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Wood Pellet Use in Sweden

A systems approach to the residential sector

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SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Abstract

This empirically based thesis deals with a biofuel market in a systems context with focus on Sweden. Fuel pellets is a new consumer market for wood products. Initially used mainly by large-scale heating plants, wood pellets expanded into the Swedish residential heating market in the mid 1990s. The overall aim of this work is to provide a deeper understanding of the system for small-scale use of densified wood fuels. The objective was to provide a mapping and logistic analysis of fuel and delivery chains primarily for wood pellets. The description includes both technical as well as economic and organisational aspects. The thesis in particular investigates i) experience from practical densification operations in the past, ii) wood pellet retailers in Sweden, iii) wood pellet consumers in Austria, Sweden and the United States, iv) imports of wood pellets, and v) forecasting of pellet consumption and inventory management for wood pellet distributors.

Previous international studies revealed that the availability of cheap raw materials for fuel production and the price and availability of the most important competing fuels: coal, oil and natural gas were important factors that have guided production and use of densified wood and bark fuels. A major network of wood pellet distributors was mapped. It was concluded from a survey to these retailers that the Swedish residential market was now firmly in place and that the price of wood pellets was competitive with prices of traditional national fuels. A majority of pellet users in Austria, Sweden and the United States were pleased with pellet heating.

One way to improve pellet distribution systems would be to optimise inventory management. An internal model for optimising inventory management, *Pell-Sim*, was constructed. For Sweden, wood pellets in 1997 represented the second most traded biofuel assortment, with 4.35 PJ or 18% of the total biofuel imports. Contrary to trade with other biofuel assortments, wood pellet trade was found to be intercontinental. There is a scope for further international exchange of knowledge about pellets and pellet technology.

Key words: biofuels, distribution, fuel trade, residential fuel market, storage, systems, upgraded fuel, wood fuel, wood pellet, wood processing residues, wood product.

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"Ett friskt öga måste se allt synligt och inte säga: Jag vill endast se grönt."

Marcus Aurelius
(ur Självbetraktelser)

Contents

Appendix

Papers I-V

The present thesis is based on the following papers, which will be referred to by their Roman numerals.

I. Vinterbäck, J. Densification of Wood and Bark for Fuel Production - a Story of 150 Years. Manuscript.
II. Hillring, B. & Vinterbäck, J. 1998. Wood Pellets in the Swedish Residential Market. Forest Products Journal 48(5):67-72.
III. Vinterbäck, J. & Roos, A. Residential Wood Pellet Heating in Austria, Northeastern US and Sweden. Submitted manuscript.
IV. Vinterbäck, J. & Hillring, B. 2000. Development of European Wood-Fuel Trade. Holzforschung & Holzverwertung. (In press.)
V. Vinterbäck, J. *Pell-Sim* - Dynamic Model for Forecasting Storage and Distribution of Wood Pellets to Residential Consumers. Manuscript.

Paper II is published with the kind permission of the Forest Products Society and Paper IV with the kind permission of the Österreichische Gesellschaft für Holzforschung.

Introduction

Background

The global oil crises in the 1970s led to many interesting solutions for replacing heating oil, one being to use wood processing residues which were densified into dry and uniform fuel. The idea of densifying wood processing residues was, however, not new. Densification technology comes originally from the coal, and wood processing industries (briquetting), where it was used as a means of residue compaction, and from the fodder industry (pelletising), where it was used to produce compressed animal feed. Development of densified wood fuels has a historical background closely related to the concentration of by-products from wood processing or to deficits of energy or both (study I).

The great extent of medium and large-scale use of densified wood fuels today in *e.g.* Denmark and Sweden is nevertheless unique in history. The fuel choices for commercial systems are very dependent on the prices of alternative fuels, which in Denmark and Sweden are strictly governed by fuel taxes. It is currently economic to use wood pellets in some of the major large-scale district heating systems in Sweden as well. The fuel choice in small-scale systems, on the other hand, is dependent on a greater number of factors than economy. This circumstance, as well as the international relevance, made it more challenging to examine small-scale systems. The residential or small-scale systems studied were in the power range of up to about 30 kW.

Fuel pellets is an example of a new consumer market for wood products. Wood pellet residential heating has been developing in North America since the early 1980s. In the mid 1990s, residential consumption expanded significantly in Europe, especially in Scandinavia and Central Europe, where Sweden and Austria have been in the forefront. Several other European countries represent new potential markets. Pellet heating is also interesting since it represents a new biomass energy technology targeted for the consumer market. The number and density of wood pellet retailers were critical to the early expansion of the residential market in Sweden, as was the availability of efficient small-scale burning equipment. These retailers were surveyed to analyse the early development of the Swedish residential market (study II).

Internationally, most interest in wood pellet heating is focused on the residential market (*e.g.* Folk & Govett, 1992). The future success of the pellet business will therefore be dependent on preferences, economic considerations and the attitudes of households. Pellets for residential heating are attractive because they are convenient (compared with conventional wood heating), efficient (uniform fuel), easy to transport and store (high energy density, low moisture content and flowable), clean, non-toxic and CO_2-neutral. These factors give wood pellets growth potential in the residential heating markets in many countries. The drawbacks of wood pellets for a residential consumer are uncertainty about the future availability of the fuel and, compared to oil, its bulkiness. In Sweden, where taxes on fossil fuels are high, residential pellet heating has been very economical compared to, *e.g.*, oil (see Table 1 below and paper II). Wood pellets are estimated to cover a substantial part of the future residential market in Sweden[1]. With these arguments in mind, a closer look was taken in study III at the socio-economics of the consumers of wood pellets in three countries where the residential pellet markets were dynamic.

In Sweden, the delivered energy amount of upgraded wood fuels has in relative terms increased faster than the corresponding amount of unprocessed wood fuels (green chips, bark, sawdust etc.) in the last decade[2]. The use of unprocessed fuels has in general three major drawbacks:

(1) Installations are expensive, with respect to both investments and operations.
(2) Furnaces and the surrounding equipment are space demanding.
(3) Fuel degradation during storage (energy loss and health risks).

To promote a major further expansion of wood fuels it is necessary that these are also able to be used in relatively cheap and less space demanding installations with minimal maintenance[3]. This can be achieved by increasing the use of upgraded wood fuels[4]. However, wood pellets are the only fuel in the group for which there are commercially available automatic burning systems for residential use. Wood pellets are small cylindrical pieces, made by densification of fine, dry particles of biomass. Wood pellets have national quality standards in Sweden (SS 18 71 20) and in several other countries (*e.g.* APFI-PF-1-88; DIN 51731; ÖNORM M 7135).

The uniformity, durability, flowability and relatively high energy density of wood pellets relative to unprocessed wood fuels make them suitable for long-range transport and trade, which is dealt with in study IV, as well as for residential storage and local distribution systems, treated in study V. The raw materials that give the lowest ash content for upgraded fuels are stem-wood assortments such as sawdust, planer shavings and dry chips from sawmills and the woodworking industry.

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[1] See, *e.g.*, press communiqué by Boverket (the Swedish National Housing Board), Elda med pellets och spar energi, 21 August 2000, cited in the Swedish daily newspaper Dagens Nyheter, 27 August 2000, p. D2. (In Swedish.)
[2] Svenska Trädbränsleföreningen. 31 May 2000. Sammanställning av produktion och utleveranser av trädbränsle 1999, GWh. Stockholm. *Mimeo.* (In Swedish.)
[3] The EU projects future gross biomass consumption to increase from 1.9 EJ in 1995 to 5.65 EJ in 2010 (COM(97)599).
[4] In Sweden, wood pellets are classified in the group of upgraded biofuels that also includes briquettes and wood powder (SS 18 71 06).

The overall production of wood pellets in Sweden increased continuously throughout the 1990s, from a 1990 total of about 10 000 tonnes[5] to about 540 000 tonnes[6] in 1999. Initially used mainly by commercial heating plants and block centrals, wood pellets successively expanded into the residential heating market (Table 1). Table 1 also shows the price development for residential vs. commercial users of wood pellets. The total number of residential pellet burning appliances installed was estimated at about 8 000 in 1997[7] and between 15 000 and 20 000 in 1999[8]. However, there is still a huge potential for residential conversion to wood pellets (discussed in study II).

Table 1. *Pellet volumes and prices including delivery (and 25% VAT for private consumers) on the Swedish market, 1995-1999*

Year	Residential volume (tonnes)	Residential price (SEK[1]/GJ)	Commercial price[2] (SEK/GJ)
1995	16 300[a]	74[a]	41
1996	25 700[a]	77[a]	44
1997	41 600[b]	84[b]	42
1998	57 000[c]	81[d]	45
1999	78 000[c]	96[e]	46

[a] Study II.
[b] Hillring (1999).
[c] Mared, J. 2000. Chairman of PiR – Pelletsindustrins Riksförbund, Stockholm. Personal communication.
[d] Based on price list from south-Sweden market leader Sydved Energileveranser AB, Kisa.
[e] Based on price list from south-Sweden market leader SÅBI Pellets AB, Vaggeryd.
[1] SEK is equal to 0.12 euro or 0.10 United States dollar (September 2000).
[2] Swedish Energy Authority. Prisblad för biobränslen, torv m.m. no. 3/1999 (value for 1995) and no. 2/2000. Aggregated prices for wood pellets and wood briquettes. (In Swedish.)

Despite the fact that the use of upgraded wood fuels is presently increasing very rapidly, the development of technologies and supporting structures is not taking place in a systematic way. In 1995, when this research commenced, the business actors in most cases were small and divided and did not have sufficient resources at their disposal for innovation and development. Technological and organisational solutions reflected this lack of resources. Shortsighted and cheap solutions dominated. This implied that measures to obtain strategically important goals in many cases never came about. Some of these important goals were to

[5] Jan-Erik Dahlström, Chairman of Pelletsklubben. Personal communication.
[6] Svenska Trädbränsleföreningen. 31 May 2000. Sammanställning av produktion och utleveranser av trädbränsle 1999, GWh. Stockholm. *Mimeo.* (In Swedish.)
[7] Laquist, A. 1998. Biobränsle till småhus. Möt bioenergin! Fact sheet No. 4. Stockholm: SVEBIO. (In Swedish.)
[8] Mared, J. 2000. Chairman of PiR – Pelletindustrins Riksförbund, Stockholm. Personal communication.

build up a broad consumer awareness about the wood pellet alternative, to make residential pellets generally available, and not only to local markets in the vicinity of pellet producers, and to make pellet systems as convenient as their competitor, oil heating.

This situation meant that it was difficult to evaluate the development potential for the various systems of upgraded wood fuels. The present situation is still characterised by suboptimal technological and organisational structures, where system components and partial systems are in separate phases of development from adopted technology, developed mainly for other causes, to prototypes and *ad hoc* solutions. There are still few mature products and complete systems operating within smooth running organisational frameworks.

Aim, objectives and hypothesis

The overall aim of this work is to provide a deeper understanding of the system for small-scale use of upgraded wood fuels. The objective was to provide a mapping and logistic analysis of fuel and delivery chains primarily for wood pellets. The description includes both technical as well as economic and organisational aspects. The major hypothesis was that wood pellets have a potential for increased residential use in Sweden. At this point, it should be emphasised that the natural point of departure for this work was to examine and develop a way of making energetic use of, and adding value to residues from, the wood processing industry rather than to solve a societal problem of energy deficit.

The systems approach

Systems analysis is a methodology for the description, analysis and planning of complex systems (Gustafsson et al., 1982). The systems perspective tries to explain the different parts of a system from the characteristics of the whole, not the entire system from the characteristics of its parts. With a systems approach it is possible to gain an idea of the general logic in a complex and aggregated subject field, to determine what is possible and reasonable and where the bottlenecks are in the development towards better system efficiency (Bertalanffy, 1968).

The systems approach characterizes the nature of a system in such a way that decision making can take place in a logical and coherent fashion and that the fallacies of narrowminded thinking can be avoided (Churchman, 1968). Moreover, scientific knowledge is used to be able to develop measures that give as adequate information as possible about the performance of the system (*ibid.*).

In general systems theory (Bertalanffy, 1968), a phenomenon is viewed as an open system that interacts with the environment and that comprises interacting subsystems. In this work, residential pellet burning can be viewed as an open system that interacts with the total system for residential heating, which is its immediate environment in society. In another area of system space, residential pellet burning also interacts with the system for large-scale energy use. Besides consumers, the following vital system components or interacting subsystems have their role in residential use of wood pellets (Fig. 1): distributors, retailers, dealers/importers and producers of wood pellets. The roles of the different actors are sometimes integrated, *e.g.* dealers and distributors or producers/importers. Other important components are producers, retailers and installation engineers of pellet appliances, chimney sweeps, environmental regulations, subsidising institutions, standards institutes and insurance companies.

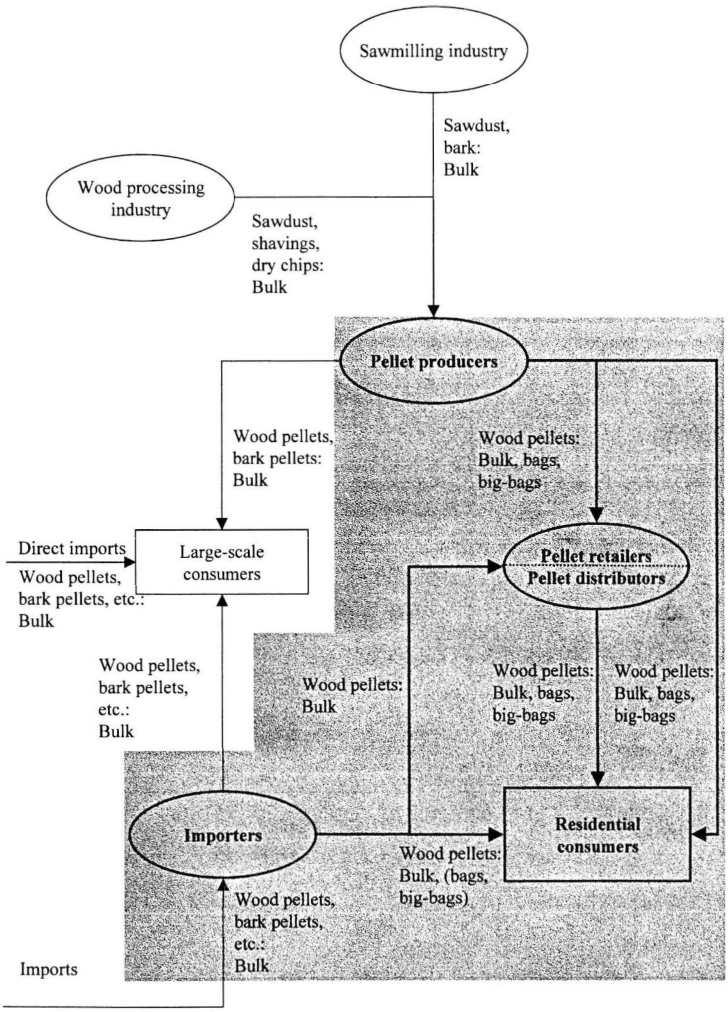

Fig. 1. The system of residential pellet flow (highlighted) in Sweden with surrounding system components, pellet types and transportation modes.

An applied systems study includes a series of steps with iterative feedback mechanisms (*e.g.* Gustafsson et al., 1982). Steps included are problem awareness, problem formulation, modelling, validation, problem solving, result evaluation, result presentation and, possibly, implementation. Study V was designed as an applied systems analysis project of its own. In study V, results gained in studies I-IV are used as input for problem awareness, problem formulation, modelling and validation.

Densification of wood and bark for fuel production

Experience from practical operations in the past (study I)

General interest in the densification of biomass has fluctuated several times since this type of fuel was first produced about 150 years ago. Study I is a literature survey done to consolidate knowledge gained in earlier experience from industrial-scale densification of wood and bark for fuel production and to identify possible critical factors for the success or failure of previous operations, targeted at both small-scale and large-scale markets. Dynamic periods of densified wood and bark fuel market development were 1930-1950 in the United States, 1945-1970 in East Asia and 1975 to the present in the United States and Europe. Important factors that have guided the large-scale production and use of these fuels were the availability of cheap raw materials for fuel production and the price and availability of the most important competing fuels: coal, oil and natural gas. The major technological breakthroughs in densification equipment were the "Pres-to-Log" and "Shimada" type extruders and the "Glomera" piston press. The "Woodex" process for pelletising of biomass initiated a development that led to the large-scale wood and bark pelletising operations of today.

Characteristics of different wood pellet market actors

Wood pellet retailers (study II)

The production of wood pellets in Sweden increased steadily throughout the 1990s to about 500 000 tonnes in 1996. Previously used mainly by large-scale heating plants, wood pellets rapidly expanded into the residential heating market. Residential heating with pellets has traditionally been considered to be impeded by high distribution costs, poor pellet quality and limited availability of efficient and reliable burning appliances.

The aim of this study was to analyse consumption patterns for wood pellets in the residential market. Data on the extent of the market, the market structure and the price level of wood pellets were assembled and analysed. The information retrieval tools were a questionnaire survey sent to pellet retailers, primarily concerning the 1995/96 heating season, and study visits, interviews and open printed sources. We asked questions about values for the heating season of 1995/96. The analyses are based on applied systems science in the respect that residential pellet burning can be viewed as an open system and the total energy market for residential heating as its immediate environment. Interacting subsystems are, *e.g.*, the pellet-burning appliance market, environmental regulations, pellet producers and energy taxes.

The average retail price for residential wood pellets based on total annual sales was 1 267 SEK[9]/tonne (74 SEK/GJ), including delivery. The average delivery cost to consumers was 228 SEK/tonne at the transportation distance of 15 km. Some 60 pellet retailers were identified as active during the measurement period. Still, only about 3% of the total pellet production was used directly by residential customers in 1995/96. The residential pellet burning equipment available in Sweden comprised several types of pellet furnaces, stokers for retrofitting of oil or firewood furnaces, pellet stoves and fireplace inserts. Air emissions (CO_2 excluded) from the residential burning of wood pellets were, at maximum power, comparable to those from oil furnaces. The principal conclusions to be drawn from this study were that the residential market for wood pellets was now firmly in place and that the price of wood pellets was competitive with prices of traditional fuels.

Residential consumers of wood pellets (study III)

Residential wood pellet heating is a modern bio-energy technology developed directly for the homeowner market whose future success will depend on preferences, economic considerations and household attitudes. The technology is spreading in many countries. Austria, Sweden and the northeastern part of the United States are areas in which residential use of wood pellets has become established, although the markets are in different stages of development. A problem connected with the marketing of new products for residential pellet burning is that there is not sufficiently good knowledge of the true market for residential pellet use. If this market is better known, it is likely that technology development would be stimulated and that distribution systems and other customer services related to pellet fuel could become better adapted. To improve marketing and focus product development, it is important to know more about consumer socio-economics, opinions and preferences.

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[9] SEK equalled 0.12 euro or 0.15 United States Dollar (December 1996).

This study is based on a comparative questionnaire survey among pellet users in Austria, Sweden and the northeastern part of the United States covering pellet technology, maintenance, operation, customer background, socio-economic characteristics and customer satisfaction. The work was done to gather information about the true pellet user and was aimed at studying differences and similarities between residential pellet markets in different countries. The goal was to reach a platform for discussions about future pellet use.

A majority of the pellet users in the three countries were satisfied with pellet heating. Residential fuel sources used earlier were different: coal in Austria, electricity in the northeastern US and wood in Sweden. Factors for customer satisfaction were similar, however, as were housing and socio-economic data. The most important factors for choosing pellet heating differed as did pellet technology, venting, distribution systems and pellet quantities consumed. Strengths and weaknesses of pellet heating from the consumer's point of view are clearly demonstrated by the results. The principal conclusion in this study was that there is a scope for an international exchange of knowledge about wood pellets and wood pellet technology.

Wood pellet importers (study IV)

Traditionally, wood fuels are used in the geographical region in which they are produced. In more recent years, this pattern has changed in northern Europe through the large-scale use of biofuels for district heating and a vast supply of recycled wood and forestry residues. The trade situation has thus come about as a result of means of control on waste and energy. Sea shipments allow for bulk transports of biofuels over long distances at low cost. The aim of this study was to analyse the mechanisms behind the expanding European trade in biofuels and the increasing Swedish import of these materials. The objectives were to describe how the import of biofuels had developed during the 1990s and to identify traded qualities and the time series for these. Another important issue was to decide whether the increase in demand for biofuel in the Swedish market in the short term had been satisfied by imports. It was important to study this phenomenon because a higher mobility of biofuel resources would, *e.g.*, make them more attractive for large-scale use.

There are none or few official sources for traded volumes of biofuels, and specifically wood fuels, in Europe. Our investigation method was a survey of market actors, importers and heating plants, and used unpublished survey material from UN/ECE[10]. Forty Swedish energy companies were thus successfully interviewed, which was a response frequency of 78%. Nearly all the plants contacted imported biofuels. To understand the trade situation, it was helpful to analyse the supply situation in the export countries and the demand situation in

[10] UN/ECE = United Nations Economic Commission for Europe, Team of Specialists on Recycling, Energy and Market Interactions: Geneva, Switzerland.

the importing countries. In this study, Germany was specifically treated as the exporter and Sweden as the importer. The most important findings were that both the Swedish imports of biofuels and the wood fuel share of the imports had increased continuously during the 1990s and that this trade included many types of wood materials and other substances, not only solid wood waste.

For Sweden, wood pellets in 1997 represented the second most traded biofuel assortment after tall oil, with 4.35 PJ or 18% of the total biofuel imports. Wood pellets had over the years been imported from several countries but also exported from Sweden to, *e.g.*, Austria and Denmark. Contrary to trade with other biofuel assortments, wood pellet trade was found to be intercontinental. Wood pellet producing resources in Europe with significant exporting capacity were located in the Baltic region. Parallel with imports, there was lively regional trade with wood pellets in Sweden and around the Baltic sea, which together constitute a future potential market area of its own.

The large Swedish CHP[11] plant in Hässelby, *e.g.*, was founder and joint owner of a pellet production operation, BioNorr, in Härnösand, Sweden. A large share of the annual production of BioNorr was shipped to Hässelby, a distance of 500 km. On the other hand, another major Swedish CHP plant, Helsingborg Energi, had invested in Canadian wood pellet production as North American pellets could compete with lower prices. In 1999, about 100 000 tonnes of wood pellets were shipped from Canada to Helsingborg. In both cases, wood pellets were transported in loose bulk by sea directly to the CHP plants. Other arrangements were cases in which Swedish producers of wood pellets had invested in foreign pellet production for export purposes or where foreign capital was invested in wood pellet production purely for export to the Swedish market. About one-third of the wood pellets purchased in Sweden in 1998 was imports[12].

Optimisation of inventory levels for wood pellet distribution (study V)

This study examined the system of wood pellet distribution to residential consumers. The distribution cost for a residential pellet consumer typically represents one-third of the per tonne price and, of which the inventory cost can be more than half. Physical distribution can be divided into two main activities, administrative and physical (Persson & Virum, 1998). Important administrative activities in physical distribution are forecasting demand and inventory control. One way to improve distribution systems would be to optimise inventory management for pellet distributors. The aim of this study was to propose improvements in pellet distribution management by using tools from systems analysis. The ultimate goal was to present an optimised storage level curve for the

[11] CHP = Combined Heat and Power.
[12] Mared, J. 1999. Chairman of PiR – Pelletindustrins Riksförbund, Stockholm. Personal communication.

mid-Sweden community of Avesta and to show how this was affected by changed assumptions in price lists from producers and traders, changes in customer base and weather-related variations in energy consumption.

An internal model for optimising inventory management, *Pell-Sim*, was constructed. This was composed of two integrated parts: a simulation unit to forecast residential wood pellet demand and a spreadsheet unit with inventory-related functions. The simulation unit was a dynamic application in the Powersim modelling language and basically regulated by daily outdoor temperatures. The residential customers of a distribution company were divided into two groups, delivery and collecting customers (study III), which were statistically treated separately. An order point system was chosen for reordering. Order quantities were then determined by the common square root or EOQ[13] method. The Powersim results were automatically transferred to the spreadsheet by means of a DDE[14] link. The forecasted pellet demand was then used to calculate optimised levels for safety stock, order point, order quantity and total inventory cost. Fig. 2 shows an example of monthly means of forecasted volumes of pellet orders and the corresponding recommended inventory pattern.

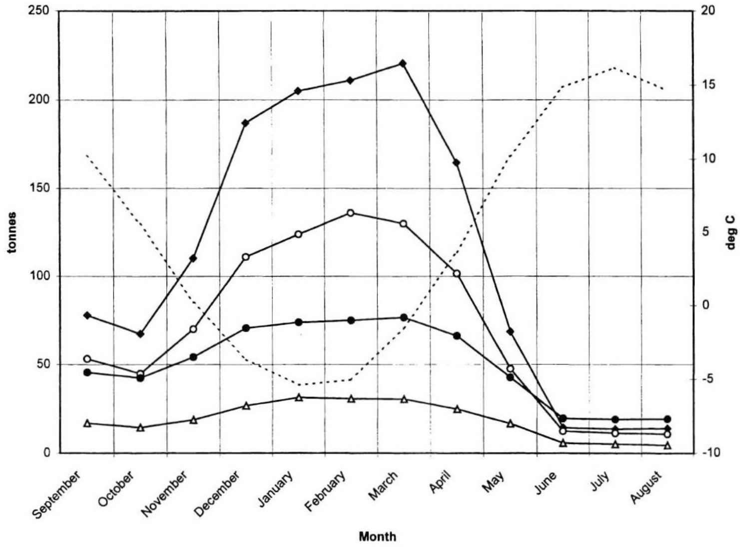

Fig. 2. Forecasted pellet orders and inventory pattern for a test sample of 200 customers (◆ = customer orders, Δ = distributor safety stock, ○ = distributor order point, ● = distributor order size). The temperature curve (- - -) shows monthly mean values for Avesta community, southern Dalecarlia, Sweden[15].

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[13] EOQ = Economic Order Quantity. The formula for EOQ is presented in paper V (formula 1).

[14] DDE = Dynamic Data Exchange, a standard Windows approach to data exchange between applications.

[15] Swedish Meteorological and Hydrological Institute. 1993. Normaltemperatur för varje dygn 1961-1990. Klimatnr: 10607. Station: Avesta. SMHI: Norrköping. *Mimeo.*

When collecting and delivery customer input inventories were normally distributed in the intervals from 0 to 3 500 kg and 6 500 kg, respectively, their annual means of total delivery were both about 7 000 kg/customer, which was the desired and empirical level. The expected pellet customer orders were negatively correlated to mean daily temperatures, lagging behind about one month. Sensitivity analyses showed that monthly results for ordered quantity and total cost were particularly sensitive to ordering and carrying costs. The *Pell-Sim* programme can easily be adapted for distributors in other geographical regions.

Discussion

The objective of this research, which was to provide a mapping and logistic description of fuel and delivery chains primarily for wood pellets, is described in condensed form in the *Pell-Sim* model presented in study V. The sub-system of pellet distribution is analysed on the basis of knowledge of the total system for wood pellets, from raw material to end use. The results reported in studies II-IV indicate that wood pellets has a potential for increased residential use in Sweden: availability of fuel vastly exceeds present demand, distribution networks are developing, small-scale pellet burning technology is improving, present pellet consumers are satisfied and there is an increased use of wood pellets in other parts of Europe. As far as the possibilities of forecasting consumer needs for pellet fuel and total inventory costs are concerned, wood pellet distribution could not be considered a bottleneck in the system for residential use, thus making residential users a large future potential market segment for densified biofuels.

From the viewpoint of the residential consumer, the system for small-scale pellet use has a development potential in the sense that it has the capacity to combine the important aspects of economy, environmental friendliness, convenience and creation of the “atmosphere” traditionally connected with wood-burning. Extended trade with pellet fuel and appliances will exert a downward pressure on the price of both. The interest of residential consumers in wood pellet heating will, however, always be very sensitive to the availability and prices of competing fuels and energy systems. The price relations in the residential market are not static because of the dynamic fuel markets. The emissions from pellet burning are continually being improved, and fully automatic appliance systems will be commercially available in few years, where de-ashing of fly-ash and ash-storage handling are also fully automised. Issues that remain to be solved are the comparatively low energy density of pellet fuel (compared to fossil fuels), which makes it relatively bulky to store, and the fact that fuel quality still needs to be improved with respect to homogeneity, durability and moisture repellency.

An important system component not been covered in this work is Swedish pellet producers. There are, however, numerous international (mainly from the United States) publications that treat production and marketing of wood pellets in detail, *e.g.* Folk & Govett (1992) and Resch (1989, 1990) (see also study I). As concerns pellet distribution, empirical data must still be gathered, *e.g.*, how common it is to have a separate distributor storage, what differences exist in storage costs between producer storage and distributor storage and how often there are problems in supplies from pellet producers.

Conclusions and recommendations

The principal conclusions to be drawn are that the Swedish residential market for wood pellets is now established and that the price of wood pellets is competitive with those of the most important competing fuels. There is a scope for international exchange of knowledge about pellet fuel and pellet technology. Bioenergy trade has increased rapidly in the past ten years, and wood pellets will represent a significant share of this in the coming years. An international standard for fuel pellets would, however, be effective in facilitating trade in fuel and appliances.

Provided that pellet fuel quality is further developed and standardised, pellet fuel will be able to effectively compete with, *e.g.,* fuel oil on a broad scale in the residential market. Wood pellets will, however, be competitive on a level with the availability of cheap raw materials. It is difficult to project whether the wood processing industry will in the future find a more profitable way to use their residuals. As is the case for all other residential heating types, wood pellets do not have the potential to be the sole fuel for residential heating in the future, but will remain one interesting alternative in a mix of several renewable energy sources.

Important areas for future technological research are to determine an optimum fuel pellet shape and to develop cost-effective production methods to make that shape. The new shape and the associated new properties of the fuel will probably increase the bulk and energy densities as well as decrease the moisture sensitivity. The pellet production process needs to be improved in a way that decreases the sensitivity of the fuel quality to variations in raw material properties. This may be obtained, *e.g.*, by treating the raw material in a steam explosion process.

Furthermore, owing to the properties of the fuel, wood pellets are very interesting for use in decentralised CHP production with Stirling engines[16]. With CHP technology connected to the ordinary central heating system, houses can become

[16] A Stirling engine is a type of heat engine that works by means of external combustion.

less dependent on the electricity grid or even become sellers of electricity in the same way as is the case today in small-scale production of wind power. Full-scale prototypes of wood pellet stoves with Stirling engines have already been demonstrated[17]. Integration of CHP technology into residential houses is an area that calls for greater research and development efforts in the coming years.

By choosing an optimal inventory policy, pellet distributors can make considerable savings that in the end will lower the price to the consumer. One promising way to reach a deeper market penetration is where the fuel distributing company stands the full risk of managing individual home pellet heating, *i.e.* a heat service concept. Applying this solution the distributing company will have the best possible control of residential pellet storage levels and thus a good leverage from, *e.g.*, the *Pell-Sim* model in forecasting its own pellet needs and optimising corresponding purchase volumes.

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