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The European wood pellets for heating market - Price developments, trade and market efficiency

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ABSTRACT

Competitive international markets imply adjustments towards competitive spatial equilibrium in which excess from one market is transferred to another and prices are equilibrated except for remaining differences that can be assigned to transfer costs. The European market for wood pellets used in small-scale heating systems has been expanding significantly over the past decade. Small scale pellet heating is arguably a mature technology, but whether the market is mature is another question. In this paper we analyse recent data on trade flows and price developments between Italy, Austria, Germany and France to understand the developments of wood pellet market efficiency and to draw conclusions about market function. The objective of this study is to establish a framework to test the European residential wood pellet market for competitive spatial equilibrium using modern trade theory. We find mainly inefficiently integrated markets with remaining positive marginal profits and detectable arbitrageurs' activity. Based on a thorough discussion of these findings and the underlying data we outline possible methodology advancements and list policy recommendations to secure access and affordability of this renewable heating commodity in the long run.

1. Introduction

The utilisation of solid and liquid bioenergy carriers has increased significantly in the past decades. As demand has grown, so has also international trade in especially ethanol, biodiesel and wood pellets. Direct international trade of bioenergy commodities increased from 200 PJ in 2004 to 610 PJ in 2015 [30]. Importing bioenergy is partly a necessity for countries with strong demand but small resources to make up for absolute shortages of domestic resources, but imports are also used for arbitrage reasons, i.e. to acquire less expensive fuel from international markets than would be available domestically.

The expanding international trade in wood pellets has been analysed in several studies, e.g. Refs. [22,38,39,47], and inventories based on projects that included data gathering exercise e.g. Ref. [12,16]. [47] conducted the first extensive study on wood pellet trade and wood pellet prices finding "relatively mature industrial pellet markets, compared to non-industrial ones, because of their advanced storage facilities and long-term price setting". The results of this study were derived from the Pellets@atlas[1] project which for the first time collected information on volumes, market prices and quality standards in the 27 EU countries, Norway and Switzerland between 2006 and 2008. Since then the wood pellet commoditisation process is regularly monitored via statistical reports conducted by the industry association Bioenergy Europe (formerly known as European Biomass Association/AEBIOM) and the International Energy Agency (IEA) Bioenergy Technology Collaboration Programme (TCP). While wood pellet trade evolved from national markets e.g. Ref. [23] and played a minor international role still in 2004 with 10% of direct international trade of bioenergy commodities, this share increased to 36% in 2015 [30]. Wood pellet markets tend generally to be divided into two main segments: the industrial (large-scale) market and a residential market segment serving smaller scale boilers for space heating and hot water preparation, further denoted as "small-scale heating market" (with boilers <100 kW). In industrial markets, wood pellets are used for the production of electricity and/or heat in centralised facilities

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[1] Based on data gathered between 2006 and 2008 in the IEE-project Pellets@tlas

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whereas residential market wood pellets are used for space heating and hot water preparation in residential buildings, but also in e.g. hotels using boilers or stoves [56] reports wood pellet demands in 2017 of about 9.7 million tonnes for residential heating, 3.4 million tonnes for commercial heating, 8.0 million tonnes for power only (mainly United Kingdom) and 3.0 million tonnes combined heat and power (CHP). Although there are interactions between the market segments, they are generally analysed separately as there are important differences in terms of both physical characteristics and market structures [49].

Main wood pellet consuming countries in 2017 and thus also main drivers for trade are next to the United Kingdom (7.5 million tonnes mainly electricity only), Italy (3.5 million tonnes), Denmark (3.3 million tonnes mainly CHP), Germany (2.1 million tonnes), France (1.5 million tonnes), Sweden (1.5 million tonnes), Belgium (1.4 million tonnes mainly electricity only) and Austria (1.0 million tonnes) [56]. Residential quality pellets made up more than 30% of total global pellet consumption in 2014 [1], with considerable trade streams towards and between the main residential wood pellets consuming countries Italy (IT), Germany (DE), France (FR), Sweden (SE) and Austria (AT). Pellets are delivered to the residential end-user either in bulk where pellet boilers dominate the market (in Germany & Austria) or purchased by the consumer in small-bags (~15 kg) especially in Italy and France where pellet stoves have considerable consumption shares [56]. Since January 2012 international bilateral wood pellet trade is statistically recorded based on a dedicated trade code and accessible via the International Trade in Goods Statistics (ITGS) database of Eurostat [17]. The improved data availability on trade as well as collected time series on residential wood pellet price developments allow us now to scientifically assess the European pellet market integration for residential heating in an unprecedented detail.

1.1. Key contribution and research question

In a liquid and competitive market, the price of a good or a commodity should - if transfer costs are accounted for - be the same in all locations. Perfectly functioning markets are however arguably a theoretical concept and in reality, prices in different locations will almost always differ slightly. Energy commodity price transmission is a well-established research field, historically focusing on the national and international trade of fossil fuels. Co-integration of US natural gas markets based on spot and future price time series have been conducted in Refs. [21,53] and with regard to the liberalisation of the European gas market in Ref. [33]. More recent publications focus on the correlation between energy prices including biofuels and agricultural commodity prices [10,11,31], the impact of variable wind power production on joined electricity markets [20] and the information spillovers of crude oil of different origins, among each other [3,55] and with the carbon market [52]. Also, Olsson et al. [39] already analysed interactions between the pellet markets of Sweden, Germany and Austria using price series up until 2008. Their conclusion was that Germany and Austria could be considered integrated markets in the sense that price fluctuations in the two countries are interconnected. Sweden however constituted a separate market. In a later publication Olsson and Hillring, (2014) find cointegration between Swedish and Danish wood pellet prices in the time frame 2001–2011.

The concept of market integration in these studies mainly focuses on the co-movement of price developments between partner countries. Energy market studies which are analysing time series of physical trade flows exist too. They focusing e.g. on the network structure of crude oil imports [13,34] but scientific literature exhibit a gap in linking price information spill overs to actual trade streams. Barrett and Li, (2002) argue that a distinction should be made between market integration, which can be evaluated based on price time series co-integration, and competitive spatial equilibrium (CSE), hence market efficiency also including actual trade dynamics. This thinking emerged from agricultural economics, where also the most influential theoretical developments and methodology application can be found until today. These studies mainly focus on wheat, maize and soya prices and respective trade flows [4,9,36,51]. Lately this approach was also used to discuss price dynamics and market relations in silicon trade for PV [54], and even the convergence of natural gas markets [6,14]. However, no studies are known to the authors addressing competitive spatial equilibrium and market efficiency of bioenergy markets.

Based on the literature analysis we are applying the theoretical framework of market efficiency and CSE analysis onto the emerging renewable bioenergy commodity market of wood pellets for residential heating. This particular bioenergy sector has the advantage of exhibiting many, geographically spread buyers and sellers internationally trading a homogenised bioenergy intermediary. These traits and the underlying data availability render this product a highly commoditised bioenergy carrier [40] and the first in line to be analysed before e.g. pellets for power production, liquid biofuels or biomethane. The objective of this study is to establish a framework to test the European residential wood pellet market for competitive spatial equilibrium. Do residential wood pellet price differences trigger trade streams? The aim is to better understand the developments of European pellet market integration as well as to draw conclusions about market functions. In return, these insights can support the discussion on how to ensure supply, demand and price stability of this market for a continuous substitution of fossil fuel based residential and commercial heating. Due to limitations in data availability but also due to their leading role in European residential wood pellet heating, we focus our analysis on the four national markets; Italy, Germany, France and Austria. The data and econometric script for the R Programming environment used for this publication can be openly accessed.[2] A data-in-brief publication is published in parallel describing in detail the utilised data sets, the data collection and preparation methodologies as well as the input such as national tax developments for the necessary data homogenisation [57].

2. Theory and methodology

2.1. Definition of market related properties and trade regimes

Barrett and Li, (2002) argue that a distinction should be made between market integration and competitive spatial equilibrium, hence market efficiency. In their terminology, if there is trade in a good between two geographically distinct markets, the two markets are by definition integrated. However, physical trade flows do not automatically mean that market fluctuations completely dissipate between the two. In order to clarify this difference, Barrett and Li emphasize the concept of competitive spatial equilibrium as a more distinct description of market interactions.

Barrett and Li present six different regimes that can be used to describe the relationship between different markets in terms of price differentials, transfer costs and trade flows:

1. Perfect integration with trade: Cross-border trade leads to competitive spatial equilibrium, i.e. all arbitrage opportunities are exhausted (arbitrage conditions are binding).

[2] https://github.com/schipfer/econometrics.

2. Perfect integration without trade: Competitive spatial equilibrium exists but arbitrageurs do not trade since they face zero marginal returns and hence are indifferent about trading or not.
3. Inefficient integration with positive marginal profits to arbitrage: Trade occurs but arbitrage opportunities are not exhausted remaining with price differences larger than transfer costs.
4. Segmented Disequilibrium: Price differences are larger than transfer costs, still no trade between the countries is triggered.
5. Inefficient integration with negative marginal profits to arbitrage: Trade occurs even though price differences are lower than transfer costs.
6. Segmented equilibrium: No trade between countries is triggered because marginal profits to arbitrage would be lower than transfer costs.

While regime 1, 2 and 6 describe a competitive spatial equilibrium, the remaining regimes indicate the presence of long-run profit-maximising strategies or short-run information failures [43]. We interpret regime 3 and 4 with foregone/or uncleared arbitrage opportunities and that positive marginal profits have not been exhausted due to short-run information failure i.e., traders did not know and could thus not act upon this opportunity. Other explanations for foregone arbitrage opportunities could be barriers like buyers valuing intrinsically the regionality of the products or the trust to established supply sources. We expect regime 5 to be induced by long-run profit maximising strategies such as over the counter (OTC-) forward- or other long-term contracts (LTCs). These contracts could explain why trade between two countries occur even though prices in the sending country are more favourable for deals on the domestic market. Other explanations for regime 5 could be short-run information failure about domestic market prices or also “significant unobservable transaction benefits (e.g. first mover advantage)” according to Barrett and Li, (2002).

To test for the different regimes in the European residential wood pellet markets we investigate the time-series characteristics of the residential wood pellet prices and bilateral trade data 1) to illustrate and quantify their characteristics and 2) to check if changing price differences did impact on the trade behaviour between these focus countries. For trade relations without co-moving prices we expect e.g. increasingly favourable price differences to increase trade. Thus, we expect arbitrageurs to partly clear marginal profits efficiently enough to observe an impact in the trade data, however not exhausting these profits which would drive the spatial markets towards equilibrium. We analyse the underlying prices time series and test for best fitting seasonal auto regressive integrated moving average models (ARIMA-models) for the trade data itself before we compare their accuracy with the accuracy of best fitting seasonal ARIMA models with price differences as exogenous variables.

2.2. Time series analysis and model comparison

A time series is defined as (weakly) stationary if its mean and auto covariance is time independent. This is when the process can be described as an autoregressive (AR) process with the parameter $|\phi| < 1$.

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

For $\phi > 1$, the series will grow exponentially and for $\phi < -1$ its amplitude grows indefinitely. In the unit root process with $|\phi| = 1$, the series will not exhibit any clear tendency to return to a long-run average. Especially for prices time series the last case is of specific interest: According to Fama [19], prices can be described as a random walk process, if all available information is always fully reflected in the current price. We can transform non-stationary time series into stationary ones by differentiation, if the mean is the reason for non-stationarity. For time series the number d of differentiations necessary in order to yield a stationary series gives its “order of integration” $I(d)$ (see e.g. Johansen, [28].

To test for unit roots in time series Phillips and Perron [45], proposed to test the null hypothesis that a time series is $I(1)$. Furthermore, and in general, two time series which are $I(1)$ will also have linear combinations of $I(1)$. However, if there exists a linear combination which can be described as an $I(0)$ process, the respective two series will not drift apart from each other indefinitely in the long run. These time series will follow a common stochastic trend and are further denoted as cointegrated [48]. Engle and Granger [15], suggested to estimate the relationship between two time series with the same order of integration by performing Ordinary Least Square (OLS) regression and to test the regression residuals for stationarity. If the null hypothesis of no-stationarity can be rejected for both sets of regression residuals, one set for each time series as dependent and independent variable, the time series are cointegrated.

Auto regressive moving-average (ARMA) models can be used for stationary time series where values depend linearly on previous values. These models consist of an AR-part with the variable being regressed on its own past values based on different time lags p as well as a MA-part with the error term being a linear combination of past error terms based on different time lags q. For processes which are $I(d)$, time series are differenced until stationarity and estimated using an auto regressive integrated moving average (ARIMA) model. Furthermore, for daily, weekly, quarterly and monthly data additional seasonal differencing is useful to overcome autocorrelation of residuals in the 24th, 7th, 4th or 12th lag respectively. Seasonal differencing can be again performed for the values, indicated by P, the error terms, indicated by Q and the one-step differentials, indicated by D. Seasonal ARIMA models can be written in the following notation:

$$ARIMA(p, d, q)(P, D, Q)_s \tag{2}$$

where (p, d, q) give the non-seasonal part and $(P, D, Q)_s$ the seasonal part with the suffix s as the number of observations for each seasonal cycle. For the general seasonal ARIMA process y_t denotes the solution of the following equation

$$\Phi(B^s)\phi(B)\nabla_s^D\nabla^d y_t = c + \beta X_t + \theta(B^s)\vartheta(B)\varepsilon_t \tag{3}$$

where ε_t is the white noise process, c the intercept and X_t the exogenous variables multiplied by its regression coefficient β (Papaioannou et al., 2016). The delta operator is defined as

$$\nabla_s^D = \left(1 - B^s\right)^D \tag{4}$$

respectively

$$\nabla^d = (1 - B)^d \tag{5}$$

and the backward shift (or lag-) operator used as

$$B^k y_t = y_{t-k} \tag{6}$$

Furthermore, the backshift polynomials are defined as

$$\Phi(B^s) = 1 - \Phi B^s - \ldots - \Phi_P B^{Ps} \quad (7)$$

$$\phi(B) = 1 - \phi_1 B - \ldots - \phi_p B^p \quad (8)$$

$$\theta(B^s) = 1 + \theta B^s + \ldots + \theta_Q B^{Qs} \quad (9)$$

$$\vartheta(B) = 1 + \vartheta_1 B + \ldots + \vartheta_q B^q \quad (10)$$

In order to identify the optimal combination of seasonal and non-seasonal model parameters and consequently also to test the added value of exogenous variables, several analytical steps are performed upon the wood pellet trade data. First the data is inspected for any anomalies. Beside the need for differentiation to stabilise the mean of the time series also the application of a logarithmic operator could be necessary to stabilise the variance of the time series. The following steps are performed using the algorithm from Hyndmann and Khandakar, (2008). The number of observations in the seasonal cycle can be mostly fixed based on the context, for the monthly data in this study we choose $s = 12$. Based on the OCSB-test [42] the time series is tested “whether the seasonal pattern changes sufficiently over time to warrant a seasonal unit root, or whether a stable seasonal pattern modelled using fixed dummy variables is more appropriate.” After adjusting to seasonal stationarity (for D > 0) or by using the original data (if D = 0), the successive Kwiatkowski-Phillips-Schmidt-Shin test (KPSS-test) [32] is used to determine the number of differences which are necessary to render the remaining series stationary. Thus, the data is tested for a unit root and in case of significance, the differenced data is tested for a unit root and so on. The test is stopped as soon as the first insignificant result is obtained. Next, values of autoregressive order p, and moving averaged q and seasonal counterparts P and Q are identified by minimising the Akaike's Information Criterion (AIC) for all permutations. The residuals of the respective models are summarised as root mean squared error (RMSE). The RMSE is minimised during the parameter estimation process for each model. By minimising the Akaike's Information Criterion (AIC), simplicity in terms of number of independently adjusted parameters within the model is traded-off against the maximum likelihood of each model [2] and the most adequate (p, d, q) and $(P, D, Q)_{12}$ combination is selected. Furthermore, the used algorithm allows for $c \neq 0$ thus includes possible constants, as drifts (for ARIMA-models) and non-zero means (for ARMA-models) where feasible.

By using the Ljung-Box portmanteau test [35], the white noise behaviour of the residuals of the combination and its respective model in question is tested. More specifically, with the Ljung-Box test we check the null hypothesis of serial correlations of the residuals, which can be rejected at a p-value greater 5%. The test requires the selection of the number of lags h which is recommended with $h = 2s$ for seasonal and $h = 10$ for non-seasonal data in Hyndman and Athanasopoulos, [25]. If the null hypothesis can be rejected, no evidence for serial correlation is given and the model is said to capture the information in the data perfectly.

After finding the optimal seasonal ARIMA-model for the wood pellet trade data, we repeat the process including this time the wood pellet price differences as exogenous variable. Therefore, the algorithm from Hyndmann and Khandakar, (2008) fits a regression with ARIMA errors. After rejecting the null hypothesis of serial correlation of the residuals of the model with exogenous variables, the seasonal ARIMA and the seasonal ARIMAX models are compared using the Bayesian Information Criterion (BIC) as well as the mean absolute scaled error (MASE):

While the AIC can only be used to compare models of one and the same data set we have to consider an augmented criteria to discuss the added value of additional exogenous variables in relation to their simple sARIMA-models. Therefore, we use the BIC, which also penalises the complexity of the model based on the number of observations of the data set. The model with the lower BIC is identified as better model in terms of simplicity and maximum likelihood.

Hyndman et al. [26],proposed the MASE to measure the relative reduction in error compared to a naïve model. Therefore, the mean absolute error of the ARIMA model is divided by the mean absolute value of the naïve model, or in case of a sARIMA by the mean absolute value of a seasonal naïve model. A MASE close to unity therefore identifies no additional predictive power of the model in question while a lower value refers to more useful models.

3. Results

In order to test if markets are integrated in terms of transmission of price fluctuations we have to first test for co-integration of the price time series. Therefore, the Phillips-Perron Test was used to test for Unit Roots in the prices time series. The test results are given in Table 1 & Table 2 with their statistical significance indicated via asterisks, differentiating between a 10% significance level (*), 5% significance level (**) and a 1% significance level (***). In addition, the lag lengths are given in parenthesis. In Table 1 the test statistics from the tests on the individual variables are summarised. The hypothesis of stationarity can be rejected for the first difference of the time series, but not for the original time series. All time series are integrated in the same order. However, the results are only truly informative for the Austrian and the German time series. 1) The French prices, even though publicly available on a monthly basis, contain non-changing values mostly over a period of three months while 2) the Italian prices are only collected and available for a period of two to four months.

In the next step a pairwise Engle-Granger test is performed for the time series, where data quality suffices (Germany and Austria) in order to determine if any of the combinations are cointegrated during various time ranges (Table 2). Therefore, the time series are OLS-regressed and the resulting residuals are tested for Unit Roots. Test results are compared with the critical values for cointegration from Phillips and Ouliaris [44], to find, that they are above the 10% confidence interval for the time period 2006–2012 but below for the periods 2000–2006, 2012–2020 and the entire time series 2000–2020. Thus, the hypothesis for no-cointegration between Austrian and German prices cannot be rejected for the 2006–2012 time period, but can be rejected for the entire price time series as well as the last seven years (2012–2020), for which also time series on physical trade streams exist and which we want to further analyse for competitive spatial equilibrium.

The prices time series furthermore indicate seasonality with prices usually being highest during the heating seasons and lowest in the spring months for all countries (see data in brief). For the year 2012 and 2014 it could be argued, that the price lows in the residential heating market were caused by oversupply due to a fire and followed shut-down in a large wood pellet power producer (RWE, Tilbury UK, February 2012) and another power producer based on

Table 1
Results from stationarity tests of the individual wood pellet prices time series.

Time series	Levels	First difference
AT	−14.222 (3)	−58.209 (3)***
DE	−12.271 (3)	−40.263 (3)***
FR	−10.969 (3)	−98.747 (3)***
IT	−19.506 (3)	−40.402 (3)***

Table 2
Results from PP-unit root test for residuals of linear combinations of Austrian and German prices.

Flow	Time periode	Parameter
DE < - AT	2000 to 2006	−21.096 (3)**
DE < - AT	2006 to 2012	−14.555 (3)
DE < - AT	2012 to Mar.2020	−36.313 (3)***
DE < - AT	2000 to Mar.2020	−36.667 (4)***
AT < - DE	2000 to 2006	−15.446 (3)
AT < - DE	2006 to 2012	−17.412 (3)
AT < - DE	2012 to Mar.2020	−31.679 (3)***
AT < - DE	2000 to Mar.2020	−35.74 (4)***

wood pellets going off the grid in Belgium in March 2014 (Max Green). Since these exceptional periods residential wood pellet prices including the diverse and changing value added tax are in general lowest in Austria, followed by Germany, France and Italy. Trade flows towards more expensive countries can be expected with trade signals becoming stronger when price spreads are larger.

3.1. Modelling of trade flow patterns with and without price differences

In Table 3 and Table 4 best fitted models for the most important bilateral trade streams and their respective accuracies and test statistics are listed. Only models passing the Ljung-Box portmanteau test of no remaining serial correlations in the residuals are listed.

Most identified optimal trade models include an unambiguous seasonality in the trade relations. The algorithm finds non-seasonal integrated moving average models only for the net-exports with Germany as a reporter and Austria as well as France as partner. However, the MASE-value for the latter trade flow has to be reported close to unity rendering the identified model the worst fit in the listed examples. For the other trade flows, best-fitting seasonal ARIMA models are identified with zero means and no trends for Germany to Austria and with a non-zero mean for net-exports from Austria to Germany. Especially for net-exports from Germany to Austria also the strongest boosting effect of increasing price differences exhibiting a positive impact on the trade behaviour can be outlined, which can also be observed to be positive in most other cases. Only for the net-export from Austria to Germany a negative impact of the exogenous price differences variable is calculated. Regarding this discrepancy of the symmetrical net-export flow from Germany to Austria, it has to be anticipated, that cumulated net-exports for the entire time frame from Austria to Germany are at about −413 thousand tonnes while cumulated net-exports with Germany as a reporter point of view are at about 841 thousand tonnes, which is one of the most striking asymmetries in the data of this double-book keeping entry system.

However, the added value of including price differences to explain trade can only be determined by comparing the best fitting models from Table 3 to the best fitting models without price differences as exogenous variables (Table 4). An extreme negative

Table 4
Best fitting models for bilateral trade streams (net-trade) **without** price differences as exogenous variable.

Flow	Model type	Const.	BIC	MASE
DE < -AT	ARIMA (0,0,1) (1,1,0)[12]		1481.92	0.75
IT < -AT	ARIMA (0,0,1) (0,1,1)[12]with drift	331	1696.97	0.66
AT < -DE	ARIMA (0,1,1)		1911.52	0.45
IT < -DE	ARIMA (2,1,1) (2,0,0)[12]		1907.55	0.61
FR < -DE	ARIMA (0,1,1) (1,0,0)[12]		1795.21	0.64
IT < -FR	ARIMA (1,1,1) (0,1,2)[12]		1538.05	0.47

example for low added-value can be seen in the trade with Germany as reporter and France as partner, where the MASE-value is significantly better when modelled without exogenous variables. The other MASE-values are comparable between the two modelling approaches but in general slightly worse (higher). However, all BIC values are slightly lower indicating better fits weighted by complexity of the model for the selected best-fitting models with prices as exogenous variables. The only exception with a lower BIC value for the best fitting model without prices as exogenous variables is found for the discussed controversial net-export flow from Austria to Germany for which profit margins counterintuitively result in less trade.

3.2. Results summary

We tested for market integration and efficiency between the most important wood pellets for heating markets using on the one hand traditional prices time series co-integration tests. On the other hand, we employed an algorithm to compare best fitting seasonal or non-seasonal ARIMA models to identify the impact of price differences on the physical trade streams between the countries.

In summary, we find integrated wood pellets for small-scale heating markets in terms of observed trade flows between Italy, Germany, Austria and France. In terms of prices only Germany and Austria could be tested for cointegration. Contrary to previous literature [8,24,39] which analysed different time frames, these time series cannot be said to be cointegrated for the 2006−2012 time period, but can be said to be cointegrated for the entire price time series (2001−2020) as well as the last eight years (2012−2020), which are subject to further investigations including physical trade flows.

Since the first publication of the wood pellet trade data on Eurostat, 100 months of trade flow data points over eight heating seasons have been recorded. We allow a model fitting algorithm to select the optimal model in terms of simplicity and maximum likelihood, combining prices and trade flows. All generated models, except the model for net-exports from Austria to Germany indicate that price differences boost trade towards partner countries where wood pellet prices are higher. Still, we have to admit, that the optimal models including price differences as exogenous variables are not found to perform significantly better than their ARIMA and sARIMA counterparts. The model pairs would have to exhibit

Table 3
Best fitting models for bilateral trade streams (net-trade) **with** price differences as exogenous variable (Ex. Var.).

Flow	Model type	Const.	Ex.Var.	BIC	MASE
DE < -AT	ARIMA (0,0,1) (2,0,0)[12]with non-zero mean	−4044	−47	1679.86	0.68
IT < -AT	ARIMA (0,1,2) (0,1,1)[12]		172	1663.58	0.7
AT < -DE	ARIMA (0,1,1)		401	1890.72	0.44
IT < -DE	ARIMA (0,1,1) (2,0,0)[12]		208	1884.7	0.65
FR < -DE	ARIMA (0,1,1)		36	1778.88	0.91
IT < -FR	ARIMA (0,1,2) (2,1,0)[12]		2	1527.38	0.51

significantly lower MASE and BIC values for the models with prices as exogenous variables to be able to say, that arbitrageurs clearing profit margins notably improve the predictability of trade between the focus countries, eventually leading towards a CSE.

Even though the proposed methodology does not provide good results based on the available prices- and trade data, first overall results can be derived from crossing these data-sets. The trade relation from Germany to Austria can be discussed as partly perfectly integrated with trade periods with remaining positive marginal profits. Based on the price differences, including also the different levels of value added tax, trade from Germany to Italy since mid-2013 and to France since the beginning of 2014 can be described as inefficiently integrated with remaining positive marginal profits and expected CSE for some parts of the time series. This also holds for the trade from Austria to all countries, with Austrian prices generally being the lowest. These trade streams reflect flows towards markets where wood pellets can be sold at a higher price level as in the originating national market. Furthermore, seasonality can be identified as an influencing parameter for overall imports, which appear to increase around May for Italy and Austria, when prices are generally lowest.

4. Discussion

The introduction of a harmonised trade code for wood pellets and the doubly-entry book keeping of monthly bilateral wood pellet trade in Eurostat opened up the possibility to analyse the market-related properties of the European wood pellets for small-scale heating market in greater detail than in previous research including Sikkema et al. [47], and Olsson et al., [39]. By carrying on the discussion of the wood pellet commoditisation process ([40] using commodity trade theory, mainly derived from agricultural economics [5] developing market related properties can be identified more accurately. The identification algorithm of optimal seasonal ARIMA models [27] is expected to allow for a generic characterisation of the trade time series as well as the discussion if market clearance from arbitrageurs can be observed.

However, applying the algorithm on the already extensive data set including 100 consecutive months does not result in significant evidence of price differences impacting on bilateral trade streams. The results presented in this paper as well as the data sets thoroughly discussed in the annexed data-in-brief mainly indicate inefficiently integrated residential wood pellet markets with periods of missed arbitrage opportunities. Collected opinions and feedback on our findings from stakeholders, experts and reviewers are presented in the following sections, and split into the discussion of our methodology and results, potential next steps and policy recommendations.

4.1. Methodology and results

Both, the underlying data and the results have to be interpreted with care, mostly because of a relative early stage of the wood pellets commoditisation process. As outlined in the results, trade flow data from Eurostat indicate discrepancies between arrivals from country A to B against dispatches from B to A [18]. gives several possible reasons for these so called asymmetries: 1) Different thresholds in various member states, 2) late or non-response by certain companies, 3) statistical confidentiality, 4) misapplication of the rules and delays, 5) different valuation of transactions and 6) triangular trade. Single authorisations for simplified procedures can be another reason for asymmetries. More specific information from statistical authorities with regard to wood pellets data would be necessary to discuss asymmetries for all focus countries. Following up upon these discrepancies with a pellet trader[11] specifically for France, misapplication of the rules during 2012 and the first half of 2013 due to an unexplainable overall import expansion after the summer of 2013 can be assumed, partly explaining the particularly poor modelling results of this trade flow.

Furthermore, the collection of residential wood pellet price data was labour intensive, involving personal communication with experts from statistical agencies and national wood pellet associations. No homogenous methodology is underlying this monthly average price data and, since it reflects the wood pellets prices paid by the small-scale end users, we are left with the question about how representative these prices are in describing cross-border trade mainly executed by traders and retailers. Possible deviations of regional prices from the national average and therefore the, in this paper ignored, importance of regional cross-border trade could shed additional light on the market efficiencies based on lower spatial resolutions. Also, different tax regimes as well as tax reforms impact on consumption and trade which we recommend to analyse with dedicated econometric tools.

4.2. Open questions and broader validity

Beside the uncertainties with regard to the underlying data, literature and case studies based on comparable methodologies and development stages of similar objects of investigation are missing. As discussed in the introduction, crossing price and trade data to investigate market efficiencies is still a relatively young research field and only slowly transferring from agricultural economics to energy economics. Where applied, CSE-studies focus on well established commodity markets based on reliable data sets such as publicly listed spot- and future contract prices. Addressing developments with regard to market efficiency of emerging commodities and in parallel with the commoditisation process itself holds potentials to support the market diffusion of renewable energy technologies and their respective energy commodities. Therefore, it would be interesting to apply the proposed methodology on trade and price developments of liquid biofuels, wood chips, biomethane or also other non-bioenergy commodities for which time series cover the commoditisation process.

Next steps with regard to analysing the market efficiency of wood pellets for residential heating would have to carefully trade-off additional explanatory variables with increasing model complexities. Even though trade between the focus countries exhibit a significant share in overall imports and exports, respective prices are also driven by imports from 3rd countries. Including these cumulated imports as exogenous variables in the model finding algorithm could improve the explanatory power of the results. Co-movements with fossil fuel and electricity prices as processing fuel input and as competitive heating commodities also including currently or potentially upcoming relevant sustainable heating fuel such as wood chips, straw pellets, pyrolysis oil or torrefied (black) pellets could be included. For now, the investigated sectors in the respective countries mainly use wood pellets produced from secondary feedstocks (sawdust, wood industry residues, shavings etc.) containing softwood. It is estimated, that almost only highest quality pellets (ENplus certification A1) are used to meet emission limits of wood pellet stoves (mainly used in Italy and France) and boilers (in Germany, Austria and Sweden). [56] Modelling trials could be advanced by estimating the share of lower and higher quality wood pellets in the trade flow data by comparing specific costs based on monetary and physical trade flows to current residential pellet prices. The market efficiency analysis could furthermore be integrated into dedicated forest sector balancing models, taking into consideration stocking behaviour and balancing supply and demand as well as the interactions with the forest-based sector (see e.g. Ref. [29], if these exercises can be finetuned to at least a monthly time resolution.

Furthermore, we want to highlight the need to observe and analyse how the convergence process of small-scale heating with the large-scale wood pellet market is developing. Within the EU, the wood pellet producers for small-scale heating are already competing against each other but will face more and more also pressure from producers initially serving large-scale combustion, intra- and extra-European imports but also due to low prices from conventional fuels. On the one hand, this development will improve market organisation through e.g. higher efficiency, supporting the intermediary character of the commodity and reduce prices for the end users. On the other hand, it will also push smaller producers out of the market unless e.g. they keep managing to convince the users to pay a premium for locally sourced and produced pellets.

4.3. Policy recommendations

Price volatilities for consumers are well below the volatility of other energy carriers. Still, the development towards a competitive spatial equilibrium should be supported to increase access and affordability of wood pellets on a long run. Therefore, the development of residential wood pellet price benchmarks could be (further) supported and a harmonised approach for the collection of residential wood pellet prices in consumer regions applied. Also, stronger efforts in the provision of other wood pellet related data, like traded quality types, monthly consumption and production quantities used feedstock as well as higher spatial resolution of trade data would be necessary to reduce risks and to increase transparency, thus increase liquidity of this market.

To increase competitiveness, a price benchmark or price indices would be necessary. Valiante et al. [50], discusses benchmark-based pricing mechanism "… to rely on the liquidity of a reference contract, which is typically a front-month futures contract." The report further discusses that markets tend to be organised with privately negotiated LTCs when a globally recognised price benchmark, dealing with specific regional issues, is too difficult to build. Residential wood pellet futures are available only since October 2015 and LTCs are rarely used [37]. Stability of trade relations ("established contacts and contracts") are mentioned as more important in this market than official financial instruments[11]. This shows that the wood pellet market for small-scale heating is far from an international recognised price benchmark and related stabilising and (spatially) equilibrating pricing mechanism.

Next to the necessity to increase competitiveness and liquidity of the wood pellet for small-scale heating market, also non-market related properties of the commodity need to be improved: To facilitate trading of wood pellets as an intermediary good, the risk of short-to medium term storage (several weeks up to several months) has to be reduced. This could be done by facilitating the acquisition of risk capital for building and using intermediary storage facilities but also by innovations to avoid losses and accidents in relation to storing solid biofuels. In a previous study we discuss the single most important trait of densified bioenergy carriers to be their improved storability [46], which should be harnessed to increase the flexibility of our energy system. To avoid shortages also a dedicated stock monitoring system could further reduce risks for consumers, and therefore and in a longer run also for other market actors. Furthermore, wood pellets are not perfectly fungible yet, even though technical and sustainable standardisation are developed and used. This is due to intrinsic valuation of non-quality related properties like pellets colour and more regional biomass supply chains. The latter is a characteristic which seems to be grown with the bioenergy market probably caused by the feelings and marketing practices relating to notions like "only regional is sustainable and/or transparent" and "import dependencies have to be avoided in general".

5. Conclusion

The discussed framework allows us to derive first conclusions on the current market functions of the increasing inter-European trade of wood pellets as a renewable energy commodity for residential heating. Analysing price co-movements and pellet trade streams simultaneously provides us with additional insights compared to existing literature which is mainly focusing on price time series alone. Respective trade relations between Germany, Austria, France and Italy are found to be mainly inefficiently integrated with remaining positive marginal profits while the activity of margin clearing arbitrageurs can be detected in the model comparisons. However, we have to admit that including price differences as exogenous variables does not significantly improve the predictive power of our residential wood pellet trade modelling efforts. Shortcomings in the underlying data, especially regarding the asymmetries in the double-book keeping entry system of Eurostat and the wood pellet prices have been outlined in this paper as well as in the corresponding data-in-brief document.

Based on the presented results and discussion, we list a set of parameters, concepts as well as the integration with market balancing models for the extension of the model fitting algorithm to analyse market efficiency developments during the initial commoditisation process more exactly. The overall aim of future research in this field could be to quantify the added-value of a theoretical mature and perfectly integrated global sustainable wood pellet market with considerable market transparency and reliable supply, demand and prices as well as price benchmarks. The methodological efforts based on wood pellets, the bioenergy commoditisation front-runner, would be helpful to support the introduction and market diffusion of other bioenergy and biogenic carbon products and commodities for a liquid and competitive intermediary market supplying the European bioeconomy for energy and material services.

Since wood pellet markets are still quite inefficient, we propose several policy recommendations in the discussion section to support the development towards a competitive spatial equilibrium. Improving market efficiency is indispensable if access and affordability of sustainable wood pellets are to be secured in the long-run, thus making sure, that investments in pellet boilers and stoves, mills and infrastructure contribute to the successful substitution of fossil fuel based heating technologies as well as help to achieve the climate targets. The lowest hanging fruit of the discussed policy instruments could be the introduction of a harmonised approach for the collection of residential wood pellet prices in consumer regions and stronger efforts in the provision of other wood pellet related data like traded quality types as well as monthly consumption and production quantities and inventories. This would significantly reduce risks, increase transparency and thereby support the equilibrating forces of this particular market.

Credit author statement

Fabian Schipfer: Conceptualisation, Methdology, Software, Data curation, Formal anlaysis, Writing, Project administration, Funding acquisition Lukas Kranzl: Supervision, Writing Olle Olsson: Methodology, Investigation, Writing, Conceptualisation Patrick Lamers: Investigation, Writing, Conceptualisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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