Wood Fuel Markets in Northern Europe

Price Formation and Internationalization

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Abstract

High fossil fuel prices and ambitions to reduce greenhouse gas emissions have increased demand for renewable energy and are changing wood fuel market structures. Wood fuels are to a rapidly growing degree used in industrial proportions and traded in commercial markets. Wood fuels are seen as a key component to achieve policy goals related to climate change, especially in the EU. In the six papers that form the basis for this thesis, prices of wood fuels in Northern Europe are analyzed by means of time series analysis to increase understanding about the factors that govern market development. In *Paper I,* it is found that whereas the Austrian and German residential-quality wood pellet markets are integrated, Sweden is a separate market. The conclusion from *Paper II* is that despite a long history of trade in wood fuels between Estonia and Sweden, the two markets cannot be considered integrated. The results from *Paper III* indicate that refined and unrefined wood fuels should be seen as two separate markets, and that forest chips prices follow different trajectories depending on whether they are used in district heating or in forest industries. In *Paper IV*, it is acknowledged that although high and volatile oil prices are an important driver for the growth in demand for wood fuels, no significant spillover from oil price developments into Swedish wood fuel prices could be discerned in the time period 1993-2010. In *Paper V*, the conclusion is that prices of industrial roundwood and unrefined wood fuels followed a common trend in Sweden in the first decade of the 21st century. *Paper VI* shows that there is a significantly higher level of market maturity and internationalization in the Danish wood pellet market compared to the wood chip market in the country. In conclusion, this thesis uncovers some of the mechanisms that affect wood fuel markets, including the differences between unrefined wood fuels – such as wood chips – and the dynamic market for wood pellets. Whereas unrefined wood fuel markets still are mainly national, wood pellet markets are becoming internationalized. As for external impacts on wood fuel prices, the influence of forest products markets seem hitherto have been more important than oil price fluctuations. Wood fuels can be an important part of the future European energy system, but the complexities of the markets must be understood more thoroughly to ensure efficient resource utilization.

Keywords: Bioenergy, wood fuels, market integration, price formation, time series analysis, prices, cointegration

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Dedication

To Kajsa & Malte, the two brightest shining lights in my life!

Changes aren't permanent, but change is.

(Neil Peart)

Klotet är bundet i sin bana, materien är frusen energi.
Den upplyste bunden i Nirvana, men forskaren är fri.

(Kjell Höglund)

Contents

List of included publications

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

I Olsson, O, Hillring B, Vinterbäck J (2011) European Wood Pellet Market Integration – A Study of the Residential Sector. *Biomass and Bioenergy* 35(1), 153-160

II Olsson, O, Hillring B, Vinterbäck J. (2012) Estonian-Swedish Wood Fuel Trade and Market Integration: A Cointegration Approach. *International Journal of Energy Sector Management* 6(1), p. 75-90

III Olsson O & Hillring B (2012b) Price Relationships and Market Integration in the Swedish Wood Fuel market. (accepted for publication in *Biomass & Bioenergy* after revisions)

IV Olsson O & Hillring B (2012c) The Effect of Crude Oil Price Fluctuations on Wood Fuel Prices (manuscript)

V Olsson O & Hillring B (2012d) Price Relationships Between Wood Fuels and Industrial Roundwood (manuscript)

VI Olsson O & Hillring B (2012e)The Danish Wood Fuel Market – Price Developments, Market Efficiency and Internationalization (manuscript)

Papers I-II are reproduced with the permission of the publishers.

Selected other publications

Olsson O. & Hillring B. (2012a),"A Global Bioenergy Market?" in *Comprehensible Renewable Energy*, (forthcoming)

Alakangas E., Junginger H.M, van Dam J., Hinge J., Keränen J. Olsson O, Porsö C., Martikainen A., Rathbauer, J., Sulzbacher L., Vesterinen, P. & Vinterbäck J. (2012) "EUBIONET III – Solutions to Biomass Trade and Market Barriers", Accepted for publication in *Renewable and Sustainable Energy Reviews*

Olsson, O., Hillring B., Hartkamp R., Skog K., Spelter H., Aguilar F., Mabee W., Gaston C., Wahl A. (2010), "Government Policies Increasingly Promote Renewable Energy Sources: Wood Energy Markets in the UNECE Region, 2009-2010", in *UNECE/FAO Forest Products Annual Market Review, 2009-10*, ISBN 978-9211170276

Olsson, O. (2009) *European Bioenergy Markets: Integration and Price Convergence*. Licentiate Thesis, Department of Energy and Technology, SLU Report vol. 012

Hillring B., Olsson O., Gaston C., Mabee W., Skog, K., Spelter, H. , Stern T. , (2008) "Record Fossil-fuel Prices Drive Wood Energy Markets: Wood Energy Markets in the UNECE Region 2007-2008" in *UNECE/FAO Forest Products Annual Market Review 2007-2008* s.95-105, ISBN 978-92-1-16990-4

Holmgren K., Eriksson E., Olsson O., Olsson M., Hillring B., Gode J., Parikka M. & Zetterberg, L. (2007) *Biofuels and Climate Neutrality – System Analysis of Production and Utilization* Elforsk Report nr 07:35

The contribution of Olle Olsson to the papers included in this thesis was as follows:

I Olsson 70%

II Olsson 70%

III Olsson 50%

IV Olsson 70%

V Olsson 60%

VI Olsson 80%

Abbreviations

AEBIOM	European Biomass Association
AR	Autoregressive
CEN	European Committee for Standardization
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DH	District Heating
DKK	Danish Kronor
EG	Engle-Granger
ECM	Error Correction Model *or* Error Correction Mechanism
EUR	Euros
ETS	Emissions Trading System
EU	European Union
JJ	Johansen-Juselius
LNG	Liquified Natural Gas
MWh	Mega Watt Hour
OLS	Ordinary Least Squares
PiR	Swedish Association of Pellet Producers
SEK	Swedish Kronor
US EIA	US Energy Information Administration
US$	US Dollars
VAR	Vector AutoRegression
VECM	Vector Error Correction Mechanism/Model

1 Introduction

The first decade of the 21st century has witnessed a remarkable growth in public awareness about the problems of energy systems based on fossil fuels. After a period of low oil prices that followed on the oil crises of the 1970's high and volatile oil prices have again become a substantial predicament (Yergin, 2008, 2011). Furthermore, public awareness about anthropogenic global warming due to greenhouse gas emissions from combustion of fossil fuels has increased significantly in the recent ten-year period. In the European Union in particular, this has manifested itself in ambitious policy goals for the reduction of greenhouse gases and the promotion of renewable energy. In 2008, the EU established the so-called "20/20/20 in 2020" goals, which stipulates that by 2020, the EU shall reduce its greenhouse gas emissions by 20%, reach a share of 20% renewable energy in the energy mix and increase energy efficiency by 20% (Council of the European Union, 2008).

These two issues –oil price vulnerability and climate change– have led to a rapid growth in demand for renewable energy. This is also the case for wood energy, the topic for this thesis. Markets for wood fuels have expanded significantly in the first decade of the 21st century, both in terms of volumes and geographical extent. For example, the global market for wood pellets has grown from about 1.5 million tonnes in 2000 to approximately 15 million tonnes in 2010. Wood pellets are also becoming a globally traded commodity with large intercontinental trade flows, in particular imports into the EU (Hillring *et al.*, 2007; WoodMarkets.com, 2012).

The rapid growth of wood fuel markets has meant that there are still much uncertainty as to the factors that affect market developments, including price changes. The aim of this thesis is to enhance the understanding of wood fuel markets with particular focus on two issues: firstly, the factors that affect wood fuel price formation and secondly, the degree to which the growing trade in wood fuels has contributed to market integration in the form of interconnection of prices in different countries. The choice to focus on Northern Europe is to a degree based on availability of price data – see section 2.3 for a more detailed discussion on this – but also on the fact that wood fuel market development has a relatively long history here. Denmark, Finland and Sweden have for several decades integrated wood fuels as a key component of energy policy. Concurrently, the Baltic Sea region has evolved into a highly dynamic region in terms of international trade in wood fuels.

1.1 Wood fuels

1.1.1 Biomass, bioenergy and wood fuels: definitions

Bioenergy designates energy derived from *biofuels*, which includes all fuels – solid, liquid or gaseous – consisting of biomass. Wood energy in turn, is derived from wood fuels, which includes all biofuels derived from woody biomass (CEN, 2004).

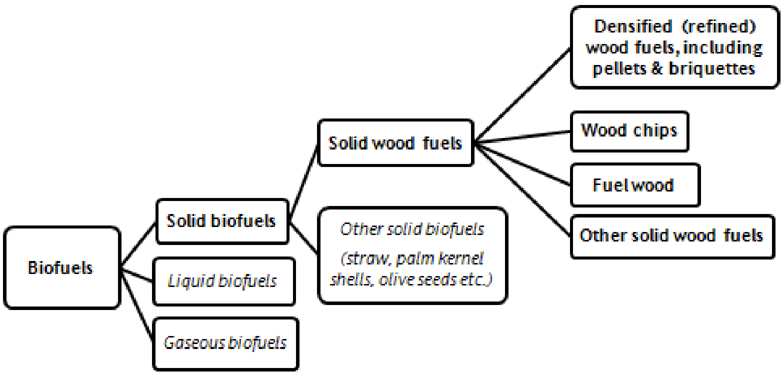

Figure 1. Categorization of solid biofuels and wood fuels

An overview of different biofuels can be seen in Figure 1, which is based on the terminology presented by Alakangas (2010). The focus in this thesis will be on solid wood fuels, which make up the vast majority of solid biofuels, as well as the majority of wood fuels traded in commercial markets. The figure shows some examples of solid wood fuels of which there are several other varieties and subcategories. Perhaps the most important distinction in terms of classification of solid wood fuels in the context of this thesis is between refined and unrefined wood fuels. The latter category includes wood fuels that are converted into energy from a form that is not changed significantly from its forest origin other than through reduction in size (e.g. through chipping or crushing). Refined wood fuels on the other hand have gone through industrial processes to achieve certain specific fuel properties. Wood pellets and wood briquettes are dried and compressed in special production facilities with the specific goal to increase energy density. One very important result of this is that wood pellets contain twice the amount of energy per weight unit compared to wood chips, which has important consequences for logistics and trade.

1.1.2 Wood fuels, greenhouse gases and climate change

The chemical energy bound in wood fuels and other biomass is converted into useful energy – e.g. heat or electricity – by means of combustion. During combustion, the carbon in the wood reacts with oxygen, thereby forming carbon dioxide, CO_2. The momentous amount of CO_2 released during combustion of wood is in the same range as that released during combustion of coal. However, the crucial difference between coal and wood lies in the fact that the CO_2 amount released during combustion of wood equals the amount absorbed by the corresponding tree during its growth (Holmgren *et al.*, 2007).

Furthermore, the CO_2 will eventually be released into the atmosphere nonetheless, as the tree finally dies and decomposes. Hence, provided that the forest in question is managed in a sustainable manner and that trees are continuously replanted, the cycle continues and no extra CO_2 is released into the atmosphere. This is the reason why bioenergy e.g. in the European Union's Emissions Trading System (ETS) is assumed to not be a net contributor to the amount of CO_2 in the atmosphere (Zetterberg, 2011).

However, it is important to acknowledge that this is a simplification of a very complex issue. To begin with, a certain amount of input energy is required in the procurement of all biofuels. For wood fuels, energy is needed for harvesting, forwarding, chipping and transportation to the combustion site. The input energy in all these steps is normally supplied by use of fossil fuels, especially diesel. Typically, the input energy used in production of unrefined wood fuels is less than 5% (Valente, 2011) and for refined wood fuels 15-20%, although the *fossil* energy input in the latter is in the range of 5% or lower (Petersen Raymer, 2006). However, all this depends on the structure of the supply chain. If wood fuels are traded long distances, e.g. between continents, this can entail a significant addition to the amount of fossil energy input, despite the fact that sea transport in general is very energy efficient (Magelli *et al.*, 2009).

Secondly, the time perspective is also of considerable importance. Over a long time horizon, the CO_2 emissions resulting either from combustion or decomposition of a tree will even out. However, combustion for energy purposes means that the emissions occur instantaneously whereas the decomposition process can take many decades. Similarly, it will take many years before a tree that is planted when the old is removed has absorbed the CO_2 released during combustion of the first tree - assuming that no additional afforestation takes place. This means that the CO_2 balance of wood fuels depends on the time frame chosen. In shorter time perspectives, some fossil fuels – especially natural gas – actually has less climate impact than wood fuels made from e.g. stumps. However, in the long run perspective, wood fuels perform superiorly to fossil fuels in this regard (Zetterberg, 2011).

1.2 Wood fuels in the European energy system

Wood is used for energy purposes in a wide range of scales in the European energy system. Traditional firewood and wood pellets are examples of fuel assortments that are used extensively for space heating in residential stoves and boilers. In several countries with developed infrastructure for district heating, wood fuels have also become an important component of the fuel supply for centralized heating plants. A very important sector in terms of the use of wood for energy purposes is forest industry, which utilizes large amounts of by-products for production especially of process heat and electricity. Finally, a large and rapidly growing source of demand for wood fuels – wood pellets in particular – is for large-scale production of electricity. In Belgium, the Netherlands and the United Kingdom, an important component of increasing the share of renewable energy in the energy mix has been to supplement and/or replace coal with wood fuels in large power stations (Sikkema *et al.*, 2011).

In the EU-27 as a whole, wood and wood waste made up about 5% of gross inland energy consumption in 2010. However, the importance of wood energy differs widely between the individual member states. In Finland, Latvia and Sweden, wood has a share of 20% or more of gross inland energy consumption, whereas the share in e.g. the United Kingdom was less than 1% in 2010 (see Figure 2).

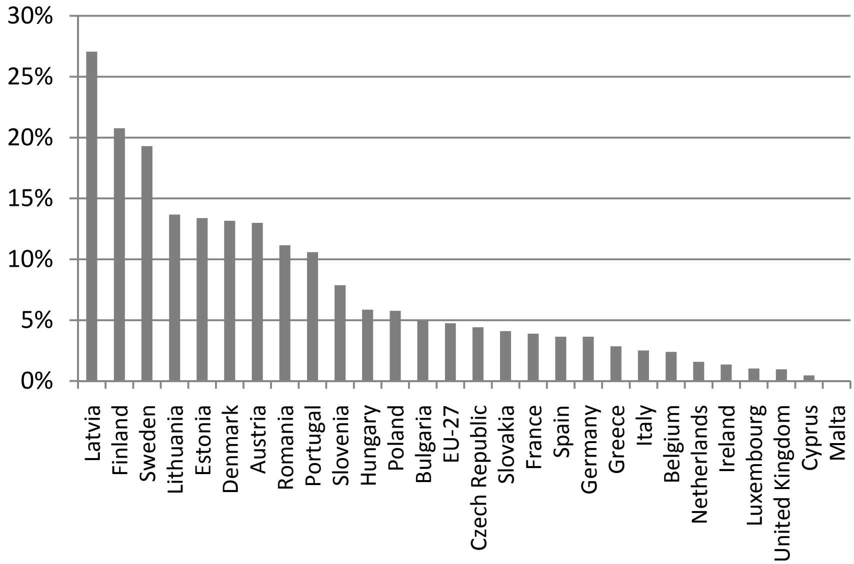

Figure 2. The share of "wood and wood waste" in the gross inland energy consumption of the EU-27 countries in 2010. (Data source: Eurostat (2012b))

However, it is important to note that significant changes can be expected in these shares between 2010 and 2020. As a part of the EU Climate & Energy Package, each member state has a specific target for what its share of renewable energy must be in 2020 for the entire EU to reach the 20% target (Council of the European Union, 2008). The targets for the 27 member states can be seen in Figure 3 along with the level that each country had reached by 2009.

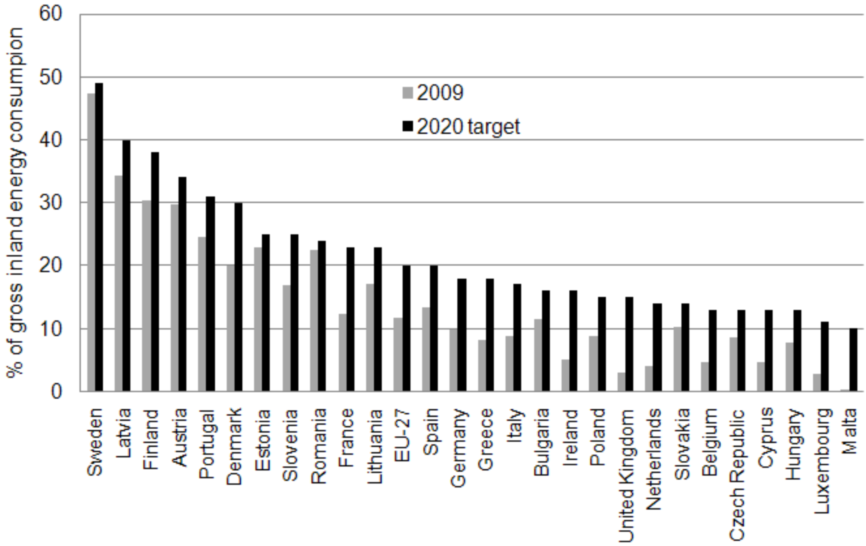

Figure 3. Targets for shares of renewable energy in gross inland energy consumption for the 27 member states of the European Union, along with 2009 levels. (Data source: Eurostat (2011))

As can be seen in Figure 3, there are large differences between the member states in this case as well. This is true both for the levels of the actual 2020 targets and the progress that has to be made in the coming decade in order to reach the targets. The Netherlands has a rather low target, 14% for 2020, but had only reached a level of 4% in 2009. In other words, the country has to more than triple its share by 2020. The United Kingdom is in a similar situation with a 3% share in 2009 and a 2020 target of 15%. Sweden is on the other edge of the spectrum with a target of 49% for 2020 and a level of 47% in 2009. Taken together, this means that there has to be substantial changes to the energy mixes of most EU-27 countries if the 20% goal for the entire union is to be reached.

In total, the supply of renewable energy in the EU-27 must increase by almost 80% if the 2020 targets are to be reached. Bioenergy is expected to make up about 57% of renewable energy in 2020 which actually is a relative decrease from a level of more than 62% in 2010. This still means that the use of bioenergy in the EU-27 must increase by 60% from 2010 to 2020 (AEBIOM, 2011). However, since large increases in the use of wood fuels are planned in countries without substantial domestic forest resources – e.g. the UK and the Netherlands – a substantial increase of international trade in wood fuels can be expected in the coming years.

1.3 International trade in wood fuels

Traditionally, wood fuels have predominantly been a local fuel in the sense that the sites of fuel procurement have been geographically close to the point of final consumption (Olsson & Hillring, 2012a). This is likely to change as a result of growing demand for wood fuels in countries without substantial domestic wood fuel resources. However, large-scale international trade in wood fuels is not a new phenomenon. Beginning in the 1990's, wood chips and pellets from the Baltic States, recovered wood from Mainland Europe and wood pellets from Canada were imported to Sweden for use in district heating plants. Although inexact official trade figures make it difficult to present comprehensive data on the imported volumes, it has been estimated that up to 25% of the bioenergy used in Swedish district heating in the late 1990's and early 2000's came from imported fuels (Hillring & Vinterbäck, 2000; Ericsson & Nilsson, 2004; Olsson, 2006). District heating plants in neighboring Denmark have also been importing wood fuels for quite some time, primarily wood chips and wood pellets from the Baltic States but also wood pellets from Sweden and Germany (EA Energy Analyses, 2010).

From the middle of the 2000's, wood fuel trade has expanded rapidly. In particular, wood pellets have become an increasingly internationally traded commodity. In 2010, global wood pellet production was estimated to be about 15 million tonnes, out of which approximately 6.6 million tonnes, or 44%, were traded between countries (Lamers *et al.*, 2012). This share can be compared to the coal market, where about 17% of the global production is traded internationally (US EIA, 2011). The world wood pellet market has hitherto been very much centered on Europe, and a substantial share of the international trade consists of intra-European trade. This was e.g. the case for the Swedish and Danish imports in the 1990's and early 2000's. However, a large and growing transatlantic trade has also developed. In 2009, when official wood pellet trade statistics first became available, 1.7 million tonnes of wood pellets were imported into the EU-27, an amount that increased to 2.6 million tonnes in 2010. Internal EU-27 trade amounted to 2.3 million tonnes in 2009 and 3.3 million tonnes in 2010 (Eurostat, 2012a).

The rationale for the EU import of wood pellets from North America and elsewhere can be found in the profits that can be realized by combining inexpensive production of wood pellets in e.g. the US with high EU demand, the latter a consequence of the "20/20/20 in 2020" goals. Despite the transport costs, wood pellets produced in North America are very competitive in the EU market, especially in large scale wood pellet consumption in heat and/or power stations, either for use in co-firing with coal or in dedicated wood fuel boilers. As for international trade in residential-market wood pellets, there is a level of intra-European trade in this market segment. However, long distance intercontinental trade has hitherto been a phenomenon almost exclusively limited to the large scale market segment (Sikkema *et al.*, 2011).

1.4 Wood fuel price formation

Several studies have been conducted that analyze the factors that affect wood fuel price formation. Much of the research on wood fuel price formation is focused on the Swedish market and emphasize the impact of three factors in particular: wood fuel production costs, intra-wood fuel competition and fossil fuel prices. Hedman (1992) analyzed price formation for different assortments of wood fuel in the Swedish market and concluded that prices for forest chips were set by costs of production. As for prices for sawmill residues, the author argued that prices were set by the willingness to pay of competing users, e.g. the particle board industry. In terms of the impact of fossil fuels, Hillring (1997) noted that there exists a theoretical basis for a connection between the prices of wood fuels and fossil fuels in that the two fuel categories are possible substitutes in e.g. heat production. However, the author concludes that high Swedish fossil fuel taxes and competition between different wood fuel assortments should keep wood fuel prices competitive to fossil fuels. This study also presented three scenarios for the future development of wood fuel prices:

- Close connection between fossil fuel and wood fuel prices
- Competition between different wood fuel assortments rather than between wood fuels and fossil fuels
- Higher wood fuel prices as a result of increasing production costs

Further developing these ideas, Hillring (1999a) argued that wood fuel prices in Sweden in the 1990's were set by production costs and that there was strong competition between wood fuel suppliers. However, the situation on the demand side was quite different due to the dominance of district heating plants, which to a certain degree had the possibility to act as local monopsonies. Hillring (1999b) argued that Swedish wood fuel market growth in the 1990's was largely driven by the high prices of fossil fuels resulting from heavy taxation. However, the Swedish wood fuel prices themselves seemed to be more dependent on intra-wood fuel competition and production costs than on fossil fuel prices, thereby indicating the gradual establishment of a distinct market for wood fuels. In terms of the impact of fossil fuel prices, Hedenus *et al.* (2010) analyze the connection between oil prices and bioenergy prices, comparing the impact of oil price shocks on ethanol prices and wood pellet prices, respectively. The conclusion was that whereas ethanol prices are closely related to oil prices, wood pellet prices have only occasionally co-moved with oil prices.

1.5 Thesis objectives

The main objectives of this thesis are:

1. Investigate to what degree the ongoing internationalization of wood fuel markets is reflected in price interconnections between countries (Paper I-II, VI)
2. Investigate the interactions between prices of different wood fuel assortments (Paper III & VI)
3. Evaluate the impact of market events in two selected associated markets – the oil market and markets for industrial roundwood – on wood fuel price development (Paper IV-V)

2 Materials and methods

The common thread of this thesis is *prices* and in particular interactions between the developments of prices of goods over time. The primary tools used to reach the objectives presented above are drawn from time series econometrics. The rationale for the use of time series in studies of economic markets can be found in the inherently dynamic constitution of markets. The actual functioning of a market, the responses to changes in supply-demand balances and their reflection in prices, can only be fully comprehended if time is taken into account.

2.1 Time series analysis and cointegration[1]

A time series can be defined as *"…a set of observations x_t, each one being recorded at a specific time t*" (Brockwell & Davis, 2002, p 1). What separates analysis of time series from other statistical data is the emphasis on the actual ordering of data. In particular, when analyzing time series data one must take into account that observations which are located close to each other in time in general tend to be related to each other to a greater degree than those that are further apart. This phenomenon is known as *autocorrelation* and is one of the most important characteristic of time series, as will be shown below.

2.1.1 Time series analysis: early history

The analysis of time series data has a rather short history in the perspective of the history of science at large. Although the time series concept might seem as a rather basic idea, its history largely takes place in the 20th century, with indirect origins in the revolutionary work by Charles Darwin in the middle of the 19th century. Darwin's theories on the process of evolution by natural selection not only sparked an intense debate on the nature of biological and

[1]This section draws partly from Olsson (2011)

human development but also became the starting point of a new field of research: evolutionary biology. This discipline was to be quite unique in that it was dynamic in its very nature and that time itself became a crucial component of the field of science. As a consequence, there was a need for statistical methods that could address analysis of time series data in a comprehensive manner (Klein, 2005). The first decades of the 20th century saw a strong development of methodologies for time series analysis, with a landmark publication by Wold (1938), that laid out the foundations for much of the theoretical framework of time series analysis. Also during this time period, applications of time series analysis became common especially in meteorology and economics. In the latter subject, a particularly popular genre of applications was to use time series techniques in attempts to discern long-term economic cycles (Morgan, 1991). After World War II, theoretical development of time series analysis continued, leading up to the publication of Box & Jenkins (1970), which presented a systematic methodology for time series analysis, especially for forecasting purposes. This made it straight-forward and relatively simple for practitioners to use time series techniques and disseminated its use to a great degree (Tsay, 2000). The interest in time series analysis was further propelled by the increasing awareness of the flaws of the traditional methods that were being used to model national economies and present macroeconomic forecasts. The models used commonly consisted of up to hundreds of equations describing the interconnections between different parts of a country's economy, and were used to forecast future developments and simulate potential outcomes of policy decisions. What became clear in the early 1970's however, was that the relatively simple Box-Jenkins approach to time series analysis tended to outperform the large complex models despite the fact that the former only used historical developments of the variable in question as input (Deistler, 1996).

2.1.2 On stationarity and autoregressive processes

A time series is said to be (weakly) stationary if its statistical properties – e.g. the mean and the variance – are time-invariant, as the simulated series shown in Figure 1.

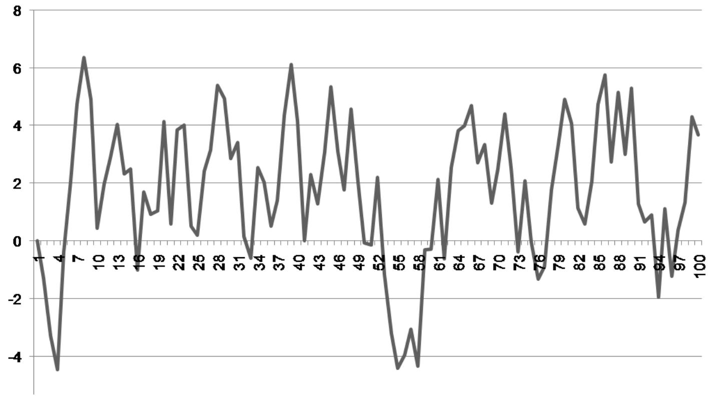

Figure 4. Example of a stationary time series (simulated by the author).

The simulated series in Figure 4 is based on an *autoregressive*, or AR, model as shown in Equation 1.

$$y_t = \varphi y_{t-1} + \varepsilon_t$$

Equation 1. An example of an AR(1) model. ε_t is *white noise*, i.e. a serially uncorrelated process that has a zero mean and a finite variance.

The autoregressive model is a rather simple but still effective and very common way of modelling time series. The model shown in Equation 1 simply says that the value of the variable y_t at a certain point in time, will be a function of the value of y_t in the previous time period plus a well-behaved random variable. A crucial part of the autoregressive model is the parameter φ, for which there are essentially three cases:

- If | φ | <1, the process is stationary and will fluctuate around an average as the simulated series in Figure 1 (where φ = 0.5).
- If | φ | >1, the series will either grow exponentially, if φ > 0, or oscillate with infinitely growing amplitude, if φ < 0.
- The final and perhaps most interesting case is the one where | φ | = 1. In this case the series will meander along the time axis without any clear tendency to return to a long-run average. This so-called *unit root process* is one example of a non-stationary time series. Although there are other forms of non-stationarity, in the following the term "non-stationary" will be used for unit root processes

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As it happens, although traditional time series analysis techniques – such as those presented by Box & Jenkins (1970) – were developed designed for use on stationary series, many real-world time series tend to be non-stationary. This is the case for commodity prices. Prices of traded goods tend to fluctuate up and down randomly over time, without any tendency to return to any well-defined average. Examples of this can be seen in Figure 5 that shows the actual development of Swedish forest chip prices from 1993 to 2010 as well as a simulated unit root representation price series based on identification of the statistical properties of the original price series.

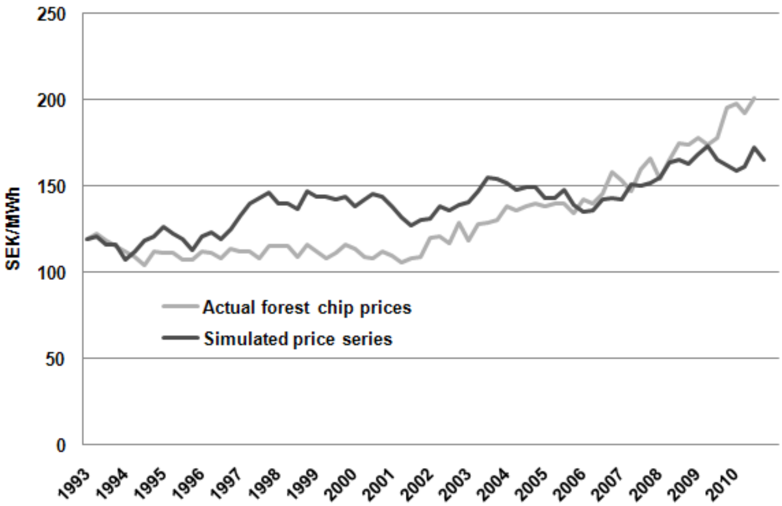

Figure 5. Actual development of nominal forest chip prices in Sweden 1993-2010 and a simulated series based on a variation of a simple autoregressive model.

A non-stationary process can be transformed into a stationary process. This was a common approach to non-stationarity in applied work up until the 1980's, before which there existed no comprehensive methodology for how to analyze unit root processes in their original levels. In order to transform unit root processes into stationarity, the processes are differenced, i.e. instead of studying the process itself, one studies the changes between each step of the process, see Equation 2.

$$\Delta y_t = y_t - y_{t-1}$$

Equation 2. The difference operator.

One way of categorizing time series is according to the number of times they have to be differenced in order to achieve a stationary process. For example, a unit root process as the one described above has to be differenced one time in order to achieve stationarity. In the time series analysis terminology, such a process is said to *be integrated of order 1*, or I(1) for short. Consequently, a process that is stationary to begin with is said to be integrated of order 0, or I(0). The term "integrated" is due to the fact that I(1) processes are made up by integrating, i.e. summing, the data points in a time series variable (see e.g. Johansen, 1997).

2.1.3 Multivariate time series analysis, cointegration and error correction

Time series analysis is in many cases performed by focusing on a single time series and by studying its properties, e.g. for the purpose of forecasting. However, more advanced analysis can be performed by using as input information not only past values of one time series, but also by studying the connection between two series over time. This is an objective that dates back to the early history of time series analysis and the attempts of economist Stanley Jevons to deduce the effect that sunspot activity over time might have on business cycles (Klein, 2005). However, in the early decades of the 20^{th} century, the research community became increasingly aware of the problems of *spurious correlation*. These is the case where two data series seem to have a statistical connection despite there being no real-world basis for such a connection (Keuzenkamp, 2000). Although spurious correlation can be found in other forms of statistical data, Yule (1926) showed that the presence of autocorrelation in time series is the reason why correlation coefficients between time series can be very high without any meaningful causal relation between them. This problem was further emphasized by Granger & Newbold (1974), who conducted simulation studies and showed the potential problems of using regression analysis on real-world time series.

The problems of spurious regressions in economics are related to the tendency of economic time series to be non-stationary. Economic time series often have unit root behaviour. A typical example is the random walk-type patterns characteristic of asset price movements in efficient markets (Malkiel, 2007). Typically, if one attempts to regress two time series that are I(1) on each other, the resulting residuals will also be I(1) and highly autocorrelated. As a consequence, statistical tests on the significance of the estimated parameters will not be valid, and the individual time series will have to be transformed in order to achieve meaningful regression results. This is however not a fully satisfactory solutions since it means restricting the analysis to a short-run perspective (Alexander, 1999). Beginning in the 1970's, a new approach to analysis of time series with unit roots was starting to develop. Sometime after the publication of the important paper by Granger & Newbold (1974), Granger had a discussion with a fellow economist, David Hendry:

> I do not remember where it took place now, but he was saying that he had a case where he had two I (1) variables, but their difference was I(0) and I said that is not possible, speaking as a theorist. He said he thought it was. So I went away to prove I was right, and I managed to prove that *he* was right.
> ((C. Granger as quoted by Phillips, 1997, p 274, with emphasis added.))

This was one of the first stepping stones towards the development of the concept of *cointegration*, which is one of the more important developments in econometrics in the last decades. One indication of this is the fact that Clive Granger and colleague Robert Engle were awarded the 2003 Nobel Memorial Prize in Economic Sciences, partly for their development of cointegration (NobelPrize.org, 2012).

Linear combinations of I(1) series will generally produce I(1) series. However, as can be deduced from Granger's description in the above quote, cointegration refers to the case where there for two (or more) variables that individually are I(1), there exists a linear combination that renders a variable that is I(0). The two series may very well individually fluctuate and drift in seemingly random manners, but the fact that they are cointegrated means that they will not drift apart from each other indefinitely in the long run. This means that the two time series will follow a common stochastic trend (Stock & Watson, 1988).

The actual idea behind cointegration appeared in the 1970's and an early presentation of the concept can be found in the paper by Granger (1981). However, the seminal paper on cointegration was conducted by Engle & Granger (1987). In this work, the authors presented formal means of testing for cointegration and also showed the connection between cointegration and a previously known concept called *error correction mechanism* or ECM. The ECM is a model approach where changes in a time series variable X_t are modeled not only by incorporating historical developments of the variable itself and in some corresponding variable Y_t, but also by including *historical deviations* from a long-run equilibrium relationship between the two variables. In other words, error correction is the mechanism that ties two cointegrated variables together and makes sure that they do not drift apart from each other indefinitely.

2.1.4 Testing for cointegration

A couple of different methods of testing for cointegration have been proposed. The approach first suggested by Engle & Granger (1987) is based on estimating the relationship between the included time series variables by using an Ordinary Least Squares (OLS) regression. The regression residuals are tested for stationarity, and if they are found to be stationary, the variables are cointegrated. The Engle-Granger method is appealing particularly due to its intuitive approach and relative straightforwardness. However, a different approach, pioneered by Johansen (1988) and Johansen & Juselius (1990) has since become more popular in applied work. This is mainly due to three reasons. First, if there is cointegration in the system in question, the Johansen-Juselius method provides very useful possibilities to analyze the relationships between the variables in more detail. Second, Johansen's method is superior when it comes to analysis of systems that contain three or more variables. Finally, the Engle-Granger approach requires the researcher to – in the bivariate case – choose one of the included variables as independent and the other as dependent, a choice which in many cases is far from obvious. Also, the test result may very well differ depending on the choice of setup, which makes it difficult to draw solid conclusions (Enders, 2003).

The Johansen-Juselius (JJ) approach is based on setting up the variables to be analyzed in a *Vector Autoregression* model of lag length *p*, or VAR(p), as is shown in Equation 3. The VAR(p) is a multivariate extension of the AR model previously discussed. Y_t is a $k \times 1$ vector containing the *k* number of variables in the model, A_0 is a matrix of constants, $A_1 \ldots A_p$ are parameter matrices and ε_t an independent and identically distributed (i.i.d.) Gaussian error term.

$$Y_t = A_0 + A_1 Y_{t-1} + A_2 Y_{t-2} + \ldots + A_p Y_{t-p} + \varepsilon_t$$

Equation 3. A Vector Autoregression (VAR) model of order p.

By setting $\Gamma_i = -(1 - A_1 - \ldots - A_i)$ for $(i=1,\ldots,p-1)$ and $\Pi = -(I - A_1 - \ldots - A_p)$, the VAR in Equation 3 can be reformulated as a Vector Error Correction Model (VECM) as seen in Equation 4.

$$\Delta Y_t = A_0 + \Pi Y_{t-1} + \Gamma_1 \Delta Y_{t-1} + \ldots + \Gamma_{p-1} \Delta Y_{t-p+1} + \varepsilon_t$$

Equation 4. A Vector Error Correction Model (VECM) model of order p.

As was discussed earlier, Engle & Granger (1987) showed that there is a one-to-one relationship between error correction mechanisms and cointegration in that the two phenomena imply each other. This means that it is possible to test for cointegration using the error correction model, which is what forms the basis for the Johansen-Juselius test for cointegration. In the test, the rank properties of the Π matrix in Equation 4 are investigated. Here, there are three cases, the results of which provide guidance as to how the system should be modeled:

1. If, for a model with *n* variables, the rank *r* is *n* – i.e. the Π matrix has full rank – the individual variables are stationary and the system can be modeled with the variables in levels by using a VAR model and e.g. testing for *Granger-causality*[2] between the variables (Granger, 1969).
2. If the rank is zero, the individual variables are non-stationary but there is no cointegration. In this case, the appropriate approach is to use the variables in first differences and estimate a VAR model similarly to the description in the case 1(Hamilton, 1994).
3. Finally, if for a model with *n* variables, the rank *r* lies in the interval $0 < r < n$, there is cointegration in the system with *r* designating the number of cointegrating relationships. If the variables are cointegrated, the Π matrix can be factorized as $\Pi=\alpha\beta^T$ in order to investigate the relationships in further detail by testing restrictions. The β matrix describes the long-run cointegration relationship whereas the α matrix contains information about the strength of the relationships. By enforcing restrictions on α, it is possible to discern whether one of the time series are leading the development of the other.

The question of which of these two cointegration tests to use – i.e. Engle-Granger or Johansen-Juselius – has been the topic of some debate. This has especially been the case for their respective performance in small samples such as the ones analyzed in this thesis. Alexander (1994) argues that the Johansen-Juselius method has superior performance whereas Gonzalo & Lee (1998) claim that the J-J method in small samples has a tendency to indicate cointegration where there is none. They recommend that applied researchers use the Engle-Granger test as a complement to the Johansen-Juselius case. In the software package used for the analysis in this thesis – *Gretl 1.9.X* – a sample-size corrected version of the J-J test is available which is used in Paper III-VI. It is not clear whether or not the recommendation to use both tests is still necessary with this version of the J-J test, but for full disclosure, the E-G test is used as a complement in all cases where the Johansen-Juselius test indicates cointegration.

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[2]This term is used to describe the situation where in a system with e.g. two time series variables X_t and Y_t, historical values of X_t can be used to improve forecasts of Y_t relative to if only historical values of Y_t were used. If this is the case, X_r is said to *Granger-cause* Y_t.

2.2 Applications of time series analysis to markets for energy & forest products

In this thesis, time series analysis techniques are applied to wood fuel price series. This is done by studying two main different forms of price relationships:

- Analysis of international market integration by investigation of relations between prices of homogeneous goods in different markets
- Relations between prices of heterogeneous goods

Another form of relationship is the vertical transmission of price changes from e.g. raw material to finished product. Although this issue is not explicitly analyzed in this thesis, it is part of the discussion in Paper V on common trends between wood fuels and industrial roundwood. For this reason, a short review of the literature on this topic is provided in section 2.2.3.

The relatively short history of organized wood fuel markets means that these issues have not been studied to a satisfactory degree. However, the phenomena that are investigated in this thesis have many similarities to issues previously studied in other fuel markets as well as in other forest products markets.

2.2.1 Geographical market integration

Geographical integration of fuel markets

Investigating the level of internationalization and international market is an important starting point to understand any commodity market (Ravallion, 1986). This is especially true for energy markets, due to their strategic nature and importance for the global economy. Furthermore, the recent decades have witnessed a gradual but game-changing process of liberalization and internationalization in energy markets (e.g. van Vactor, 2004):

> In the past, one could spend a career dealing with natural-gas or electricity issues in a specific region. In the 1990's, it was impossible to explain developments in one market without understanding complex linkages with other parts of the energy complex.
>
> (Kaminski & Prevatt, 2004, p 272)

The degree of internationalization in energy markets has crucial implications not only for market actors, but also for energy policy makers:

> Policy initiatives applied to markets that are incorrectly perceived to be regionalized or unified may produce perverse economic incentives and lead to undesirable outcomes.
>
> (Sauer, 1994, p 107)

Oil market integration

In terms of analysis of the internationalization of fuel markets, oil is the commodity that has been studied to the greatest degree. The interest is not surprising given the vital role of oil for the global economy (e.g. Hamilton, 2011). Although the oil market for quite some time was casually seen as a global market (Adelman, 1984), there has been a certain degree of debate on this issue. To begin with, to speak of the "oil market" is by nature a simplification, but one that is seldom acknowledged. Crude oil is in reality a rather heterogeneous commodity which can vary in chemical composition – most importantly in sulphur content and viscosity – which means that there will always be price differences between crude oil varieties (Fattouh, 2011). The same relation applies to crude oil prices in different regions of the world, due to transport costs. However, if the oil market is globally integrated, prices all over the world should move together over the long run, with prices only differing due to transport costs and/or quality differences. This issue has been analyzed in a number of studies in the recent decades (Sauer, 1994; Gulen, 1997, 1999; Bachmeier & Griffin, 2006; Kim *et al.*, 2007) and the general consensus is that for most practical purposes, the world oil market is indeed integrated.

Gas market integration

Markets for natural gas have traditionally been very dependent on pipeline infrastructure, a factor which has characterized much of the market structure. Furthermore, the high level of regulation in supply systems meant that gas markets in both Europe and the US were quite rigid phenomena up until the 1990's. In the last two decades however, liberalization and deregulation have begun to reshape gas markets on both sides of the Atlantic (van Vactor, 2004). This has prompted scholars to investigate to what degree the changing conditions have led to market integration across national and state borders.

De Vany & Walls (1993) found that the opening of US natural gas networks had led to increased interstate market integration, but that the continental US could not be considered a common natural gas market. King & Cuc (1996) came to a similar conclusion. Cuddington & Wang (2006) studied the time period 1993-1997 and found that the lower 48 US states were separated into two gas markets, with a split between the East/Central and Western parts of the country. The reason for the split was a lack of pipeline infrastructure, which constituted an obstacle to market interconnections. However, in a more recent study, Mohammadi (2011) concluded that US natural markets indeed were integrated, although certain imperfections in the market remain, as is indicated by Brown & Yücel (2008).

In Europe, the process of gas market deregulation has proceeded more slowly than in the US and at different paces in different countries. The UK market is seen as the most liberalized in Europe, whereas the process is proceeding quite slowly in many other countries (Yanrui, 2011). Asche *et al.*(2002) analyzed the German gas markets in order to assess the degree of market integration based on prices paid to different gas exporters. The result indicated that prices for Russian, Norwegian and Dutch gas supply were cointegrated. As for European gas markets in general, prices seem to be converging, but there is some disparity in the literature as to whether the European gas market is in fact integrated (Siliverstovs *et al.*, 2005; Neumann *et al.*, 2006; Bourbonnais & Geoffron, 2007; Robinson, 2007).

Given that the level of integration within the European and North American continents is somewhat disputed, it is perhaps no surprise that integration between the continents has not fully developed. Siliverstovs *et al.*(2005) analyzed the level of integration between Japan, Europe and the US and found that whereas the European and Japanese markets are integrated, the US is a separate market. As was noted above, an important reason for the slow development of natural gas market integration is the dependence on pipelines for transportation. However, growing shares of the global trade in natural gas is carried out by ship transport of Liquefied Natural Gas (LNG). Although trade in LNG first emerged in the 1960's, recent reductions in costs of liquefaction, LNG tanker construction and re-gasification is leading to increased shares of gas trade being carried out by sea transport. LNG is expected to bring about a larger degree of integration between continental markets, but it is unclear whether it is possible for gas markets to reach the level of sophistication found in oil markets (Neumann, 2008). However, the growing importance of LNG in the creation of intercontinental gas market linkages has become evident in recent years with the development of a gas surplus in the United States. The rapidly growing production of unconventional gas in the US has led to a situation where LNG cargoes destined for US terminals are redirected to Europe. In turn, this has put a downward pressure on European natural gas prices (Medlock III *et al.*, 2011). This implies that LNG is indeed already contributing to integration of North American and European gas markets.

Coal market integration

As for natural gas markets, research about the level of geographical coal market integration has evolved from an analysis of whether national markets are integrated to whether there is intercontinental market integration. Solomon & Pyrdol (1986) studied the US coal market in order to delineate regional markets *within* the country, coming to the conclusion that *"...coal markets are highly unstable and inefficient*" (Solomon & Pyrdol, 1986, p 122). In Europe, coal production in the post World War II period has been heavily subsidized and protected by national governments in various ways. This has meant a restriction of market forces which has made it difficult to assess the level of market integration. However, with the gradual liberalization of EU energy markets, the protected status of the European coal industry has diminished. Ellerman (1995) argued that the world coal market is globally integrated and that the US acts as a swing supplier, similar to the role that Saudi Arabia played in the oil market up until the mid-1980's (Yergin, 2008). In other words, the price of coal in all other regions is determined by the US price, and more precisely the productivity in the US coal industry. The conclusions from this study was however not based on quantitative analysis which instead was carried out later by Wårell (2006), who nonetheless mainly concurred with Ellerman in the view of the existence of a global coal market, albeit with interruptions in the 1990's. According to Li (2008), world coal markets are indeed integrated, but they were not so before 2000. Zaklan *et al.* (2012) finally, argued that the level of integration in the global coal market is "significant, but incomplete".

Geographical integration of liquid biofuel markets

Although the market volumes of biodiesel and bioethanol exceed those of commercially traded solid biofuels, the same cannot be said for the level of internationalization in the respective markets. In 2008, about 30% of all wood pellet production was traded between countries. For biodiesel, the corresponding figure was 27% whereas only 7% of world bioethanol production was exported (Junginger *et al.*, 2010). This is a result of differences in market structures of the respective fuels. Whereas the market for bioethanol is completely dominated by Brazil and the United States – which are both the two largest consumers and the two largest producers of bioethanol – the biodiesel market has hitherto been dominated by European consumers, with Germany as the dominating market in Europe (Olsson & Hillring, 2012a). As for the level of market integration in liquid biofuel markets, the available research seems to have focused on ethanol markets. Liu (2008) tested for cointegration between the ethanol markets of the Brazil, the European Union and the US. The conclusion was that ethanol prices in the three regions cannot be considered cointegrated. The prices were subsequently differenced and analyzed using a Vector Autoregression model, and the authors find that there is Granger-causality from the US and Brazil to the EU. In other words, ethanol prices in the European Union are influenced by prices in Brazil and the US but not the other way around. Rajčaniová *et al.* (2011) however, conducted a similar analysis and concluded that ethanol prices in Brazil and the US are cointegrated, but that there is no significant connection between Brazil and the US on the one hand and Europe on the other hand.

Geographical integration of markets for roundwood and forest products

Although most forest products are traded internationally to a substantial degree, globalization seems to have proceeded further in processed forest products than in roundwood. Nyrud *et al.*(2004) analyzed the development of forest products prices in different continents since 1962 in order to determine the level of international market integration. They conclude that whereas the markets for wood-based panels and pulp are globally integrated, this is not the case for roundwood and newsprint. However, prices for the latter two are converging, which is an indication of an ongoing market integration process.

In general, studies of geographical market integration have been conducted from a more regional perspective, primarily in European and North American contexts. Uri & Boyd (1990), Jung & Doroodian (1994) and Murray & Wear (1998) analyzed the level of integration in the US continental market for softwood roundwood. The consensus points to an integrated market. Stevens and Brooks (2003) conduct a similar analysis but include Alaskan and Canadian prices, and their results point to these two markets being integrated with that of the Pacific Northwest of the continental US. As for lumber markets, there is some discrepancies as to the results of studies of North American lumber market integration. Nanang (2000) analyzes softwood lumber prices in different Canadian provinces and conclude that Canada as a whole cannot be considered an integrated market for softwood lumber. Yin & Baek (2005) focus on the level of market integration in US softwood lumber markets and argue that the US does indeed constitute a single economic market for softwood lumber. Finally, Baek (2006) argues that North America indeed is an integrated market for softwood lumber in that there are significant connections between prices in the US and Canada.

Studies on European roundwood market integration have primarily focused on the situation in Northern Europe and the Baltic Sea area. Riis (1996) analyzed annual Danish and Swedish roundwood prices in the time period 1954-1992 and concluded that the two markets are integrated. Thorsen (1998) expanded this approach to include prices from Denmark, Finland, Norway and Sweden over the time period 1951-1991. The conclusion was that the markets in the four countries were strongly integrated and that Finland and Sweden acted as price leaders, i.e. the prices in Denmark and Norway were sensitive to price changes in Finland and Sweden. Toivonen *et al.*(2002) studied price series of sawlogs and pulpwood in Austria, Finland and Sweden from 1980 to 1997. They argued that the Swedish and Finnish markets were integrated, whereas the Austrian market was a separate entity. Mäki-Hakola (2002) analyzed price series for several different sawlog and pulpwood assortments in Estonia, Finland, Germany and Lithuania in order to determine the level of market integration between the countries. Pulpwood markets were concluded to be integrated to some degree whereas no signs of integration could be found for sawlog markets. Later however, Mäki-Hakola (2004) analyzed roundwood prices for Austria, Czech Republic, Estonia, Finland, Germany, Lithuania and Norway, and argued that sawlog markets in fact were integrated to a larger degree than pulpwood markets. Toppinen *et al.*(2005) analyzed roundwood prices in Estonia, Finland and Lithuania to determine the level of market integration between the three countries. The only markets that were found to be integrated were the Finnish-Lithuanian and Estonian-Lithuanian markets for spruce sawlogs. Hänninen *et al.*(2006) analyzed prices of sawlogs and sawnwood in Austria, the Czech Republic, Estonia and Finland over the time period 1995-2003 and found that prices were converging. This implied that markets are gradually becoming increasingly integrated. Mutanen & Toppinen (2007) analyzed the connection between the Finnish and Russian roundwood for six different assortments of sawlogs and pulpwood. In general, the two markets were not deemed to be integrated, with the exception of the market for spruce sawlogs, which was found to be integrated with Finland acting as price leader.

2.2.2 Relationships between prices of heterogeneous commodities

Aside from the relations between homogenous products in different geographical locations, the relationship between different commodities is a key factor in understanding of a specific market. This issue has been especially prevalent in energy markets, where a variety of studies have been conducted aimed at analysis of the relationships between different fuels. Of particular interest has been the question of the influence of the oil price on the prices of coal and natural gas. Yücel & Guo (1994) analyzed annual prices for coal, natural gas and oil over the time period 1947-1990 and concluded that there was a long-run relationship between the three fuels. Ellerman (1995) however, argued that in a historical perspective, the price of oil has not been instrumental for the development of coal prices. Instead, productivity developments in the coal mining industry have been the key component. Although oil price increases have increased the demand for coal, the author argues that coal *prices* have not been affected to significant degree. Serletis & Rangel-Ruiz (2004) investigated the connection between the prices of oil and natural gas in the US, and argued that there has been a decoupling of the traditional connection between the prices of oil and natural gas. This claim was however disputed by several authors. Bachmeier & Griffin (2006) evaluated the degree of interconnection between the prices of coal, natural gas and oil in the United States. Whereas they found substantial connections between the prices of oil and natural gas, the linkages between coal and the other two fuels were only very weak. Villar & Joutz (2006) also found a long-run connection between US oil and natural gas prices, and that natural gas prices are influenced by oil prices but not the opposite. Brown & Yücel (2008) reached a similar conclusion, as did Hartley *et al.*(2008). The latter argued that the rationale for the link between the prices of the two fuels is the possibility to switch between natural gas and oil products in certain boilers. Mohammadi (2011) analyzed US prices of coal, oil and natural gas for the time period 1970-2007 and determined that whereas oil prices have a unidirectional impact on natural gas prices, coal prices are unaffected by oil price fluctuations.

The relation between fuel prices in the European energy market has been the topic of several studies. Asche *et al.*(2006) studied the UK energy market from 1995 to 1998 and found that energy prices in general –including prices for natural gas and electricity – were determined by fluctuations in the oil market. Panagiotidis & Rutledge (2007) investigated the connection between oil and natural gas markets in the United Kingdom from 1996 to 2003. They found that prices were cointegrated and that hence there was a long-run connection between the prices of the two fuels. Bencivenga & Sargenti (2010) analyzed the connection between oil and natural gas prices in a US as well as a European context. They found that the connection between the two was stronger in Europe than in the United States, which they attributed to the more deregulated energy markets in the US.

Recently, researchers have aimed to assess the spillover from oil prices to prices of liquid biofuels. Balcombe & Rapsomanikis (2008) analyze the interconnections between oil, sugar and bioethanol in the Brazilian market. Their conclusion is that the prices are cointegrated and that oil prices have a significant impact on bioethanol prices, although the effect is indirect, acting through the sugar market. High oil prices lead to high sugar prices which in turn lead to increased prices of bioethanol, which in Brazil is produced mainly from sugarcane. Serra *et al.* (2008) conducted a similar analysis in the US market, where corn (maize) is the most important feedstock in ethanol production. The authors concluded that US ethanol prices respond to price changes in both corn and crude oil prices. Zhang *et al.* (2009) also studied the oil-ethanol connection in the US market and found that there was spillover from oil prices to ethanol prices. Serra & Zilberman (2009) analyzed the Brazilian ethanol market in this context and conclude that not only are actual price levels in bioethanol affected by oil price fluctuations, volatility in oil prices also spill over into ethanol prices. Pokrivčák & Rajčaniová (2011) studied the connection between oil prices and bioethanol prices in a European context. They find no cointegration between oil prices and ethanol prices in the German market, but when they estimate a VAR model in first differences, they do find Granger-causality from the oil price to the price of bioethanol.

2.2.3 Price transmission along production chains

Another strand in the literature concerning interconnections between prices of goods centers on vertical connections, i.e. the relationship among prices at different stages in a production chain. Gjolberg & Johnsen (1999) analyzed the connection between prices of crude oil on the one hand, and oil products on the other hand. The conclusion was that most oil products share a long-run trend with crude oil and that the prices of the products are influenced by crude prices. However, prices for heavy fuel oil – used e.g. as fuel for ships – did not seem to seem to have a strong relationship to crude oil prices. Asche *et al.*(2003) reached a similar conclusion. Lanza *et al.*(2005) however, argued that product prices can in fact be useful in explaining price developments in crude oil prices.

In forest products markets, Zhou & Buongiorno (2005) analyzed the transmission of prices of products in different stages of production in the US forest industry sector. They found that there is a relationship between the prices of lumber and the price of sawtimber, with the lumber prices Granger-causing sawtimber prices.

2.3 Data

The input data used in this thesis consists of wood fuel price series, collected over time. The prospects of fruitful research utilizing a quantitative approach are by nature reliant on the availability of data of sufficient quality. As for the characteristics that a dataset suitable for time series analysis and cointegration analysis should have, this is the topic for some debate in the literature.

First, there is the matter of the actual number of observations necessary. Haldrup (2003) argues – but provides no specified rationale – that a minimum of 30 observations over time is necessary in each series to be used in bi- and multivariate time series analysis of market phenomena. This criterion is met in most applied studies in the literature although there are exceptions. For example, Bourbonnais & Geoffron (2007) carry out cointegration tests with only 15 time series observations.

However, Hakkio & Rush (1991) argue that it is misleading to restrict the focus to the number of observations in each time series. One most also take into account the frequency at which the observations have been recorded. Economic time series data frequencies range from several values per day – as in certain financial datasets – to data recorded as infrequent as once per annum – as for some macroeconomic variables. This means that an appropriate dataset should also cover a certain time *span* in order to enable productive analysis. Again, for certain phenomena, a time span of a couple of days would be more than sufficient to capture the important properties of the time series in question. In other cases, several decades of data is necessary, if one studies slow-moving fluctuations such as e.g. the population of a country.

Regardless of whether the data requirements are formulated in terms of number of observations or time span, the availability of wood fuel data suitable for this kind of quantitative analysis is limited (Toppinen & Kuuluvainen, 2010). The relative immaturity of wood fuel markets implies that e.g. reactions of prices to market events could be rather slow and thus that a long time span – at least several years – is necessary in order to fully capture market characteristics. However, long wood fuel price series are in general not readily available in most European countries (Olsson *et al.*, 2010). The countries analyzed in this thesis stand out in the availability of wood fuel price series, which is an important reason for the choice in this work to focus on Northern Europe, where the availability of time series of wood fuel price statistics tend to be of better quality compared to other parts of Europe and the world[3]. As for the frequency of the data series analyzed herein, the data in Paper II-VI are quarterly whereas the data in Paper I are recorded on a monthly basis.

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[3]Finland, a very important country in terms of wood fuel market development, has published quarterly wood fuel prices since the end of the 1990's. However, in 2007, the price series for "fuel chips" in the Finnish statistics was discontinued. In its place came a new series called "forest chips" (Statistics Finland, 2012) but the break in the data series and the uncertainties as to if and how the two series can be spliced together is the reason why Finland is not included among the countries analyzed in this thesis.

3 Results

This section provides summaries of the six papers that form the basis for this thesis. Full versions of the papers are found as appendices in the printed version of this thesis. Note that some of the papers are still in manuscript form, which means that the versions included herein might differ from the versions that may later be published in journals. The numeration of the papers is based on chronological order.

3.1 Paper I: *European Wood Pellet Market Integration – A Study of the Residential Sector* (Olsson *et al.*, 2011)

3.1.1 Introduction

European wood pellet markets have been growing rapidly in the 2000's, both in the large-scale market segment – where wood pellets are used for production of heat and/or electricity – and in the residential heating market segment. In the latter market segment, wood pellet-fuelled boilers and stoves are used for space heating as an alternative to heating oil or natural gas. Not only have markets grown in sheer volumes, but also in geographical extent. It is estimated that about 30% of global pellet production was traded across national borders in 2008, although in the time period that is covered in this paper (2004-2008) no official statistics on pellet trade flows were available. This paper analyzes the level of market integration in Europe through cointegration analysis of pellet price levels in three different countries: Austria, Germany and Sweden.

3.1.2 Materials and Methods

The theoretical basis for the analysis in this paper is the so-called *Law of One Price*, which states that in a functioning market, the price of a certain good should be the same in all locations if prices are expressed in the same currency. The Engle-Granger test for cointegration is applied to wood pellet price series in different countries in order to analyze the level of international market integration. If prices in two regions are cointegrated, the respective markets can be viewed as integrated. As was reviewed in section 2.2.1, this approach has previously been used in analysis of markets for several energy commodities, including crude oil, natural gas and coal.

The data used is monthly wood pellet prices for residential consumption in Austria, Germany and Sweden from January 2004 to June 2008, denoted in €/metric ton. The Swedish prices have been converted from SEK to Euros by using monthly averages of exchange rates.

3.1.3 Results

The results of the cointegration tests show that the Austrian and German wood pellet prices are cointegrated and thus can be considered a common market for wood pellets. However, the Swedish prices are not cointegrated with either of the other two countries. The implication is that Sweden seems to be separated from the common German/Austrian wood pellet market.

3.1.4 Discussion

A problem with interpreting the results from the cointegration tests conducted herein is that in the time period which this study focuses on, there were no reliable data available on wood pellet trade flows between countries. From 2009 and onwards, this has been remedied to some degree by the introduction of a specific customs code for wood pellets. However, this was not present in 2004-2008 which makes it difficult to clearly say whether the lack of cointegration in prices is due to *a)* no trade in wood pellets between Sweden and the continent or *b)* there is trade but still no cointegration in prices. Based on previous estimations of European trade flows, it seems that *a)* is in fact the more probable case. In other words, there was little or no trade in wood pellets between Sweden on the one hand and Austria and Germany on the other hand during the time period in question.

The question is then what the reason for the absence of trade might be. Geographically, it seems that there is no major difference in distance from Germany to Austria compared to from Germany to Sweden. However, whereas trade in wood pellets for industrial use is very much possible only by sea, small-scale trade in wood pellets is carried out using road transport which means that the sea boundary between Germany and Sweden might act as barrier in this case. Furthermore, Germany and Austria share many characteristics that are not shared by Sweden, e.g. a common currency and the same language. These are issues that in other studies have been shown to be informal obstacles to trade and market integration. Furthermore, wood pellet standards coordination has been more thoroughly implemented in Germany and Austria, whereas the national Swedish standard dominates in the Swedish market. This is also likely a contributing factor to the lack of market integration. All in all, this study shows that although wood pellet markets are not strictly limited by national borders, there is still some way to go before it is possible to speak about a truly European market for residential wood pellets.

3.2 Paper II: *Estonian-Swedish Wood Fuel Trade and Market Integration: A Cointegration Approach* (Olsson *et al.*, 2012)

3.2.1 Introduction

The Baltic Sea area has been an important region for wood fuel market development for at least two decades. Following the collapse of the Soviet Union in the early 1990's, a substantial trade in different forms of wood developed with e.g. roundwood and wood chips were imported from the Baltic States and Russia to Denmark, Finland and Sweden. The trade also included different forms of wood fuel, the demand for which was growing in Sweden and Denmark in particular. Imports to Sweden from the Baltic States consisted of both unrefined wood fuels – e.g. wood chips or low quality roundwood – and refined wood fuels such as wood pellets.

An important factor to clarify in order to understand any market is to what degree national markets are integrated. Market integration can be defined in several ways, but the most accepted definition puts focus on prices, and more specifically the extent to which price fluctuations in one country spills over into another. In this study, the Estonian-Sweden wood fuel trade is examined with special focus on whether the two markets have been integrated as a result of the trade.

3.2.2 Materials and Methods

In this study, cointegration analysis is used to analyze the interaction between the wood fuel markets in Estonia and Sweden over the time period 1998-2010. Prices for unrefined wood fuel sold to large-scale consumers in both countries are analyzed and the price pair is tested for cointegration. However, since an important part of the end price paid for unrefined wood fuels consists of transport costs – due to the bulky nature of the cargo– this must be taken into account. For this reason, prices are tested for cointegration both without transport costs and with the inclusion of transport costs that have been estimated by using an index of bulk transportation costs in the Baltic Sea area during the time period in question.

3.2.3 Results

The results from the cointegration tests of the relationship between the Swedish and Estonian wood fuel prices do not show that the two price series are cointegrated. This conclusion is the same regardless of whether the estimated transport costs between the two countries are included or not. In the context of market integration, this result indicates that the wood fuel markets in the two countries cannot be considered integrated.

3.2.4 Discussion

According to the cointegration tests of the wood fuel price series, the two countries cannot be considered integrated. This is somewhat surprising since there has been a quite substantial trade in unrefined wood fuels between the two countries in the time period in question. These trade flows should contribute to connections between the markets, which in turn ought to reflect in price developments over time. There does seem to be some interaction between the markets in that when wood prices in Estonia rose to very high levels in 2007-2008, the Swedish import from Estonia dropped drastically. However, over the whole time period, the prices do not interact to the point where one could conclude that the markets are integrated. This is an issue that must be discussed further.

One important question is whether the data gives an accurate representation of the prices paid in the cross-Baltic trade. The prices used are quarterly values, whereas the contracts used for the import last at least for one full year and are often multi-year supply arrangements. This means that there could be a substantial lag between the time when supply/demand fluctuations are reflected in quarterly prices and the point when the international trade contract terms are adjusted accordingly. Furthermore, there is very little research available as to the structure of the contracts in question and whether they e.g. include any clause of price indexation. A similar discussion is relevant for exchange rate fluctuations and whether the quarterly exchange rate changes between the Estonian and Swedish currencies used in the tests reflect how these issues are handled in the actual market.

Also, the issue of whether the transport costs estimations are accurate could also be a confounding factor, since the index that is used for estimation of the fluctuations are based on a general Baltic bulk shipping index which might differ from actual costs in this particular case. All in all, there are many question marks regarding the structure of the international trade in unrefined wood fuels. Therefore, it is suggested that further research in this area utilizes a more qualitative approach with focus on contract arrangements and suppliercustomer relationships. This is important knowledge in order to obtain a better understanding of the rapidly growing international wood fuel markets.

3.3 Paper III: *Price Relationships and Market Integration in the Swedish Wood Fuel Market* (Olsson & Hillring, 2012b)

3.3.1 Introduction

Sweden has been a forerunner in terms of wood fuel market development in comparison with most other countries. Beginning in the 1970's, a key part of Swedish energy policy has been to replace fossil fuels with bioenergy, in particular wood fuels. This strategy was further emphasized with the introduction of carbon taxation in the early 1990's, which set the stage for the emergence of an actual market for wood fuels. The development and structure of this market in the time period 1993-2010 is in focus in this paper. In particular, two issues are in focus:

1. The relationship between prices of different fuels within the district heating sector on the one hand and the forest industry sector on the other hand.
2. The relationship between the prices paid for homogeneous fuels in the two sectors.

3.3.2 Materials and Methods

A unique feature in the Swedish wood fuel market is that wood fuel prices have been collected on a regular basis for a number of different fuels since the early 1990's. The dataset analyzed herein contains price series of five different wood fuel categories: 1) forest chips sold to district heating plants, 2) forest chips sold to industrial consumers, 3) forest industry by-products sold to district heating plants, 4) forest industry by-products sold to industrial consumers and 5) refined wood fuels (pellets & briquettes) sold to district heating plants. The relationship between the price series is investigated by means of cointegration analysis according to the Johansen-Juselius approach. As a complement, the Engle-Granger test for cointegration is also used.

3.3.3 Results

The results from the cointegration tests are that forest chips and industrial by-products sold to district heating plants are cointegrated, which is logical since these two assortments are viewed as substitutes by the market. However, the two are not perfect substitutes. The prices of refined wood fuels used in district heating does share a common trend with forest chips and industrial by-products. This implies that refined and unrefined wood fuels should be seen as two separate markets. As for the fuels used by industrial consumers, prices of industrial by-products and forest chips are not cointegrated. As for the connection between the prices of homogeneous fuel assortments in the two consumer groups, the prices paid by district heating plants for industrial by-products are cointegrated with the prices paid for industrial by-products by industrial consumers. However, the prices of forest chips in the two categories were not cointegrated, but instead followed two separate trajectories..

3.3.4 Discussion

The results presented above show several important aspects of the Swedish wood fuel market. First, it seems that district heating plants view forest chips and industrial by-products as substitutes and switch between the two assortments depending on which is most economical at a given time. This means that the prices of the two will maintain the same long-run trajectory.

Second, the prices paid by industrial consumers and district heating plants for industrial by-products also follow the same long-run path which implies that they compete for the same resource.

Thirdly, the prices of refined wood fuels seem to be moving separately from the prices of the other (unrefined wood fuel) prices series. This is perhaps not surprising given the fact that refined wood fuels are rarely used in the same boilers as unrefined wood fuels such as forest chips or bark. Instead, refined wood fuels are either used in dedicated boilers for base load or - more commonly - peak load. Furthermore, refined wood fuels are also used in the small scale residential sector which introduces an important factor into this market, one that is not present in the market for unrefined wood fuels to a comparable extent. Also, the market for refined wood fuels –especially wood pellets – is more internationalized than markets for forest chips and industrial by-products. This means that factors outside the Swedish market itself might be influencing refined wood fuel prices.

Finally, it is noteworthy that the prices paid by industrial consumers for forest chips are not cointegrated either with the prices of industrial by-products or with the prices of forest chips in the district heating sector. This implies that there is a certain degree of inefficiency in the Swedish wood fuel market.

3.4 Paper IV: The Effect of Crude Oil Price Fluctuations on Swedish Wood Fuel Prices (Olsson & Hillring, 2012c)

3.4.1 Introduction

An important feature of wood fuel markets is that they are connected closely to two very significant but also distinctly different economic sectors, the energy sector and the forestry/forest industry sector. The degree of influence that each of these two sectors has on wood fuel markets has however not been thoroughly investigated.

In this paper, the interaction between energy markets in general and wood fuel markets is investigated. This is done by analyzing the impact that the price of crude oil – arguably the most important indicator of the global energy market as a whole – has had on wood fuel prices in Sweden in the time period 1993-2010.

3.4.2 Materials and Methods

The connection between crude oil and wood fuel prices is analyzed by use of cointegration and Vector Autoregression (VAR) models. The data used consists of on the one hand Brent crude oil prices as published by the International Monetary Fund and on the other hand of Swedish wood fuel prices, collected by Statistics Sweden and published by the Swedish Energy Agency. The prices analyzed are of a quarterly frequency and the oil prices have been converted from US$/bbl to SEK/MWh using quarterly averages of SEK/US$ exchange rates.

3.4.3 Results

The results from the analysis do not give any statistically significant indication of oil price fluctuations spilling over into wood fuel prices. The cointegration tests do not give any indication of cointegration between oil on the one hand, and refined or unrefined wood fuels on the other hand. In the absence of cointegration, the connection between the oil price and the wood fuel price series is analyzed by setting up a VAR model using first differences of the individual variables as input data. There are no signs of Granger-causality between the variables, which otherwise could have been a sign of interconnection between the price series.

3.4.4 Discussion

According to the results of the tests presented herein, the connections between oil prices and Swedish wood fuel prices seem not to be very strong. Based on evidence from previous studies, oil prices are however likely to influence wood fuel markets in the long run. Higher oil prices mean greater incentives for energy consumers to invest in equipment to use other forms of energy, which means a long-run increase in demand for wood fuels.

The absence of interconnections in a shorter time perspective is noteworthy, as well as somewhat counterintuitive. However, in the light of previous research on the possible mechanisms by which an oil price increase could spill over into wood fuel prices, the lack of oil-wood fuel price interconnection is less surprising. To begin with, as for the case of increasing oil prices spilling over wood fuel prices through higher wood fuel production costs, previous studies indicate that fluctuations in world market oil product prices have a rather small impact on production costs. This is especially true for the current case since the actual product price of e.g. diesel fuel in Sweden is a rather small part of the price paid by the consumer due to the high taxes that dominate fuel prices (as in many European countries). As an example, from the beginning of 2007 to summer of 2008, actual product prices doubled but this only increased the consumer price by about 40%. All in all, this means that very large oil price fluctuations are necessary for them to impact wood fuel production costs and prices to any substantial degree.

A similar case can be made for the possible oil-wood fuel price connection resulting from the two fuel categories being cointegrated as a result of being substitute fuels. Taxes on heating oil used in e.g. district heating have been raised in several steps in Sweden since the early 1990's. This has effectively priced oil out of the district heating sector except for the use in peak load boilers. In other words, the gap between wood fuel prices and prices of heating oil is so large that wood fuel prices would have to double or triple before it makes economic sense to switch to heating oil.

As for the last possible connection between oil prices and wood fuel prices, price indexation, this is a question that is difficult to address due to the absence of comprehensive knowledge about fuel supply contract structures. However, given that no connection is found between oil and wood fuel prices, such indexation – if it at all exists – is bound to be unusual.

3.5 Paper V: Price Relationships Between Wood Fuels and Industrial Roundwood in the Swedish Market (Olsson & Hillring, 2012d)

3.5.1 Introduction

A key characteristic of wood fuel markets is their connection to energy markets on the one hand and forestry and forest industry on the other. The latter relationship takes on a number of different forms. First, much of wood fuel production is integrated into forestry operations in general and carried out by forest companies. For example, procurement of logging residues for energy purposes is by necessity done with final fellings, where the latter are perfomed with the main purpose of extracting roundwood. Second, by-products from forest industries, particularly sawmills, are an important source of wood fuel supply. This includes both by-products that are used directly as fuels and by-products used as raw material in production of refined wood fuels such pellets and briquettes. Third, due to growing demand for wood fuels, energy companies – e.g. district heating plants – are occasionally competing with pulp & paper mills over certain roundwood assortments.

All these factors imply the presence of a common trend among the developments of the prices of industrial roundwood – saw timber and pulpwood – and wood fuels. In this paper, this connection is analyzed quantitatively by applying time series analysis to price series of industrial roundwood and refined and unrefined wood fuels.

3.5.2 Materials and Methods

In this study, we apply the cointegration approach to quarterly time series of Swedish prices of saw timber, pulpwood, forest chips and refined wood fuels. The analysis covers the time period 1999-2011. Wood fuel prices are collected from the series compiled by the Swedish Energy Agency and roundwood prices are from statistics published by the Swedish Forest Agency.

3.5.3 Results

The Johansen-Juselius and Engle-Granger cointegration tests are used to test the interconnections between the price series. The results show that the prices of forest chips are cointegrated with both roundwood assortments, although it should be pointed out that the results from one of the tests are ambiguous. As for the refined wood fuels, none of the tests show refined wood fuels to be cointegrated with either sawtimber or pulpwood.

3.5.4 Discussion

Whereas the tests showed signs that unrefined wood fuels – here represented by forest chips – are cointegrated with saw timber and pulpwood, the prices of refined wood fuels were not cointegrated with either of the roundwood assortments. This implies that there is a long-run connection between the prices of roundwood and forest chip but not between roundwood and refined wood fuels. The connection between forest chips and roundwood is noteworthy because in a previous study, no cointegration was found between forest chips and world market oil prices. In other words, Swedish forest chips price fluctuations seem to have more to do with developments in the Swedish forest sector than with oil price fluctuations.

An important question is why no connection is seen between refined wood fuels and the roundwood assortments. A contributing reason could be that the whole production process of forest chips is more tightly connected to the forest sector. The main part of the procurement and production of forest chips takes place within the forest operations, after which the chips are delivered to e.g. a CHP plant for combustion. Production of refined wood fuels on the other hand involves a lot more input costs, e.g. in the form of personnel and electricity. This might mean that actual connections with forest operations become relatively less important for price formation. Furthermore, there is plenty of international trade in wood pellets – the most important refined wood fuel assortment – which means that domestic Swedish factors might be less important for price formation.

3.6 Paper VI: The Wood Fuel Market in Denmark – Price Development, Market Efficiency and Internationalization (Olsson & Hillring, 2012e)

3.6.1 Introduction

Denmark is well known for the successful implementation of wind power into the country's energy system. However, in terms of contribution to Denmark's total energy consumption, solid biomass fuels constitute the most important form of renewable energy. Solid biomass fuels used in Denmark include straw, but primarily consist of different forms of wood fuels. Consumption of wood fuels takes place in small-scale applications such as residential wood pellet boilers, district heating networks that supply villages and smaller towns with centralized heat and finally large scale production of electricity and heat.

This study investigates the Danish market for two important wood fuels in the medium- and large scale sectors of the Danish energy system: wood chips and wood pellets. Consumption of both these fuels has grown rapidly in the recent decade which has contributed to increasing the share of biomass in Danish energy consumption to more than 16% in 2010. However, the two markets differ in some important characteristics. For example, whereas the Danish wood chip market is to 85-90% supplied domestically, the wood pellet market in Denmark consists of 90% imported pellets.

The markets are studied by applying time series analysis to a dataset containing quarterly prices paid for wood chips and wood pellets by Danish district heating plants in the time period 2001-2011.

3.6.2 Materials and methods

The dataset analyzed in this study contains average prices paid for the two wood fuel assortments by Danish DH plants. However, the highest and lowest price paid in each quarter is also recorded in the statistics. This is used in the first step of this study, where the development of market efficiency in the Danish wood fuel market is investigated. This is done by studying the development of the relative price range over time. If the relative price range is decreasing, this should indicate an increasingly efficient market.

The second part of the study makes uses cointegration analysis to assess whether there exists a common trend among the prices of the studied wood fuel assortment, as well as their connection to a third solid biofuel assortment in the Danish market: straw.

Cointegration analysis is also used in the third part of the study where the connection between wood fuel prices in Denmark and Sweden is investigated to determine the level of market integration between the two countries.

3.6.3 Results

In the first part of the study, the development of price dispersion for wood chips and wood pellets was investigated. The result is that whereas the level of price dispersion for wood chips has remained relatively constant over the investigated time period, the price dispersion for wood pellets has decreased considerably.

In the second part of the study, the results from the cointegration analysis indicate that whereas there are interactions between the prices of wood chips and straw, there are no notable interconnections between the pellet prices and any of the other two fuels.

In the analysis of the level of market integration between the Danish and Swedish wood chips and wood pellet markets, the results show indications of market integration between the wood pellet markets in the two countries. For the wood chip markets, no such indication can be discerned.

3.6.4 Discussion

The results herein provide some important findings as to the development of the Danish wood fuel market in the first decade of the 21st century. To begin with, it is clear that there are notable differences between the markets for wood chips and wood pellets. The absolute price range for wood pellets has decreased over the time period in question, which should be a sign of an increasingly efficient and transparent market. In contrast, wood chip price dispersion has by and large remained at a constant level. This is likely a result of the overall development in market maturity in the wood pellet market. The combustion-related and logistical advantages of wood pellets, as well as a well-developed standardisation process has contributed to an increasingly mature market where international trade has become a key characteristic, especially in Denmark.

The differences between the wood chip and wood pellet market were further emphasized in the analysis of the interconnections between the prices of the respective fuels. Whereas there were no indications of cointegration between wood chips and wood pellets, there were interconnections between the prices of straw and wood chips. This is logical, since these fuels are substitutes to a certain degree and district heating plants have the possibility to switch between them depending on relative price levels.

Finally, the differences in the level of internationalization in the wood chip and wood pellet markets was underlined by the signs of market integration between Sweden and Denmark that were found for wood pellets but not for wood chips.

4 Discussion

4.1 Review of thesis objectives and general conclusions

The work presented in this thesis has investigated wood fuel markets in Northern Europe by analyzing different price relations over time. Three key issues – first presented in section 1.5 – have been investigated:

1. The level of international market integration in wood fuel markets (Paper I, II & VI).
2. The interactions between prices of different wood fuels (Paper III & VI).
3. The connections between wood fuel prices and prices of two related commodities: oil and industrial roundwood (Paper IV & V).

As an introduction to this final thesis chapter, the results from the thesis pertaining to these three objectives are presented.

4.1.1 International market integration

To begin with the level of international market integration in wood fuel markets, an overall conclusion from Paper I, II and VI is that the broad categorization "wood fuel markets" is insufficient. The reason is that the results from the studies on international wood fuel market integration seem to differ according to whether unrefined or refined wood fuels are in focus. Whereas Paper I and VI give indications of international market integration in wood pellet markets, the corresponding analyses of unrefined wood fuel markets in Paper II and VI give no such indication.

4.1.2 Interactions between prices of different wood fuels

Given the differences between unrefined and refined wood fuels in this regard, the results from Paper III and Paper VI on the price relationships between different wood fuels are perhaps not surprising. The general conclusion from these studies is that price developments for unrefined and refined wood fuels tend to follow different trajectories. Hence, it is necessary to view the two as separate markets. The fuels *within* the unrefined wood fuels category can on the other hand be seen as belonging to the same market in Sweden, at least for district heating, as was seen in Paper III. A similar conclusion was drawn for wood chips and straw from the study of the Danish market in Paper VI. The distinctly separate price development seen in Paper III of the prices of forest chips used by industrial consumers does however indicate the presence of inefficiencies in the Swedish wood fuel market.

4.1.3 Interactions between wood fuel prices and prices of oil and industrial roundwood

Paper IV and V focused on the interconnections between the prices of wood fuels and the prices of oil prices and industrial roundwood in the Swedish market. Here as well, the difference between unrefined and refined wood fuels must be stressed. Whereas the results from the analysis in Paper V gave indications of a long-run relationship between prices of unrefined wood fuels on the one hand and sawtimber and pulpwood on the other hand, this was not the case for refined wood fuels. In the light of this it is interesting to note that the results in paper IV on the effect of the oil price on Swedish wood fuel prices give the same result for both refined and unrefined wood fuels, i.e. that no significant connection can be seen between oil prices and wood fuel prices.

In the following, some aspects of these results will be discussed.

4.2 Wood fuel price formation

Hillring (1997) presented three scenarios for the then-future development of wood fuel prices in Sweden:

1. That there would be a strong connection between the prices of wood fuels and fossil fuels
2. That intra-wood fuel competition would be more important for price formation
3. That wood fuel prices would become higher due to gradually increasing production costs

To begin with, fossil fuel prices seem not to have had a significant impact on wood fuel prices. Increasing oil prices have no doubt contributed to the growth in wood fuel demand in Sweden and elsewhere, but in the time period studied in Paper IV, wood fuel *prices* have not been impacted to a discernable degree. This argument is similar to the one made for US coal prices by Ellerman (1995). However, oil prices do act as an important *indirect* long-term driver of wood fuel prices. High oil prices have – together with policy measures promoting renewable energy – been a key reason for the growing demand for wood fuels. In Sweden, this demand has grown to the point at which the supply of inexpensive wood fuels is becoming scarce and more difficult fuel assortments – including small diameter roundwood from thinning as well as stumps – are necessary to meet demand (Björheden, 2011). This is pushing marginal costs upwards, thereby leading to higher market prices. Thus, hypothesis 1 and 3 are connected. However the indirect character of the influence of the oil price does not indicate a "strong connection" between the prices of wood fuels and fossil fuels. It is important to note here the difference in this context between the wood fuel markets studied herein and the markets for bioethanol. As was discussed in section 2.2.2, several studies show that there is a strong connection between the oil price fluctuations and the price development of bioethanol.

Secondly, results from Paper III indicate that there is a significant degree of competition between different wood fuel assortments. Prices of forest chips for use in the district heating sector and industrial by-products are cointegrated, which is a sign of intra-fuel competition. If fuel consumers switch between the two categories depending on relative price levels, this introduces competitive pressure on fuel suppliers to reduce costs. In other words, hypothesis 2 in the list above seems to be vindicated.

4.3 Impacts of international trade on European wood fuel markets

Results from the studies presented in Paper I, II & VI indicate that in the time periods of study, European wood fuel markets have not been fully integrated across national borders. However, it seems that there are important differences between refined and unrefined wood fuels. There are indications in paper I and paper VI that wood pellet markets – the residential market segment in Paper I and the large-scale market segment in Paper VI – are integrated across borders. The studies of unrefined wood fuels in Paper II and Paper VI on the other hand, give no indication of international market integration.

The effects of international trade in wood pellets have already had substantial effects on the national wood pellets markets of Northern Europe. In paper III, the relations between different assortments of wood fuels in the Swedish market are analyzed. The prices for refined wood fuels (pellets & briquettes) seem to be disconnected from the market events that rule market events for forest chips and industrial by-products. One explanation for this disconnection was the more international character of the market for wood pellets. Although Swedish district heating plants still source a large share of their fuel supply domestically, imports have become increasingly important in the 2000's, especially for wood pellet supply. From 2001 to 2010, the share of imported pellets in the Swedish market grew from 19% to 30% (PiR, 2012). This has likely acted as a form of ceiling on wood pellet prices paid by large-scale consumers. Furthermore, there is a disconnection between the prices of sawmill by-products and refined wood fuels. In 2001, prices of industrial by-products were less than 40% of the prices of refined wood fuels, whereas in 2010, the quota was 62% (Swedish Energy Agency, 2011). The combination of low-cost imports and higher raw material prices is leading to shrinking margins and a more difficult competitive environment for pellet producers in the Nordic countries. This became evident in late 2011, when the bioenergy group Vapo shut down several pellet production sites in Finland. In early 2012 two Swedish pellet producers announced that they were cutting down production and laying off personnel (Vapo Oy, 2011; Woodnet.se, 2012).

The results in this thesis did not indicate that markets for unrefined wood fuels such as wood chips are integrated across borders in the sense that prices in different countries are cointegrated. However, this does not mean that there are no interactions between national markets for unrefined wood fuels. One sign of this was seen in Paper II, where the drop in Swedish wood fuel imports from Estonia in 2008 was most likely connected to the rapid increase in Estonian wood fuel prices. Another example can be found in a connection between the Norwegian and Swedish wood fuel markets. As part of a response to the 2008-2009 global economic crisis, the Norwegian government introduced a subsidy for clearing of roadside vegetation to support rural development, reduce wildlife highway accidents and contribute to mitigation of climate change (Stortinget, 2009). As it turns out, 50% of the wood fuels produced in this program have been exported to Sweden for use in a pulp mill boiler (Hillring *et al.*, 2012). Whether or not this effect was intended is unclear from the formulation of the policy, but it is certainly an interesting example of the effects of combining national energy policies with increasingly international wood fuel markets.

4.4 Market liquidity vs. supply chain sustainability?

A noteworthy new phenomenon in the wood pellet market is the gradual establishment of trading in pellet futures contract initiated by APX-Endex in late 2011. This could be seen as natural step in the gradually increasing maturity of wood fuel markets, but a few question marks can be raised in connection to this.

To begin with, although the establishment of derivative contracts is meant as a tool for risk management and to reduce market insecurity, financialization of commodity markets can have consequences that are less than benign. O'Sullivan (2009) is an example of authors who argue that the rapid increase and subsequent drop in oil prices in 2008 was not based on fundamental supply/demand balances in the physical oil market, but rather a product of financial speculation in oil derivatives. This implies that wood fuel pricing patterns could possibly change in the near future as financialization introduces previously absent components to the process of price formation.

Secondly, far from all futures contracts that are launched become successful. According to Brorsen & Fofana (2001), trading in most new futures contracts is in fact terminated within 10 years of introduction. They argue that the key to the success of futures trading in a commodity is whether or not there is an active cash market. A high level of vertical integration in a market is conversely connected with unsuccessful futures contracts. An example of this is the crude oil market, where spot markets and later futures trading only emerged in the 1970's and 80's with the breakdown of the vertical integration structure dominated by multinational oil companies (Parra, 2010).

Whether or not the cash market for wood pellets is sufficiently active for the wood pellets futures contract to be long-lived remains to be seen. Several large European energy companies – e.g. Vattenfall and RWE – seem to opt for vertical integration as their tool of preference to handle price and supply risks (Kinney, 2011). This choice is likely to be related to several different issues - including quality issues and security of supply - but one very important rationale for utilities to become involved in the entire supply chain is to ensure that the supply chain lives up to certain standards in terms of sustainability.

Wood fuel markets are by and large a product of policy measures aimed at reducing environmental impacts of energy conversion. Hence, it is expected by the public as well as policy makers that wood fuels meet certain requirements in terms of minimum environmental impacts. Although explicit criteria for wood fuels and other solid biofuels have not yet been established by the EU, such specifications will – in one form or another – likely be necessary in order for wood fuels to maintain their position as a form of energy that is favoured by policy makers. Although there has been fierce debate about other forms of bioenergy, e.g. bioethanol and biodiesel made from palm oil, wood fuels have hitherto been relatively uncontroversial. However, this is changing. For example, in a recently released report, Greenpeace (2011) are highly critical of the Canadian wood pellet industry. This is just one indication that sustainability and minimal environmental impacts are vital components of any wood fuel supply chain. However, verifying that environmental criteria are up-to-standard requires comprehensive controls of the entire procurement system.

A conundrum is how guarantees of a sustainable supply chain can be combined with a liquid cash market for wood fuels needed to enable successful futures trading. Mathews (2008) discusses this issue in a liquid biofuels context, and proposes that the solution is to include "proof of origin" documentation in the commodity specification, in addition to technical quality requirements. A similar approach has indeed been used by APX-Endex in the development of its wood pellets futures contract, where all cargoes must be delivered along with documents certifying that the pellets in question are produced comply with at least one of three selected sustainability schemes (APX-Endex, 2011). Whether this is a successful method of dealing with the market liquidity/chain-of-custody dilemma remains to be seen, as the APX-Endex is only in its introductory phase.

4.5 Cointegration, market adjustments and time span

The relationships analyzed in this thesis are all selected based on the existence of a theoretical rationale for the presence of a long-run common trend between the commodities analyzed. However, in several cases, no such common trend was identified. For example, no cointegration was found between Swedish and German/Austrian wood pellet prices, nor between Swedish and Estonian prices of unrefined wood fuels, nor between global prices of crude oil and Swedish wood fuel prices. Yet, in all these cases economic theory suggests the presence of a long-run relationship, be it due to the mechanisms of geographical arbitrage to force prices towards a long-run equilibrium or a connection between oil and wood fuels due to fuel switching. Although several reasons for the absence of long-run connections are discussed in the individual papers, one issue that is relevant in all these cases is time span, as first presented in section 2.3. Since wood fuel markets are still rather immature and undeveloped, it is likely that the interactions between market events and price changes are quite slow. In other words, it is possible that in the cases herein where no cointegration was found, the reason is simply that the time spans used herein – at most less than two decades - are simply too short to capture the processes that force prices together. For example, in the very long run – say half a century – prices of oil and wood fuels might very well turn out to be cointegrated, as this time span allows for replacement of e.g. capital-intensive combustion equipment. Similarly, if wood fuel markets continue their rapid development of internationalization, cointegration analysis of wood fuel prices in Sweden and Estonia over the time period 2010-2020 is likely to indicate the presence of a common trend.

4.6 Suggestions for future research

In evaluating the results in this thesis, it is important to emphasize that the internationalization of wood fuel markets is only in its very early stages in the time periods that were in focus. Hence, future studies using better data as input might very well show a more internationalized wood fuel market than the evidence in this thesis indicates. As several commercial price reporting agencies have now begun tracking wood fuel prices, the availability of data suitable for the type of quantitative analysis carried out herein will likely increase considerably in the near future.

4.6.1 Analysis of future wood fuel price formation

In terms of price formation, it is probable that there are differences between the mechanisms that have governed the North European market in these pioneering years of market development and the new era of wood fuel market development that is now unfolding. Wood fuel market growth in Europe will likely continue in all scales of consumption. However, from now (2012) to 2020, growing shares of the volume increase in the EU is expected to consist of pellets with non-EU origins aimed at electricity production. As an example, the power station in Tilbury, UK will by itself every year consume an amount of wood pellets equal to the total annual Swedish production (PiR, 2012; Geiver, 2012). As wood pellets are commonly used as an alternative to - or co-fired with - coal, the connection between coal prices and wood pellet prices will likely become strong, with carbon emission prices as the third part of the equation. A future cointegration relationship might well be $P_{Pellets} = P_{Coal} + P_{Carbon} + Spread$ or $Spread = (P_{Coal} + P_{Carbon}) - P_{Pellets}$. In the latter case, the *Spread* is positive when it is profitable to use pellets instead of coal, if any differences in electrical generation efficiency between fuels are taken into account. A similar indicator is already provided by the price reporting agency Argus in its weekly publication *Argus Biomass Markets* (see e.g. Argus Media, 2011). As market actors begin to exploit any arbitrage opportunities, the *Spread* should take on a stationary pattern, reflecting a cointegration relationship between the prices of coal, carbon emissions and pellets. In the long run, an analogous relationship with natural gas prices is likely. Analysis of these interconnections will provide important insight into the wood fuel price formation of the future.

4.6.2 The growing importance of transport costs

A factor that will become increasingly important with the internationalization of wood fuel markets is transportation costs, and especially the costs of sea transport. As has been discussed e.g. by Dahlberg (2010), transportation costs became a prohibitive factor for some transatlantic wood pellet trade flows a few years back. Since transportation costs still make up an important share of consumer prices of wood fuels, it is imperative to take this into account. This also means that the connection between oil prices and wood fuel prices could strengthen as the use of oil products in the supply chain increases. Due to the large trade flows of wood pellets across the Atlantic from North America to Europe, it would also be highly interesting to conduct cointegration analysis of the connection between wood pellet prices in North America and in Europe. This could prove very fruitful to determine the importance of North American pellet production for European markets.

4.6.3 Interaction between large-scale and residential wood pellet markets

In this thesis, the residential market for wood pellets was studied in Paper I and the large-scale market for wood pellets was included in some form or another in all papers except Paper II. However, the interconnection *between* these two market segments has been investigated only to a very small degree (see e.g. Takeuchi & Helby, 2004). This is clearly an interesting topic that needs to be analyzed further.

4.6.4 Wood fuels and the future development of the forest industry at large

Paper V indicated the presence of a common trend among prices of forest chips and industrial roundwood. One reason for this is that certain assortments of small-diameter roundwood are sometimes used as raw material in pulp & paper production and sometimes as fuel, depending on market conditions and relative willingness to pay in the two sectors. As was noted in paper V, certain thinning operations are now planned and conducted specifically to allow for flexible end-use of the removed wood. This enables the seller to choose among a broader array of potential buyers than if the thinning operations are performed to produce e.g. pure pulpwood. Such practices are likely to contribute to a strengthening of the ties between prices of pulpwood and wood fuel and blur the line between wood fuel and industrial roundwood. The border is likely to become increasingly vague as forest industries diversify away from traditional products such as newsprint into e.g. production of transportation fuels. Potentially, pulpwood-quality roundwood will evolve more in a direction where it becomes a raw material whose end-use is determined dynamically depending on current market conditions. The impact that these changes might have on wood fuel market developments and forest industry strategies is clearly an interesting topic for further investigation.

4.6.5 Intercontinental wood pellet market integration and future trade patterns

In analysis of wood fuel market development and of wood fuel trade patterns, it is important to acknowledge the importance of policy measures in explaining direction and volumes of trade flows. Perhaps the most obvious example of this is the export of wood pellets from North America to Europe. The imperative rationale for this trade is the discrepancy in policy measures between the two continents. A change in policy in either region could potentially change the trade patterns drastically. If the US introduces a more ambitious policy in terms of reducing its use of fossil fuels, a growth in domestic demand for wood pellets would likely follow. In turn, European market actors would be facing strong competition for wood pellets produced in Canada and the US. Similarly, growing Asian demand for wood fuels could mean that wood pellets produced especially on the western side of the North American continent are directed to Japan, South Korea and China instead of Western Europe. This is especially worth taking into the account in the light of the Fukushima disaster which is expected to change much of Japanese energy policy (Austin, 2011). All these issues have hitherto been analyzed sparsely. In other words, there are plenty of knowledge gaps to fill until full understanding has been reached about the mechanisms of the international wood fuel market.

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