a more narrow specific range of additive needed to eliminate ash melting problems during the combustion of feedstock from both barley straw and furniture bi-products.

Important stakeholders in this R&D work could benefit from this work. The findings should be utilized and there should be an effective communication of the results to industry.

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8 Appended Papers

Paper I

The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters.

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The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters

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ABSTRACT

Converting solid biomass into pellets through densification greatly improves logistical handling and combustion processes. Raw material properties can affect pellet quality. This study investigated how storage and drying methods for wood (*Pinus sylvestris* L.) used as a raw material for pellet production influenced pellet durability, bulk density and energy consumption. The pelletization experiments were performed using a Sprout Matador M30 press (nominal production capacity 3.5 tonnes/h). Results showed that pelletization of 11 months stored wood compared to fresh material and high drying temperature (450 °C) compared to 75 °C resulted in higher energy consumption, probably due to increased friction in the matrix caused by the loss of extractives. However, the pellets produced were of higher density than those made from fresh material dried at a low temperature. The latter had the highest durability. Increased energy consumption showed no correlation with pellet durability.

1. Introduction

The densification of biomass into pellets makes standardization of wood fuel easier and improves its marketability. Pellets also have certain properties that make them easy to transport, handle and burn. This is especially important for smaller combustion systems (<1 MW). Pellets have several advantages compared to unrefined fuels such as wood chips, including a considerably higher density, lower moisture content, more homogeneity, higher transport efficiency and better handling properties. During thermo-chemical conversion to heat in stoves or boilers, fuels with more consistent properties make it easier to regulate the combustion process, and consequently reduce capital and maintenance costs. These types of fuels also routinely result in higher combustion efficiencies and lower emission levels than other non-densified biomasses.

Traditionally, pellets are mostly made from sawmill residues. However, this resource is limited. Therefore the industry is looking for alternative raw materials [1]. One potential feedstock that could be used to increase pellet production in Norway is Scots pine (*Pinus sylvestris* L.) pulpwood, due to its availability in certain areas of Norway and its lower price compared to Norway spruce (*Picea abies* L.) [1].

The Norwegian pellet market is mainly made up of smaller combustion plants that generally have higher quality demands than larger units. Standards have been developed to simplify biomass trade [2,3]. Pellet standards specify quality parameters such as durability and bulk density. However, an understanding of raw material characteristics and production process is essential to produce high quality pellets [4].

Durability is one of the most important pellet properties. Low durability results in more fines, which may create problems during transport, storage, feeding and combustion. Fines in pellets significantly increase the slide angle of the fuel, since the fines act as a binder between each pellet. Fines also reduce end user comfort due to dust exposure. During the combustion phase, dust often passes through the combustion chamber unburned, resulting in higher emissions and fuel residues in the boiler/stove [5,6].

Another important property is bulk density, since the fuel is fed by volume, not weight. Variations in bulk density can cause large variations in combustion efficiency. It is preferable that volume-to-weight ratios remain stable over time. Furthermore, feedstock that is relatively homogeneous, such as Scots pine pulpwood, might result in more stable bulk densities as compared to by-products from the lumber and woodworking industry.

Pellets are normally extruded without additives. Binding the wood particles into a pellet requires a temperature of about 110–130 °C [7]. At this temperature, the lignin softens, which binds the particles together [8,9]. This temperature occurs in the pellet matrix due to

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friction caused by extruding the material through the die. The pressures in pellet dies are estimated to 750 MPa [10]. The pellet industry reports a typical energy consumption of 75 kWh/tonne of pellets in extruding wood to pellets. The amount of energy consumed will vary with different raw materials, moisture levels and use of additives. This is mainly due to differences in friction between the die and material used [11].

During the production process, several variables influence how well the pellets bind, particularly the shape and pressure length of the matrix [7,12], the size of the raw material particles [13,14] and the moisture content of the raw material [7,14,15]. The moisture content is considered to be the most important parameter [15]. Lower moisture content will result in excessive temperatures in the matrix, causing rapid thermal decomposition of the pellet surface, which results in production problems [15]. If the moisture content is too high, the pellets fall apart [7,12]. This is likely due to excessive internal pressure from steam generated inside the pellet. Therefore, the raw material must have a moisture content that is optimal [15]. For wood raw materials, the optimal range is normally between 7 and 12%. The optimum varies for different wood types and production settings [12].

It is common to add steam during production. Steam heats the raw material and makes it more plastic, resulting in higher pellet durability [15,16]. Further, different tree species have different properties that affect the pelletizing process [17] and the pellet properties [7,18]. Holm et al. [17] found that higher pressure is needed to release pellets of beech (*Fagus sylvatica* L.) than for Scots pine. Samuelsson et al. [18] found higher bulk density and mechanical durability for Norway spruce than for pellets from fresh sawdust or Scots pine.

Logistics, transport issues and yearly harvesting conditions may require the manufacturers to store the raw material. Storage can alter the composition of the material [19], affect the pelletizing process and the properties of the pellets [18]. These relationships depend on storage time and methods as well as on the moisture content of the stored material. The most common storage method at pellet factories is to stockpile the wet raw material in large piles as chips or sawdust. Normally the piles are exposed to the weather due to the need to make the system as cost-effective as possible. This kind of storage method generally causes substantial changes in the material [19]. The extractive content will be reduced, and hemicelluloses, cellulose and lignin will degrade [20].

Nielsen et al. [11] found that a reduction in extractives resulted in increased friction between the wood material and the pellet matrix, suggesting that extractives have a lubricating effect in the die. They also found that pellet made of extractive-free materials tended to have higher strength. Finell et al. [21] found increased pellet strength and density with decreasing content of free fatty and resin acid. Samuelsson et al. [18] found a positive effect of storage on durability due to the loss of extractives. Some pellet producers separate and mix stored and fresh material to achieve optimal quality [4].

To produce high quality pellets, the feedstock has to be dried to a moisture content of about 10% (raw weight). Since it is not possible to reach such low moisture contents by natural drying, the material has to be artificially dried. However, a wide range of temperatures and retention times can be used in the drying process [22]. One of the most common drying methods used in the industry is drum drying, with use of flue gas with temperatures of around 450 °C as the drying medium in an inert atmosphere. Although the residence time in industrial drum dryers, with such temperatures, is only a few minutes, considerable losses of volatile components have been measured [22].

Drying can also be undertaken using temperatures below 100 °C. This minimizes the substance loss. Low-temperature dried materials might require less energy to pelletize since extractives are considered to have a lubricating effect.

Wood from Scots pine has relatively high extractives contents [18], compared to other softwood species such as Norway spruce. Substantial changes in the extractive content during storage and drying are expected [14], particularly when drying Scots pine at high temperatures.

The effect of raw material storage on pellet quality has been tested in several studies [4,11,18], but information about how the drying method influence the raw material characteristics and pellet quality, particularly in interaction with storage, is still limited. Extractive content is an important factor when it comes to these questions. Therefore a better understanding of how storage and drying influence the pellet production and the quality of the pellet produced, also with regards to extractive content, is pertinent in order to develop more optimal pellet production processes. Since Scots pine has relatively high amounts of extractives, it should be a suitable species to study.

The aim of this study was to investigate how storage, in interaction with drying temperatures, influences the mechanical properties of Scots pine pellets, as well as the energy consumption used in the process. The effect of extractive content on pellet properties was also investigated.

2. Materials and methods

2.1. Preparation of the materials

The raw material was chipped from unbarked stemwood from a pine stand located in Bygland in Setesdal in Southern Norway (EUREF N 6 533 862, E 82 480) at 220 m a.s.l. The stand was classified as F14 in the Norwegian site class system [23].

The first part of the material (Stored) was harvested in April and chipped in May 2008, and was stored in a 6 metre high pile for 11 months, until April 2009. The average chip moisture content at the start of the storage period was 41%. After storage (April 2009) the average moisture content had increased to 60%. The material in the chip pile was mixed before further use. The second part of the material (Fresh) was harvested and chipped in April 2009.

The low temperature drying was undertaken in a container with a perforated bottom. The chip layer was 0.6 m thick. The drying medium, which was blown through the chips, was ambient air heated to a temperature of 75 °C. This was done in batches during May 2009. The drying time was approximately 5 days, and samples were taken during the drying period to achieve the desired moisture content.

The high temperature drying was also undertaken in May 2009 in an industrial Saxlund drum dryer at Statoil's pellet factory in Säffle, Sweden. The dryer used flue gas from a wood dust burner and had a capacity of 8 tonnes evaporation per hour. The flue gas inlet temperature was 450 °C.

Table 1
Variables definition.

Abbreviation	Explanation	Unit	Variable type
R	Part of the residuals explained by replicate number	–	Random
S	Part of the residuals explained by the sample number	–	Random
St	Steam added or steam not added	–	Categorical
F/S	Fresh or stored material	–	Categorical
F	Fresh material	–	–
S	Stored material	–	–
DM	Drying method used for the raw material	–	Categorical
LT	Drying with low temperature	–	–
HT	Drying with high temperature	–	–
Moi	Moisture content of the raw material	% wet basis	Continuous
Ext	Extractive content in raw material	mg/g dry basis	Continuous
T	Raw material temperature at pellet press inlet	°C	Continuous

The four different raw materials (HT-Stored, LT-Stored, HT-Fresh and LT-Fresh (Table 1)) were dried to obtain three samples from each with a range in raw material moisture contents between 7 and 13% within each of the four different raw materials. This is a range where it can be expected that pellets will have acceptable properties from the pellet press used in the study.

2.2. Pellet production experiments

The pellets were produced in a Sprout Matador M30 pellet press with a nominal production capacity of 3.5 tonnes of wood pellets per hour. The pellet press has a rotating matrix and fixed, but adjustable press rolls on the inside. A matrix with an 8 mm hole diameter and 60 mm pressure length was used. The pellet press was located at Møre Biovarme AS's pellet factory in Sykkylven, western Norway. The raw material was fed into the production line immediately before the hammer mill, and was stored in a raw material feedstock bin prior to being fed into the pelletizing press.

The experiments were run using a pre-warmed matrix. Before samples from each replicate were taken, the pelletizing process was run for approximately 4 min to achieve a steady state. Samples were taken over a period of 15 s every second minute. The samples were collected directly from the pellet press. Three samples were first taken before steam was added in the cascade mixer. Four minutes after steam was first added, 3 additional samples were taken. The total time used for each replicate was approximately 20 min. All samples were cooled before the sample bags were sealed. For each of the 12 replicates (3 replicates from each of the 4 material types), 6 samples (3 without steam added, and 3 with steam added) were taken, giving a total of 72 samples. One minute before each pellet sample was taken, samples of the raw material were taken from between the cascade mixer and the pellet press.

Material was fed into the process at as constant a feed level as possible, within and across replicates. Power consumption was logged continuously, which enabled us to calculate the energy required by the pellet press. A thermocouple was mounted in the cascade mixer to record the temperature during the entire experiment.

2.3. Analyses of the material

All raw material samples collected after the cascade mixer were analysed for moisture content [24]. For each replicate the extractive content was analysed for the last raw material sample without steam addition and for the last raw material sample with steam addition. We used a modified version of the Soxhlet method, heated with microwave [25,26] to analyze the extractive content. The first raw material samples from each replicate were sieved for particle size distribution [27]. The particle size distribution of the different raw materials was similar for the 4 categories studied (Fig. 1).

The durability and the bulk density, using CEN 15210 [28] and CEN 15103 [29] respectively, were analysed for each of the 72 pellet samples taken. For each replicate, the last pellet sample collected before steam was added to the raw material and the last after steam was added to the raw material, were analysed for particle density according to CEN 15150 [30].

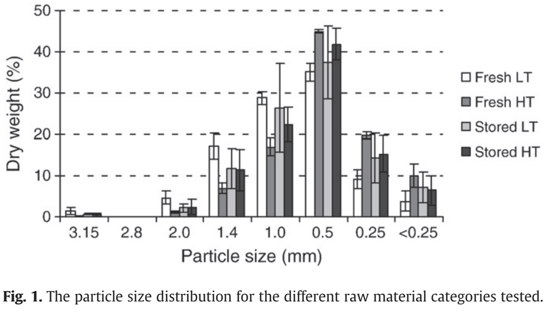

Fig. 1. The particle size distribution for the different raw material categories tested.

2.4. Analysis of the data

First, simple regressions between the most important explanatory variables and the dependent variables Power, durability and bulk density were done. Further, two multiple basis models with interaction effects (Model 1 and Model 2, both mixed models) were developed. This was done to get more complete statistical pictures of the relationships between the variables. The different variables in Model 1 and Model 2 are defined in Table 1. Figs. 2, 4 and 6 show the simple regression models. Figs. 3, 5 and 7 show profile plots for the multiple mixed models. The effects of storage, drying method, moisture content and steam addition were investigated in Model 1. In Model 2 the storage and drying variables were replaced with the extractive content. Two separate models were used since the extractive content was correlated with the variables Fresh/Stored (F/S) and Drying method (DM).

Replicate number (R) and sample number nested within replicate number (S[R]) were random effects in the models. The other effects were fixed. β represents the intercept in the model. The different α values represent the fixed effects, while b_1 and b_2 represent the random effects part and e represents the residual part. Residuals from the models were used to manually calculate the RSquare values, since the software used takes the random effects into account when calculating the RSquare values.

In Model 1, all fixed effects are categorical variables except moisture content, which is continuous.

$$\begin{aligned} y = \beta + b_1R + b_2S[R] + \alpha_1F/S + \alpha_2DM + \alpha_3Moi + \alpha_4St \\ + \alpha_{13}F/S{*}Moi + \alpha_{23}DM{*}Moi + \alpha_{12}F/S{*}DM + e \end{aligned} \tag{1}$$

In Model 2 all fixed effects are continuous variables.

$$y = \beta + b_1R + \alpha_1Moi + \alpha_2Ext + \alpha_3T + \alpha_{12}Moi{*}Ext + e \tag{2}$$

3. Results and discussion

3.1. Energy consumption

The energy required for an extruding process is mainly a result of the friction between the material and the matrix.

The electrical power needed for pressing pellets decreased linearly with increased moisture content of the raw material (Fig. 2a, simple linear regression). This is in accordance with Larsson et al. [15]. The decrease in energy needed with increasing moisture content was more substantial for the fresh material than for the stored material (Model 1.1, Table 2, Fig. 3). This partly explains the considerable variations around the graph for the relationship between the power consumption and moisture content when only simple linear regression was used (Fig. 2a). Part of the raw material moisture content effect might be due to less stiff and more ductile wood particles entering the die. Still, steam addition did not reduce the energy needed significantly. This might be due to the short residence time for the moisture added by the steam and amount of steam added.

Pellets made by pressing stored raw materials required more energy than fresh materials (Fig. 2b). This is probably due to the loss of extractives during storage [31]. However there was no significant difference in the energy needed when pelletizing raw materials dried at different temperatures (Model 1.1, Table 2) even though the extractives content was lower for the high temperature dried material. The effect of extractives content on energy consumption during production (Model 2.1 and Fig. 2c) indicates that extractives

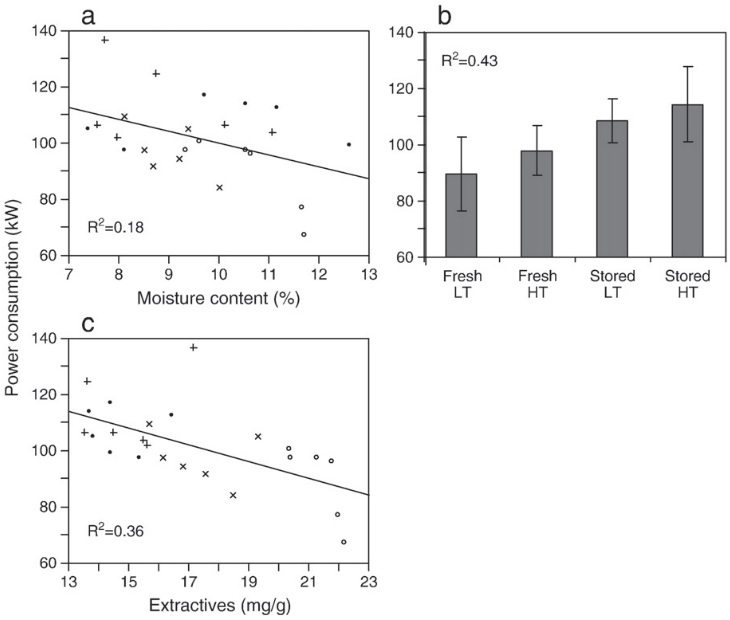

Fig. 2. The correspondence between the energy used by the pellet press and (a) the moisture content (wet basis) of the raw material, (b) different raw material categories and (c) extractive content of the raw material (◦Fresh LT; × Fresh HT; • Stored LT; + Stored HT).

act as a lubricant in the pressure channel. This is in accordance with Nielsen et al. [11] and Samuelsson et al. [18].

Higher extractives content reduced the energy needed for producing pellets (Fig. 2c). In Model 2.1 the effect of extractive content, moisture content, temperature of the feed stock material and the interaction between moisture content and extractives content were included even if the p values were between 6 and 10% (Table 2). The total model (Model 2.1, Table 2) showed that the role of extractive content on the power consumption increased with increasing moisture contents. This can be seen from Fig. 3. When the moisture content was approximately 7% (wet basis), an increase in extractives content did not reduce the energy used. Raw material entering the pellet press at a higher temperature consumed less energy (Model 2.1). The parameter estimates in Model 2.1 are reasonable, since increasing temperature and moisture content make wood less stiff [16].

The difference in energy consumption between the material requiring least energy and the material that consumed the most was 27% (Fig. 2b). For a pellet factory producing 40 000 t/year, this difference is the equivalent of an energy demand of about 1 GWh.

3.2. Pellets durability

Durability of 92% and 96% was achieved with raw materials having moisture contents of 7% and 12.5% respectively (Fig. 4a). The durability of the pellets was highest when the moisture content was approximately 12%. The positive effect of raw material moisture contents up to 12% is in agreement with the practical experience

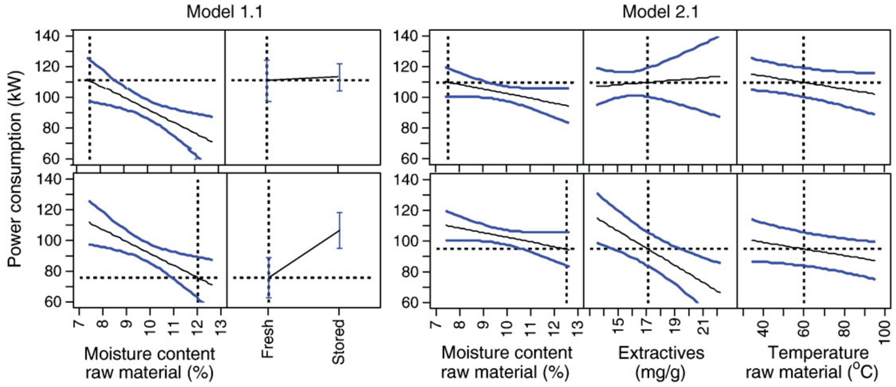

Fig. 3. Profiler figure illustrating the interaction effects in Model 1.1 and 2.1. The models predict the power consumption (Table 2). The upper profiler illustrates the model at 7.5% moisture content, and the lower profiler the model at 12.5% moisture content.

Table 2
Model statistics for power consumption during pellet production.

	Model 1.1		Model 2.1	
Model statistics				
RSquare	0.58		0.58	
RMSE	10.0		10.2	
N	24		24	
Parameter estimates and P-values for the covariates in the model				
Parameter	Parameter estimate	P-values	Parameter estimate	P-values
Intercept	147.0	<0.0001	177.0	<0.0001
F/S	–	0.0013	–	–
DM	–	NS	–	–
Moisture raw material	−4.70	0.0076	−3.0	0.10
Ext	–	–	−1.9	0.056
T	–	–	−0.21	0.073
Moi*Ext	–	–	(Ext − 17.1)*(Moi − 9.6)	0.049
F/S*Moi	–	0.056	–	–
Parameter estimates for categorical variables				
F/S (F)	−7.7		–	
F/S (S)	7.7		–	
F/S*Moi (F)	(Moi − 9.6)*(−3.2)		–	
F/S*Moi (S)	(Moi − 9.6)*3.2		–	

observed in the industry. The reduction in pellet durability at moisture content above 12% is reasonable due to a possible increase in steam pressure inside the pellets. Higher moisture content in the raw material also results in excessive moisture content in the pellets [3]. Larsson et al. [15] found somewhat higher optimal material moisture content (14.5%) for pellets from reed canary grass. The moisture content was the variable that reduced the durability residual variance most (Model 1.2, Table 3). This was observed in all assortments of the raw material, except for the fresh material that was dried at high temperature, where moisture content had no substantial effect (Model 1.2, Table 3).

Table 3
Model statistics for durability models.

	Model 1.2		Model 2.2	
Variance components for the random variables (% of total)				
R	14.5		14.4	
S [R]	0.4		–	
Residual	85.1		85.6	
Test statistics				
RSquare	0.73		0.65	
RMSE	0.72		0.90	
N	67		24	
Parameter estimates and P-values for the covariates in the model				
Parameter	Parameter estimate	P-values	Parameter estimate	P-values
Intercept	92.1	<0.0001	89.0	<0.0001
F/S	–	<0.0001	–	–
DM	–	0.41	–	–
Square(Moi)	0.032	<0.0001	0.032	0.0003
Ext	–	–	0.18	0.017
F/S*DM	–	0.0005	–	–
F/S*(Square(Moi))	–	0.021	–	–
Parameter estimates for categorical variables				
F/S (F)	0.54		–	
F/S (S)	−0.54		–	
DM (HT)	0.01		–	
DM (LT)	−0.01		–	
F/S*DM (F(HT))	−0.43		–	
F/S*DM (F(LT))	0.43		–	
F/S*DM (S(HT))	0.43		–	
F/S*DM (S(LT))	−0.43		–	
F/S*Moi (F)	(Square(Moi) − 92.3)*(−0.012)		–	
F/S*Moi (S)	(Square(Moi) − 92.3)*0.012		–	

Pellets produced from fresh raw materials had significantly higher durability than those produced from stored materials (Model 1.2, Table 3) (Fig. 3b). The difference in durability between fresh and stored raw materials was 1.08% (±0.54%) (Model 1.2, Table 3). A

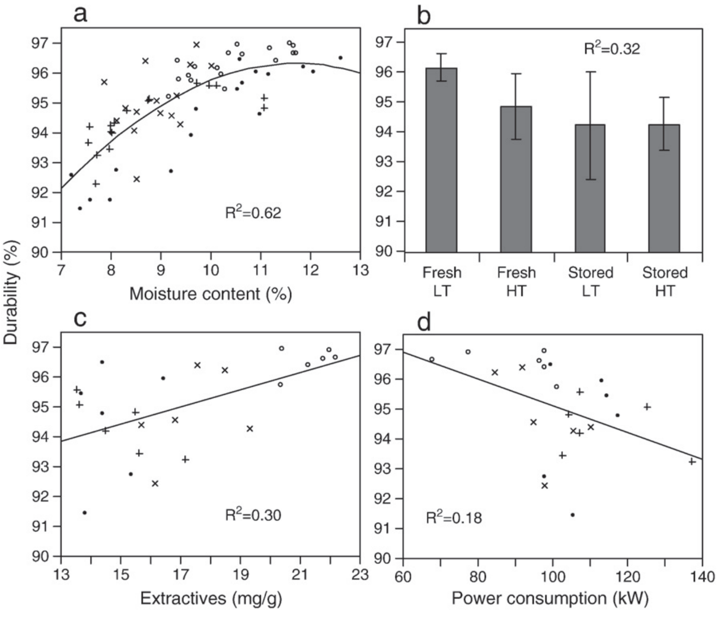

Fig. 4. The influence of: (a) the moisture content (wet basis) of the raw material, (b) different raw material categories, (c) extractive content and (d) energy use on pellet durability (◦ Fresh LT; × Fresh HT;• Stored LT; + Stored HT).

positive correlation between extractive content and durability was obtained as shown in Model 2.2 (Table 3) and Fig. 4c. The higher durability in fresh materials pellets could, therefore, be a result of the higher extractive content in these raw materials. The extractives content, (expressed as mg per g dry weight (±one standard deviation)) for the different types of materials were: fresh dried at 75 °C: 21.3 ± 0.8 (±one standard deviation), fresh dried at 450 °C: 17.3 ± 1.4, stored, dried at 75 °C: 14.7 ± 1.0 and stored material dried at 450 °C: 15.0 ± 1.4. Moisture content had a more evident effect on durability in pellets made from stored material compared to fresh material. This interaction effect can be seen in Fig. 5. The results show that fresh raw materials were favourable when the pellets were produced from raw materials with low moisture contents. For high moisture contents stored materials was slightly favourable.

The positive effect of increased extractive content on pellet durability found in this study indicates that extractives can have, at least partially, a binding effect in addition to lignin (Model 2.2, Table 3) (Fig. 4c). Kaliyan and Morey [9] stated that potential binding components in biomasses are lignin, water soluble carbohydrates, protein, starch and fat. The binding effect from extractives might lead to a less brittle pellet, which might be better in terms of durability. On the other hand, increased extractive content might result in pellets with a lower density and less strength due to a lubricant effect in the die [11]. Our study found a negative correlation between extractive content and density. However, the pellet strength was not investigated. A lubricant effect in the pellet press and the binding effect on the pellets due to extractives might explain the negative correlation found between energy consumption and durability (Fig. 4d).

The negative correlation between durability and storage time found in this study is opposite to what was reported in a recent study [18]. An interaction effect between moisture content and the Stored/Fresh variable was found in our study (Fig. 5 and Table 3). The divergent results might be caused by differences in raw material properties like different moisture content level used under the experiments. It might also be caused by differences in process equipment.

The chemical composition of wood fuel is likely to change during storage as a result of microbial activity [20]. Depending on the fungal species present, lignin, hemicelluloses and cellulose will be selectively degraded. Lignin is known to function as a binding agent in wood pellets [9]. However, the effect of lignin content was not investigated in this study.

The drying method did not reduce the residual variance significantly. Nevertheless, a significant interaction was found between the drying method and whether the material was fresh or stored. When the raw material was fresh, low temperature drying gave higher durability than high temperature drying. This might be due to the higher extractive content in the low temperature dried raw material.

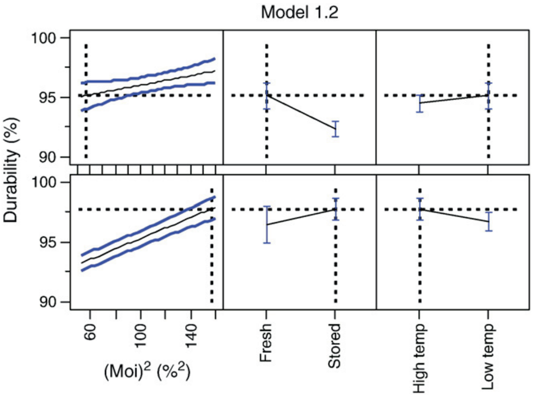

Fig. 5. Profiler figure illustrating the interaction effects for the durability predicted in Model 1.2 (Table 3). The upper profiler illustrates the model at 7.5% (√56) moisture content, and the lower profiler the model for 12.5% (√156) moisture content.

Steam added to the raw material did not affect the durability significantly. Neither the temperature of the material entering the press nor the interaction between the square of moisture content and the extractive content reduced the residual variance significantly.

3.3. Bulk density of the pellets

The bulk density depends on pellet density and the length distribution of the pellets. In this study, the pellet density explained 40% of the bulk density variance (Fig. 6d). The rest of the variance could be due to pellet length distribution and measuring error. A certain measuring error is expected, since pellet densities were measured using only a minor part of the volume on which bulk density measurements were based. The pellet density was explained by the same explanatory variables as the bulk density.

The bulk density increased from 660 to 760 kg/m^3 as the moisture content decreased from 13% to 7% (Fig. 6a). This most probably is partly due to the increase in particle density with decreasing moisture content. The moisture content to bulk density relationship was less substantial at lower moisture contents (Fig. 6a). Addition of steam did not affect the bulk density significantly.

Pellets produced using high temperature dried raw materials had a bulk density that was 19.8 kg/m^3 higher than pellets produced from low temperature dried raw materials (±9.9 kg/m^3, Model 1.3, Table 4). Pellets from stored materials had a bulk density that was 14.4 kg/m^3 higher on average than fresh materials. Both drying methods and the effect of storage in interaction with raw material moisture content reduced the residual variance significantly (Model 1.3, Table 4). The effect of moisture content on bulk density was greatest for the fresh and low temperature dried raw material (Model 1.3, Table 4). The effects of storage time and drying method on pellet density and bulk density most probably are results of extractives losses. Finell et al. [21] and Samuelsson et al. [18] found that a decrease in extractive content increased the pellet density. The bulk density decreased as the concentration of extractives in the raw material increased (Fig. 6c). This probably is due to the lubricant effect of the extractives in the pellet press, resulting in less pressure in the matrix, which in turn gives lower pellet density [18,21]. The effect was greatest when the moisture content was high (Model 2.3, Table 4). For the drier raw material (7-8%), the extractives content had no effect on the bulk density. Fig. 7 illustrates this interaction effect.

The bulk density also increased with increasing temperature of the raw material entering the pellet press. The effects of moisture content and extractives content found were in agreement with results reported by Nielsen et al. [7], and Nielsen et al. [11] and Rhen et al. [12], respectively. The significant interaction found between moisture content and extractives content has not been reported earlier.

The energy consumption was positively correlated with pellet density. This is related to how the pellet density depends on the friction and the pressure created in the dies [7,14]. Since the friction between the raw material and the die is important for both pellet density and energy consumption, models describing bulk density and energy consumption were explained by the same explanatory variables (Model 2.1 (Table 2) and Model 2.3 (Table 4)).

3.4. Remarks on the experimental setup and residual variance

In Figs. 2, 4 and 6 each variable is investigated separately with simple regressions in each sub figure. This gave a large residual variance. The residual variances were reduced considerably for the models where also interaction effects were included (Tables 2–4) (Figs. 3, 5 and 7).

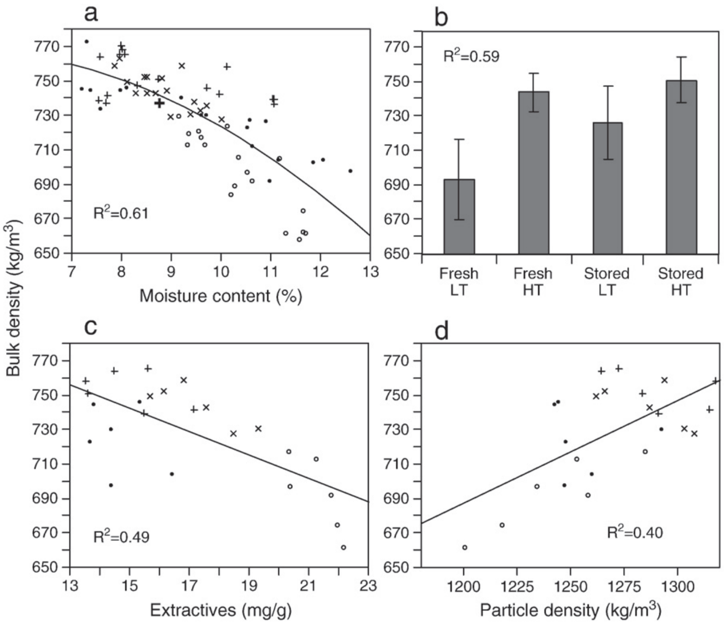

Fig. 6. The influence of: (a) the moisture content (wet basis) of the raw material, (b) different raw material categories, (c) extractive content and (d) particle density on pellet bulk density (◦ Fresh LT; × Fresh HT; • Stored LT; + Stored HT).

The experiments were performed in an industrial pellet press that demanded a large volume of material. Therefore, only 3 replicates of each of the 4 material categories were made. However, 6 parallel samples (3 with steam and 3 without steam) were taken from each replicate to study the variation within and between the independent replicates. The random variable replicate number explained approximately 15% of the pellet durability rest variance (Model 1.2, Table 3). For bulk density, the replicate number variance component was as high as 40% (Model 1.3, Table 4). However, this large variance was considerably reduced when extractive content was introduced to the model (Model 2.3, Table 4). The remaining residual variances might be explained by differences in machine settings and air temperature and humidity between the different replicates, along with measurement errors. The variance between the different parallels within each replicate was small, indicating that the production within each replicate was stable (Tables 3 and 4).

Table 4
Model statistics for bulk density models.

	Model 1.3		Model 2.3	
Variance components for the random variables (% of total)				
R	40.6		–	
Residual	59.4		100	
Model statistics				
RSquare	0.87		0.90	
RMSE	8.8		10.0	
N	71		24	
Parameter estimates and P-values for the covariates in the model				
Parameter	Parameter estimate	P-values	Parameter estimate	P-values
Intercept	789	<0.0001	841	<0.0001
F/S	–	<0.0001	–	–
DM	–	<0.0001	–	–
Square(Moi)	−0.62	<0.0001	−0.73	<0.0001
Ext	–	–	−3.46	0.0016
T	–	–	0.27	0.032
MoiR*Ext	–	–	$(Ext - 17.1)*((Moi - 94)*(-0.064))$	0.056
F/S*Moi	–	<0.0001	–	–
DM*Moi	–	0.025	–	–
Parameter estimates for categorical variables				
F/S (F)	−7.2		–	
F/S (S)	7.2		–	
DM (HT)	9.9		–	
DM (LT)	−9.9		–	
F/S*Moi (F)	$((Moi)^2 - 92)*(-0.27)$		–	
F/S*Moi (S)	$((Moi)^2 - 92)*0.27$		–	
DM*Moi (HT)	$((Moi)^2 - 92)*0.16$		–	
DM*Moi (LT)	$((Moi)^2 - 92)*(-0.16)$		–	

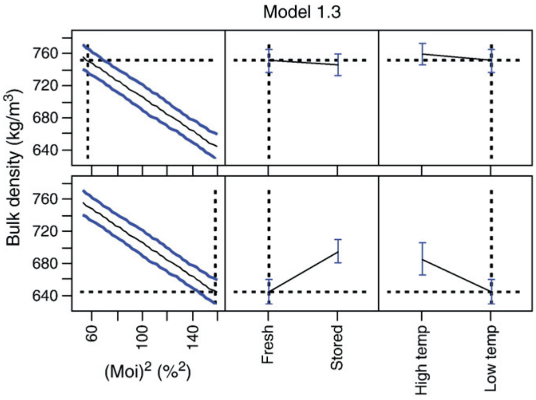

Fig. 7. Profiler figure illustrating the interaction effects for the bulk density predicted in Model 1.3 (Table 4). The upper profiler illustrates the model at 7.5% (√56) moisture content, and lower profiler the model at 12.5% (√156) moisture content.

4. Conclusions

Storage and high drying temperature of the raw material resulted in greater energy use during pelletization compared to drying at low temperature. The loss of extractives in the former may have led to higher friction in the matrix. However, the same factor could also be responsible for the higher pellets density. Pelletization of the fresh material, dried at a low temperature, required low energy consumption and resulted in the highest durable pellets but low pellets density. The mild effect of low temperature drying on the concentration of extractives in fresh wood could be a contributing factor in improving the binding of pellets and retaining their lubricant effect in the pellet press. This could explain the negative correlation found between durability and energy consumption.

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Paper II

Wood-Pellet Heating in Norway: Early Adopters' Satisfaction and Problems That Have Been Experienced.

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Article

Wood-Pellet Heating in Norway: Early Adopters' Satisfaction and Problems That Have Been Experienced

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Abstract: Given the vital role of early adopters during the early stage of wood-pellet heating development, this study aims to explore the factors that explain the overall satisfaction among the early adopters of this type of heating as well as the problems experienced with wood-pellet heating in Norway. Ordinal regression was used to analyze empirical data which was collected from a mail survey in autumn 2008. The response rate of 45% was composed of 669 early adopters of wood-pellet heating. Findings show that both economic factor (*i.e.*, cost) and technical factors (*i.e.*, pellet stove performance) have played a significant role in early adopters' overall satisfaction with wood-pellet heating. The most common problems experienced are igniter failure in the pellet stove, lack of committed and competent suppliers/vendors, more time and effort than expected during maintenance, and fines from pellets both during handling and combustion.

Keywords: early adopters; satisfaction; technical problems; wood-pellet heating; Norway

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1. Introduction

Environmental problems, such as climate change, are important issues today. The question of how to meet present needs without sacrificing the ability of future generations to satisfy their needs is thus a central topic in the debate over sustainable development. The convergence toward a sustainability path depends to a great extent on the diffusion of environmentally friendly technologies. In fact, the diffusion of these technologies is often slow and tedious [1,2]. The diffusion of wood-pellet heating in Norway is one of the examples. Little attention has been paid to the empirical study of customers' perceptions of wood-pellet heating. Therefore, this study contributes to a better understanding of the case by meeting two objectives. First, it aims at revealing factors explaining early adopters' satisfaction with using wood-pellet heating. Second, this paper also presents subjective perceptions about maintenance time as well as problems related to wood-pellet stoves, suppliers of wood-pellet stoves and wood pellets. This paper provides empirical evidence about the factors influencing household satisfaction with wood-pellet heating and their typical problems so that intervention favoring further diffusion of wood-pellet heating could be appropriately designed.

2. Wood-Pellet Heating

Home heating accounts for approximately 50% of an average household's energy use, being the largest share of energy consumption in Norwegian residential sector. The Norwegian heat market is characterized by a dominance of individual heat sources, such as electric radiators, logwood stoves, and air-to-air heat pumps, rather than central heating using water-based heating systems. Approximately 5% of Norwegian households use common central heating and less than 1% have access to district heating [3,4]. The most important energy carrier in Norwegian households is electricity due to the public investment in hydropower construction from 1960 to 1990, which provided a large capacity of cheap electricity [5]. Figure 1 shows the market share of various types of heating systems in Norway [6]. Norwegian households generally combined different types of heating systems and the combination of electric heating and wood stove is the most popular system [7].

Norway's commitment to the Kyoto Protocol which restricts the increase of greenhouse gas emissions has led to policies favoring the increased use of heat pumps, wood-pellets, thermal solar energy, *etc.* [5]. Therefore, the Norwegian government plans to reduce and then phase out remaining oil-based heating systems by supporting alternative heating systems which are presumed to be environmentally friendly. Figure 1 illustrates the 65% reduction in oil-based heating systems in 2009 compared with 2006. However, among the Nordic countries, Sweden is the country that has significantly reduced oil use in the residential sector so that the level of oil use per person is about 30% of that of Norway [7]. This has been made possible by replacing oil-based heating systems with district heating, water-based heat pumps and pellet boilers [8].

The pellet market in Norway is currently only a niche market, in contrast to some European countries such as Sweden, Austria, and Denmark in which wood pellets have been well-developed and well-utilized for heating, mainly in the residential sector. At the moment, the main application of wood-pellets in Norway is small-scale heating in households. Wood-pellet heating is particularly interesting for the Norwegian market because wood-pellets are normally produced out of clean saw dust and shavings, which are residues from the wood-based industry. A life-cycle assessment shows that wood-pellet stoves can result in overall environmental and climate benefits in Norway compared to oil-based heating system [9]. Furthermore, given the fact that wood is the second dominating heating system in Norway, replacing wood stoves with pellet stoves may contribute to lower emissions as pellet stoves burn significantly cleaner than wood log stoves [10]. Table 1 presents emission comparison of different wood log fireplaces and woodpellet stove which shows the large potential for low emissions achievement with woodpellet stove.

Figure 1. Heating system adopted by Norwegian households in 2006 and 2009, by percentage. Note: Norwegian households generally utilize more than one type of heating system. Source: [6].

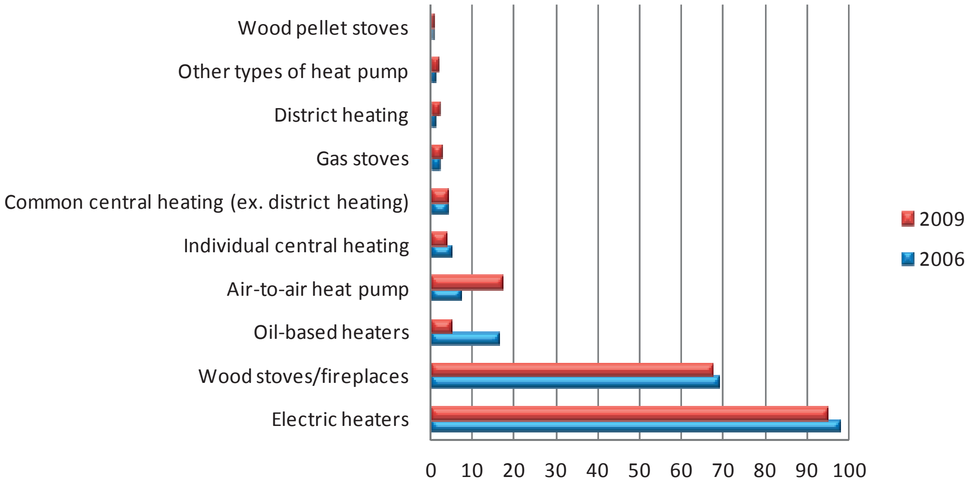

Table 1. Arithmetic average emissions levels in mg/m^3 at 13% O_2 from small-scale biomass combustion applications at standard reference conditions.

	Load (kW)	Excess Air ratio	CO (mg/m^3)	C_xH_x (mg/m^3)	Particles (mg/m^3)	NO_x (mg/m^3)	Temp (°C)	Efficiency (%)
Wood-stoves	9.33	2.43	4,986	581	130	118	307	70
Fireplace inserts	14.07	2.87	3,326	373	50	118	283	74
Heat storing stoves	13.31	2.53	2,756	264	54	147	224	78
Pellet stoves	8.97	3.00	313	8	32	104	132	83
Catalytic wood-stoves	6.00	-	938	-	-	-	-	-

Source: [11].

To persuade households to decide on wood-pellet heating, a subsidy scheme of up to 20% of total installation cost of wood-pellet heating was introduced in 2003. A study investigating the effect of this subsidy scheme to the adoption of wood-pellet heating indicated that only 1215 out of 3671 households who received grants had actually installed wood-pellet heating [12]. Therefore, the market for wood-pellet heating remains low and is stagnating [3]. According to Statistics Norway, it was reported that the market share of wood pellets was 0.3% and 0.7% in 2006 and 2009 respectively (see Figure 1). A previous study of the opportunities and barriers for wood-pellet heating in Norway came to the conclusion that the largest barriers were in fact on the demand side [13]. The study found that plant pellet production plant was currently operating under-capacity due to lack of wood-pellet demand. This study therefore complements the previous study by exploring subjective perceptions from the end-users' perspective.

The present study however does not claim that an extremely high adoption rate of wood-pellet heating is desirable from an environmental perspective as research on the optimal balance of heating systems in Norway needs to be investigated beforehand. This study is merely focusing on how to improve a potential system, *i.e.*, wood-pellet heating that is under-utilized.

3. Background Theory

A low level of acceptance of new technology is actually not new phenomenon in adoption and diffusion studies. One particular technology may take less than a decade to diffuse while another technology may take more than a century to be well-accepted by society. Studies to stimulate and/or accelerate technology diffusion can be approached at either macro- or micro-levels, qualitatively or quantitatively. Some studies have focused on supply side of the process, e.g., Grübler [14]; others on the demand side, e.g., Rogers [15].

As the present study focuses on demand side, it therefore uses insights from Diffusion of Innovation (DoI) theory by Rogers [15] which has been widely used in various application domains such as agriculture and information technology. According to DoI, the adoption of innovation has generally been through different phases from initial slow growth to accelerating and eventually to maturity and decline. The first phase of adoption involves innovators and is then followed by early adopters once the benefits start to become apparent. Early adopters are vital because they provide information to other consumers that are critical before marketing release. After an innovation crosses the chasm, the early majority comes into play, followed by late majority and laggards respectively.

DoI theory also highlights that innovation decision is dependent upon individuals' perception of an innovation's characteristics; relative advantage, compatibility, complexity, trial ability, and observability. Jeyaraj *et al.* [16] demonstrated that perceived innovation characteristics determined the acceptance of information technology applications. Relative advantage referring to the degree to which an innovation/a technology is perceived to be superior to previous/existing technology can be measured in terms of social prestige, convenience or satisfaction. Using the concept of satisfaction as an indicator of adoption decision has been proposed and applied in some studies, e.g., Nyrud *et al.* [17]. The concept of satisfaction assumes that dissatisfaction towards a technology may lead to a need of a new technology type, whereas satisfaction with existing technology convinced consumers to keep their technology, exerting a significant impact on consumer loyalty [18]. Mahapatra *et al.* [8] demonstrated that when low quality and expensive pellet boilers appeared on the market this was leading to dissatisfaction among early adopters of pellet heating systems who might have passed this information to others, and ultimately to low market penetration. Sopha *et al.* [19] have indicated that those who would choose wood-pellet heating in the future seems to be satisfied with the existing wood-pellet heating, stressing the importance of exploring factors contributing to the satisfaction /dissatisfaction of using wood-pellet heating. Furthermore, Nyrud *et al.* [17] demonstrated that satisfaction towards wood stoves could predict the future use and the willingness to recommend to others. Given the vital role of early adopters, it is thus important to investigate the early adopters' perceived satisfaction towards wood-pellet heating.

Furthermore, as the wood-pellet market is still at an early stage of development, there is a dynamic aspect in technology development which will then impact on the structure of the wood pellet system. For example, developments in pellet quality and the convenience of using wood-pellet stoves will shape the future wood-pellet market. Therefore, during this stage, not only economic factors but also technical factors are vital. This is demonstrated by Nyrud *et al.* [17]; satisfaction concerning wood stoves in Norway is mainly related to the performance of the device. With respect to technology, there are many factors involved. Time and effort required for operation and maintenance of wood-pellet heating was found to be significant and impacted negatively on satisfaction [17]. The pellet stove is a relatively new technology which was first marketed in the USA in 1983 [12]. One of the success factors of wood-pellet development in Austria is that Austrian legislation enforces stringent emission standards for boilers, guaranteeing the boiler quality and enforcing the R&D efforts of boiler producers to improve technical performance of installations [20]. On the other hand, one of the barriers of wood-pellet development in Finland is that there is no standard for combustion equipment, leading to the collapse of consumers' confidence [21]. Moreover, the lack of after-sales service has already been seen as a problem for wood-pellet development in Finland [21]. With respect to pellet quality, according to Nashoug and Pedersen [13] there was a varying quality of pellets in Norway. Pellet quality was also perceived as a barrier in Finland where the pellets did not endure the mechanical wear caused by storage and transport [21]. In contrast, the certification system of pellets has facilitated the development of wood pellets in Austria [20]. Considering the issues raised in the literature mentioned, this study focuses on technical factors; namely maintenance time, pellet stove performance, suppliers/vendors and pellet quality.

With respect to the economic factor, the generous subsidy is one of the driving forces behind the wood-pellet heating development in Austria. Conversely, cost was found to be barrier for wood-pellet development both in Finland and in Norway [11,21]. Therefore, the present study focuses on both technology-related factors (technical factors) and cost (economic factor) that explain consumer satisfaction.

4. Methodology

4.1. Data Collection

A mail survey was conducted in autumn 2008 to collect data. 1500 questionnaires were sent to wood-pellet users in Norway which represents almost all the users. The list was acquired from wood-pellet companies in Norway. The response rate after three weeks was 34.6%. After a reminder was sent out, additional responses from 150 were received and this makes a total response rate of 44.6% (669 responses). Several respondents did not answer the entire questionnaire, and therefore the response rate varies for each question. The quantitative survey for the present study is also used for the study reported in Sopha *et al.* [19] and Sopha *et al.* [22]. The analysis in the present study is however built on different variables which have never been used in both the previous studies except for the cost measure (see Table 2).

Table 2. Name and definitions of variables used in the analysis.

Variable	Name	Description
Dependent	Wood-pellet satisfaction	Perceived overall satisfaction of wood-pellet heating (5-point Likert scale, high score = high satisfaction)
Independent	Maintenance time	Perceived maintenance time (5-point Likert scale, high score = less time)
Independent	Pellet stove	Perceived pellet stove performance (5-point Likert scale, high score = high satisfaction)
Independent	Supplier of stove	Perceived service provided by stove vendor/supplier (5-point Likert scale, high score = high satisfaction)
Independent	Pellet quality	Perceived pellet quality (5-point Likert scale, high score = high satisfaction)
Independent	Cost	Perceived cost of wood-pellet heating (7-point Likert scale, high score = very expensive)

A household is the unit of analysis, implying that the response from the questionnaire represents a household. Hence, one member of the household, on behalf of a household, answers the questionnaire.

To test if the sample varied significantly from the regional distribution of all households in Norway, sample analysis was conducted and indicated that the sample shows an insignificant difference with respect to age when comparing to age distribution of population registry (Chi^2 = 45.423; df = 73; p = 0.995). Even though the regional distribution of wood-pellet sample is significantly different from that of population registry (Chi^2 = 488.028; df = 18; p < 0.000), this sample is representative for all Norwegian wood-pellet users, as it accounts for roughly 80% of all wood-pellet users in Norway.

To test non-response bias, a Chi^2 test is performed to compare the original and the response sample by provinces/districts. The tests revealed that there is no statistical difference between the original samples and response samples for wood pellet sample (Chi^2 = 2.031; df = 13; p = 1.000). Thus, a self-selection bias could not be found with respect to regional distributions. Other data on the original population to test self-selection bias in the response samples are not available. It might, therefore, be possible that self-selection processes result in an undetected bias. In addition, given the higher number of satisfied adopters in this sample (see Table 3), dissatisfied adopters are under-represented.

Table 3. Profiles of respondents' response on both dependent and independent variables.

Dependent variable	**Frequency (%)**
Wood-pellet satisfaction	$N = 456$
1 = not at all satisfied	7 (1.5%)
2	3 (0.7%)
3	29 (6.4%)
4	172 (37.7%)
5 = very satisfied	245 (53.7%)
Independent variables	**Means (S.D.)**
Maintenance time	2.64 (1.39)
Pellet stove	3.99 (1.04)
Supplier of stove	3.69 (1.19)
Pellet quality	3.71 (1.02)
Cost	3.56 (1.60)

4.2. Analysis

The analysis is divided into two parts to meet two objectives. The first analysis is to identify technical factors explaining early adopters' satisfaction. Ordinal regression was then selected to deal with ordinal nature of the dependent variable, *i.e.*, overall satisfaction of using wood-pellet heating. The independent variables are perceived maintenance time, perceived performance of wood-pellet stoves, perceived service provided by suppliers/vendors and perceived pellet quality, which are treated as continuous variables. Table 2 present the names and definitions of variables used in the analysis.

The second part of the study is to document responses from open questions with respect to maintenance time and the most experienced problems related to pellet stove, suppliers/vendors and wood-pellets. This part provides a more detailed explanation of the specific issues investigated in the first part.

5. Results

5.1. Ordinal Regression—Early Adopters' Satisfaction

Table 3 presents profiles of the sample based on responses to the dependent and independent variables in the survey. Participants with missing values in predictive variables had to be excluded from the study so that the final analysis is based on a sample of 456 respondents. The table shows that 91% of the sample is satisfied with wood-pellet heating, whereas only about 2% shows dissatisfaction.

The tests shown in Table 4 were conducted to assess model fit and the model's ability to predict the dependent variable. Based on the results in Table 4, the regression model fits well to the empirical data.

The regression coefficients, Wald test statistics, and significance for each of the variables are presented in Table 5.

When applying a $p < 0.05$ criterion of statistical significance, perceived stove performance and cost are found to be significant whereas perceived maintenance time and perceived service by suppliers/vendors are found to be marginally significant. Pellet quality is found to be non-significant ($p = 0.882$).

The threshold of categories 3 and 4 is significantly different from zero, implying that they substantially contribute to the values of the response probability in different category. The threshold of categories 1 and 2 is found to be non-significant, implying that the cutting points are not truly different and thus these categories need to be combined. The result indicates that the overall satisfaction of wood-pellet heating was significant associated with pellet stove performance and cost, whereas pellet quality is found to be non-significant to explain overall satisfaction of wood-pellet heating.

Positive regression coefficients of maintenance time, pellet stove and stove suppliers/vendors indicate that households who rate higher levels on these variables are likely to be more satisfied with wood-pellet heating. Negative regression coefficient of cost shows that the household is likely to be less satisfied with the increase of wood-pellet cost.

Table 4. Regression analysis.

Test	Result	Remark [a]
Test of Parallel Lines	*Chi* ^{2} = 12.954; *df* = 15; *p* = 0.606	Non-significant result indicates a well fitting model
Model Fitting	*Chi* ^{2} = 182.795; *df* = 5; *p* < 0.001	A well-fitting model is significant by this test
Goodness of Fit: Pearson Deviance	*Chi*^{2} = 1189.127; *df* = 1431; *p* = 1.000 *Chi*^{2} = 611.535; *df* = 1431; *p* = 1.000	A well-fitting model is non-significant by these tests
Pseudo R-Square: Cox and Snell Nagelkerke	0.330 0.385	The higher, the better (less than 1). Approximations to OLS R^2, not to be interpreted as actual percentage of variance explained

[a] Source: [23].

Table 5. Ordinal regression for wood-pellet users' satisfaction.

Variable	B	Wald χ^2	*df*	*p*
Threshold 1 *vs.* 5	−0.466	0.458	1	0.499
Threshold 2 *vs.* 5	−0.034	0.003	1	0.958
Threshold 3 *vs.* 5	1.778	8.171	1	0.004 **
Threshold 4 *vs.* 5	4.839	51.685	1	<0.001 ***
Maintenance time	0.153	2.909	1	0.088 ^{ms}
Pellet stove	1.123	67.038	1	<0.001 ***
Suppliers of stove	0.193	3.702	1	0.054 ^{ms}
Pellet quality	−0.016	0.022	1	0.882
Cost	−0.233	9.804	1	0.002 **

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ^{ms} marginal significance (ms) $p < 0.1$.

Table 6 displays the accuracy of the classification results for the satisfaction response category against the actual response category. The model demonstrated moderate prediction accuracy (50%) for all five categories combined.

Table 6. Accuracy of the classification for response categories.

		Predicted response category					
		1	**2**	**3**	**4**	**5**	**Total**
Actual response category	**1**	1	0	3	2	1	7
	2	0	0	0	3	0	3
	3	0	0	6	21	2	29
	4	0	0	1	87	84	172
	5	1	0	1	46	197	245
	Total	2	0	11	159	284	456

5.2. Perceived Problems Related to Wood-Pellet Heating

5.2.1. Maintenance Time

Table 7 displays the maintenance time each week experienced by early adopters. Most users respond that maintenance time less than 50 minutes per week is required for wood-pellet heating.

Table 7. Perceived maintenance time (N = 609).

Maintenance time (minutes/week)	**Number**	**%**
Less than 50	487	80
51–100	103	17
101–150	18	3
Above 150	1	0

5.2.2. Stove-Related Problems

Table 8 depicts the main problems of wood-pellet stove experienced by early adopters. It seems that the most familiar problem is related to the igniter, an electrical element which is heated to about 300–400 °C to start pellets to fire. Other common problems are related to control system, fuel feeding system and noise.

Table 8. Stove-related problems (N = 443). Note: Respondents are asked to name only one the most experienced stove-related problem.

Problem	**Number**	**%**
Igniter failure	108	24
Inappropriate combustion	99	22
Control system	45	10
Fuel feeding system	27	6

Table 8. *Cont.*

Problem	Number	%
Noise	27	6
Operations (unstable, stop)	20	5
More work than expected	16	4
Users guidance—too complicated	10	2
Backfire	8	2
Expensive (service and/or spare-parts)	6	1
Glass windows (safety, dangerous for children)	4	1
No Problem	*73*	*16*

5.2.3. Supplier-Related Problems

Table 9 shows experienced problems related to suppliers/vendors. Lack of commitment to consumers refers to unwillingness to provide service or no response toward consumers' request. Discontinuation of pellet-stove sales could be due to that suppliers/vendors are either no longer selling pellet stoves or are in bankruptcy.

Table 9. Supplier-related problems (N = 324). Note: Respondents are asked to name only one the most experienced supplier-related problem.

Problem	Number	%
Lack of commitment to consumers	78	24
Lack of competence	76	23
Long delivery time for spare-parts	24	7
Discontinuation in selling pellet stoves	22	7
Long distance	8	2
No Problem	*116*	*35*

5.2.4. Pellet-Related Problems

Table 10 displays most problems related to pellets. About half of the reported problems are about fines/dust from pellets both during handling and combustion. Fuel properties of pellet include densities, length, fines and moisture that differ over time. This may result in a new adjustment of the pellet stove which is not suitable for consumers.

Table 10. Pellet-related problems (N = 408). Note: Respondents are asked to name only one the most experienced pellet-related problem.

Problem	Number	%
Dust	210	51
Non-stable fuel properties (over time)	35	9
Moisture	25	6
Too much ash	18	4
Varying pellet size (too long pellets)	10	2
Energy expectation in fuel	5	1
No Problem	*105*	*26*

6. Discussions

This study investigates the explanatory variables of early adopters' satisfaction concerning wood-pellet heating in Norway. The wood-pellet market in Norway is at the moment in the early development stage, the role of early adopters hence becomes important as they may either facilitate or hinder further adoption of wood-pellet heating. Early adopters, conveying subjective evaluation of wood-pellet heating, serve as a role model for potential adopters, thus reducing uncertainty (skepticism) about wood-pellet heating. Moreover, they may also provide feedback information on wood-pellet heating performance needed for improvement. Therefore, this study contributes to help policy makers to design effective intervention by providing empirical evidence about whether or not wood-pellet heating is satisfying from the households' perspective, providing information on factors leading to satisfaction, as well as providing facts on the most problems experienced by early adopters.

Results demonstrate that about 91% of early adopters are relatively satisfied with wood-pellet heating. Results also indicate that overall satisfaction toward wood-pellet heating is significantly influenced by both technical factors (*i.e.*, pellet stove) and economic factor (*i.e.*, cost). Studies have indicated that the lack of appropriate technology hinder the development of wood pellets, in addition to the economic barrier such as high investment cost [11,20,21]. Nyrud *et al.* [17] also emphasized the importance of superior system performance before a public campaign. Furthermore, Sopha *et al.* [22] simulating households' decision-making in response to various interventions, demonstrated that the relative advantage of wood-pellet heating should be realized not only in one area but also in many areas simultaneously with respect to functional reliability, supply security, indoor air quality, required work, and cost. The need for simultaneous development is also emphasized by Egger and Öhlinger [24] who suggested that key success for wood-pellet market establishment relied on all factors in market which functioned at the same time; from good quality pellet, standardized stove/boiler, distribution network, competent installers, until there was willingness among consumers to use wood-pellet heating. This actually corresponds with the design principles for effective carbon emission reduction programs for household sector by Vandenbergh *et al.* [25]. They suggest that program success critically depends on the combination of financial incentives and other design principles such as simplicity, quality assurance, and marketing.

The pellet stove is found to be a significant explanatory factor concerning the satisfaction of using wood-pellet heating. The most common problems with pellet stoves are related to igniter failure, inappropriate combustion, control system, fuel feeding system and noise. The problem with noise is also reported in the previous study on wood-pellet heating in Norway [12]. It implies that technology development for the pellet stove is urgently needed. It is also worthwhile to note that "glass windows" are perceived to be unfavorable by a few respondents due to safety considerations. Conversely, "glass windows" are preferred due to aesthetic concerns because the stove is not only serves its functional purpose but also performs a symbolic presentation of Norwegian homes [12]. For this reason, a neat design of the pellet stove is important to attract consumers [12,26]. Both maintenance time and vendors/installers reach marginal significance. The difficulty related to maintenance time and effort could be handled by fully automatic operation [26]. It seems that, based on the findings, maintenance time of wood-pellet heating should be less than 50 minutes/week to make wood-pellet heating even more interesting. With respect to the problem related with service provided by suppliers/vendors, although 38% respondents show their satisfaction, it is worthwhile to mention that about 24% of responses confirmed their lack of commitment to the consumers, e.g., suppliers/vendors do not respond to consumers' inquiries and 23% confirmed that there was a lack of competence. Long delivery time for spare-parts, and discontinuation of selling pellet stoves are other problems mentioned as the third and fourth highest on the list. Lack of knowledge/skills was a barrier for wood-pellet development in Finland [21]. Therefore, improving suppliers' commitments and competences could be one of areas where action is required.

Pellet quality is found to be a non-significant variable for explaining satisfaction. 26% of responses allege to have no problem with pellet quality. However, this result is at odds with the work by Nashoug and Pedersen [13] who documented that the variation in the quality of pellets is one of the barriers for pellet development in Norway. The explanation could be that pellet quality has been developed and standardized. Hence, the quality of pellets is no longer perceived to be dissatisfying. At the same time, this result indicates that there exists dynamicity of technology development. Nevertheless, the main problem related to pellet quality is "dust" which is persistently perceived as a problem by adopters [13] and adopters of this study.

With respect to cost, our results imply that the higher the cost, the higher probability of dissatisfaction when using wood-pellet heating. It is necessary to note that the limitation of this study is that cost refers as a total cost which involves both investment and operational cost. It would be beneficial to differentiate between investment and operation costs so that appropriate intervention could be targeted to the specific area. Sopha *et al.* [22] used a similar sample as this study but analyzed a different part of the questionnaire. They confirmed that high investment cost is the highest barrier rated by the respondents. High investment cost was actually named by some works as a barrier to adopt wood-pellet heating. For instance, Bjørnstad *et al.* [12] documented that only about 33% of households receiving grants actually installed wood-pellet heating because of the high investment cost as well as the uncertain benefits. According to Nashoug and Pedersen [13], investment cost for pellet burning is about twice as high as investment in ordinary wood-burning stoves (in cost/KW). Moreover, some buildings lack the fundamental pre-requisites such as chimney, or room for pellet storage so that it is expensive to remodel them. The investment cost barrier was also experienced in Finland [21]. With respect to operational cost, Sopha *et al.* [22] indicated that operational cost is the third important attribute in a heating system decision which is in agreement, to some extent, with Nyrud *et al.* [17] who demonstrated that operational cost was not significant in explaining satisfaction with wood heating in Norwegian households.

Last but not least, this study concerns the subjective evaluation of the respondents which does not necessarily correspond to the actual/objective issue. For instance, the same price of a pellet stove may be perceived differently; some may consider it expensive and others may regard it to be cheap, depending on the contextual factors in which one is situated, thus providing richer insights.

7. Conclusions

This study uses the ordinal regression method to model the relationship between the early adopters' overall satisfaction with wood-pellet heating and the explanatory variables concerning both the financial factor (cost) and the technical factor (maintenance time, pellet stove, suppliers/vendors, and pellet quality). Everything except pellet quality was found to be significant. The research findings provide the compelling evidence that both cost and pellet stove performance have played a significant role in early adopters' overall satisfaction with wood-pellet heating in Norway. Due to the significance of the pellet stove, technological improvements to alleviate the most common problems, *i.e.*, igniter, inappropriate combustion, control system, fuel feeding system and noise, are thus necessary. With respect to cost, it seems that financial support is still necessary; however, it should be complemented with intervention supporting technical factors. Although marginally significant, committed and competent suppliers/vendors as well as automation may stimulate a higher satisfaction level for wood pellet heating. The findings also indicate that pellet quality is no longer perceived to be a barrier as it was previously, implying the occurrence of technology dynamicity. Given the recent weak development of the wood-pellets market in Norway, *i.e.*, lack of vendor commitment and competence, immature technology and finally; low electricity prices, it seems that the market share of wood-pellets heating systems might not go any further than today's level.

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Paper III

Norwegian households' perception of wood pellet stove compared to air-to-air heat pump and electric heating.

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Norwegian households' perception of wood pellet stove compared to air-to-air heat pump and electric heating

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ABSTRACT

In 2003, the high dependency on electric heating combined with the high electricity price prompted a significant number of Norwegian households to consider alternative heating systems. The government introduced economic support for wood pellet heating and heat pumps. In contrast to the fast growing heat pump market, this financial support has not resulted in a widespread adoption of wood pellet heating. This paper studies factors that influence the choice of heating system based on Norwegian households' perceptions. Electric heating, heat pump and wood pellet heating were compared, with a special focus on wood pellet heating. This study was conducted as a questionnaire survey on two independent samples. The first sample consisted of 188 randomly chosen Norwegian households, mainly using electric heating; the second sample consisted of 461 households using wood pellet heating. Our results show that socio-demographic factors, communication among households, the perceived importance of heating system attributes, and the applied decision strategy all influence the Norwegian homeowners. The significance of these factors differs between the two samples and the preferred type of anticipated future heating system. Strategies for possible interventions and policy initiatives are discussed.

1. Introduction

Norwegian public investment in the construction of hydropower plants between 1960 and 1990 provided a large capacity of cheap electricity (Christiansen, 2002) and consequently led to an increased dependency on electricity for heating. Approximately 70% of Norwegian households use electricity as the main heating source, especially in the residential sector (Statistics Norway, 2006). Because the demand for electricity has grown to match the average supply and because the production is significantly affected by precipitation, Norway is at times a net exporter of energy. However, when energy consumption exceeds production, Norway imports energy. While the Norwegian production of electricity is almost 100% regenerative, the imported energy is generated from various sources including nuclear power and fossil fuel. Several grids have been built to facilitate future electricity exports to other European countries because it is argued that every kWh of electricity exported replaces a kWh of electricity produced abroad based on fossil energy sources.

Even as Norway occasionally imports electricity from other countries, it has enormous bio-energy resources in its forests. As heating accounts for approximately 50% of energy use in households (Larsen and Nesbakken, 2005; REMODECE Project, 2006), shifting the prevalent heating system from electric to renewable, e.g. wood pellet, can help mitigate environmental problems caused by importing energy and/or the construction of additional hydroelectric power plants. Thus, Norwegian government has supported alternative heating systems for households to overcome the electricity dependency and reduce electricity consumption. The choice of a particular heating system by Norwegian households is therefore an important issue.

The Norwegian Commission on Low Emissions has proposed a transition to CO_2-neutral heating through an increased use of heat pumps, wood pellets, thermal solar energy systems, etc. (Norwegian Strategy Group, 2006). Many attempts have been made to establish a market for heat pumps and wood pellet heating. Subsidies were introduced to defray the costs for individual households to install alternative heating systems and reduce electricity consumption. In 2003, Enova, established in 2001 as a public enterprise owned by the OED (Ministry of Petroleum and Energy), ran a subsidy scheme that provided for up

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to 20% of the total investment costs for all types of heat pumps and wood pellet heating solutions (Innstilling til Stortinget fra energi-og miljøkomiteen nr. 133, 2002–2003). The number of installations of air-to-air heat pumps more than doubled between 2002 and 2003. This boost was mainly caused by subsidies accompanied by an increase in the price of electricity (Markusson et al., 2009). As the market share of air-to-air heat pumps increased significantly, the subsidy scheme was discontinued in 2007. Although the market development of wood pellet stoves was much less dynamic, the subsidies for wood pellet systems did not go uninterrupted due to a lack of funding and claims by the organization of ordinary wood-stove manufacturers that the government should also provide subsidies for ordinary wood stoves. At the same time, Norway is steadily increasing its wood pellet production (Peksa-Blanchard et al., 2007) which improves the availability of wood pellets in the market. Despite these interventions, the market diffusion of wood pellet heating has been rather slow. It is reported that in 2006 only 3 out of 1000 households had pellet stoves (Statistics Norway, 2006).

This paper first aims to identify factors motivating current users of electric heating system to choose either air-to-air heat pump or wood pellet as a replacement heating system. The second goal is to identify factors motivating wood pellet users to shift their main heating system away from wood pellet heating and back to either an electric heating or an air-to-air heat pump. This study contributes to the understanding of the rationale that causes a Norwegian household to choose one type of heating system over another. Three types of heating systems are examined: direct electric heating (the standard technology), individual wood pellet stove (hereafter used interchangeably with wood pellet heating), and air-to-air heat pump (hereafter referred to as heat pump). Wood pellet stove and heat pump were chosen because these two systems are the most commonly used alternatives to electric heating in Norway. However, the paper focuses on wood pellet heating rather than on heat pump because the adoption of the latter has been much faster than that of the former. For this reason no sample of heat pump users was surveyed.

2. Theoretical background

Understanding consumer choice is a pre-requisite to develop strategies to encourage pro-environmental consumer behavior. Purchasing decisions are made at either the individual or the household level. Household decision making differs from individual decision making because households often consist of several members who may have different preferences, and consequently the final decision usually represents a compromise, in the same way that children might influence the choice of a holiday destination. Lackman and Lanasa (1993) indicated that many purchasing decisions of families were not the outcome of an individual choice but influenced to a great extent by other family members. Lindhjem and Navrud (2009) documented that the two primary explanations for why Norwegian households favored environmental goods more than individuals were that incomes of both adults and the partner's opinion were taken into account. As the selection of heating system usually requires a large financial investment, and includes at least two adult members of a household, this decision is defined as a decision taken at a household level for the purpose of further discussion.

Previous Norwegian studies and other studies on the choice of heating system have focused on socio-demographic factors, household characteristics, communication and heating systems attributes as influencing factors (Brottemsmo, 1994; Nesbakken and Strøm, 1994; Nesbakken, 1998; Kasanen and Lakshmanan, 1989; Scodari and Hardie, 1985; Mahapatra and Gustavsson, 2008). Based on previous studies, factors from four different areas are taken into consideration in order to explain the choice of heating system: socio-demographic factors, communication among households, heating system attributes, and the decision strategy applied by the households.

2.1. Socio-demographic factors

Previous studies on the choice of heating system have been able to show that a number of socio-demographic factors such as age, income, education and region influence this decision (Mahapatra and Gustavsson, 2008; Scodari and Hardie, 1985; Nesbakken and Strøm, 1994; Kasanen and Lakshmanan, 1989). Age is relevant as older people can be expected to be more traditional than young people with respect to the acceptance of new technologies (Brown and Venkatesh, 2005). Since wood pellet heating and heat pump are considered as emerging technologies, age is anticipated to be a possible factor in this study. Household income strongly affected investment behavior for heating in the previous study conducted by Nesbakken and Strøm (1994) as those with a high income level prefering electric heating. The total income of the household rather than just the income of the head of the household is measured in this study, to provide a more realistic figure of the available resources. Prior results regarding the influence of educational level on the choice of a heating system are inconclusive. Scodari and Hardie (1985) demonstrated that education had an inverse effect on the probability of a household to acquire a wood stove. It could be that well-educated people in New Hampshire lived more often in larger cities where wood heating seemed less appropriate or practical. A Finland case studied by Kasanen and Lakshmanan (1989) confirmed that people with a higher educational background who lived in urban areas and Western Finland tend to choose modern systems at that time, i.e. central heating with air or direct electric heating, rather than central heating with water. To further investigate this factor, the educational level was included.

In addition to socio-demographic factors, regional differences constitute another important determinant as regional constraints might limit the selectable alternatives. Kasanen and Lakshmanan (1989) showed that the conservatism and relative prosperity of Western Finland may explain why this region is more in favor of central heating than other regions. Furthermore, it is also expected that regional differences in climate and resource availability affect the choice. In the north and inland of Norway, the average temperature is lower than in the south and the coastal regions. This causes variations in heating needs, which in turn affects the costs of alternatives. With respect to resource availability, even though wood pellets could technically be transported anywhere in the country, the transportation costs may become prohibitive in remote areas. Region, as a variable covering spatial variations, was therefore included in this study.

2.2. Communication influencing adoption

A recent study of Swedish households applied the innovation-decision model (Rogers, 2003) to discuss various factors influencing the choice of a heating system, i.e. socio-economic, mass media and interpersonal communication, as well as heating system attributes (Mahapatra and Gustavsson, 2008). According to (Rogers, 2003), communication habits influence consumers when it comes to adopting or rejecting an innovation. Interpersonal communication conveys not only information but also the degree and intensity of feelings and conviction. Consequently, consumers often rated information gained through personal communication as most important, especially when they perceive a high risk, or when they are generally susceptible to interpersonal influence (Gilly et al., 1998). The number of peers to whom a household recommends a heating system is applied as a proxy of a household's communication habit in this study. This variable also reflects a household's satisfaction with a certain type of heating system because people are more likely to recommend a heating system to others if they are satisfied. On the contrary, if a household is dissatisfied with a certain heating system, it is likely to advise peers against buying it. The latter aspect was not included in the study.

2.3. *Perceived importance of heating system attributes*

Households also differ in what they perceive to be important heating system attributes when they are making their decision. According to (Rogers, 2003), innovation attributes can explain 49–87% of the variance of adoption. Many studies on wood pellet adoption have also indicated that perceived innovation attributes play a crucial role in the adoption (Mahapatra and Gustavsson, 2008; Kasanen and Lakshmanan, 1989; Tapaninen et al., 2009). Based on former studies on the choice of a heating system (Nesbakken and Strøm, 1994; Nesbakken, 1998; Kasanen and Lakshmanan, 1989; Mahapatra and Gustavsson, 2008), this study operationalizes the specific wood pellet heating attributes as follows: functional reliability, indoor air quality, investment costs, operation costs, upkeep work, and fuel supply security. We asked the respondents to estimate the subjective importance rather than about the performance of each heating system with respect to these attributes in order to identify the information on which households focus when making their choice.

2.4. *Decision strategies influencing adoption*

Lark (1989) pointed out that people make use of information when forming their expectations, but they differ in the way they exploit and in their abilities to process this information. Decision strategies, which were derived from consumer behavior theories, have been applied in diffusion simulation studies of green products (Janssen and Jager, 2002; Jager, 2006; Schwoon, 2006; Schwarz and Ernst, 2009). The four decision strategies, Repetition, Deliberation, Imitation and Social Comparison, as well as the circumstances people are most likely to engage them in, are discussed here. The four strategies are characterized by two main dimensions: reasoned vs. automated processing and individual vs. social processing (see Table 1). Reasoned processing implies that one is elaborating on need fulfillment, taking all possible alternatives into account. People are generally motivated to think about other alternatives when they are not satisfied with their current system (Janssen and Jager, 2002). On the contrary, automated processing implies that one is using relatively simple heuristics to make a decision, habitually repeating the originally deliberate choices as long as the results satisfy one's needs. Individual processing implies that the consumer is gathering and processing information without considering the behavior of others as a main source of information, whereas social processing implies that the consumer is observing the behavior of others as a means to acquire information (Jager, 2000). Based on both dimensions the four types of decision strategy were derived.

Table 1
Meta-theory (adapted from Jager, 2000).

Decision strategy	Automated processing	Reasoned processing
Individually determined	Repetition	Deliberation
Social determined	Imitation	Social comparison

Repetition: Consumers will habitually consume the product that they consumed previously. This process applies mainly to situations where consumers are highly satisfied with the product they have in use and are able to easily consume it, uncertainty is relatively low, product use is less publicly visible and the needs in question are more individually relevant. Therefore, finding alternative opportunities or increasing their own abilities is not necessary.

Deliberation: Consumers will evaluate all possible alternatives and consume the product with the highest need satisfaction. This process applies mainly to situations where consumers are dissatisfied with their current product and in which it is difficult to consume it, uncertainty is relatively low, product use is less publicly visible and the needs in question are more individually relevant. Thus, consumers are forced to look for alternative opportunities or increase their abilities.

Imitation: Consumers will consume the product that most of their social network consumes. This process applies mainly to situations where consumers are satisfied with the product they use and where it is easy to consume it, but the uncertainty is relatively high, product use is publicly visible and the needs in question are more socially relevant. Due to social network influence, a change occurring in the network will affect their behavior although the decision makers are relatively satisfied with current product.

Social comparison: Consumers will perform a social comparison by comparing the utility of the product previously consumed and the product that most of their social network consumes and selecting the product yielding the highest need satisfaction. This process applies mainly to situations where consumers are dissatisfied with the previously used product and where it is difficult to consume it, as well as where uncertainty is relatively high, product use is publicly visible and the needs in question are more socially relevant.

The decision strategy a household applies may affect the rate of adoption of a product or technology. For example, when households deliberate, they are likely to find out about an innovation in its early stage. When they engage in social processing, they may learn about the innovation from others later in the diffusion process, but if they habitually repeat their behavior they may remain unaware of the innovation. For this reason, the decision strategy that household use is a critical factor in the innovation adoption process. By identifying the decision strategy used by Norwegian households to purchase a heating system it is possible to identify interventions that may change consumers' behavior. Addition of this factor to the heating system choice model is a novel contribution of this study.

3. Data collection

Data was collected with a survey in 2008. A mail survey was chosen to acquire representative information on the national level, testing the influence of a combination of already established predictors from other studies (Brottemsmo, 1994; Nesbakken and Strøm, 1994; Nesbakken, 1998). A pilot study for testing and refining the written questionnaire was conducted first with 35 households. Then 1500 questionnaires were sent to Norwegian households drawn as a random sample from the population register. The sampling was done by the Norwegian research company Sentio. A random sample rather than a stratified random sample was chosen because we did not have access to stratification variables for Norwegian households during the sampling procedure. We increased sample size to compensate for the negative effect of sampling bias in a simple random sample (see Lohr, 2009, for a discussion of different sampling techniques). Only homeowners were chosen as respondents because they have the authority to make decisions about heating systems independently. This sample, hereafter referred to as population sample, represents households who do not use wood pellet heating. About 1500 additional questionnaires were sent to wood pellet users in Norway. The second sample represented almost the complete population of wood pellet users in Norway. The list was acquired from wood pellet companies in Norway.

After three weeks, the response rates in the population sample and wood pellet sample were 10.3 and 34.6%, respectively. Over 137 additional responses from the population sample and 150 from the wood pellet sample were received after a reminder was sent out. This resulted in a response rate of 19.4% (291 responses) for the population sample and 44.6% (669 responses) for the wood pellet sample. Participants with missing values in predictive variables had to be excluded from the study so that the final analysis is based on a population sample of 188 respondents and a wood pellet sample of 461 respondents.

3.1. Bias

To test if the random population sample of 1500 varied significantly from the regional distribution of all households in Norway, a Chi^2 test comparing the distribution of households over Norway's nineteen provinces in the sample to the expected distribution based on data from population registry was conducted without a significant result ($Chi^2=17.633$; $df=18$; $p=0.480$). In other words, the composition of the original population sample was representative of the regional distribution of Norwegian households. Even though this is not the case for the wood pellet sample ($Chi^2=488.028$; $df=18$; $p<0.000$), this sample is representative of all Norwegian wood pellet users, as it accounts for roughly 80% of all wood pellet households in Norway.

To test possible self-selection effects, a chi-square test to compare the original and the response sample with respect to distribution of the provinces was also performed for both groups. The tests showed that there was no statistical difference between the original and the response population sample ($Chi^2=8.623$; $df=18$; $p=0.979$) and wood pellet sample ($Chi^2=2.122$; $df=18$; $p=0.999$). Thus, a self-selection bias with respect to regional distributions could not be found. Other data on the original population to test for self-selection bias in the response samples were not available. It might, therefore, be possible that self-selection processes resulted in an undetected bias, especially as the response rate in the two groups differed.

4. Empirical analysis

Multinomial Logistic Regression (MLR) was selected to deal with the 3-alternatives categorical nature of the dependent variable. The independent variables income, education, region, number of peers and decision strategy were dummy coded using the highest category as a reference. The continuous independent variables included were age and perceived importance of all heating system attributes. Tables 2 and 3 present the names and definitions of variables used in the analysis.

The empirical analysis was conducted in two parts. The first part of the analysis addressed the first objective of the paper, which is to identify factors that would motivate the population sample to choose environmental heating systems, either a heat pump or a wood pellet stove, as their future primary heating system. Electric heating is selected as a baseline category for the first MLR. The second analysis addresses the second objective, i.e. identifying factors that would motivate the wood pellet sample to choose either electric heating or a heat pump in the future. The baseline category for this analysis is therefore the wood pellet stove.

Table 2
Names and definitions of dependent variable used in the analysis.

Category	Description
1	I would choose electric heating as my future heating system to replace my current heating system
2	I would choose a heat pump as my future heating system to replace my current heating system
3	I would choose wood pellet heating as my future heating system to replace my current heating system

Table 3
Names and definitions of independent variables used in the analysis.

Variable	Description
	Socio-demographic factors
Age	Respondent's age
Household income level	1 = less than NOK 250 000 2 = NOK 250 001–NOK 550 000 3 = more than NOK 550 000
Education level	1 = elementary school 2 = high school 3 = university
Regional group	1 = Østfold, Åkerhus, Oslo, Hedmark, Oppland (East) 2 = Buskerud, Vestfold, Telemark, Aust-Agder, Vest Agder (South) 3 = Rogaland, Hordaland, Sogn og Fjordane (West) 4 = More og Romsdal, Sør-Trøndelag, Nord-Trøndelag (Mid-Norway) 5 = Nordland, Tromsø, Finnmark (North)
	Communication
Number of peers	Number of people to whom households recommended a heating system 1 = 0 2 = 1–5 peers 3 = 6–10 peers 4 = 11–15 peers 5 = 16–20 peers 6 = more than 20 peers
	Perceived importance of heating system attributes
Functional reliability	The importance of functional reliability in the decision process (5-point Likert scale, high score = high importance)
Indoor air quality	The importance of indoor air quality in the decision process (5-point Likert scale, high score = high importance)
Investment costs	The importance of investment costs in the decision process (5-point Likert scale, high score = high importance)
Operation costs	The importance of operation costs in the decision process (5-point Likert scale, high score = high importance)
Upkeep work	The importance of upkeep work in the decision process (5-point Likert scale, high score = high importance)
Fuel supply security	The importance of fuel supply security (price and availability) in the decision process (5-point Likert scale, high score = high importance)
	Decision strategy
Decision strategy	1 = choose the same as previous heating system (repetition) 2 = choose heating system that has maximum utility (deliberation) 3 = choose heating system that most neighbors/friends use (imitation) 4 = compare the existing heating system to the one most neighbors/friends use and choose the best between the two (social comparison)

5. Results

Tables 4, 5 and 6 present profiles of the population sample and the wood pellet sample based on responses to the dependent and independent variables in the survey. The Chi^2 tests in Tables 4 and 5 represent a test of the assumption that the wood pellet sample has the same distribution of answers as the population sample.

Table 4 shows that the population sample clearly prefers heat pumps as their future heating system whereas the wood pellet sample prefers either wood pellet heating or a switch to heat pump technology.

Table 5 reports results for socio-demographic, communication and decision strategy variables. The population sample is dominated by those with a high level income and university education; conversely, the wood pellet sample is dominated by those with a medium level income and education to the high school level. All regions are represented in the population sample, while the wood pellet sample resides predominantly in the East and South of Norway. When compared to the population sample, the wood pellet sample applies the deliberation strategy more often and the repetition strategy less frequently, consistent with a relatively higher number of peers of the households from the wood pellet sample.

Table 6 shows that there is no significant difference in age between the respondents in the population sample and in the wood pellet sample. The table also shows that there is no significant difference between the two samples regarding the perceived importance of heating system attributes.

The prerequisites for applying MLR were tested. Multicollinearity of the factors was not considered a problem because the available diagnostics (the variance inflation factor/VIF) never exceeded 2.27. As a rule of thumb, a VIF of more than 10 indicates multicollinearity; however, in a weaker model, a VIF above 2.5 may be a cause for concern (Allison, 1999). The tests shown in Table 7 were conducted to assess model fit and the model's ability to predict the dependent variable.

The logistic regression coefficients, Wald test statistics, and odds ratios for each of the variables are presented in Table 8 for the population sample and in Table 9 for the wood pellet sample.

When applying a $p<.05$ criterion of statistical significance, age, indoor air quality and decision strategy (repetition vs. social comparison) are found to be significant, whereas fuel supply security reaches marginal significance ($p<.10$) for the choice of a heat pump.

For the choice of a wood pellet stove, age and region (West vs. North) are found to be significant, while operation costs, income (medium vs. high), education (high school vs. university) reached marginal significance.

When applying a $p<.05$ criterion for statistical significance, the variables age, income (medium vs. high) and operation/maintenance work show significant effects while region

Table 4
Profiles of respondents based on the dependent variable.

Sample **Future choice**	**Population** **($N=188$)**	**Wood pellet** **($N=461$)**	**Chi^2 test**
Electric heating	32 (17.0%)	11 (2.4%)	$Chi^2=150.616$; $df=2$; $p<0.001^{***}$
Heat pump	141 (75.0%)	201 (43.6%)	
Wood pellet stove	15 (8.0%)	249 (54.0%)	

Table 5
Profiles of respondents based on categorical independent variables.

Sample **Variable**	**Population** **($N=188$)**	**Wood pellet** **($N=461$)**	**Chi^2 test**
Household income level			$Chi^2=34.154$; $df=2$; $p<0.001^{***}$
Less than NOK 250 000	18 (9.6%)	68 (14.8%)	
NOK 250 001 – NOK 550 000	65 (34.6%)	258 (56.0%)	
More than NOK 550 000	105 (55.9%)	135 (29.3%)	
Education level			$Chi^2=27.025$; $df=2$; $p<0.001^{***}$
Elementary school	9 (4.8%)	79 (14.5%)	
High school	61 (32.4%)	218 (47.3%)	
University or higher	118 (62.8%)	179 (38.2%)	
Region			$Chi^2=255.798$; $df=4$; $p<0.001^{***}$
East	55 (29.3%)	79 (17.1%)	
South	21 (11.2%)	313 (67.9%)	
West	53 (28.2%)	17 (3.7%)	
Mid-Norway	38 (20.2%)	37 (8.0%)	
North	21 (11.2%)	15 (3.3%)	
Decision strategy			$Chi^2=46.274$; $df=3$; $p<0.001^{***}$
Repetition	47 (25.0%)	41 (8.9%)	
Deliberation	109 (58.0%)	367 (79.6%)	
Imitation	3 (1.6%)	1 (0.2%)	
Social comparison	29 (15.4%)	52 (11.3%)	
Number of peers			$Chi^2=141.649$; $df=5$; $p<0.001^{***}$
0	77 (41.0%)	39 (8.5%)	
1–5	75 (39.9%)	206 (44.7%)	
6–10	23 (12.2%)	115 (24.9%)	
11–15	6 (3.2%)	37 (8.0%)	
16–20	1 (0.5%)	13 (2.8%)	
More than 20	6 (3.2%)	51 (11.1%)	

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; n.s.=not significant.

Table 6
Profiles of respondents based on the continuous independent variables.

Sample	Population (N=188)		Wood pellet (N=461)		Significance test
Variables	***Mean***	***S.E.***	***Mean***	***S.E.***	
Age	50.29	0.899	48.43	0.507	Anova $F(1.647)=3.601$; $p=0.058$; n.s.
Functional reliability[a]	4.49	0.056	4.63	0.024	Mann Whitney U test $Z=-1.388$; $p=0.165$; n.s.
Indoor air quality[a]	4.22	0.063	4.16	0.037	Mann Whitney U test $Z=-1.230$; $p=0.219$; n.s.
Investment costs[a]	3.93	0.074	3.88	0.043	Mann Whitney U test $Z=-1.089$; $p=0.276$; n.s.
Operation costs[a]	4.39	0.059	4.52	0.028	Mann Whitney U test $Z=-1.334$; $p=0.182$; n.s.
Upkeep work[a]	4.28	0.062	4.25	0.036	Mann Whitney U test $Z=-1.066$; $p=0.287$; n.s.
Fuel supply security[a]	4.41	0.065	4.55	0.031	Mann Whitney U test $Z=-1.038$; $p=0.299$; n.s.

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; n.s.=not significant.

[a] 1=not important, 5=very important.

Table 7
Regression analysis.

Test group	Population	Wood pellet	Note
Ratio (valid cases to independent variables)	15.67	38.42	Minimum requirement:10, see Hosmer and Lemeshow (2000)20, see Peduzzi et al. (1996)
Goodness of fit:			Adequate fit corresponds to non-significance of the test.
Pearson	$Chi^2=261.593$ $df=302$; $p=0.955$	$Chi^2=668.817$ $df=832$; $p=1.000$	
Deviance	$Chi^2=178.215$ $df=302$; $p=1.000$	$Chi^2=55.079$ $df=832$; $p=1.000$	
Classification accuracy	0.755 (1.28 times better)	0.657 (1.45 times better)	Both models perform better than chance
Pseudo *R*-Square:			approximations to OLS R^2, not to be interpreted as actual percentage of variance explained
Cox and Snell	0.254	0.222	
Nagelkerke	0.333	0.280	

(East vs. North) and indoor air quality reach marginal significance for the choice of electric heating.

The variables region (East vs. North), number of peers (less than 6 vs. more than 20), functional reliability, indoor air quality, fuel supply security and decision strategy (repetition vs. social comparison) were statistically significant, while region (South vs. North), number of peers (6–15 peers vs. more than 20 peers) show a marginal significance for the choice of a heat pump.

6. Discussion

The regression analysis (Table 7) indicates that the regression model is supported by the empirical data and able to perform better than chance in reproducing the observed classification of the respondents. Supported by the non-existence of multicollinearity, this indicated that the factors selected for analysis are relevant explanatory factors for the future choice of a heating system.

6.1. *Determinants of possible heating system choice in the future for the population sample*

This section discusses the factors that might motivate the respondents from the population sample to choose either a heat pump or a wood pellet stove, as their future heating system, and possible interventions derived from these results.

Age is statistically significant for the choice electric heating over a heat pump as well as for the choice of a wood pellet stove. This result is also in line with the results of a Swedish pellet diffusion study conducted by Mahapatra and Gustavsson (2008) revealing that older people find it more difficult to change their behavior as they have become accustomed to their existing heating system and therefore will be less likely to install a new kind of heating system. This might be taken as an indication that younger people are more open to considering new technologies.

The region a respondent lives in shows a significant influence on the choice of heating system. Those who reside in the West of Norway are more likely than those in the North to choose electric heating rather than a wood pellet stove. This result resonates the findings of a previous study of heat pump and wood pellet adoption that was conducted after the subsidy for households was introduced in 2003 (Bjørnstad et al., 2005), showing that heat pumps were mostly adopted in western Norway, whereas wood pellet stoves were adopted in Hedmark, Oppland, and Nord-Trøndelag. This could be explained partially by the milder climate in the west coast area that makes electric heating a more practical heating option. The fact that Rogaland, alongside Oslo and Akershus, is among the regions with the highest average household income in Norway (Statistics Norway, 2009) is consistent with the findings of Nesbakken (1998) who confirmed that the higher the income, the higher the probability to choose electric heating over wood-based heating.

Indoor air quality is implied to be a disadvantage related to the use of a heat pump, because households who consider indoor air quality to be especially important are unlikely to choose this kind of heating system. The problem could be associated with the assumed dust recirculation caused by a heat pump.

Table 8
Multinomial logistic regression for future choice of a heating system in the population sample for reference category Electric Heating.

Factor	Variable	*B*	Wald χ^2	*df*	*p*	Odds ratio
	Heat pump vs. Electric heating					
Socio-demographic	Age	−0.056	7.573	1	0.006^{***}	0.945
	Income level (level 1 vs. 3)	0.757	0.699	1	0.403	2.133
	Income level (level 2 vs. 3)	−0.095	0.036	1	0.850	0.910
	Education level (level 1 vs. 3)	0.963	0.506	1	0.477	2.619
	Education level (level 2 vs. 3)	−0.172	0.113	1	0.736	0.842
	Region (region 1 vs. 5)	−1.297	1.245	1	0.265	0.273
	Region (region 2 vs. 5)	−1.731	1.909	1	0.167	0.177
	Region (region 3 vs. 5)	−1.629	1.944	1	0.163	0.196
	Region (region 4 vs. 5)	−1.682	1.972	1	0.160	0.186
Communication	Number of peers (0 vs. >20)	−16.122	0.000	1	0.996	0.000
	Number of peers (1−5 vs. >20)	−16.200	0.000	1	0.996	0.000
	Number of peers (6−10 vs. >20)	−16.110	0.000	1	0.996	0.000
	Number of peers (11−15 vs. >20)	0.119	0.000	1	1.000	0.000
	Number of peers (15−20 vs. >20)	−0.115	0.000	1	1.000	0.000
Heating system attribute	Functional reliability	−0.520	1.235	1	0.266	0.595
	Indoor air quality	−0.732	4.497	1	0.034^{*}	0.481
	Investment costs	0.439	2.110	1	0.146	1.552
	Operation costs	−0.154	0.150	1	0.699	0.858
	Upkeep work	−0.004	0.000	1	0.990	0.996
	Fuel supply security	0.574	3.799	1	0.051^{ms}	1.776
Decision strategy	Decision strategy (type 1 vs. 4)	−1.600	3.913	1	0.048^{*}	0.202
	Decision strategy (type 2 vs. 4)	−0.199	0.076	1	0.783	0.820
	Decision strategy (type 3 vs. 4)	−1.571	1.001	1	0.317	0.208
	Wood pellet stove vs. Electric heating					
Socio-demographic	Age	−0.122	7.570	1	0.006^{***}	0.885
	Income level (level 1 vs. 3)	−15.474	0.000	1	0.993	0.000
	Income level (level 2 vs. 3)	1.664	3.827	1	0.050^{ms}	5.283
	Education level (level 1 vs. 3)	0.069	0.001	1	0.972	1.072
	Education level (level 2 vs. 3)	−2.135	3.557	1	0.059^{ms}	0.118
	Region (region 1 vs. 5)	−2.433	2.418	1	0.120	0.088
	Region (region 2 vs. 5)	−2.855	2.473	1	0.116	0.058
	Region (region 3 vs. 5)	−3.379	4.381	1	0.036^{*}	0.034
	Region (region 4 vs. 5)	−1.642	1.137	1	0.286	0.194
Communication	Number of peers (0 vs. >20)	−18.396	0.000	1	0.995	0.000
	Number of peers (1−5 vs. >20)	−19.219	0.000	1	0.995	0.000
	Number of peers (6−10 vs. >20)	−18.110	0.000	1	0.995	0.000
	Number of peers (11−15 vs. >20)	−0.637	0.000	1	1.000	0.529
	Number of peers (15−20 vs. >20)	−15.548	–	1	–	0.000
Heating system attribute	Functional reliability	−0.304	0.193	1	0.661	0.738
	Indoor air quality	−0.528	1.004	1	0.316	0.590
	Investment costs	0.314	0.490	1	0.484	1.369
	Operation costs	−1.202	3.421	1	0.064^{ms}	0.301
	Upkeep work	−0.333	0.332	1	0.565	0.717
	Fuel supply security	1.045	2.282	1	0.131	2.844
Decision strategy	Decision strategy (type 1 vs. 4)	−1.109	0.715	1	0.398	0.330
	Decision strategy (type 2 vs. 4)	−0.578	0.245	1	0.620	0.561
	Decision strategy (type 3 vs. 4)	−13.379	0.000	1	0.998	0.000

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; ms (marginal significance) $p<0.1$.

Bjørnstad et al. (2005) identified dust on the filter of the inside of a heat pump as the second highest problem rated by households. Nevertheless, this problem is not necessarily due to technical shortcomings of the heat pump as it is rather part of a learning process to recognize that for an optimal performance the various components of a heat pump need regular inspection and maintenance/cleaning (Bjørnstad et al., 2005). Providing information on heat pumps and facilitating a faster learning process is important so that the problems that are raised in the early marketing stage of a new technology are not perceived as technological drawbacks.

Decision strategy is a significant factor, and respondents use repetition over social comparison to choose electric heating over a heat pump. This result suggests that they are satisfied with their existing heating system and will repeat this choice in the future.

The result suggests on the other hand, that those who are likely to choose a heat pump perform a social comparison; a reasoned and socially determined decision. One possible motivation for considering a change could be influence from active promotion of heat pumps as an alternative heating system. Households' use of the social comparison strategy could reflect their dissatisfaction with their current heating systems, and therefore they search for an alternative. Because a heat pump is considered a new technology, uncertainty is relatively high. This motivates households to compare their choices with those of other households. Applying this decision strategy, the examined households should use other households in their social network as a means to acquire information. As purchasing a new heating system involves a large investment, households are forced to elaborate on alternatives, investing more cognitive effort in the

Table 9
Multinomial logistic regression for future choice of a heating system for the wood pellet sample for reference category Wood pellet stove.

Factor	Variable	*B*	Wald χ^2	*df*	*p*	Odds ratio
	Electric heating vs. Wood pellet stove					
Socio-demographic	Age	0.131	9.125	1	0.003***	1.140
	Income level (level 1 vs. 3)	−0.904	0.547	1	0.460	0.405
	Income level (level 2 vs. 3)	−2.873	6.302	1	0.012*	0.057
	Education level (level 1 vs. 3)	−1.892	1.148	1	0.284	0.151
	Education level (level 2 vs. 3)	0.076	0.005	1	0.942	1.078
	Region (region 1 vs. 5)	−2.999	2.765	1	0.096^{ms}	0.050
	Region (region 2 vs. 5)	−2.481	2.498	1	0.114	0.084
	Region (region 3 vs. 5)	0.592	0.099	1	0.753	1.807
	Region (region 4 vs. 5)	−1.163	0.246	1	0.620	0.312
Communication	Number of peers (0 vs. >20)	−14.933	0.000	1	0.989	0.000
	Number of peers (1−5 vs. >20)	−0.983	0.800	1	0.371	0.374
	Number of peers (6−10 vs. >20)	−1.627	1.667	1	0.197	0.197
	Number of peers (11−15 vs. >20)	1.527	1.301	1	0.254	4.602
	Number of peers (16−20 vs. >20)	−14.536	0.000	1	0.995	0.000
Heating System attribute	Functional reliability	0.634	0.503	1	0.478	1.885
	Indoor air quality	−0.892	2.773	1	0.096^{ms}	0.410
	Investment costs	−0.502	0.984	1	0.321	0.605
	Operational costs	0.072	0.012	1	0.913	1.075
	Upkeep work	−1.767	8.772	1	0.003***	0.171
	Fuel supply security	0.109	0.035	1	0.852	1.115
Decision strategy	Decision strategy (type 1 vs. 4)	−0.904	0.243	1	0.622	0.405
	Decision strategy (type 2 vs. 4)	−1.494	1.090	1	0.296	0.224
	Decision strategy (type 3 vs. 4)	−8.501	–	1	–	0.000
	Heat pump vs. Wood pellet stove					
Socio−demographic	Age	−0.007	0.471	1	0.493	0.993
	Income level (level 1 vs. 3)	−0.246	0.450	1	0.502	0.782
	Income level (level 2 vs. 3)	−0.355	1.809	1	0.179	0.701
	Education level (level 1 vs. 3)	−0.181	0.262	1	0.608	0.834
	Education level (level 2 vs. 3)	−0.049	0.038	1	0.846	0.952
	Region (region 1 vs. 5)	−1.346	3.864	1	0.049*	0.260
	Region (region 2 vs. 5)	−1.106	2.988	1	0.084^{ms}	0.331
	Region (region 3 vs. 5)	−0.844	1.000	1	0.317	0.430
	Region (region 4 vs. 5)	−0.609	0.703	1	0.402	0.544
Communication	Number of peers (0 vs. >20)	2.129	16.506	1	0.000***	8.405
	Number of peers (1−5 vs. >20)	1.387	12.162	1	0.000***	4.001
	Number of peers (6−10 vs. >20)	0.756	3.241	1	0.072^{ms}	2.129
	Number of peers (11−15 vs. >20)	0.922	3.050	1	0.081^{ms}	2.514
	Number of peers (15−20 vs. >20)	0.305	0.167	1	0.683	1.357
Heating system attribute	Functional reliability	0.883	13.446	1	0.000***	2.418
	Indoor air quality	−0.366	6.037	1	0.014*	0.693
	Investment costs	0.084	0.377	1	0.539	1.088
	Operation costs	0.269	0.685	1	0.408	1.184
	Upkeep work	0.224	1.917	1	0.166	1.251
	Fuel supply security	−0.710	12.314	1	0.000***	0.492
Decision strategy	Decision strategy (type 1 vs. 4)	−1.165	5.620	1	0.018*	0.312
	Decision strategy (type 2 vs. 4)	−0.200	0.369	1	0.543	0.819
	Decision strategy (type 3 vs. 4)	−16.669	0.000	1	0.996	0.000

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; ms (marginal significance) $p<0.1$.

decision process. From the interventionist perspective, changing the opinion that a household holds regarding the social appropriateness of the choice of a heat pump and thereby changing societal norms are possible interventions to motivate these households to change their behavior and replace electric heating with a heat pump. Possible means could be media campaigns including trustworthy models (e.g., celebrities with a good reputation) or providing key actors in the social networks with tailored information fitting the need of the target group.

Education has a marginally significant effect on the probability of choosing wood pellet heating. This can be taken to mean that those who have a higher education level are prepared to try an emerging and renewable technology such as the wood pellet stove; however, education shows no significant influence on the probability of choosing a heat pump. This might be because this technology is already established in Norway. In addition, income also shows a marginally significant impact on the choice of a wood pellet system. Those with a medium-level income, unlike those with high or low income, prefer wood pellet stoves over electric heating. Scodari and Hardie (1985) showed the same outcome for wood stove acquisition in New Hampshire, US. This effect is not easy to interpret. It may be that two processes overlap: People with low income might perceive the high investment costs as an obstacle to installation of a wood pellet stove whereas people with a high income do not care about the long term savings from lower fuel prices of wood pellet heating compared to electricity.

Fuel supply security reaches a marginal significance regarding its influence on the probability of choosing a heat pump, whereas operational costs reach marginal significance concerning the choice of wood pellet heating. The more important fuel supply security is in decision making, the more likely households are to choose a heat pump rather than electric heating. This can be explained by the fact that a heat pump requires less electricity than standard electric heating units to meet the same heating demand. Those who are likely to choose a wood pellet stove rather than electric heating are those who consider operational costs to be less important. It can be inferred that the operational costs of a wood pellet stove are perceived to be higher than those of electric heating by the respondents in this sample. Operational costs and fuel supply security seem to cause concern in the population sample, suggesting that the development of the environmental heating system market can be promoted by using the low operational costs as an argument and providing reliable fuel supply.

It is worth noting that the number of households that choose wood pellet heating is quite small (only 8% of the population sample's respondents). Most of them prefer heat pumps, followed by electric heating. This means that the results for wood pellet heating must be interpreted with care. This also conveys low observability of wood pellet heating in this sample, meaning that wood pellet heating might not be recognized by most households due to its small market share. This is also the case for solar energy technology (Labay and Kinnear, 1981). To increase the observability of wood pellet stoves, existing networks of wood pellet users must be supported. As wood pellet users (see Table 5) communicate with other households more than others do, they may serve as nodes in their social networks or are at least part of a well-functioning social network. As such this group could offer advice to potential consumers and create awareness when they are at the point of making a real investment decision. This would ensure that the pellet option is at least considered when deciding about the future heating system. This network forms the vehicle through which the advantages of wood pellet heating are communicated. Studies indicated that communication with adopters could increase the probability of adoption (Frambach, 1993; Midgley et al., 1992). It is therefore essential that policy makers have a thorough understanding of those households that are in influential positions.

6.2. Determinants of possible heating system choice in the future for the wood pellet sample

This section introduces the influential factors that explain when wood pellet adopters continue to keep wood pellet heating as their main heating system or switch to either electric heating or a heat pump in the future. The discussion also includes possible strategies that could be applied to increase the uptake of wood pellet stoves.

Age has a significant influence on the choice of electric heating, but it is insignificant concerning the choice of a heat pump. Those who currently use wood pellet heating are more likely to choose electric heating rather than continuing to use wood pellet stoves as they grow older. This is consistent with the results that electric heating is preferred by older people. This could be due to the fact that it requires less work compared to the wood pellet stove, e.g. loading/unloading pellets, cleaning the stove, etc.

Income once again shows a significant influence on the choice of electric heating. Those with a high income prefer electric heating, whereas those with a medium income prefer wood pellet stoves. The same result has also been shown for the population sample discussed above.

Region has a significant impact on the choice of a heat pump and a marginally significant impact on the choice of electric heating. Those who reside in the East and those who live in the South are more likely than those who live in the North to choose wood pellet stoves over electric heating or a heat pump. This could be due to the fact that the biggest wood pellet producer in Norway is located in Hedmark. The short distance between producer and consumers results in an easy and reliable access to wood pellets for households in the East and in the South. As a main reason of the electric heating lock-in is easy access and fuel price fluctuation was proven to be a significant influence for the shifts of heating system (Brottemsmo, 1994), these imply that the fuel supply plays an important role to heating system adoption in Norway.

The results suggest that those who are most likely to continue choosing the wood pellet stove apply the decision process of repetition rather than social comparison. This behavior reflects their satisfaction with the wood pellet stove. Factors that contribute to the satisfaction and dissatisfaction with wood pellet stoves merit further study to identify the areas for improvement. Alternatively, another possible strategy to promote wood pellet stoves would be to give positive reinforcement/rewards to those who repeat their choice. Rewards could be quantity discounts for the purchase of wood pellets.

As the same result can also be found in the population sample, it can be generalized that the decision about the acquisition of a heat pump is dominated by a strategy of social comparison. Accordingly, the purchase of a heat pump is influenced by the market share of this technology. This finding is in line with the results of a previous study of heat pump adoption confirming that recommendation from other users is the most important motivation to install a heat pump (Bjørnstad et al., 2005). Social influence is strong in the decision for a heat pump but this does not imply irrationality in decision making. The strategy of social comparison most likely supports a rational decision, but the information needed for decision making is acquired from the social network instead of other sources. The consistent result of social comparisons dominating the decision for a heat pump gives an indication that this aspect of a household's decision making process should not be ignored by policy makers.

Contrary to heat pump market, there are not yet a sufficient number of people using wood pellet heating to form a social reference group. Once a critical number of people use a product is reached, market behavior often changes and other factors drive the adoption process, a change that is called a 'chasm' in the diffusion literature (Moore, 1999). The market for wood pellets seems still to be in its early stage before this chasm, which makes interventions such as continued subsidy necessary to achieve a critical mass of wood pellet users that can drive the market as opinion leaders in a later stage.

It is worth noting that about 43% of current wood pellet users prefer heat pumps as their main heating system in the future. Only about half of the wood pellet users anticipate continuing with the choice of wood pellet heating. The result shows that those who are dissatisfied with their wood pellet stove are likely to compare their existing heating system with that preferred by most members of their social network (which would usually be a heat pump). The dissatisfaction could be due to bad experience with the wood pellet stove or with aging. As the results show that those who perceived functional reliability more important are unlikely to continue using wood pellet heating, improving functional reliability should be a priority.

Even though investment and operational cost as heating system characteristics fail to be significant aspects of the decisional process, there is an interesting finding showing that those with high level income prefer the use of electric heating although the investment in wood pellet stoves should be affordable. This raises the question why people who are able to afford wood pellet stoves prefer to choose electric heating. One possible explanation could be that electric heating appears to be the most convenient heating source as almost no maintenance work is required. Some households, for example older people, could perceive the necessary work related to the use of a wood pellet stove too difficult because of physical limitations. Another possible explanation is that these households value their time and time spent on maintaining and operating a wood pellet stove might be considered wasted. Finally, people with high incomes could be less affected by fluctuating electricity prices on the market and therefore do not perceive this advantage of wood pellet stoves as much as people with less income.

The results indicate that those who recommended a heating system to more than 20 peers are most likely to keep on using wood pellet heating. This means that those who plan to continue using wood pellet heating in the future seem to show more opinion leadership than those who want to change to heat pumps. However, it has to be repeated that recommendation against a heating system was not recorded in this study, so it might be possible that wood pellet users dissatisfied with wood pellet heating have opinion leadership in the negative direction. Recommendation behavior reflects people's satisfaction/dissatisfaction with their current heating system, i.e. households will not recommend a heating system if they are not satisfied with it. This implies that those who give recommendation to more than 20 peers are satisfied with using a wood pellet stove. The fact that wood pellet heating adoption is low indicates that recommendation by adopters is not enough to enhance the adoption rate. The relative advantages of wood pellet stoves should be made more visible before choosing a communication based strategy to enhance wood pellet adoption. Once the technology-related factors of wood pellet heating are perceived as advantageous, the communication behavior of wood pellet users might contribute to further adoption. The improvement of the subjective evaluation of the system attributes of wood pellet stoves should be the main concern for increasing wood pellet adoption.

Interestingly, the importance of investment cost was found to be statistically insignificant in both the population sample and the wood pellet sample. However, including income as a variable has reduced the explanatory power of investment costs because income and the importance of investment costs are related to each other. Eliminating income from the regression equation to test this assumption resulted in a significant impact of investment cost.

6.3. Limitations

Although this study adds the dimension of decision strategy to the baseline models for selection of a heating system, some limitations should be highlighted. Firstly, the dependent variable has limitations. The question designed for the dependent variable was intended to ask for only one main/primary heating system. However, because Norwegian households usually have more than one type of heating, it might be possible that they are unclear about which is their main heating system. Less than 4% of all respondents chose two heating systems when answering the question. They were included in the analysis by selecting one of their chosen heating systems. Secondly, the study only modeled anticipated choice and not real choice as people may eventually choose different heating systems than they intend to. A retrospective study of heating choice or a longitudinal study would have addressed this problem. Thirdly, the communication factor only included the number of people to whom the household has recommended a heating system, but not against. Adding another variable to cover this would have been insightful regarding the aspects of negative peer communication on product diffusion. Fourthly, the different sizes of the samples are another problem as it is easier to get significant results in a larger sample. The extremely small group of wood pellet users preferring electric heating as their future heating system and households in the population sample preferring wood pellet stoves made the respective results rather weak compared to the others. Fifthly, this study is based only on quantitative data, complementing the study by qualitative interviews would gain insight into the more complex processes of decision making that a simple regression analysis is not able to reveal. Sixthly, the sample drawn from the population registry was not stratified because there was no access to stratification variables. This might have lead to a sampling bias in the population sample. Seventhly, people choosing imitation as their decision strategy should not evaluate the importance of heating system attributes at all. Not providing a "do not know" option in those questions forced them to give an answer that probably was not relevant for them. However, this group is small in both samples. Only 1.6% in the population sample and 0.2% in the wood pellet sample were using the imitation strategy. And finally, this study has not researched the optimal balance of heating options relevant for Norway, i.e. the authors do not hold a bias toward 100% adoption of wood pellet stoves over other type of heating systems. Issues of sustainability and forest management would need to be taken into consideration before making any conclusion on this matter.

The results of this study are relevant to Norway and should be interpreted within the context of the specific market situation. However, the framework of proposed influential factors can be applied and tested empirically in different countries. The significance of factors might vary between different countries due to country-specific market situations. While socio-demographic factors, household communication, and heating system attributes are not unprecedented in heating system adoption studies, the decision strategy applied by the household is a new addition to this model of heating system choice. The results clearly show that decision strategies play an important role in the choice of a heating system in Norwegian households, and therefore, they merit further investigation. As this study focused on electric heating, heat pump and wood pellet stove, other types of heating system may require different heating system attributes to be analyzed. However, most heating system attributes used in this study should be relevant for all types of heating systems.

7. Conclusion

This paper has met the objective of identifying factors that influence the heating system purchasing decision made in Norwegian households. To summarize, the results have important implications for the diffusion of sustainable heating systems in Norway. Different policies are needed for different groups of households. For example, households consisting of younger people should be prioritized in programs promoting heating systems based on new technologies. Region-related constraints also have to be considered as they may limit the heating options available. Although only marginally significant, fuel supply security and operational cost seem to be two relevant factors in the decision for sustainable heating systems. This implies that sustainable heating systems should be able to offer reliable fuel supply and low operational cost to compete with electric heating and focus their marketing strategy on these aspects. Financial support seems still necessary due to low market share of wood pellet heating. Additional research is needed to determine the appropriate conditions to increase the number of wood pellet users sustainably.

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Paper IV

Effects of lignosulfonate and marble sludge additives on the mechanical properties of pellets of barley husk and straw fuel pellets.

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Effects of lignosulfonate and marble sludge additives on the mechanical properties of barley husk and straw fuel pellets

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Abstract

Husk and straw from barley represent a large feedstock source for biomass fuels. Pelletization is a densification pathway that makes logistics and storage more efficient with a compaction ratio of up to 1:10. However, the amount of fines and the high ash content reduce the quality of the fuel. Lignosulfonate and marble sludge are two additives that might improve straw and husk fuel quality. The objective of this experimental work was to determine the effects of additives on the mechanical quality of pellets. In an ordinary feed pellet factory, 18 samples of both feedstocks were produced with different additive ratios. It was found that both lignosulfonate and marble sludge improve the durability of the pellets from barley husk. The barley straw durability improved upon the addition of lignosulfonate, but opposite results were found for marble sludge.

Key words: Barley straw, Barley husk, Pellets, Lignosulfonate, Marble sludge, Durability

1 Introduction

The utilization of biomass is seen as an important contribution to the substitution of conventional fossil energy and to the reduction of climate change. There are several pathways for recovering energy from biomass. Nowadays, combustion is the most widely used technology for the production of usable energy from biomass [1]. However, the combustion of biomass for heat and power production is often limited due to the inherent properties of raw biomass materials, including low energy/volume densities, high moisture content and high ash-forming matters.

Biomass pelletization, which is an efficient method for upgrading solid biomass fuel, is well known and widely applied. The pelletization of biomass materials for energy purposes has only been practiced for a couple of decades. As a result of pelletization, biomass materials can be significantly upgraded with enhanced calorific value, energy density and homogeneity. Additionally, pelletization can considerably improve the economics of biomass in terms of logistics. The costs that are related to the transport, storage and handling of biomass pellets are considerably lower than those of raw biomass materials [2-4].

The bulk densities of different biomass feedstocks vary over a wide range from 40 to 400 kg m^{-3}. The bulk densities of the unprocessed feedstocks of straw and husk are very low with levels as low as 40 kg m^{-3} [5]. These feedstocks are not dense compared to the feedstocks of wood, such as chips, in which density levels of 100-300 kg m^{-3} are common [6]. Pellets might reach densities of 600-750 kg m^{-3}. A wide bulk density variation might lead to combustion regulation challenges, and pelletization lowers this variation range.

Currently, side products from the sawmill industry are the main feedstock for early developed pellets in the energy industry. However, this resource base is limited and depends on the trading conditions in the wood-working industry [7, 8]. These problems have led to the search for alternative biomass fuels that can be upgraded to pellet fuel. Raw materials from the agricultural sector could be an important feedstock. Examples of such raw materials include different straw and husk fuels.

In Norway, straw production is relatively small, 420 kilotons per year, and husk has production levels of 25 kilotons, which can contribute 7 PJ of energy to heat [9]. In other agricultural rich areas, such as the USA and Canadian mid-west areas, huge amounts of feedstocks are available [10-14]. However, the harvesting, logistics and population of pelletization plants have to be incorporated into a system that would make these products available in the market [15, 16]. This system is achievable but depends on the final cost of the pellets that can compete in the market.

An increasing moisture content reduces the net heating value in fuel. Low-moisture fuels also produce less negative impacts due to degradation and fuel handling during storage and transport. Small scale furnaces often require drier fuels than larger boiler systems. Before pelletization, the feedstock must be dried naturally or artificially to a certain level depending on the type of feedstock [5].

Smaller combustion units for commercial use need to have reduced investment costs to be economically competitive. Additionally, the amount of time and cost of operating and maintaining such equipment are crucial. Pellets lead to good possibilities of better operations with simplified equipment [17]. However, the pellets must be of good quality in terms of their durability and ash properties because these properties strongly influence the operation of a boiler.

Pellets that are made of agricultural feedstocks often have lower durability than wood-based pellets. This phenomenon is mainly due to a lower content of lignin constituents [18]. Durability is important with regard to logistics and boiler performance [19, 20].

To improve the mechanical properties of biomass pellets, several binders/additives have been tested and used in the commercial market [17, 21]. Starches from different species, such as potato and maize, have been suggested and studied as organic binders for enhancing the durability of biomass pellets [22]. Inorganic binders, such as caustic soda (NaOH) and marble sludge ($CaCO_3$), have also been investigated and exhibited the ability to improve the mechanical properties of pellets that were produced from certain biomass fuels [23]. Additionally, wood from pine was used as an additive to upgrade the properties of pellets from agricultural feedstocks [24]. Fossil additives have been proposed, such as paraffin, palmitin, anthracite coal and lignite coal, in amounts from 4 to 20%; however, such additives are often not acceptable from a market view because they not are renewable [21]. The use of these additives can also lead to difficult taxation or legislation issues.

Kaliyan and Morey have given an overview and discussed the factors that influence the strength and durability of pellets [25]. To improve the durability, the addition of binders or the mixing of feedstocks might be alternatives to the control of other feedstock and production parameters that influence the durability factors.

When a binder is considered necessary, the most used pellet binders, in both the wood pellet industry and the animal feed industry, are lignin-based binders. When bordering the glass transition point, lignin creates a new mechanical interlock between stiff particles [26]. This phenomenon occurs when the temperatures during pelletization are above 60-120 °C [27]. Lignin-based binders are normally developed from different pulp processes as a side product. The most available lignin-based products are in the form of lignosulfonates, but kraft lignin and lignin residue from hydrolysis can also be used as binders [26, 28-30]. Lignosulfonates have a high sulfur content, which might produce a negative impact in terms of pollution issues during the combustion of end products [31]. It is expected that lignin residues from the production of ethanol from the cellulose/hemicellulose parts of wood might produce a surplus of non-yeast-able lignin components in the future [32, 33].

Additives would also contribute energy and/or ash. Lignin-based additives have high gross energy levels, but the lignosulfonate energy is lower due to the high sulfur content from the sulfite dissolving process [26, 34]. Inorganic components in additives would increase the total amount of ashes; however, if this component produces less melted ashes, the overall result would be beneficial.

In addition to their rather poor physical properties, pellets that are produced from agricultural residues might have higher ash contents and wider variations in the composition of ash forming elements [19-21]. The ash content of agricultural residue pellets is high with levels from 3-5% [22-24]. This content causes sintering and slagging problems during the combustion of these pellets in combustion appliances. Previous works have shown that the formation of low temperature melting potassium silicates is the main reason for the initiation and promotion of ash melting and sintering during combustion [19, 25]. Ash sintering and slagging problems are more severe in a small scale combustion unit due to the long residence time of ash residues on the grate [4]. This fact limits the possibility of this feedstock reaching large parts of the markets [20].

One possible approach to minimizing ash slagging during agricultural pellet combustion is to add different inorganic species to the feedstock prior to combustion. The additive can alter the ash chemistry and reduce the formation of melted ash fractions [35-38]. Calcium-based additives, i.e., lime and marble sludge, are especially effective in restraining or even eliminating ash sintering and slagging during the combustion of different biomass pellets [35, 39].

Additives might be costly and difficult to add separately at combustion plants. Tobiasen et al. listed the following important combustion parameters when additives is used: a) the additive particle size distribution, as smaller particles have larger surfaces for reactions, b) the reaction temperature and time, c) the composition, i.e., the active compounds in the additive, and d) the stoichiometry, i.e., the amount of additive [34].

This paper suggests the addition of lignosulfonate and marble sludge to barley straw and barley husk pellets. Both marble sludge and lignosulfonate are used in animal feed production [40-43]. Lignosulfonate is only used to improve the durability of feed pellets, while marble sludge is used for several nutritional purposes. However, the effects of a marble sludge additive on the pellet production process and properties have rarely been investigated with respect to pelletization for energy purposes [44].

Lignosulfonate is used to improve the durability of straw and husk fuel. Marble sludge, which has the primary additive purpose of improving the ash melting properties, might also impact the mechanical quality of the pellets. Lignosulfonate might improve the durability when a large amount of marble sludge is added. Both selected additives are available in large amounts with relatively low prices which makes the proposed solution economic feasible. Furthermore, both additives are in forms that are useable without pre-treatment for an even mechanical distribution in the pellet feedstock. The marble sludge that was used is a surplus residue from clay manufacturing to the paper industry.

Several studies on straw pellets have been performed on the laboratory scale using small pellet machines or single pellet dies to study the processing parameters and feedstocks [5, 45]. The experiments in this paper were performed with industrial equipment to increase the pellet densities to industrial levels and thereby validate the achieved results [46, 47].

The objective of this work is to study how the mechanical properties of barley straw and husk pellets are affected by the addition of different levels of selected additives.

2 Materials and methods

2.1 Materials

Straw from barley from areas around Nes, Hedmark in Norway were collected after the harvest season in the autumn of 2010 (UTM / EURef 89: East: 0278993.66, Nord: 6746058.09). Barley husk was collected from the Felleskjøpets mill in Stange, Hedmark, Norway. This husk was the residue from the refining process of barley grain.

The barley grain was dried artificially with hot air. The straw was naturally dried in the field before collection. Since the manufacturing of pellets is performed in large-scale batches, and pre-controlled moisture cannot be obtained within large batches practically. The feedstock moisture could also diversify within each batch. The moisture was measured for both feedstocks when they were received at the pellet plant, see Table 6.

The feedstock materials were received as is at the pellet factory from the harvesting field and the grain milling plant. At the pellet factory site, the straw was cut into a smaller size using a high grade cutter (JF high grade cutter FCT 900). Both feedstocks were milled in a hammer mill (Champion, model unknown) with 3.75 mm sieves. After milling, the material had the particle size distribution that is shown in Fig. 1. Note that the barley husk has a narrower particle size distribution than the barley straw.

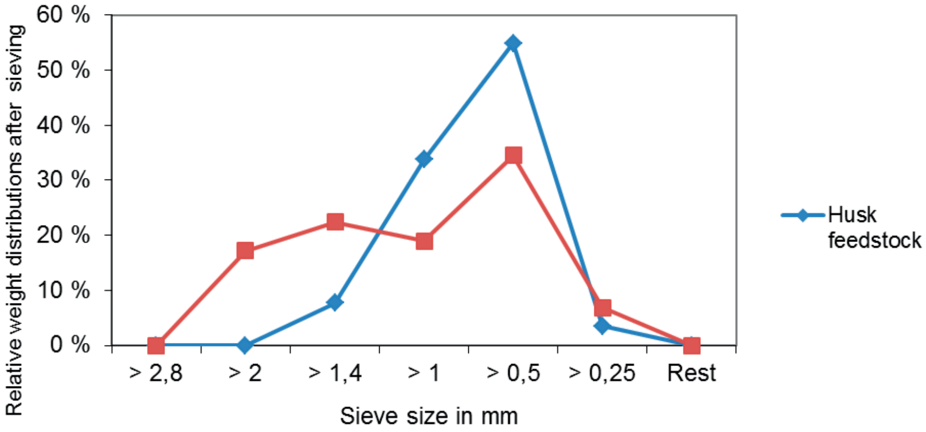

Fig. 1. Relative particle size distribution of the husk and straw feedstocks after grinding before pelletization.

Lignosulfonate was acquired from Borregaard Ind Ltd. (Lignobond DD), and marble sludge ($CaCO_3$) was acquired from Visnes Kalk AS. The properties of the feedstocks and lignosulfonate are shown in Table 1. The values were measured according to the standards that are given in Table 5.

Table 1
Properties of the feedstocks and lignosulfonate additives.

Property	Lignosulfonate	Barley husk	Barley straw
Moisture content (wt. %)	7.0	10.20	9.1
Ash content (wt. %-db.)	23.00	4.10	3
Sulfur (wt. %-db.)	6.46	0.14	0.071

Chlorine (wt. %-db.)	<0.011	0.13	0.077
Carbon (wt. %-db.)	42.50	46.40	48.4
Hydrogen (wt. %-db.)	4.50	6.00	5.8
Nitrogen (wt. %-db.)	0.13	2.00	0.72
Oxygen (calculated-db.)	23.40	41.20	41.9
Net Calorific value (MJ kg^{-1} db.)	15.42	18.93	19.355

Marble sludge, $CaCO_3$, is an additive without any organic content, and its properties can be seen in Table 2.

Table 2
Properties of the marble sludge additive (data from Visnes Kalk AS).

Property	$CaCO_3$
Density (kg m^{-3})	2730.00
$CaCO_3$ (wt. %-db.)	98.40
CaO (wt. %-db.)	0.05
$MgCO_3$ (wt. %-db.)	0.91
MgO (wt. %-db.)	0.44
Fe_2O_3 (wt. %-db.)	0.11
Al_2O_3 (wt. %-db.)	0.05
Gross calorific energy (MJ kg^{-1} db.)	0.00
Moisture content (wt. %)	0.0

Both additives are in solid form with particle sizes below 20 µm.

The ash deformation temperatures of the selected feedstocks and additives were measured in an ash fusion analyzer (Fig. 2). In a previous work, the addition of marble sludge increased the melting temperature of the ashes from barley straw and husk by over 250 °C [48]. The lab-scale sintering tests also showed that the severe sintering and melting behaviors of the two ashes were eliminated upon the addition of marble sludge. The additive mixture ratios were developed from this work and are shown in Table 4.

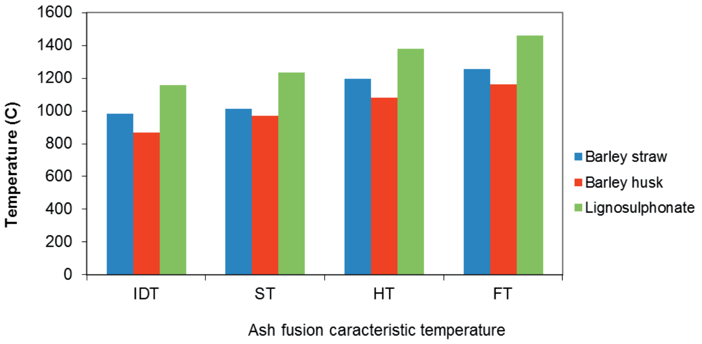

Fig. 2. Measured ash deformation temperatures [48].

2.2 Pellet manufacturing

The pellets were manufactured at a feed pellet mill in ordinary production (nominal capacity of 3000 tons year^{-1}) at Nes, Hedmark, Norway. The manufacturing was performed in ordinary mode with hot equipment. The drier (Atlas 2.5 tons h^{-1} evaporator) was operated in cold mode without heat because the feedstock was pre-dried. Fig. 3 shows a simplified setup of the manufacturing line. The pellet press (Kahl Akamat Herba-A/5K) is equipped with a cascade mixer. Additives were added continuously to the cascade mixer and blended with raw feedstock. More details on biomass pellet production with additives can be found in a previous work [49]. After pelletization, the temperature in the pellets was lowered in an updraft cooler (Maskinbyg AS) with ambient air. The layout and capacities of the factory are common for smaller (< 6000 tons year^{-1}) pellet feed production plants, and the properties of the pellet press are shown in Table 3.

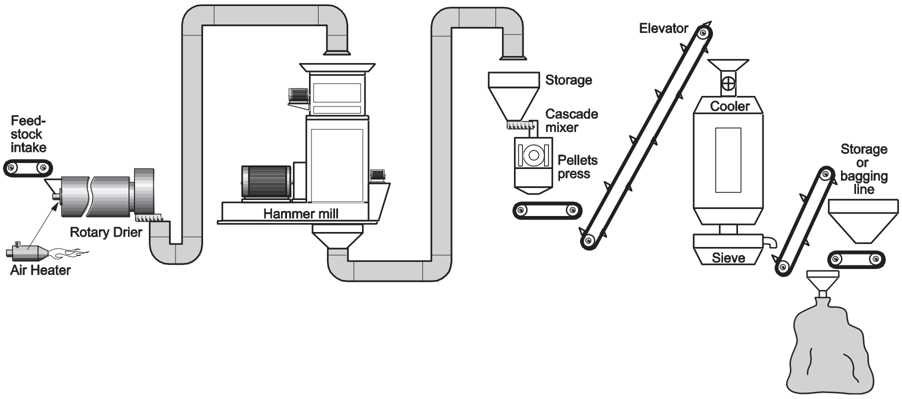

Fig. 3. Simplified flow diagram of the straw/husk pellet manufacturing plant.

No water or steam was added. Afterwards, the actual production and additive amounts were calculated on a weight basis. Table 4 shows the actual ratio of the feedstock and additives.

Table 3
Properties of the pellet press.

Property	Value
Nominal capacity	2 Ton h^{-1}
Engine power	Max. 250 A – 230 Volt
Die type	Horizontal matrix
Die outer diameter	750 mm
Die inner diameter	500 mm
Diameter of holes	8 mm
Number of holes	1120
Diameter of rollers	175 mm
Number of rollers	3
Press channel length	60 mm

2.3 Methodology

According to preliminary ash fusion tests [48], the addition of different levels of marble sludge, up to 4% (wt. %/wt. % of dry fuel), can significantly increase the melting temperatures of the ash that is produced from rich straw and husk. Up to 4% was selected because the added amount of marble sludge should not be high enough to cause trouble for pellet production due to increased friction. Lignosulfonate binders were selected based on levels that have been used in the feed industry [50]. Pellets were manufactured in 18 batches that were approximately 300 kg each. The batches were manufactured over 3 working days. Between each run, the equipment was cleaned and all of the manufactured products were collected and weighed. In Table 4, the actual manufactured recipes are shown.

Table 4
Run order and mixing wt. %-db. (of the produced pellets) of the selected additives.

Batch	Raw material	Lignosulfonate wt. %	$CaCO_3$ wt. %
0	Straw	0.00	0.00
1		1.42	0.00
2		2.16	0.00
3		3.08	0.00
4		0.00	4.04
5		0.89	0.89
6		2.08	2.08

7		1.94	3.88
8	Husk	0.00	0.00
9		1.03	0.00
10		1.86	0.00
11		2.57	0.00
12		0.00	1.85
13		0.92	2.76
14		0.91	3.66
15		0.95	4.76
16		0.00	3.65
17		2.00	4.00

Three samples approximately 20 kg each were collected from each batch before cooling at ¼, ½ and ¾ of the manufacturing time for each batch. Each sample was placed on plastic sheets on the ground for cooling to ambient temperature. The manufacturing was performed over 3 days.

Several tests were performed on the samples. Table 5 describes what tests were performed and what standards were followed.

Table 5
Standards that were followed for the test procedures of the produced pellets and feedstocks.

Test performed	Standard
Feedstock moisture	NS-EN 14774-2
Pellet moisture	NS-EN 14774-2
Durability	NS-EN 15210-1:2009
Pellet particle density	CEN/TS 15405:2006
Bulk density	NS-EN 15103
Ash content	NS-EN 14775
Particle size distribution	NS-EN 15149-2
Calorific value	NS-EN 14918/ASTM
Sulfur and chlorine content	NS-EN 15289
Carbon, nitrogen and hydrogen content	NS-EN 15104:2011/ASTM 5373
Oxygen (calculated)	ASTM D 5373
Ash deformation temperatures	ISO 540:1995

The power that was used for the pellet machine was measured continuously by a data logger (LabView), which logged the actual consumption by measuring the current and voltage. The power and energy that were used for production were calculated from the average power consumption during the sampling period.

2.4 Scanning electron microscopy (SEM) analysis

SEM was used to study the bonding mechanism of the prepared biomass pellets and any possible influence from the additives. The pellets that were produced from the different fuels with and without an additive were mounted on stubs using double-sided cellotape and were coated with Au. Electron micrographs were recorded using a scanning electron microscope (Hitachi S-3000). Multiple images were taken for each type of pellet.

2.5 Data analysis

The statistical software JMP® from SAS Institute was used for statistical analysis. First, the variables were tested separately using a simple regression analysis. Next, an ANOVA model was used for the raw material type, amounts of lignosulfonate and of marble sludge additives and their interaction effects. The amounts of the two additives were continuous variables. Additionally, the raw material moisture content was included in the model. Non-significant variables were excluded.

3 Results and discussion

3.1 Moisture

The mean moisture content for all of the straw feedstocks is 11.7 wt. % and for the husk feedstocks is 11.5 wt. %. The corresponding mean values for the straw pellets and husk pellets are 8.6 wt. % and 10.6 wt. %. The mean values and standard deviations are shown in Table 6.

Moisture is an important factor for durability, and it has been suggested that increasing the moisture increases the durability to approximately 20% of the incoming feedstock for barley straws [24, 51]. For other agricultural feedstocks, such as wheat straw pellets, big bluestem pellets, corn stover pellets and sorghum stalk pellets, moisture levels of approximately 12-13% in the finished pellets are regarded as optimum [52]. Additionally, in animal feed production, moisture control and addition is important with regard to the durability of the end product [53].

The lower mean moisture for the straw pellets than for the husk pellets might be explained by the higher specific energy consumption, see Fig. 8.

Table 6
Parameters for each run.

	Feedstock moisture wt. %		Pellets moisture wt. %		Bulk density kg/m^3		Particle density kg/m^3	
Batch	**Mean**	**St. dev.**	**Mean**	**St. dev.**	**Mean**	**St. dev.**	**Mean**	**St. dev.**
0	10.81	0.98	8.42	0.08	0.67	0.00	1.25	0.00
1	11.75	0.57	8.07	0.49	0.67	0.01	1.23	0.01
2	11.04	0.21	9.77	0.91	0.66	0.03	1.25	0.02
3	11.91	1.06	9.96	0.64	0.64	0.00	1.23	0.01

4	13.42	0.35	6.59	0.27	0.69	0.00	1.29	0.02
5	11.91	0.45	9.54	0.70	0.63	0.03	1.24	0.02
6	11.30	0.29	9.74	0.77	0.67	0.01	1.27	0.02
7	11.48	0.71	7.03	0.39	0.71	0.03	1.32	0.01
8	12.49	0.60	10.98	0.14	0.68	0.00	1.24	0.01
9	11.88	0.15	11.42	0.13	0.66	0.01	1.23	0.03
10	12.09	0.35	9.45	0.58	0.69	0.02	1.26	0.00
11	12.91	0.08	10.65	0.35	0.69	0.01	1.25	0.01
12	12.18	0.16	9.88	0.48	0.66	0.02	1.27	0.00
13	12.12	0.29	10.84	0.52	0.67	0.01	1.26	0.01
14	11.78	0.34	9.98	0.75	0.68	0.01	1.28	0.01
15	12.11	0.41	10.50	0.39	0.69	0.01	1.27	0.00
16	13.85	0.23	11.01	0.42	0.69	0.01	1.28	0.00
17	13.64	0.32	11.25	0.41	0.70	0.00	1.28	0.00

Husk is treated more homogeneously than straw from the field. This treatment might explain the higher standard deviation within the straw batches than in the husk batches. The very low standard deviation for the pellet particle density indicates a very stable production.

3.2 Proximate analysis

The amounts of ash and proximates are shown in Fig. 4.

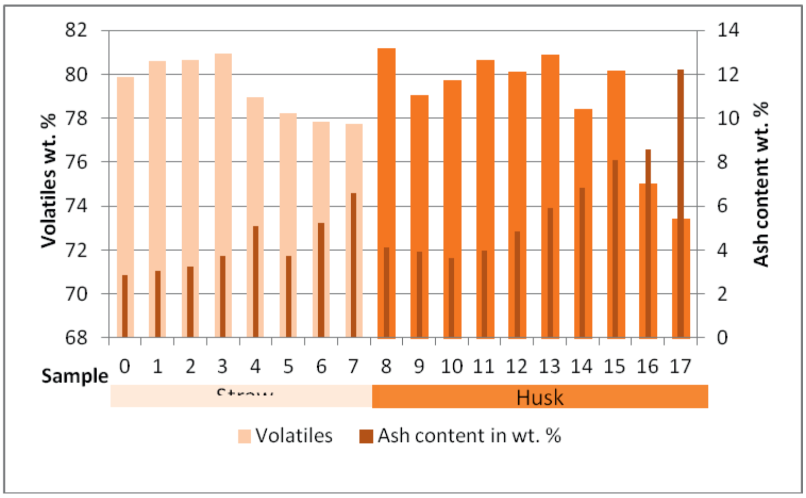

Fig. 4. Proximates and ash analysis of the pellet samples. Bars indicate volatile matter and lines indicate ash content.

The addition of marble sludge and lignosulfonate contributes to the ash and reduces the volatiles. This phenomenon is caused by the inorganic components in the additives, see Table 1 and Table 2. The high ash contents for batches 16 and 17 might be explained by the differences in the feedstock properties.

3.3 *Addition of lignosulfonate*

A significant positive effect of the lignosulfonate additive on the pellet durability was found for the straw raw material (Fig. 5). For the husk raw material, the effect was not significant. The positive effect on the pellet durability due to lignosulfonate addition appears to hold over the whole range of additive that was used (0-3.5%). The distribution in the data is considerable, especially for the husk raw material, and gives low R^2 values.

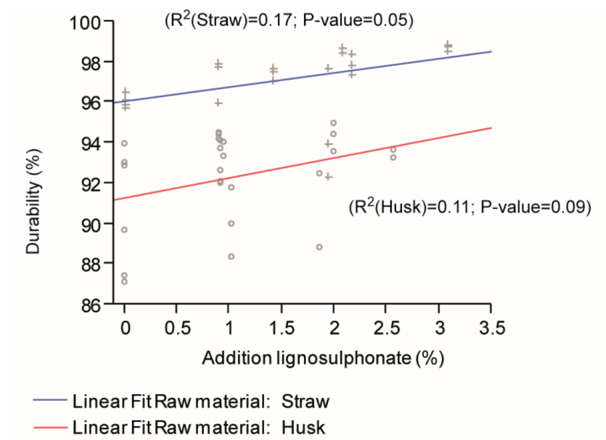

Fig. 5. Simple regression models for the pellet durability upon the addition of lignosulfonate in the production of straw and husk pellets.

When the temperature is above the lignin glass transition point, the durability is improved by an increase in the mechanical interlock forces. The results might have exhibited higher durability results if the moisture level had been higher; moisture increases the effect of lignosulfonate [18, 54]. To achieve the demand for durability within property class A1 for standard NS-EN 14961, both husk and straw need additives. Increased moisture levels could lower the need for lignosulfonate addition.

3.4 Addition of marble sludge

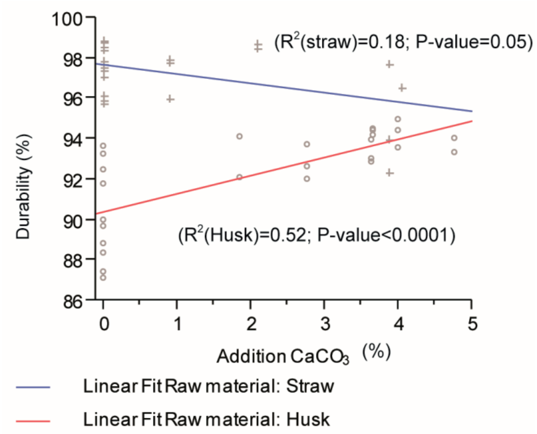

Fig. 6. Simple regression models for the pellet durability upon the addition of marble sludge in the production of straw and husk pellets.

A significant positive effect of marble sludge addition on the pellet durability was found for the husk raw material (P-value: <0.0001), while a negative effect was found for the straw pellets (P-value: 0.05). Within the range of additive that was used (0-5 wt. %), the average husk pellet durability increased from 90% to 94%. Within the same range, the straw pellet durability decreased from 98% to 96% (Fig. 6). The large distribution in the data makes it difficult to conclude whether the effect on the pellet durability due to marble sludge addition is linear or not.

Razuan [22] found that the marble sludge that was used as a binder in palm kernel cakes did not have an effect on the tensile strength before 3.0% and up to 5.0%, and the durability was not measured.

3.5 Particle density

The pellet particle density increased with increasing amount of marble sludge additive for both the straw and husk pellets (Fig. 7). The increase in the particle density was greater for the straw than for the husk pellets. The particle densities of both the straw and husk pellets were above 1.2 kg dm^{-3}. The high increase for both the husk and straw is most likely due to the high particle density of the marble sludge, approximately 2.7 kg dm^{-3}. The addition of lignosulfonate did not affect the particle density of the pellets.

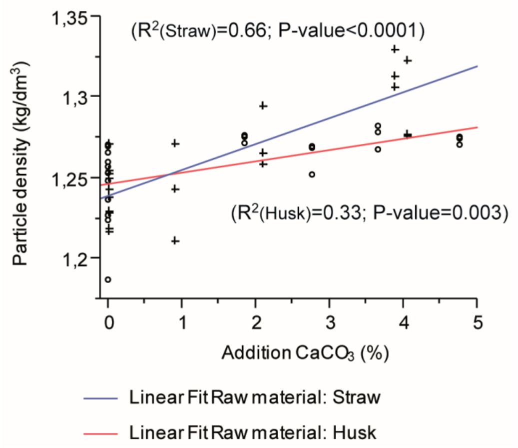

Fig. 7. Simple regression models of the effect of marble sludge addition on the particle density of the straw and husk pellets.

3.6 Energy use

The pelleting of the straw raw material was significantly and considerably more energy demanding than husk pelleting (Fig. 8). There are no significant differences among the energy uses within each category for the different additive amounts. The energy use in the straw was in the range of 120 – 143 kWh tons^{-1}. The corresponding value for husk pelletization was 58-78 kWh tons^{-1}.

Reed and Bryant reported an energy level of 16-49 kWh ton^{-1} for straw [55]. The higher energy consumption in this trial compared with the earlier report might be due to differences in the matrix length/diameter and differences in the moisture level [24, 51] . The relatively large difference between the straw and husk in this trial might be caused by the somewhat higher moisture content in the husk and also by the smaller and more evenly distributed particles sizes of the husk, as shown in Fig. 1 [5, 56].

The addition of marble sludge did not have any significant effect on the energy consumption during the pellet production of husk and straw. For energy consumption during pellet production, the variables of the moisture contents of the raw materials were tested both separately and in interaction with the amount of lignosulfonate additive. Neither of these variables was significant. The moisture in the actual feedstock was from 10-14 wt. %, which might not be enough to fully utilize the lubrication benefit of lignosulfonate addition [26].

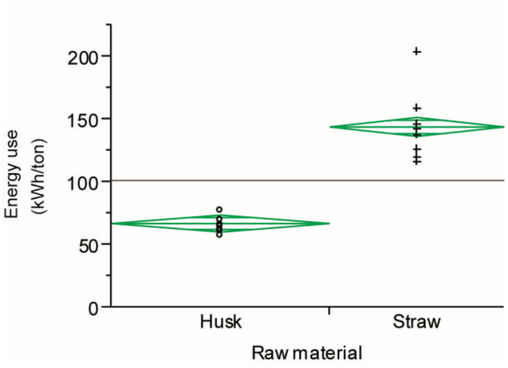

Fig. 8. Energy use during the production of the husk and straw pellets.

3.7 Interaction effects

Significant interactions were found between the raw material types and amounts used of the two additives. These interactions explained the large variations found in the simple regressions models. All of the variables were significant, except for the interaction between the raw material and the addition of lignosulfonate (P=0.058) (Table 7). However, this variable was used in the model because it was near significance at the 5% level.
No significant results were achieved for other variables, such as the feedstock moisture, energy consumption and durability except that the straw and husk had significant differences. The raw material moisture content and energy consumption were also tested in the same model but had no significant effect. All of the significant interaction effects do explain much of the considerable variations in the simple regression models. For the whole model, the R^2 value was 0.86.

When no additives were used, the straw pellets had a significantly higher durability than the husk pellets. Upon the addition of one or both additives, the differences in the durability between the straw and husk pellets were reduced to no significance. The uses of the tested additives are therefore more preferable in terms of pellet durability for the husk than for the straw raw material.

Table 7
Statistics of the model for pellet durability depending on the raw material type, amounts of additives and interaction effects.

R^2	**0.86**	
RMSE	**1.26**	
N	**48**	
Parameter	**F Ratio**	**Prob > F**
Raw material	138	<0.0001
Addition of lignosulfonate (%)	18	0.0018
Addition of $CaCO_3$ (%)	8	0.026
RM*AddLigno	6	0.058
RM*Add$CaCO_3$	46	<0.0001

AddLigno*AddCaCO$_3$	13	0.0067

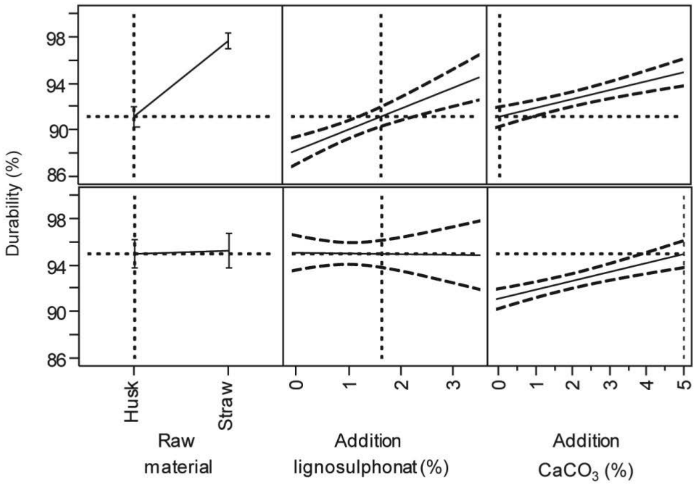

Fig. 9. Profiler figure based on the statistics from the total model for the effect of lignosulfonate addition on the pellet durability for the husk raw material with no marble sludge additive (upper profiler) and 5% marble sludge addition (lower profiler).

Fig. 9 and Fig. 10 visualize the total model. The long-dashed lines visualize the standard deviation curve.

A positive effect of lignosulfonate addition was found for husk raw material wen no marble sludge was used. The durability increase is shown in Fig. 9 (b) and increase up to 94% when 3.5% lignosulfonate is added.

For the husk raw material with no marble sludge addition, a significant positive effect of lignosulfonate addition on the pellet durability was found (Fig. 9). The positive effect on the pellet durability due to lignosulfonate addition was present over the whole range that was used, up to 3.5% of the additive. The addition of marble sludge also had a positive effect on the pellet durability. However, when a considerable amount of one of the additives was used, no positive effect on the pellet durability was found for the other additive (Fig. 9 (c)). If a high amount of marble sludge additive was used for husk pelleting, the lignosulfonate additive had no additional significant effect on the pellet durability.

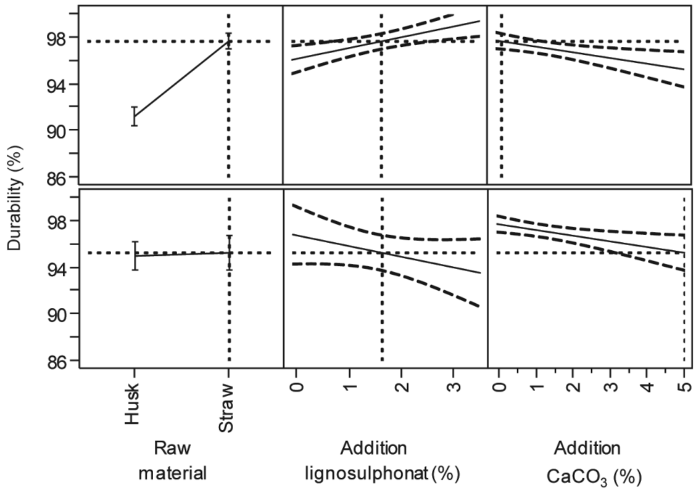

Fig. 10. Profiler figure based on the statistics from the total model for the effect of lignosulfonate addition on the pellet durability for the straw raw material with no marble sludge additive (upper profiler) and the straw raw material with 5% marble sludge addition (lower profiler).

A significant positive effect of lignosulfonate addition on the durability was found for the straw pellets without marble sludge addition, Fig. 10 (b). The effect of 3.5 wt.% addition of lignosulfonate increase the durability to 99% from 96% without lignosulfonate additive. The positive effect on the durability due to lignosulfonate disappears upon the addition of marble sludge. When a 5% marble sludge additive was used, a negative but insignificant trend of lignosulfonate addition was observed for straw, Fig. 10 (e).

3.8 Additives distribution

The marble sludge additives appear to be evenly distributed on the surfaces of the pellets. Fig. 11 and Fig. 12 show the distribution of the additives on the pellet surfaces. The white areas are the marble sludge additives. An even distribution of additives might lead to improving the additives efficiency during combustion.

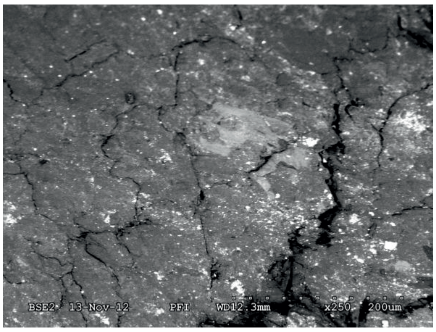

Fig. 11. Surface of the barley straw pellets with an additive, sample #4 with 250x magnification.

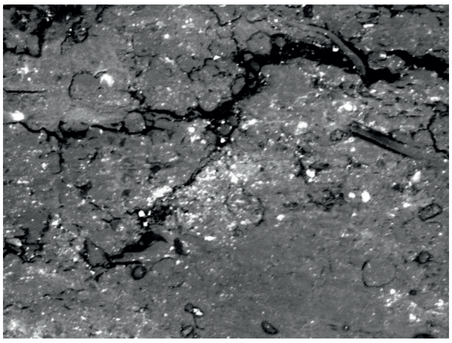

Fig. 12. Surface of the barley husk pellets with an additive, sample #14 with 250x magnification.

4 Conclusion

The lignosulfonate additive has a significant positive effect on the pellet durability for both the straw and husk raw materials when marble sludge is not also used. The positive effect on the pellet durability was larger for the husk, which had the lowest durability without any additives, than for the straw pellets. However, when marble sludge was added to reduce the ash melting point in both the husk and straw pellets, no significant effect of lignosulfonate addition was found on the durability.

Both the lignosulfonate and marble sludge additives had no significant effect on the energy use during pellet production at actual moisture levels. The particle density was affected by the marble sludge additives.

These results indicate that marble sludge is a preferable additive for husk-based pelletized fuels because it improves the mechanical pellet quality and can also improve the ash melting point. Furthermore, lignosulfonate improves the mechanical quality and can reduce the negative mechanical quality impact of marble sludge addition on straw feedstock.

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Paper V

Slagging Characteristics during Combustion of Biomass Pellets and Effect of Additives.

Geir Skjevrak, Liang Wang, Johan E. Hustad.

To be published.

Paper VI

Pelletizing and Combustion Behaviours of Wood Waste with Additives Mixing

Geir Skjevrak, Liang Wang, Michael Becidan, Øyvind Skreiberg.

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Pelletizing and Combustion Behaviors of Wood Waste with Additives Mixing

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***Abstract*-Pelletizing and combustion behaviors of wood waste with and without additive addition were investigated in this study. It was found that the wood waste pellets have a high potential for slag formation during combustion and can cause operational problems. With additives addition, no significant changes were observed regarding mechanical properties of the wood waste pellets. Sewage sludge addition was found to have positive effects on NO_x and CO emissions during combustion. Both sewage sludge and marble sludge addition have evident influence on slag formation during combustion. Sewage sludge addition reduced the formed slag amount and sizes, and therefore improved the boiler operation. Marble sludge eliminated the slag formation during the wood waste pellets combustion.**

Keywords-component; wood waste; pellets; combustion; emissions; ash.

I. INTRODUCTION

Today biomass is utilized as a fuel resource for combustion in different combustors with aim of power and heat production. In Nordic countries, biomass pellets are widely burned in residential boilers and burners for heat production. However, due to limited amount of conventional fuels (i.e. saw dusts and cutter shavings), more new raw materials are entering the feedstock market for pellets production. As one of them, wood waste from furniture industry is attractive due to relative low price and the large amount available. [1-3]. The wood waste can be collected and transported to a local pellet production unit. After pelletization, the wood waste is upgraded to a more valuable fuel with higher energy density and homogeneity, and can be burned directly in a simplified pellets furnace and boiler for heat production with several benefits. When the feedstock is only treated mechanically, the pellets normally achieve the highest quality class. However, as a fuel for combustion, the pellets produced from the wood waste are often troublesome due to high contents of problematic ash forming elements in the raw materials. These ash forming elements usually include K, Na, Si and Cl. New chemical compounds or eutectics will form during the combustion process as results of combinations and interactions between these ash forming elements [4-5]. These new formed chemical compounds and eutectics have low fusion temperatures and are present as sticky melts at combustion temperatures. As the amounts of melted chemicals and eutectics are high enough, the fuel ash sintering and consequent slagging will take place in the combustion region. The ash sintering and slagging will disturb the combustion process and the system operation. The boilers need to be shut down often for cleaning the formed slag and agglomerates. It is also a potential for damages on the grate and thereby a need for changing the damaged components when removing large size slag particles. It has been well studied and stated that K and Na play a central role in ash melting and sintering processes together with Si and Cl. Previous studies reported that fuels with high slagging tendencies are often characterized with high contents of K and Si. In addition to the inherent K and Si in the fuels, some woodworking industry treats the material with contamination procedures: (1) sanding paper when polishing surfaces which might give a high exposure of sanding dust; (2) wood residue handled within untreated concrete walls and floors might be contaminated by concrete dust and soil particles. The enhanced Si content from contaminations will lead to more severe ash slagging [5].

Nowadays, the primary market for pelletized wood in residential use is for small and medium size grate integrated furnaces and boilers. Ash slagging problems will reduce the accessibility of these combustion appliances for the wood waste and the efficiency of the combustion systems. Utilization of additives has been proved an efficient way to abate ash related problems during biomass combustion. Additives refer to a series of chemicals or solid materials that can alter the ash chemistry and fusion behavior by chemical reactions and physical adsorption processes. For example kaolin has the ability to increase the biomass ash melting temperatures and capture the problematic K released from biomass combustion. It will help to decrease the risk for ash sintering, slagging and fouling deposit formation during biomass combustion.

In this study, two additive candidates were tested; marble sludge and sewage sludge. Both of the two additives are available in large amounts and are low cost resources. This paper investigates the effects of additives addition on (1) mechanical properties of the wood waste pellets; (2) emissions from combustion of the pellets in a 1.2 MW_{th} grate boiler; (3) ash behaviors during pellets combustion.

II. EXPERIMENT METHOD

A. *Fuel and additives*

The raw materials for pellets production are collected from furniture industries in Sykkylven, Norway. The two additives, marble sludge and sewage sludge, were obtained in granular and slurry form, respectively. The fuel and additives were characterized by performing proximate analysis, according to ASTM 780 and 879, and ultimate analysis with a CHNS/O elemental analyzer (Vario MACRO CHNS).

The pure wood wastes were transported to the pellet plant and pelletized in a conventional pellet machine, Sprout Matador M40. The wood waste was first milled in a hammer mill equipped with a 5 mm sieve. Then the milled materials were transported to a cascade mixer and conditioned by steam addition. The wood waste was pressed into pellets by passing a rotating vertical die. Both additives were air dried and ground into fine powders. To produce the wood waste pellets with additive addition, the additives were introduced directly into the cascade mixer by a adding tube. The blending ratios of additive to fuel were controlled by adding a specified amount of additive powders per time unit into the cascade mixer. The fuel and additives were then mechanically mixed. Two additives to fuel blending ratios were chosen based on performed ash melting tests; corresponding to 4 wt% and 8 wt% additives in the fuel. The produced pellets were stored in big bags. Representative samples were collected for investigating their mechanical properties according to standard NS-EN 14961. Durability tests on produced pellets were performed according to standard NS-EN 15103. Standard CEN-TS 15150 was used for particle density testing and NS-EN 15103 for bulk density measuring. Finally, fines from manufacturing were measured in accordance with NS-EN 15149-1 and 15149-2.

The combustion tests were carried out in a boiler manufactured by Termiska Processer AB. This boiler is equipped with a horizontal grate and a moving scraper. The nominal output of the boiler is 1.2 MW_{th}. To measure the combustion temperatures in the boiler, seven thermocouples were placed in the vicinity of the grate and along the moving direction of the fuel (pellets). Positions and identifiers for the thermocouples are shown in Figure 1. An experiment, including logging of the combustion temperature, started when the nominal output of the boiler was reached. The boiler was operated at full load for 4-5 hours. Boiler operation parameters including airflow, airflow distribution, draught, fuel, oxygen content in the flue gas and movement of the ash scraper were kept equal for all runs. The flue gas from the boiler was analyzed with a Testo 350/454 XL flue gas analyzer. Neither temperature or flue gas results from start-up nor shutdown sequences were utilized. After each combustion test, the ash left on the grate was collected and classified by visual observation. In addition, slag samples were cut and examined by light microscopy.

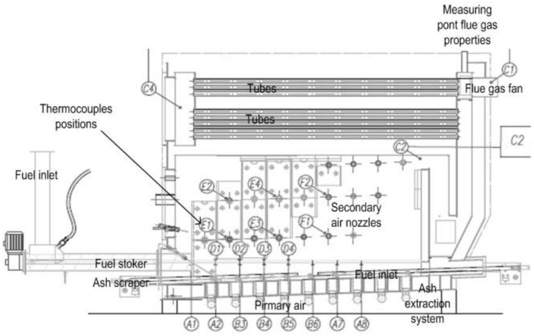

Figure 1. Schematic drawing of boiler and arrangement of the thermocouples

III. RESULTS AND DISCUSSION

A. *Fuel and additives properties*

The fuel and additives properties are presented in Table 1. The wood waste is characterized by high volatile content, low ash content and high heating value. Both the sewage sludge and marble sludge have high ash contents. For the sewage sludge, high carbon and nitrogen contents and a relatively high heating value were measured. It indicates that the sewage sludge will contribute to the energy and heat production, but with potentially a high emission level of NO_x during the combustion process. Since calcium carbonate is the main component of marble sludge, only the ash content was measured.

TABLE I. FUEL AND ADDITIVES PROPERTIES

	Wood waste	**Sewage sludge**	**Marble sludge** [a]
Proximate analysis (wt %)			
Volatile matters	84.08	53.61	a
Ash content	0.71	41.7	98
Fixed carbon	15.21	4.69	a
Ultimate analysis (wt%)			
Nitrogen	0.81	7.28	a
Carbon	50.20	45.23	a
Sulfur	0.14	1.86	a
Hydrogen	6.47	7.62	a
Oxygen [b]	42.38	38.01	a
Heating value (MJ/kg, d.b.)	19.9	17.5	a

[a] not analyzed ; [b] by difference; d.b.: dry basis

B. *Properties of produced pellets*

Five types of pellets were produced and combusted in this study; (1) pure wood waste pellets (Pure), (2) wood waste pellets with 4 wt % sewage sludge addition (SS4), (3) wood waste pellets with 8 wt % sewage sludge addition (SS8), (4) wood waste pellets with 4 wt % marble sludge addition (MS4) and finally (5) wood waste pellets with 8 wt % marble sludge addition (MS8) The properties of the produced pellets were evaluated by performing the standard test methods mentioned above.

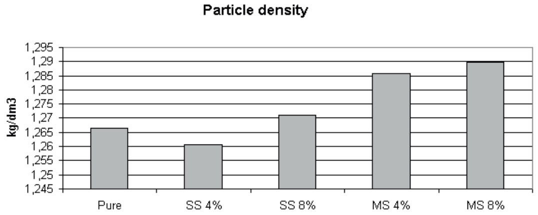

Figure 2. Particle densities of produced pellets

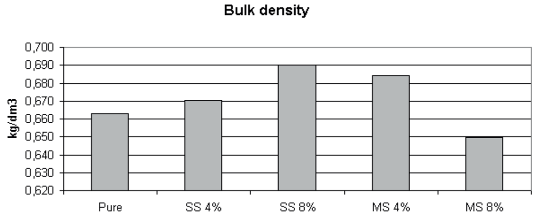

Figure 3. Bulk densities of produced pellets

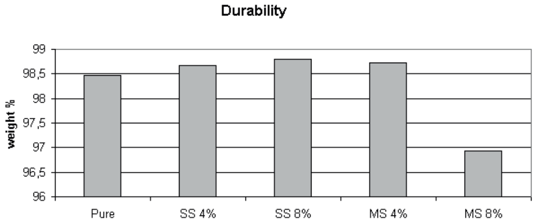

Figure 4. Durability of produced pellets

Figure 2 shows the results for the particle density. Since marble sludge has a higher bulk density it is expected that the particle density would increase when using this additive. However, the bulk density (Figure 3) does not follow the development of the particle density. This might be due to differences in the length of the pellets. The durability of the pellets (Figure 4) illustrates that there might be a positive effect from additives, contributing to bonding the particles in the pellets. However, this effect might reach a limit for 8 wt % $CaCO_3$ [6].

Surplus fines were sieved to analyze the fines' particle size distribution. Figure 5 shows the distribution of fines particle sizes from the different pellets. The grade curve indicates that a part of the marble additive is not kept in the wood pellets, but is lost in the fines. The fines sizes are also in accordance with the particle size of the marble additive. It confirms that parts of the marble sludge did not stay in the structure of the pellets, but were separated out of the pellets by mechanical forces during the sieving process. As shown in Figure 6, only a small amount of fines were produced from the pure wood waste pellets and the pellets with sewage sludge addition. However, for the wood waste pellets produced with 8 wt % additives, around 2.5 % pellets mass are lost as fines. It is probably due to lack of ability of thermoplastic wood particles to bond high levels of non-thermoplastic additives like marble sludge.

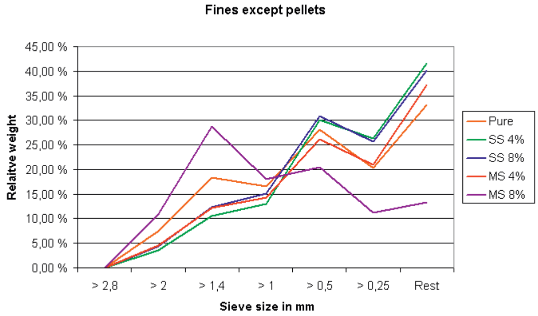

Figure 5. Distribution of particle sizes of surplus fines from produced pellets

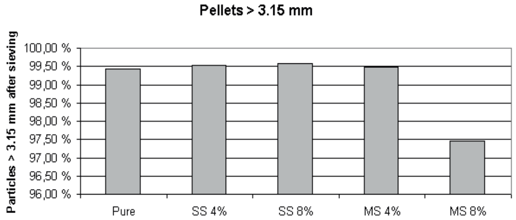

Figure 6. Fines content of produced pellets

C. *Combustion test results*

Combustion of the added samples is performed at equal conditions. Figure 7 show that the O_2 levels (as measured) in the flue gas are similar with that measured from wood waste pellets combustion, compared to pure wood waste combustion with additives addition. It means that the additives addition has little influence on the overall combustion process. The CO emission level decreased dramatically due to sewage sludge addition. It suggests that the combustion conditions were improved when using sewage sludge as additive. The NO_x emissions, where the major contribution is from nitrogen in the fuel, increase with the use of sewage sludge. This is in accordance with the ultimate analysis and the higher nitrogen content in sewage sludge. Due to the inert property of the marble sludge, it did not affect the combustion behavior of the wood waste pellets. The decreased NO_x values are probably due to the dilution effect from the CO_2 released during decomposition of $CaCO_3$. The CO level both increased and decreased, indicating more variable combustion conditions with marble sludge as additive.

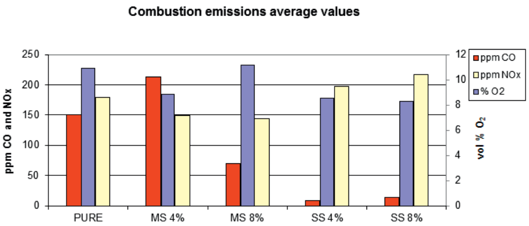

Figure 7. Emissions (as measured) from combustion of wood waste pellets with and without additives addition

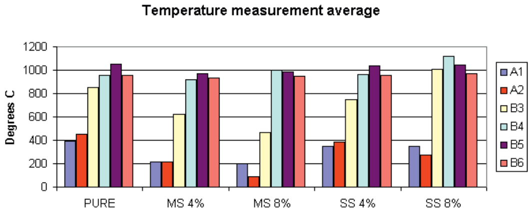

Figure 8. Temperatures measured in the five combustion tests

Figure 8 shows the temperature distribution in the length direction of the grate. Thermocouple A1 and A2 is placed in the first section of the grate, where the drying and pyrolysis phase of the fuel occurs. The rest of the thermocouples (B2-B6) are placed further along the grate where the main combustion takes place. The arrangement of the thermocouples is shown in Figure 1. It can be seen that addition of additives did not influence the combustion temperatures to a large extent. But the results indicate that addition of incombustible additives moves the drying and pyrolysis zone backwards on the grate. The highest combustion temperatures were recorded for the pellets with 8 wt % sewage sludge addition. The higher combustion temperatures also occurred earlier on the grate and were probably due to higher reactivity of sewage sludge compared to pure wood waste pellets. In addition, differences between the measured temperatures from the different combustion tests might be due to different bulk densities, and hence different local stoichiometry, since fuel is entered on a volumetric basis.

IV. ASH SINTERING AND SLAGGING

After each combustion test, the ash residues on the grate were collected and classified. The ash residues that melted and sintered into larger sizes than 3 mm are named as slag. The rest of the ash residues collected is called bottom ash. Representative slag samples were selected and cut for photographing by light microscopy. The images taken from slag collected from combustion of wood waste pellets with (a) 4 wt % sewage sludge and (b) 4 wt % marble sludge addition are shown in Figure 9. It was found that a large amount of ash from pure wood waste combustion melted and formed aggregates hard as stone. From these aggregates, no individual ash particles can be observed, which implies severe melting of the wood waste ash during combustion [7]. The light microscopy images taken from the wood waste pellets slag confirm the combustion test results. The picture (Figure 9-a) shows that the slag has a continuous structure and a homogeneous phase, which corresponds to complete melting of the ash during the combustion process. For the slag collected from wood waste pellets combustion with 4 wt % sewage sludge addition, the melted ash fraction decreased. The slag has a more fragile structure and smaller sizes. The light microscopy image (Figure 9-b) shows a significant reduction of continuous phases compared with the slag structure presented in Figure 9-a. The hollow voids relates to a less compact structure of the slag. These slags are possibly crushed during fuel/ash bed moving and therefore improve the combustion process. For the combustion of the wood waste pellets with marble sludge addition (Figure 9-c), only a small amount of ash residues were present as slag, that are easily crushed by hand force. It means that the slag formation during wood waste combustion has been totally eliminated due to the marble sludge addition. The collected slag samples were mainly consisting of calcined calcium carbonate. This is why the sample area in the light microscopy image has a relatively darker color compared to the sample areas in Figure 9-a and Figure 9-b. The combustion tests showed that the sewage sludge and marble sludge addition has positive effects on the slag formation during wood waste pellets combustion. The wood waste ash melting temperature was increased due to addition of sewage sludge and marble sludge, which resulted in less amounts of melts formed at combustion temperature, and less slag formation consequently. In addition to this, the marble sludge may also dilute the wood waste ash by a large surplus amount of calcium [7]. Since the calcium is inert at high temperature, it will not contribute to the ash melting and slag formation. The presence of inert calcium may restrain the accumulation of ash melts and the slag formation as well.

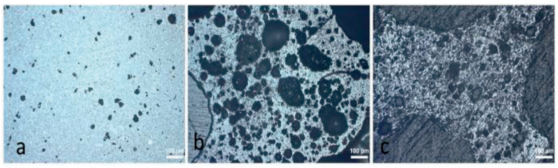

Figure 9. Light microscopy images taken from slag collected from (a) wood waste pellets combustion; (b) wood waste pellets + 4 wt % sewage sludge; (c) wood waste pellets + 4 wt % marble sludge

V. CONCLUSIONS

The primary goal in this study was to investigate effects due to additives addition on the mechanical properties of pellets. The performed work shows that The sewage sludge additives improve the particle density and durability of the pellets. However, for a high addition of 8 wt % marble sludge a clear negative effect on this quality parameter was found.

Compared with other four types of produced pellets, more fines were collected from the wood waste pellets with marble sludge addition. Combustion tests results showed that additives have an improvement potential on flue gas emissions. Also, the operational stability during the tests was also improved with additives in the fuel.

Combustion results showed that the pure wood waste pellets tested in this study have a high slagging tendency, with a large amount of ash formed as slag and aggregates on the grate during combustion. These slags are hard to break and handle by the ash screw, and will need to be cleaned manually and will probably damage the grate. However, with sewage sludge addition, slags of smaller sizes and more fragile structures were formed. Less amount ash melts were observed in the collected slag, which indicates that sewage sludge addition has positive effects on wood waste pellets ash melting behavior. For this reason, the operation of the boiler was improved. The marble sludge addition eliminated the slag formation totally during wood waste pellets combustion. Only some aggregates were left on the grate, which are easily broken by hands. The marble sludge is suggested to be used as a highly efficient additive to reduce slagging during problematic wood waste pellets combustion.

ACKNOWLEDGEMENT

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Paper VII

Effects of Sewage Sludge and Marble Sludge Addition on Slag Characteristics during Wood Waste Pellets Combustion

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Effects of Sewage Sludge and Marble Sludge Addition on Slag Characteristics during Wood Waste Pellets Combustion

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ABSTRACT: The objectives of the present work were to investigate the effects of sewage sludge and marble sludge addition on slagging tendency and obtain better understandings for slag formation processes during the combustion of problematic wood waste pellets. Wood waste pellets produced with and without additives were combusted in a boiler (1.2 MW_{th}) with continuous measurements of the combustion temperature and flue gas composition. The chemical composition, mineral phase, and microchemistry of the collected bottom ash and slag were examined by X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM/EDX). Reference wood waste pellets showed a high slagging tendency with 34 wt % of the ingoing fuel ash formed as slag on the grate. XRF and SEM/EDX analyses revealed high contents of Si, K, and Na in the slag and a clear correlation among the three elements. It implies melted fractions of the slag consist of alkali silicates indirectly observed as glass phases by XRD analysis. The severe slagging of wood waste pellets was reduced distinctly upon addition of marble sludge. For two marble sludge added combustion tests, less than 3 wt % of the ingoing fuel ash formed as low sintering degrees slag. The mineral compositions of the resultant slag were changed from low melting point silicates to high temperature melting calcium based silicates, oxides, and hydroxides. SEM/EDX revealed enhancement of Ca and Mg in the melted slag, which were possibly originated from marble sludge and dissolved in ash melts. This may lead to release of alkali metals from the ash melts thereby reducing the formed melt amount. In addition, marble sludge addition restrained sintering and accumulation of melted ash into a continuous phase and resulted in fragile slag particles. Addition of 4 wt % sewage sludge has a minor effect on the slag formation of wood waste pellets combustion. The sizes and sintering degrees of the formed slag were considerably decreased and the mineral compositions in the slag were dominated by high temperature melting corundum and calcium silicates. The enrichment of kalsilite observed in the slag was probably caused by the reactions of aluminum silicates in the sewage sludge with potassium from the fuel. The corundum, calcium silicates, and kalsilite have higher melting temperatures and thus gave a lower ash melt fraction in the slag. However, as a result of the addition of sewage sludge, both the ash content and the Si level of ingoing fuel pellets were enhanced. Thereby the formed slag amount increased slightly for the combustion of the 8 wt % sewage sludge blended wood waste pellets.

1. INTRODUCTION

Today, combustion is still the most applied technology for biomass utilization worldwide.[1] However, biomass has a number of challenging properties that make it more difficult to handle and combust than traditional fossil fuels. Prior to combustion, biomass materials need to be pretreated to obtain more homogeneous and favorable fuel properties.[2,3] Pelletization is an efficient way to upgrade biomass fuels for obtaining increased energy density and reducing costs for storage, handling, and transport.[3]

Biomass pellets have been proven to be well suited for various combustion appliances, including dedicated stoves, burners, and boilers.[2−4] During the last few decades, biofuel pellets production has increased significantly, which causes raised prices and a shortage of conventional raw materials for pellet producing (i.e., sawdusts and cutter shavings). Therefore, new raw materials are required to meet the increasing resource demands, which are preferably cheap and available in a large amount.[2] However, compared to the conventional woody biomass feedstock, some new raw materials (i.e., agricultural residues and wood wastes) have considerable variations in total ash content and composition of ash forming matters.[4−11] Ash slagging and sintering have been often observed in different pellet combustion appliances. These problems have resulted in reduced accessibility and performance of the combustion appliances, as well as extra system cleaning and maintenance costs.[4−7]

The slagging tendency during the combustion of the biofuel pellets is sensitive to amounts and compositions of fuel ash forming matters.[4−7] High slagging tendencies have been more often observed during combustion of ash rich biomass pellets. However, the ash sintering may even occur as combustion of standard wood pellets (i.e., stem wood pellets), which are normally classified as “first class” fuel due to low ash contents.[6] Variations of fuel ash compositions may also cause different slag formation tendencies and properties.[5] Several studies have demonstrated strong connection between the Si and alkali metal content in the fuel with slagging tendencies in different combustion appliances.[5,6,9] During biomass pellets combustion, silicon rich ash residues may react with alkali species to form low temperature melting alkali silicates.[9] Materials and particles with locally formed sticky silicates on surfaces may attach and adhere to form aggregates on the grate.[4−9] Therefore, the chemical compositions of formed slag are dominated by silicates melt. With a long-term accumulation, these sintered/melted aggregates grow in size and strength and form slag consequently. In addition, virgin woody biomass fuels are often contaminated by sand, soil,

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or dust during transport, storage, and treatment processes. The contaminations often contain active silica and react with melted fuel ashes to form a more silica rich melt at high temperatures, which enhances slag formation during combustion.[10,11] For pellets produced from agricultural wastes, apart from the formation of alkali silicates, reactions between the other ash-forming elements, i.e., K and P may also play a crucial role in initiating and enhancing slag formation.[7,9]

Utilization of additives to abate ash related problems in biomass combustion applications has been studied in recent decades.[12−21] Most of these studies have focused on reducing agglomeration in fluidized beds, fouling deposits, and high temperature corrosion in bench scale reactors and utility boilers. Only a few studies have been carried out to mitigate slag formation by using additives during biomass fuels combustion in residential appliances. By adding limestone, severe slagging was eliminated during the combustion of problematic stemwood raw material.[22] It was due to formation of high melting temperature silicates and oxides in the resultant slag instead of low melting point silicates, which have low sintering degrees and small sizes.[22] In another study, lime addition significantly reduced the slag formation when phosphorus-rich fuel cereal grains (barley, rye, and wheat) pellets were combusted in a residential burner. This was attributed to the formation of more high temperature melting calcium potassium phosphates in the ash residues with the lime addition.[10] The other calcium based additive, calcite, showed the evident reducing effects on slag formation during corn stover pellets combustion.[23] The calcite addition contributed to formation of high melting points calcium magnesium silicates and reduction of the glass fraction in the slag. Kaolin has dissimilar effects on slag formation during the combustion of biofuel pellets produced from different raw materials. For problematic raw wood materials that are rich in silicon, only a minor decrease in slagging tendency was found when kaolin was added with an additives-to-fuel ratio of 0.5 wt %.[22] On the other hand, kaolin showed high capability to abate slag formation during the combustion of pellets produced from agricultural wastes. Evident reduction of slag formation has been observed during the combustion of corn stover and oat pellets with the addition of kaolin.[23,24] It was suggested that the low slagging tendencies observed in these two studies were attributed to reactions between the active components (kaolinite and metakaolinite) from kaolin with potassium containing species from the fuel. This resulted in a change from relatively low melting point silicates to high temperature melting silicates in the bottom ash and slag.[23,24] These reactions were confirmed by the depletion of glass phases (low melting point silicates) and the absence of slag during the combustion tests.[23,24]

Considering the relatively high costs of commercial additives (i.e., kaolin), cheaper alternatives with high antislagging capacity and accessibility need to be identified and tested. Sewage sludge, as a byproduct from wastewater treatment plants, is reported to have positive effects to prevent ash related problems during biomass combustion.[13,14,16,17,19−21] A certain amount of sewage sludge addition resulted in reduction of deposition and high temperature corrosion during the combustion of biomass fuels in CFB boilers.[13,14,16,17] It was suggested that alkali metals released during biomass combustion could be captured by aluminum silicates, phosphates, and sulfur from the added sewage sludge. This reduced the concentrations of problematic alkali species in the flue gas and fouling deposits on the testing probe surface consequently.[13,14,16,17] The tendency toward ash sintering has previously been evaluated, showing positive results when wheat straw and waste wood combusted with sewage sludge blending. By adding an amount of sewage sludge corresponding to 5 wt % of the fuel mass, the initial melting temperature of waste wood and wheat straw ash were enhanced by 100 and 200 °C, respectively.[21] In another study, the addition of 2 wt % sewage sludge was enough to increase the bed agglomeration temperature by about 100 °C when problematic wood/straw pellets were combusted in a fluidized bed boiler.[20] Similar enhancing effects of sewage sludge addition on bed agglomeration temperatures were also stated by Andersson et al.[19] However, no studies have been previously published about the effects of sewage sludge addition on slag formation and characteristics during combustion of problematic biomass pellets. Calcium-based additives have been proved to be efficient to abate ash slagging problems. In this study, marble sludge, an industrial waste material, was tested as a candidate additive due to its high calcite content ($CaCO_3$).

The purpose of this study was therefore to investigate the effects of sewage sludge and marble sludge on slagging tendencies during the combustion of pelletized wood waste in a boiler (1.2 MW_{th}). The effects of additives on slag formation processes and characteristics are particularly emphasized in this work.

2. EXPERIMENTAL SECTION

2.1. Fuel and Additives. The wood wastes used in this study were originally from the furniture industry. These wastes are currently being collected, pelletized, and combusted in a boiler for heat production. Severe ash slagging occurs on the grate during the combustion of the pellets, which requires frequent shutdown, cleaning, and maintenance of the boiler. Sewage sludge was obtained as granules from a wastewater processing plant. The marble sludge was obtained as slurry waste from a marble processing plant with calcite as the main component. Both the received sewage sludge and marble sludge were further air-dried and ground into fine powders less than 1 mm prior to being pelletized with the wood wastes. Before pellets production, ashes from wood wastes with each additive blending in additive-to-fuel ratios of 1−10 wt % were produced. The sintering tendencies of the ash residues were evaluated by performing standard ash fusion tests. Two additive blending ratios (4 and 8 wt %) were selected for further pellets production considering optimal ash melting points. Five types of pellets were produced and used for further combustion tests. In the pelletizer (Sprout-Matador M30), the raw wood wastes were milled to 5−6 mm and then transported to a cascade mixer. After conditioning in the mixer, the ground materials were pressed into pellets by passing a rotating vertical ring die. To produce additive blended pellets, the pelletizer was started to run with pure wood waste pellets production around 15 min to reach the ordinary processing temperature. After the nominal capacity of pelletizer was achieved, the fine additive powders were fed continuously into the cascade mixer by a feeding tube. In the cascade mixer the wood wastes and additive particles were blended and stirred by mixing paddles. Then the mixtures of the wood waste and additive were pushed through channels in the ring die to produce pellets. The mass flow of the wood wastes entering the mixer was constant during pellets production. The ratio of the additive blended with fuel was adjusted by changing the mass of additive entering the mixer per unit time. In this way, desired additive-to-fuel mass ratios were achieved in the produced pellets. Five types of pellets were produced under similar pelletizing conditions to

Table 1. Characterization of Studied Fuel and Additives

	testing method	wood waste	sewage sludge	marble sludge
		proximate analysis (wt %, d.b.[a])		
volatiles matter	ASTM E 872	84.08	53.61	[c]
fix carbon[b]		15.21	4.69	[c]
ash content	ASTM D 1102	0.71	41.7	98
		ultimate analysis (wt %, d.b.)		
C	ASTM E 777	50.20	45.23	[c]
H	ASTM E 777	6.47	7.62	[c]
N	ASTM E 778	0.81	7.28	[c]
S	ASTM E 775	0.14	1.86	[c]
O[b]		42.38	38.01	[c]
heating value (MJ/kg d.b.)		19.9	17.5	[c]
		ash forming elements (wt %)		
SiO_2	XRF	22.75	26.71	0.2
Al_2O_3	XRF	6.26	31.74	0.8
CaO	XRF	26.13	13.08	95.12
K_2O	XRF	14.47	0.69	0.02
Na_2O	XRF	11.37	0.47	0.22
P_2O_5	XRF	2.33	16.96	0.02
TiO_2	XRF	3.08	0.45	0.06
Fe_2O_3	XRF	4.52	6.80	0.57
MgO	XRF	5.77	1.08	2.99
SO_3	XRF	4.07	2.27	0.05
Cl	XRF	0.21	0.10	[c]

[a] d.b: dry basis. [b] By difference. [c] Not detected.

reduce the variation of the characteristics among the produced pellets.

2.2. Ash Content and Fusion Behavior of Produced Pellets. The ash contents of raw materials and five pellets were measured according to the standard ashing method (ASTM 1102), and were used to determine the actual additive-to-fuel ratios in produced pellets. The fusion temperatures of the residues from ash content measurements were determined according to standard ISO 540:1995. Cubic specimens were produced from each ash sample and sent into an ash fusion analyzer (Carbolite CAF Digital). The specimens were then heated from 400 to 1600 °C with a heating rate of 6 °C/min under oxidizing atmosphere. The external shapes of each ash cube (deformation, shrinkage, and flow of the cubic specimen) were recorded and characterized. Four characteristic temperatures were determined: initial deformation temperature (IT), softening temperature (ST), hemisphere temperature (HT), and flow temperature (FT).

2.3. Combustion Tests. Pellets produced from wood waste with and without additives addition were combusted in a STEP-FIRE boiler (TPS Termiska Processer AB, Sweden). The boiler has a capacity of 1.2 MW_{th}, and is equipped with a moving ash pusher and a screw to handle residues from the fuel combustion. Each combustion test lasted for 5 h, corresponding to total ingoing pellet amounts from 1.0 to 1.6 tons for the different combustion tests. The boiler was operated at full load (1.2 MWth with continues fuel feeding) except for the startup and shutdown sequences. Measurements of O_2, CO, NO_x, and CO_2 were performed with a conventional gas analyzer. Combustion temperatures were continuously measured by seven thermocouples placed horizontally over the grate and along the fuel moving direction. A similar thermocouple arrangement in a boiler was illustrated in another study.[25] All ash residues left on the grate after combustion were collected and sieved into two groups: (i) melted ash/agglomerates with sizes larger than 3 mm classified as slag, and (ii) the rest of ash residues including melted ash particles smaller than 3 mm and nonmelted ash on the grate (bottom ash).[5−7] After sieving, the amounts of the bottom ash and the slag were quantified. According to visual evaluation, the sintering degrees of ash residue after each combustion test were classified in four degrees. The following criteria proposed by Öhman et al. were adopted:[5−7,11] Category 1: ash residues without sintering; Category 2: partly fused and sintered ash; Category 3: totally sintered ash as smaller blocks or agglomerates; Category 4: completely melted in the form of larger blocks and lumps.

2.4. Chemical Analysis of Collected Bottom Ash and Slag. The chemical compositions and mineral phases of collected bottom ash and representative slag were examined by X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses. The concentrations of the main elements quantified by XRF (Bruker, S8 Tiger) analysis are presented as oxides. XRD analyses were conducted by scanning the ground samples with an X-ray diffractometer (Bruker D8 Advance) equipped with a Cu k-alpha radiation and LynxEye detector. Semiquantitative analyses were performed for the collected data by using the TOPAS evaluation program plus the ICDD-PDF2 database. The microchemistry and morphology of the slag samples were examined by a scanning electron microscopy (SEM) coupled with energy dispersive X-ray analysis (EDX). Prior to SEM/EDX analysis, the representative slag samples were cut and photographed. Afterward,

Table 2. Ash Fusion Behavior of Wood Waste With and Without Additives

	nonadditive	+ sewage sludge		+ marble sludge	
desired additive-to-fuel ratio (wt %)		4	8	4	8
ash content (wt %)	0.72 ± 0.04	2.24 ± 0.03	3.87 ± 0.05	4.42 ± 0.05	8.68 ± 0.04
achieved additive-to-fuel-ratio (wt %)		3.7	7.4	3.6	7.8
ash fusion temperature (° C)					
IDT	1068	1122	1146	1164	1178
ST	1152	1178	1248	1266	1284
HT	1166	1272	1474	1440	1464
FT	1180	1342	1494	1466	1476

they were embedded into epoxy, ground and polished to obtain flat cross sections, then coated with carbon and carefully examined by SEM/EDX spot and area mapping methods. The microprobe was operated with a voltage of 20 kV and a beam current of 10 nA.

3. RESULTS AND DISCUSSION

3.1. Combustion Test Results and Slagging Tendencies. The characteristics of the raw wood waste and additives used in this study are presented in Table 1. The most significant ash forming elements in wood waste were Si, Ca, K, and Na. Considering the severe slagging behaviors observed during the combustion of wood waste pellets, the results of the ash forming elements analysis agreed with previous studies.[5,6] Namely high slagging tendencies are frequently observed from the combustion of fuels that are rich in Si and alkali elements. The major ash forming elements contained in the sewage sludge are Si, Al, Ca, and P. A large amount of Al in sewage sludge ash is attributed to the use of aluminum sulfate ($Al_2(SO_4)_3$) as a phosphorus precipitation agent during wastewater treatment. As expected, Ca was the dominating element in marble sludge. The results from the ash content measurements and fusion tests are summarized in Table 2. As presented in Table 2, achieved additive-to-fuel ratios in produced pellets were close to the desired values. It suggests that the way to add the additive to raw wood wastes is reliable and reproducible for further industry application. However, the ingoing fuel ash contents were increased considerably due to additives blending. Ash fusion tests showed that the ash from pure wood waste started to melt at about 1068 °C and was totally fused at 1180 °C. The ash melting process took place over a short time interval, with totally melted glassy residue left on the sample holder surface after the tests. This observed poor ash fusion property indicates a high slagging tendency of wood waste pellets. For the ash produced from wood waste pellets with additives blended, the initial ash deformation temperatures were enhanced by 60−110 °C. The notable increase of ash flow temperatures implies the abundance of the high temperature melting substances due to the addition of additives, which did not melt until a high enough temperature.

For all five combustion tests, continuous measurements of combustion temperature and flue gas were performed. The recorded maximum temperatures in the region where slag was formed were about 1060 to 1090 °C during the combustion of pure wood waste pellets. Because the thermocouples were in the vicinity of the grate, the real temperatures in the fuel/ash bed were estimated to be about 100 °C higher than the measured values.[23,25] This temperature was high enough to cause intensive wood waste pellets ash melting based on the ash fusion test results. The measured temperatures did not vary a lot during the combustion of additive blended pellets. The detected maximum and minimum combustion temperatures were 1100 and 1030 °C, which were recorded during the combustion of wood waste pellets with 4 wt % sewage sludge and 4 wt % marble sludge addition, respectively. Considering ash fusion tests listed in Table 2, changes of temperatures in the fuel/ash bed due to addition of the additive may not have distinct effects on slag formation. The emission levels of CO were reduced from 30 to 10 and 14 ppm during the combustion of wood waste pellets with 4 and 8 wt % sewage sludge addition, respectively. The gas emissions from experiments with marble sludge were stable, except for a slight decrease of NO.

As Figure 1 illustrates, the slag formation of wood waste pellets with/without additives blended are expressed as the fraction of ingoing fuel ash that formed as the slag. Severe slagging was observed from the wood waste pellets combustion, which was consistent with the ash fusion test results. A large amount (34 wt %) of the ingoing fuel ash formed as slag with high sintering degrees (labeled 3 and 4). It can be seen in Figure 2 that the slag consists of totally melted ash with a dense structure, which is a block large in size and extremely hard to break. Marble sludge addition led to an evident reduction of the amount of formed slags. Only about 1.5 and 2.5 wt % of ingoing ash formed as slag on the grate, when wood waste pellets combusted with 4 and 8 wt % marble sludge addition. The sintering degree of formed slags was low (sintering degree 1) and no ash melts were found by visual observation (Figure 2). The slag samples were fragile and easily pressed into powder using fingers. The 4 wt % sewage sludge addition had a minor effect on the slag formation with 26 wt % of the ingoing fuel ash being formed as slag. An even larger amount of slag, 38 wt % of the ingoing ash, was formed during the experiment with addition of 8 wt % of sewage sludge. However, upon the sewage sludge addition, sintering degrees of produced slag were relatively low (sintering degrees 2−4). A large fraction of slag particles with breakable structures was formed, therefore considerably improving the boiler operation. A representative slag sample is shown in Figure 2. Instead of containing completed ash, the slag was formed due to sintering of ash particles with less ash melt observed. The color of the slag changed from dark black to brown−yellow after sludge addition, which represented a change of chemical composition in the slag.

3.2. Chemical Composition of Formed Slag and Bottom Ash. The elemental compositions of the slag and bottom ash are shown in Figures 3 and 4. The dominating elements in the slag from the combustion of pure wood waste pellets are silicon, calcium, potassium, and sodium, thus plausibly consisting of different silicates. With the addition of sewage sludge, the aluminum and phosphorus contents in the slag were greatly enhanced.

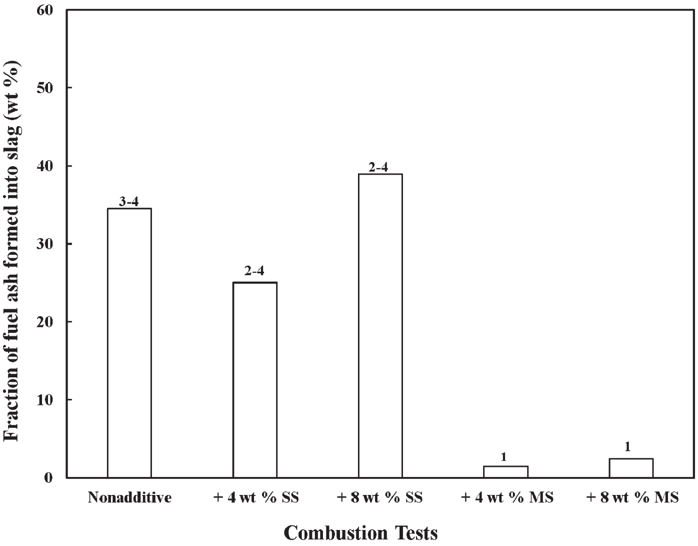

Figure 1. Fraction of fuel ash that formed slag during the combustion of wood waste pellets with and without the addition of additives. SS: Sewage sludge; MS: marble sludge.

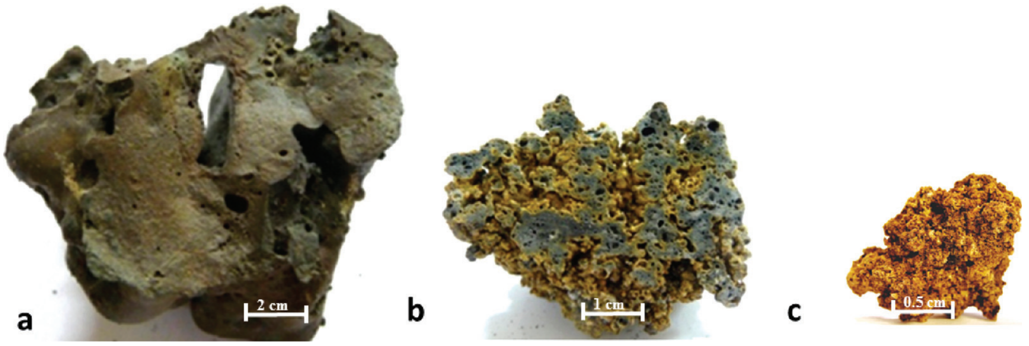

Figure 2. Slag samples collected from combustion of (a) wood waste pellets, (2) +4 wt % sewage sludge, (3) +4 wt % marble sludge.

When marble sludge was used as additive, significantly high calcium concentrations were determined from the collected slags. For the ash residues from combustion of wood waste pellets, titanium may originate from the paint on the furniture waste surface, which remained in the ash residues. The notable chlorine content shown in Figure 3 is due to the presence and decomposition of plastic components or glues in the wood wastes. The enrichment of aluminum/phosphorus and calcium in the bottom ash is caused by the addition of sewage sludge and marble sludge, respectively. Further, by comparing the chemical compositions of slag and the corresponding bottom ash (Figures 3 and 4), it can be seen that the distribution of the main ash forming elements did not vary significantly, except for a high chlorine content detected from the bottom ash from wood waste pellet combustion.

The crystalline phases in the collected samples (slag and bottom ash) were further identified by XRD. The crystalline phases observed in the slag and corresponding bottom ash are listed in Table 3. It should be noted that slag and bottom ash samples are mixtures of materials in crystalline and amorphous phases, and the latter one cannot be observed by XRD directly. The ratios between the crystalline and amorphous phases strongly depend on the fuel ash composition, the thermal conversion temperatures and conditions.[7,10] The mineral phases identified in slag samples from wood waste pellet combustion are akermanite, perovskite, and kalsilite, and only the last one contains potassium. Compared with the high K and Na contents detected in the slag by XRF (Table 1 and Figure 3), only a small amount K or Na bearing mineral phases were identified by XRD. The evident deficiency of K and Na in the slag may be attributed to the formation of low melting point alkali silicates, which existed as amorphous phases in the slag and were not observed by the XRD. In the bottom ash, a small amount of sylvite (KCl) was identified as shown in Table 3. Considering high alkali and chlorine content in the wood wastes ash (Table 1), sylvite is readily formed during fuel decomposition and may melt to initial ash sintering at a low temperature range. However, the crystalline

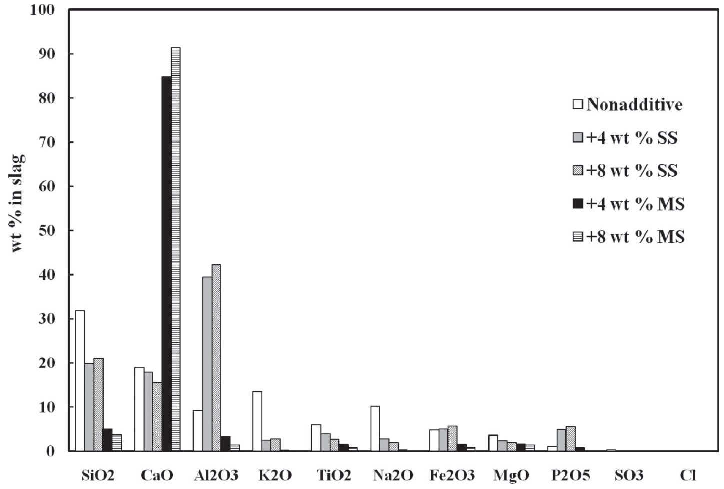

Figure 3. Elemental compositions (given as oxides) of the formed slag samples obtained from XRF analysis.

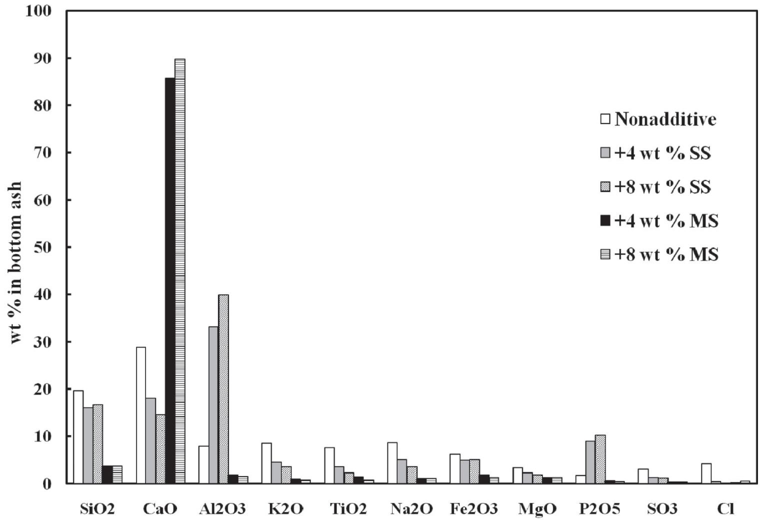

Figure 4. Elemental compositions (given as oxides) of the formed bottom ash samples obtained from XRF analysis.

sylvite may break down at as low as 800 °C.[26] Potassium could either vaporize during breakdown of sylvite or accommodate in the amorphous silicates melt, especially for Si-rich fuel.[26] This may explain no detection of crystalline sylvite in the slag. However, during shutdown and cooling of the experiment, the sylvite (KCl) may also be crystallized from the flue gas, which condenses on the bottom ash particles and was observed by XRD.[9] The identification of mineral phase plagioclase and microcline in the bottom ash implies reactions between alkali metals and Si in the fuel during combustion. In addition, contamination of sand minerals to wood wastes during transport and storage may also contribute to the observation of these two mineral phases. It has been reported that plagioclase and microcline are not thermodynamically stable at high temperatures.[10] They may react with already melted ash with formation of more Si-rich low melting point glassy phases, which enhance ash slagging in biofuel pellets combustion appliances.[10,11]

Upon adding sewage sludge, more aluminum-containing mineral phases were observed from bottom ash and slag by XRD, which is in accordance with the high aluminum concentrations illustrated in Figures 3 and 4. Corundum (Al_2O_3) was a dominating mineral phase identified from both the bottom ash and slag, which originated from sewage sludge due to decomposition of $Al_2(SO_4)_3$ during combustion. A large amount of Ca-based silicates were observed in the slag accompanied by significant reduction of akermanite ($Ca_2MgSi_2O_7$) and perovskite

Table 3. Crystalline Phases Identified in Bottom Ash and Slag by XRD Analysis (wt %)

	nonadditives		sewage sludge				marble sludge			
			+ 4 wt %		+ 8 wt %		+ 4 wt %		+ 8 wt %	
crystalline phase	slag	bottom ash	slag	bottom ash	slag	bottom ash	slag	bottom ash	slag	bottom ash
$Ca_2MgSi_2O_7$ (akermanite)	49	17	3	8	3	5	5		2	
$CaTiO_3$ (perovskite)	45	50	3	9		2	3	3	1	2
$KAlSiO_4$ (kalsilite)	6		12		14					
$KAlSi_3O_8$ (micocline)		8		12		13				
CaO (lime)							46	54	56	60
$CaSiO_3$ (wollastonite)			5		7		5	3	2	1
$CaAl_2Si_2O_8$ (anorthite)			30		34					
Al_2O_3 (corundum)			22	25	25	28				
SiO_2 (quartz)			8	10	13	15				
$Ca(OH)_2$ (portlandite)			3				12	15	7	9
Mg_2SiO_4 (ringwoodite)			9		2					
$MgAl_2O_4$ (spinel)			5		2					
$MgCO_3$ (magnesite)		2					5	2	7	2
Ca_2SiO_4 (larnite)		2		5		7	9	5	6	2
$Ca_2Al_2SiO_7$ (gehlenite)				8		10				
KCl (sylvite)		8								
$NaAlSi_3O_8$ (plagioclase)		7		9		11				
MgO (periclase)		6		3			2		3	1
$CaCO_3$ (calcite)				8		4	9	13	10	16
$CaMg(CO_3)_2$ (dolomite)				3		5	3	5	6	7
sum	100	100	100	100	100	100	100	100	100	100

Table 4. EDX Spot Analysis on Slag Samples[a]

spot	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	P_2O_5	Fe_2O_3	MgO	TiO_2
slag from nonadditive wood waste pellets combustion									
1	[b]	0.31	[b]	[b]	56.37	[b]	[b]	[b]	43.32
2	33.63	11.42	28.27	19.23	2.35	2.34	0.48	2.01	0.27
3	33.91	16.82	18.99	18.12	4.22	2.61	0.42	1.34	3.57
slag from wood waste pellets combustion with 4 wt % sewage sludge addition									
1	0.55	87.95	0.73	0.81	1.42	7.37	0.61	0.50	0.06
2	29.88	34.82	6.34	14.54	5.17	3.42	1.51	3.81	*0.51*
3	33.36	31.84	4.60	12.96	3.47	9.64	0.70	2.73	0.70
4	31.56	8.96	17.43	2.26	30.13	3.18	1.47	4.90	*0.11*
slag from wood waste pellets combustion with 8 wt % sewage sludge addition									
1	96.02	0.01	1.50	2.14	0.01	0.23	0.01	0.02	*0.06*
2	28.56	22.01	15.67	10.24	6.71	10.71	3.25	1.86	0.09
3	0.43	87.68	0.54	1.05	1.59	6.94	0.78	0.87	0.12
slag from wood waste pellets combustion with 4 wt % marble sludge addition									
1	[b]	[b]	0.49	0.05	96.11	1.57	[b]	1.73	0.05
2	33.20	18.21	15.7	11.81	7.36	4.59	0.04	6.64	2.79
3	31.31	15.21	17.23	15.23	9.56	3.34	0.02	6.31	1.79
slag from wood waste pellet combustion with 8 wt % marble sludge addition									
1	26.01	17.43	12.12	7.78	25.74	3.28	[b]	7.62	*0.02*
2	0.02	0.05	1.25	0.89	95.98	1.65	[b]	0.26	[b]
3	2.33	1.93	5.16	4.43	80.23	1.44	[b]	4.48	[b]

[a] The spots were chosen from the same area as the EDX mappings shown in Figures 4−8. [b] Below detection limit.

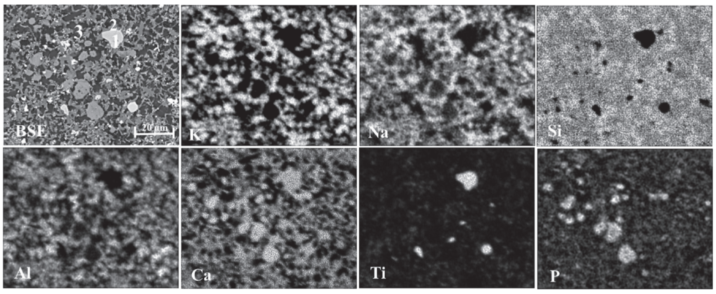

Figure 5. Backscattered electron (BSE) image and elements mapping of slag sample formed during the combustion of wood waste pellets.

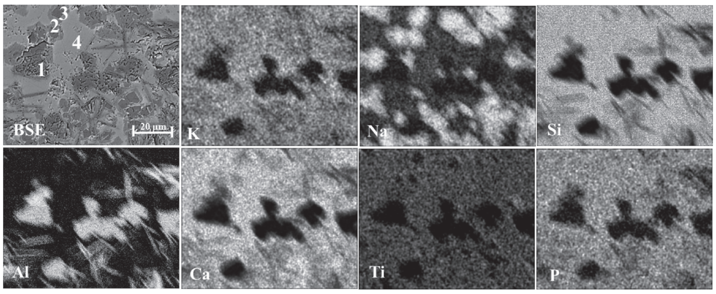

Figure 6. Backscattered electron (BSE) image and elements mapping of slag sample formed during the combustion of wood waste pellets with 4 wt % sewage sludge addition.

($CaTiO_3$). In addition, the kalsilite content was increased considerably in the slag, which indicates reactions between aluminum silicates (e.g., zeolites) from the sewage sludge and potassium from the wood waste fuel. With aluminum silicates as the main composition, zeolites have been suggested to be a main component in sewage sludge to react with problematic alkali-containing species from biomass fuels, which abate alkali-related depositions and agglomeration in combustion experiments.[13,14,16,19,21] Thus, sewage sludge addition to wood waste pellets changed the compositions of slag from the mainly low melting points alkali silicates to be dominated by the alkali aluminum silicates, Ca based silicates, and aluminum oxide. All the newly formed mineral phases have high melting points and thus give a lower melt fraction in the slag.[22,27,28] This agrees with the present combustion experience where slag with relatively lower sintering degrees and less glassy phases were formed during the combustion of wood waste pellets with the sewage sludge addition (Figure 2). However, more quartz was identified in bottom ash and slag, which is related to enhancement of the reactive silica level in the fuel ash due to the sewage sludge addition. Furthermore, the ingoing fuel ash contents increased from 0.72 ± 0.04 to 1.61 ± 0.03 and 3.87 ± 0.05 wt % as a result of blending 4 and 8 wt % sewage sludge to the wood waste pellets, respectively. It has been proved that the amounts of formed slag during biomass pellets combustion correlate well with total ash and the Si contents in the fuel. Accordingly, despite reduction of slag sintering degrees, the addition of 4 wt % sewage sludge only resulted in a minor decrease in the amount of formed slag. A higher sewage sludge (8 wt %) addition ratio gave rise to fraction of ingoing ash formed as slag on the grate, see Figure 1.

When adding marble sludge to wood waste pellets, more wollastonite and larnite were formed with evident reductions of akermanite and elimination of kalsilite in the slag. All mineral changes mentioned above indicate that the added marble sludge provides calcium to react with silica in the fuel. Thus the marble sludge addition resulted in formation of high melting temperature calcium silicates and may reduce available silica reactive to form low melting point alkali silicates. This process was accompanied by a considerable reduction of the melted fraction in the slag.[23] It was noted that with the marble sludge addition, mineral compositions of bottom ash and slag were dominated by lime (CaO), calcite ($CaCO_3$), and portlandite ($Ca(OH)_2$).[24,29] All these calcium-containing phases have high melting temperatures and did not contribute to slag formation during combustion. Dominating of these calcium phases in both slag and bottom ash indicates a surplus of the marble sludge that did not react. Therefore, a dilution effect from marble sludge on the wood waste ash should be taken into account in terms of slag formation.

3.3. SEM−EDX Analysis. The collected slag samples were prepared and examined by SEM−EDX analyses. Figures 5−9 illustrate representative SEM images of the cross-sectioned slag samples, and the elemental mapping of each scanned area. The chemical compositions of assigned spots are measured and listed in Table 4. In Figure 5 (spot 1), a strong correlation between calcium and titanium is vividly presented as several white zones in the Ca and Ti element maps, which was confirmed by the high Ca and Ti concentrations detected in the same area. These Ca- and Ti-rich zones represent the formation of perovskite ($CaTiO_3$) in the slag that was identified by XRD. The Ca- and Ti-rich perovskite phase is covered by interstitial areas that are dark

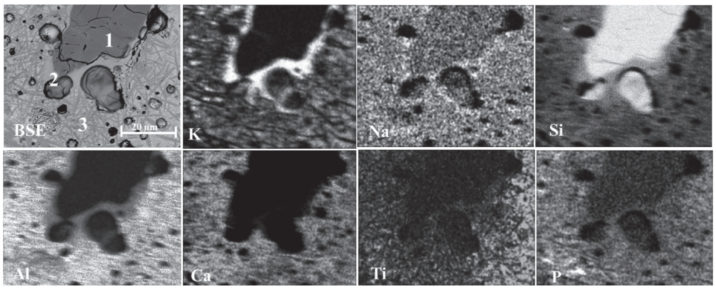

Figure 7. Backscattered electron (BSE) image and elements mapping of slag sample formed during the combustion of wood waste pellets with 8 wt % sewage sludge addition.

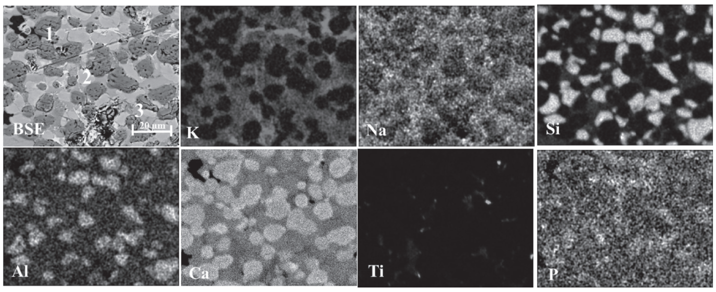

Figure 8. Backscattered electron (BSE) image and elements mapping of slag sample formed during the combustion of wood waste pellets with 4 wt % marble sludge addition.

and gray in the BSE image. High concentrations (spots 2 and 3) and clear correlations of K, Na, and Si in these areas imply the formation of different alkali silicates. During combustion, these low temperature melting silicates fused into a continuous and homogeneous phase to trap fuel/ash residues and inert materials (i.e., perovskite). After long-term combustion, these sintered materials may accumulate and grow into large size dense aggregates, which therefore become slag on the burner/boiler grate.[4,5]

Figure 6 illustrates that sewage sludge addition resulted in a slag sample with a more heterogeneous morphology and elements distribution. Grains with a rough surface in irregular and needle shapes can be seen in the BSE image, which are shown as bright zones in Al elemental map. Al is the dominating element (spot 1) detected from these grains with the presence of a small amount of other elements. This indicates that these grains should be the corundum identified by XRD, which was not fused or "dissolved" in the ash melts. Corundum grains illustrated in Figure 6 could explain the detected high melting points of ashes produced from sewage sludge blended wood waste pellets (Table 2). The inert corundum grains may support the skeleton and slow down shape change of the tested ash specimens under heating.[30] Due to gradual changes of the external shape, the ash specimens were characterized by higher melting temperatures according to the standard ash fusion characterization method. The smaller rhombic dark areas shown in Figure 6 are rich in Na, K, Al, and Si (spot 3), which are covered by one thin gray layer with the same elemental compositions but a higher Al concentration (spot 2). This indicates the reaction of alkali metals in the fuel with aluminum silicates from sewage sludge. The rest of the light gray areas in the BSE image represent melted ash that glues the corundum and alkali aluminum silicates grains together. The EDX mapping and spot analyses revealed that elements Si, K, and Ca are abundant in these areas with small amounts of Al, Na, P, and Fe. Thus the melted fractions of the slag plausibly comprised mainly potassium calcium silicates.[31] This assumption was in agreement with the XRD analysis results, in which no crystalline phases containing K−Ca−Si system were identified. Figure 7 shows the SEM−EDX analysis results for a slag sample from the wood pellet combustion with 8 wt % sewage sludge addition. A sand/soil particle with silicon as the main element embedded into the melted ash, which is clearly revealed by EDX mapping and spot analysis (spot 1). This particle is covered by a layer with a continuous and compact phase, in which high K and Na contents (spot 2) were detected with small amounts of aluminum and calcium in the same spot. This indicates that the sand particle has reacted with alkali metals or was partly dissolved in the melted ash. This finding is consistent with the XRD analysis results that more quartz was identified in the slag upon sewage sludge addition. However, the silica from sewage sludge was not thermally stable but reactive to form a more silicon-rich melt, which contributed to more slag formation.[10] In addition, a large amount of needle shaped grains were observed by SEM−EDX analysis with aluminum as dominating element (spot 3).

Figures 8 and 9 present the SEM−EDX mapping and spot analyses of the slag samples from the combustion of wood waste pellets with marble sludge addition. In Figure 8, two areas can be distinguished in the BSE image which have different gray scale intensities and represent differences of chemical compositions in each area. The first zone has darker gray color discretely distributed with a rough surface, where calcium is the dominating element revealed by EDX spot analysis (spot 1). The second

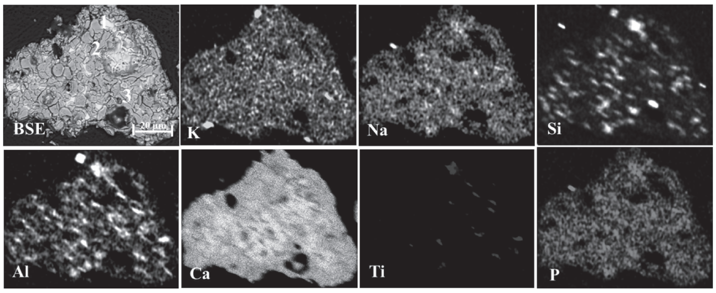

Figure 9. Backscattered electron (BSE) image and elements mapping of slag sample formed during the combustion of wood waste pellets with 8 wt % marble sludge addition.

zone is light gray and has a continuous smooth surface. In this zone the silicon and aluminum are abundant (spots 2 and 3), which have strong correlations with K and Na shown in the elemental maps. Therefore, the light gray zone plausibly represents the formation of low melting temperature alkali silicates as melted ash, which was "invisible" for the XRD.[7,10,11] However, the relatively high amount of calcium and magnesium were detected in the same areas (spots 2 and 3). This indicates that these two alkali earth metals are dissolved into the melt, which may enhance the release of alkali from the melt and reduce the melt fraction in slag.[26,32] In addition, as a result of adding marble sludge, a proportional increase of the amount of ingoing ash has to be considered. Due to dilution effects from a surplus of marble sludge (calcite), the slag physical formation process was different from that of pure wood waste pellet combustion. As shown in Figure 8, the melted ash was embedded with a large amount of calcium-rich grains from the calcined marble sludge. Consequently the ash melt did not accumulate into large blocks with a homogeneous structure, which only acted as glue to bond the calcite grains together. The calcium-rich aggregates with brittle structures were easily broken into small pieces when the fuel/ash bed on the grate was moved by the ash pusher. This process was accompanied by a distinct reduction of both amounts and particle sizes of the formed slag. The dilution effect from marble sludge to slag is evident upon the combustion of wood waste pellets with 8 wt % marble sludge addition. The slag sample shows more discontinuous morphology with calcium being the dominating element, as revealed by SEM/EDX analyses (Figure 9 and spots 2 and 3). Only a small amount of melted ash can be observed by the element maps, which appear as several bright spots and are confirmed by EDX spot analysis (spot 1).

4. CONCLUSIONS

A severe slagging tendency was observed during combustion of problematic wood waste pellets in this study. About 34 wt % of the ingoing fuel ash formed as slag with dense structures and large sizes. This high slagging tendency can be explained by the formation and melting of alkali-rich silicates during combustion, which appeared as amorphous phase and could not be identified by XRD directly. The results of XRF and SEM−EDX analyses supported the assumption with detection of high amounts of Si, Na, and K and a strong correlation between them in the formed slag.

Compared to pure wood waste pellets combustion, the addition of 4 wt % sewage sludge had a minor decreasing effect on the slagging tendency. Instead of formation of large blocks consisting of completely melted ash during wood waste pellets combustion, slag particles with breakable structures and smaller sizes were formed due to sewage sludge addition. The mineral compositions of the formed slag were dominated by corundum, Ca-based silicates, and alkali aluminum silicates. All these phases have high melting temperatures, which contributed to reduction of the ash melt fraction in the slag and slag sintering degrees. However, as a result of the addition of sewage sludge, both the ash content and the Si level in the fuel pellets were enhanced, which resulted in a slightly increase of formed slag amount for combustion of the 8 wt % sewage sludge blended wood waste pellets.

By adding the marble sludge, the severe slagging tendency during wood waste pellets combustion was reduced distinctively. Less than 3 wt % of the ingoing fuel ash was formed as small and fragile slag particles. Following marble sludge addition the observed low slagging tendency can probably be attributed to (i) change of the composition of formed slag from relatively low melting point silicates to high melting point calcium silicates and oxides; (ii) the dissolving Ca and Mg from the marble sludge in the ash melt enhanced the alkali release from the melt and reduced the amount of formed melt. In addition, due to a surplus of marble sludge, the strong dilution and restraining effects from the marble sludge caused changes in the slag physical formation process.

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