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Fuelwood S4 as a Forest Bioenergy Resource in Poland: Price and Sales Volume Dynamics

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Abstract

This study aims to examine fuelwood S4 as a forest bioenergy resource in Poland by analysing real price dynamics, sales-volume changes and short-term price–volume relationships in 2005–2024. This study contributes to the literature by linking the S4 fuelwood assortment with local biomass-energy availability and by analysing its monthly price–volume dynamics in an institutionally managed primary timber market. Monthly data from the State Forests National Forest Holding for five species groups—pine, spruce, oak, beech and birch—were used. The analysis combined descriptive statistics, seasonal indices, stationarity and cointegration diagnostics, Granger-type predictive tests and autoregressive distributed lag (ARDL)-type fixed-effects dynamic panel models. The results show that sales volume was more volatile than real prices and displayed strong seasonality, with the highest average sales in March and the lowest in January. Pine accounted for the largest share of sales volume, while oak and beech represented higher-priced segments. Between 2005 and 2024, total timber sales increased by 27.1%, whereas S4 fuelwood sales increased by 77.0%. The diagnostics did not provide consistent evidence of a stable long-term equilibrium between real prices and sales volume; therefore, the main econometric analysis focused on short-term dynamics. Lagged real price changes were positively and significantly associated with subsequent sales-volume dynamics, and this relationship remained robust across alternative lag specifications. The sum of lagged real-price coefficients was positive and statistically significant in all ARDL-type specifications, ranging from 1.053 to 2.162, with Wald-test p-values from <0.001 to 0.018. The findings indicate that fuelwood S4 should be interpreted not only as a timber assortment, but also as a limited forest bioenergy resource whose market behaviour is shaped by species structure, seasonal patterns and short-term adjustment within an institutionally managed timber sales system.

Keywords: fuelwood; S4 assortment; forest biomass; bioenergy; timber market; real prices; sales volume; econometric analysis; ARDL-type model; Poland

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1. Introduction

The energy transition, fuel price instability and the growing importance of energy security have sustained strong interest in renewable energy sources. Biomass is an important renewable energy carrier because it can be used in solid, liquid and gaseous forms, and its applications include heating, electricity generation and transport [1,2]. Unlike some renewable energy sources, biomass can be stored and used during periods of increased energy demand, which strengthens its role in local and regional energy systems [1,3]. In European Union (EU) policy, the development of renewable energy sources is supported, inter alia, by the Treaty on the Functioning of the European Union, Directive 2018/2001/EU and its

amendment by Directive 2023/2413/EU [4–6]. In this context, solid biomass remains an important component of renewable energy, particularly under conditions of decarbonisation, fossil fuel price instability and the search for alternative heat sources [3,7,8].

Forest biomass occupies a specific position in the bioenergy sector. It is linked to forest management and the wood industry, as well as to energy markets and local heating needs. At the same time, its use for energy purposes is increasingly assessed in the context of greenhouse gas emissions, biodiversity protection, competition for wood and the future availability of woody resources in Europe [9–11]. The potential of biomass is not unlimited. It depends, among other things, on resource availability, competition with material uses of wood, supply structure, transport costs and the requirements of sustainable forest management [3,12,13].

Fuelwood represents a specific segment of forest biomass. Unlike more processed fuels, such as wood pellets, it is less standardised and more dependent on local availability and traditional heating practices [14–16]. Globally, fuelwood remains one of the oldest and still widely used sources of energy, especially in households and regions with limited access to modern energy carriers [17,18]. The literature indicates that fuelwood use is strongly spatially differentiated and depends on household income, the availability of alternative fuels, local heating practices and climatic conditions [14,15,19]. In Europe, fuelwood performs a different function than in many developing countries. It is used primarily for space heating, often in small-scale heating appliances such as stoves, fireplaces and boilers [20–22]. Its importance increased particularly under the conditions of the energy crisis and high gas and electricity prices [7,23]. In southern Norway, wood consumption for heating increased by approximately 40% in 2022, replacing part of electricity consumption, which reflected households' response to high energy prices [24]. Studies conducted in France showed that the choice of wood as a heating fuel is associated with household income, energy prices and the technological characteristics of heating systems [14]. Stojilovska et al. [15] indicated that in Central and Southern Europe, fuelwood may be not only a fuel but also a strategy for coping with energy poverty. A similar importance of fuelwood for rural households was shown in studies from Hungary and Slovenia, where firewood remains an important element of household heating systems [21,22]. Kożuch et al. [23] also demonstrated an increasing trend in the consumption of primary woody biomass in Europe, with fuelwood harvesting and consumption increasing particularly in Czechia, Germany, Estonia, Denmark and the United Kingdom, despite decreases observed, among others, in France and Spain. This means that fuelwood should be perceived not only as a product of forest management, but also as a resource of economic and social importance.

The importance of fuelwood should, however, be interpreted with caution. On the one hand, locally available wood may reduce dependence on fossil fuels, strengthen household energy security and reduce vulnerability to energy price spikes [15,16,23]. On the other hand, excessive or uncontrolled energy use of wood may create pressure on forest resources, greenhouse gas emissions, air pollution and adverse health effects [9,25]. Life cycle assessment (LCA) studies also indicate that the environmental balance of firewood and pellets depends, among other things, on combustion technology, fuel form and supply-chain length [26]. Fuelwood should therefore be treated as a local resource with considerable energy potential, but one that requires monitoring and sustainable use.

Poland, due to its transition away from coal and its substantial woody biomass resources, represents an interesting case for studying fuelwood as an important biomass energy resource. Previous studies on woody biomass in Poland have covered forest resources, wood-industry by-products, wood chips, pellets and the energy potential of fuelwood and residues from roundwood processing [12,13,16]. The results of these studies indicate that the availability of woody biomass depends on forest structure, species compo-

sition, harvesting conditions, raw material moisture content, seasonality, regional resource distribution and competition for raw material [12,13]. Wood pellets are more strongly linked to international trade and industrial supply chains [27,28]. Fuelwood differs from this segment because it is more local, less processed, more closely related to the direct heating needs of households and more dependent on the organisation of sales on the primary timber market [14–16].

A particularly interesting assortment is medium-sized S4 fuelwood, sold on the Polish primary timber market. Its availability depends on the age and species structure of stands, harvesting plans and schedules, assortment classification, local resource conditions and sales procedures. For this reason, changes in S4 sales volume should not be interpreted solely as a simple supply response in a fully competitive market. It is more appropriate to treat them as short-term adjustments in sales volume within the timber sales system managed by the State Forests National Forest Holding (SF NFH). This perspective combines the forest, energy and social dimensions of the fuelwood market.

Previous studies on fuelwood, biomass and forest product prices indicate that the dynamics of these markets are most often analysed using time-series methods, forecasting models, cointegration and panel approaches. In relation to fuelwood and biomass, autoregressive integrated moving average (ARIMA) and seasonal autoregressive integrated moving average (SARIMA) models, artificial neural networks (ANNs) and hybrid ARIMA–ANN models have been used to identify trends, seasonality and irregular price fluctuations [29–32]. In studies on timber market integration and price linkages, cointegration tests, vector error correction models (VECMs) and Granger causality tests have been applied, indicating that wood and biomass markets often exhibit limited integration, strong seasonality and differentiated responses to demand and energy shocks [33–37]. Previous studies on woody biomass availability have also emphasised the role of forest structure, species composition, harvesting conditions, raw material quality, moisture content, transport costs and competition with material uses of wood [12,13,16]. Despite these contributions, little attention has been paid to the short-term relationship between real fuelwood prices and sales volumes in institutionally managed primary timber markets. This gap is particularly important for S4 fuelwood in Poland, which functions as a clearly identifiable forest assortment strongly linked to retail sales. Knowledge of these short-term price–volume relationships may support the monitoring and organisation of fuelwood supply within the State Forests timber sales system. The novelty of this study lies in its species-level analysis of short-term price–sales relationships for S4 fuelwood within the institutionally managed State Forests timber sales system, thereby moving beyond aggregate assessments of fuelwood markets and woody biomass resources. The econometric approach combined stationarity and cointegration diagnostics, Granger-type predictive tests and ARDL-type fixed-effects models. This approach was used because the dataset includes monthly observations for several tree species and this study focuses on short-term lagged relationships between real prices and sales volume. It also allows species-specific differences and recurring monthly patterns to be taken into account.

The aim of this study is to assess the dynamics of real prices and sales volume of S4 fuelwood in Poland and to identify short-term relationships between changes in real prices and subsequent sales dynamics. Particular attention is paid to seasonality, species differences and lagged responses of sales volume to changes in real prices. This approach makes it possible to better understand the role of S4 fuelwood as a forest bioenergy resource functioning within an institutionally managed timber sales system.

2. Market Background: Fuelwood S4 as a Local Biomass Energy Resource in Poland

2.1. Fuelwood as an Energy Resource for Individual Consumers in Poland

Fuelwood continues to play an important role in household energy supply, particularly in rural and local areas where the use of solid fuels for heating remains significant. Unlike more processed biomass fuels, such as pellets or wood chips, fuelwood is directly linked to the primary timber market. Its availability depends not only on household heating demand, but also on local forest resources, the organisation of timber sales and the principles of assortment classification.

The importance of fuelwood should also be considered within the broader context of the wood economy. In Poland, wood is regarded as a strategic raw material [38], while previous studies have shown that wood-derived by-products and residues perform an important role in both material and energy uses [39–42]. Against this background, S4 fuelwood occupies a specific position, as it does not constitute a typical stream of industrial biomass, but rather an assortment directly associated with retail sales and household energy consumption.

For this reason, the analysis of S4 prices and sales volumes provides a better understanding of the role of locally available forest biomass in supplying households with heat, particularly under conditions of changing prices of other energy carriers.

2.2. Fuelwood-Related Assortments and the Share of S4 in Total Timber Sales

In the primary timber market in Poland, several assortments that could be used for energy purposes were offered during the study period. These included, among others, S2AC, defined as medium-sized energy wood available until 2019; M2ZE, wood residues in the form of chips; M2BE, wood residues in the form of bales or bundles; S4, medium-sized fuelwood; and M2, small-sized fuelwood commonly referred to as branchwood (Table 1) [43–45]. Among these assortments, S4 wood is of particular importance, as it is closely linked to the retail market and to the potential use of wood as a household energy carrier. Throughout the analysed period, S4 represented the lowest-quality medium-sized assortment in the dimensional and quality hierarchy of roundwood and was intended primarily for fuel purposes. It was mainly sold through retail channels to individual buyers. According to the technical documents used in the State Forests timber sales system, S4 was recorded throughout 2005–2024 as a separate fuelwood assortment. Therefore, the long-term comparison of S4 prices and sales volume refers to the same identifiable assortment category across the whole study period [45,46].

For some of the other assortments, particularly M2, the interpretation of sales volumes and price levels is more difficult. Part of M2 wood may have been harvested under the self-harvesting system, in which the buyer bears the cost and responsibility for extracting and preparing the raw material. In such cases, the recorded price does not reflect the full cost of preparing fuelwood, but rather the price of raw material left for harvesting and further preparation by the final consumer. Against this background, S4 wood provides a more homogeneous and comparable basis for assessing the primary fuelwood market in Poland.

Between 2005 and 2024, total timber sales in the State Forests National Forest Holding increased from 31.95 million m^3 to 40.61 million m^3, representing a 27.1% increase. Over the same period, the sales volume of S4 fuelwood rose from 2.10 million m^3 to 3.72 million m^3, corresponding to an increase of 77.0%. Fuelwood, comprising the S4 assortment and small-sized M2 wood, accounted on average for 11.8% of total timber sales in the State Forests National Forest Holding in 2005–2024, equivalent to an average of 4.41 million m^3 per year. Within this structure, medium-sized S4 fuelwood accounted on average for 7.9% of

total sales, corresponding to approximately 2.95 million m^3 annually. The highest share of fuelwood in total sales was recorded in 2022–2024, when it averaged 14.4%. This indicates that the importance of fuelwood assortments increased faster than total timber sales. It also points to a clear structural shift towards a higher share of fuelwood, particularly after 2021 (Figure 1).

Table 1. General characteristics of selected assortments potentially suitable for energy purposes in the State Forests timber sales system.

Assortment Code	Description	Physical Form	Typical Buyer/Market Channel	Period of Availability/Remarks
S2AC	Medium-sized energy wood	Medium-sized roundwood or stacked wood	Business or institutional buyers	Available until 2019
M2ZE	Small-sized wood residues in the form of chips	Chips	Business or institutional buyers	Included in Order No. 24/2021
M2BE	Small-sized wood residues in the form of bales or bundles	Bales/bundles	Business or institutional buyers	Related to M2E; low sales volume
S4	Medium-sized fuelwood	Stacked fuelwood	Individual buyers/ retail sales	Available throughout 2005–2024; main assortment analysed
M2	Small-sized fuelwood, commonly referred to as branchwood; partly linked with self-harvesting arrangements	Small-sized wood	Individual buyers/ retail sales	Available throughout 2005–2024; partly self-harvested

Note: The table is based on the State Forests assortment terminology, Order No. 24 of the Director-General of the State Forests of 27 April 2021 [43], and the approach presented by Radomska et al. [44]. Potential suitability for energy purposes does not necessarily mean actual energy use.

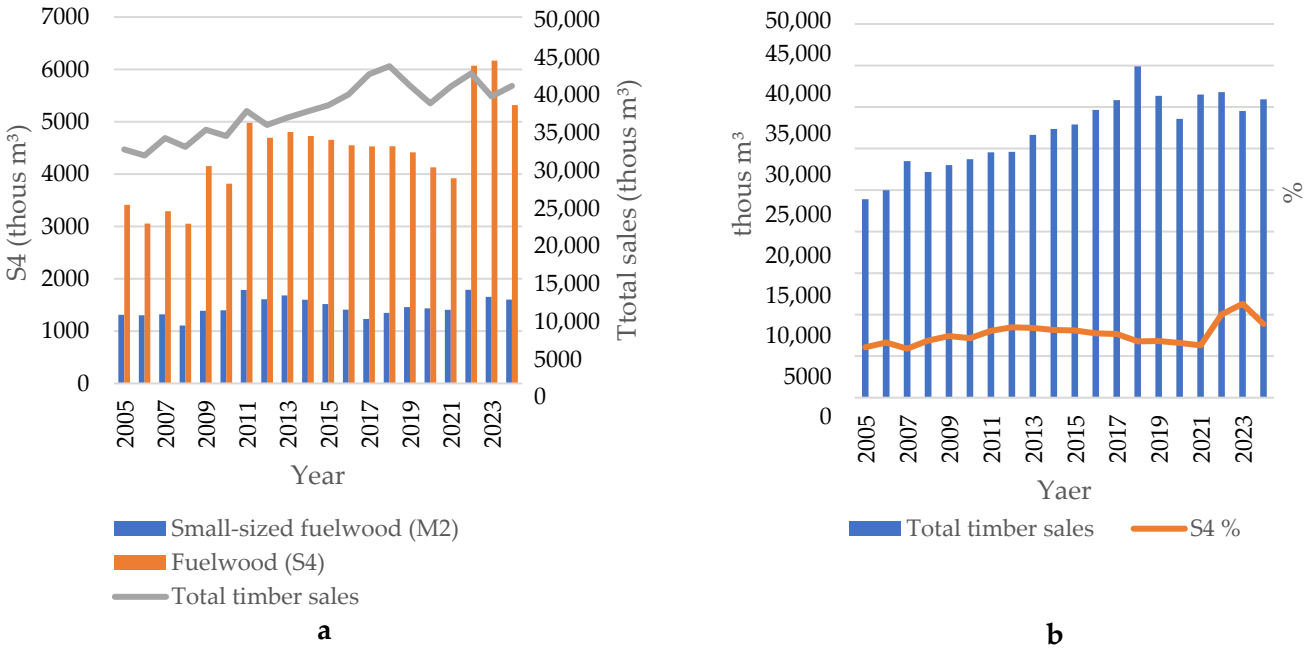


Figure 1. Timber and fuelwood sales in the State Forests National Forest Holding in 2005–2024: (**a**) total timber sales and sales of fuelwood assortments S4 and M2; (**b**) total timber sales and the share of S4 fuelwood in total timber sales. Values are expressed in thousand m^3.

In 2005–2024, sales of S4 fuelwood were characterised by greater variability than total timber sales in the State Forests National Forest Holding. The coefficient of variation for S4 was 24.5%, compared with 9.9% for total sales. Between 2021 and 2022, total timber

sales in the State Forests National Forest Holding increased by 4.4%, whereas sales of medium-sized S4 fuelwood rose by as much as 70.3%, and sales of small-sized M2 wood by 27.3%. Such a strong increase in S4 volume, accompanied by only a modest increase in total sales, suggests that the growing importance of fuelwood resulted not only from an overall increase in timber sales, but also from a change in the assortment structure of sales.

Over the entire analysed period, non-coniferous S4 wood was slightly more important than coniferous S4 wood. The average share of non-coniferous wood in the S4 structure was 53.6%, compared with 46.4% for coniferous wood. The maximum sales volumes for both groups were recorded in 2023: 2.32 million m^3 for non-coniferous S4 and 2.19 million m^3 for coniferous S4. This means that the increase in the importance of fuelwood after 2022 concerned both non-coniferous and coniferous assortments, although non-coniferous wood slightly predominated over the entire period.

These results justify further analysis of S4 fuelwood as a locally available forest bioenergy resource within the State Forests timber sales system. The empirical analysis therefore focuses on monthly S4 sales volumes, real prices and short-term price–volume relationships.

2.3. Technical Characteristics of S4 Fuelwood

According to the technical requirements applied in timber trade within the State Forests National Forest Holding, medium-sized S4 wood is classified as stacked wood intended for fuel purposes. The dimensional requirements allow nominal lengths ranging from 1 to 3 m, while standard lengths include, among others, 1.20 m, 1.80 m, 2.40 m and 2.50 m. The minimum top diameter under bark is 5 cm, whereas the bottom diameter is not limited.

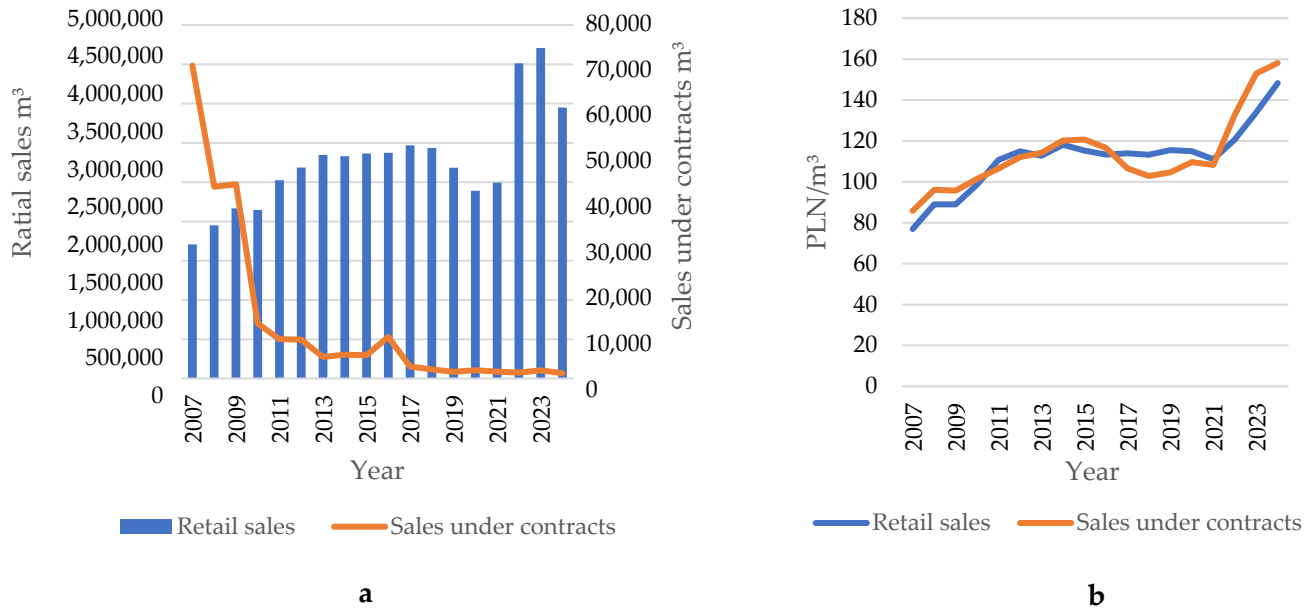
In terms of quality, the S4 assortment is characterised by the lowest requirements among medium-sized wood assortments. Defects such as single- and multi-sided curvature, discoloration, charring, deep insect galleries and the presence of foreign bodies are permitted. Soft rot is allowed on up to 50% of the end-face area. These requirements confirm the fuelwood character of this assortment and distinguish it from medium-sized wood intended for industrial processing [45,46].

2.4. Retail Character of the S4 Fuelwood Market

The distribution structure of S4 fuelwood is a key element in assessing its role as a local household energy resource, since this assortment was sold almost exclusively through retail channels. In 2007–2024, sales of S4 fuelwood were dominated by retail sales. Over this period, 49.73 million m^3 of S4 fuelwood was sold through retail channels, accounting for 99.5% of the total sales volume of this assortment. Sales based on contracts were marginal, amounting to 0.23 million m^3, or only 0.5% of total S4 sales (Figure 2).

The average annual volume of retail sales of S4 amounted to 2.76 million m^3, whereas contract-based sales averaged only 12.6 thousand m^3. In 2007, retail sales of S4 amounted to 1.71 million m^3, while in 2024 they reached 3.45 million m^3, representing an increase of 102.1%. The highest retail sales volume was recorded in 2023, at 4.21 million m^3. At the same time, contract-based sales of S4 systematically lost significance. Their volume decreased from 70.8 thousand m^3 in 2007 to 1.2 thousand m^3 in 2024, corresponding to a decline of 98.3%. The share of contract-based sales in the total S4 sales volume decreased from 4.0% in 2007 to below 0.1% in the final years of the study period.

The dominance of retail sales confirms that S4 fuelwood is directly linked to the local market of individual consumers and households. This further supports the interpretation of S4 not only as a forest assortment, but also as a local biomass energy resource used in household heat supply.



a **b**

Figure 2. Fuelwood S4 sales by sales channel in the State Forests National Forest Holding in 2007–2024: (**a**) sales volume; (**b**) prices in retail sales and sales under contracts. Sales volume is expressed in m^3 and prices in PLN/m^3.

Differences between distribution channels were also reflected in nominal price levels. In 2007–2024, nominal prices of S4 fuelwood increased in both retail and contract-based sales. The retail price increased from 76.91 to 148.31 PLN/m^3, i.e., by 92.8%, whereas the contract-based price rose from 85.83 to 158.14 PLN/m^3, corresponding to an increase of 84.2%. Prices in both channels were similar. The average retail price was 111.71 PLN/m^3, while the average contract-based price was 113.65 PLN/m^3, only 1.8% higher. However, differences between sales channels varied over time. After 2021, prices in contract-based sales again exceeded retail prices, with the largest difference recorded in 2023, at 19.01 PLN/m^3. The strongest increase in nominal prices in contract-based sales occurred between 2021 and 2022, when it reached 22.7%, compared with 8.6% in retail sales. At the same time, retail prices were slightly more stable: the coefficient of variation was 14.5%, compared with 16.4% for contract-based sales. This indicates that the retail segment of the S4 market, directly linked to local consumers and households, was characterised by lower price variability (Figure 2).

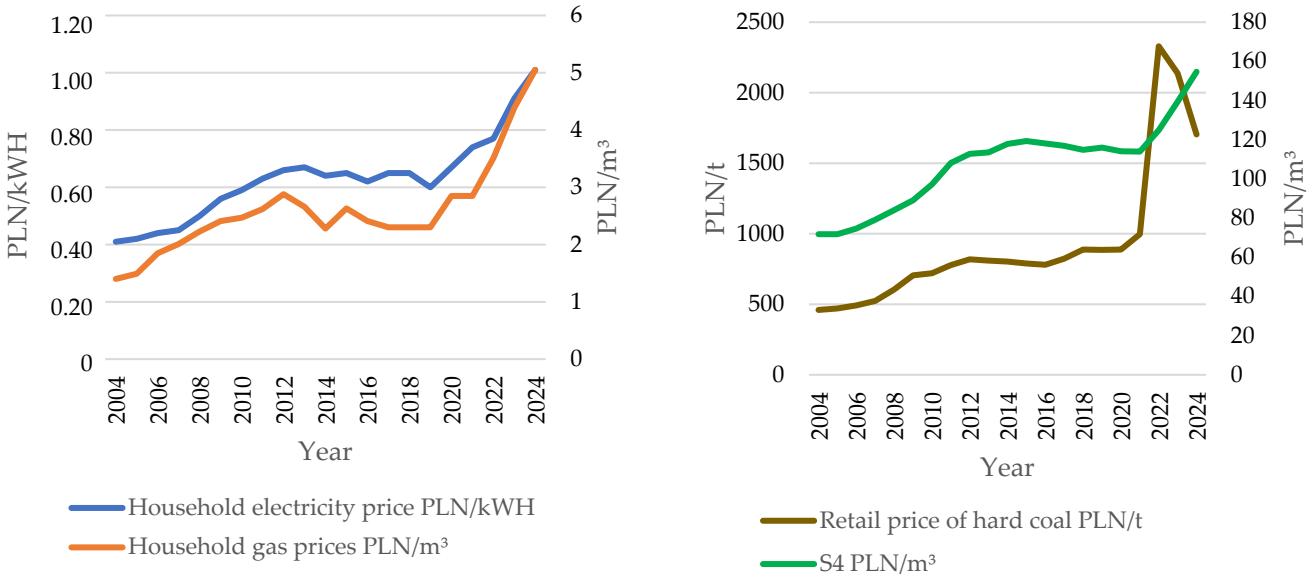
2.5. Fuelwood (S4) Prices Compared with Selected Household Energy Carriers

A comparison of price dynamics for selected household energy carriers indicates that S4 fuelwood was characterised by the slowest price increase over the entire analysed period. Between 2005 and 2024, the nominal price of S4 increased from 71.76 PLN/m^3 to 154.68 PLN/m^3, representing an increase of 115.6%. Over the same period, the nominal price of electricity for households increased by 146.3%, the price of natural gas by 260.7% and the retail price of hard coal by 270.6% (Figure 3). The price growth dynamics of natural gas and hard coal were more than twice as high as those observed for S4 fuelwood.

In nominal price terms, these results indicate that S4 fuelwood was characterised by lower price growth than the other analysed household energy carriers. This is also supported by the coefficient of price variation, which amounted to 20.5% for S4, compared with 23.7% for electricity, 32.5% for natural gas and 54.8% for hard coal.

From the perspective of the household energy-price environment, this suggests that S4 fuelwood may have represented a relatively price-stable and locally available supplementary biomass resource. Its significance should therefore be interpreted cautiously, as

a supplementary local biomass energy resource, rather than as direct evidence of lower useful heat costs or household energy behaviour.



a **b**

Figure 3. Price dynamics of selected household energy carriers in Poland in 2005–2024: (**a**) household electricity prices, expressed in PLN/kWh, and household natural gas prices, expressed in PLN/m^3; (**b**) retail hard coal prices, expressed in PLN/t, and S4 fuelwood prices, expressed in PLN/m^3.

In summary, among the analysed household energy carriers in Poland, S4 fuelwood showed the lowest nominal price increase and the lowest price variability. This result should be interpreted as a nominal price-context comparison, because the analysed fuels differ in physical units, calorific value, conversion efficiency and heating technologies.

Taken together, these observations justify the analysis of S4 fuelwood not only as a forestry assortment, but also as a local biomass energy resource. Its increasing share in total timber sales, strong growth after 2021, retail-market orientation and potential relevance for household heating, and relatively lower price dynamics compared with other household energy carriers indicate that S4 fuelwood represents an important segment of the local bioenergy market.

3. Materials and Methods

3.1. Data and Variables

The study was based on monthly data on S4 fuelwood sales in Poland for the period 2005–2024. The dataset included sales volume and prices for five main tree species: pine, spruce, oak, beech and birch. These species were selected because they represent the main groups of S4 fuelwood sold on the Polish primary timber market and include both coniferous and broadleaved fuelwood assortments.

Two variables were used in the empirical analysis: S4 fuelwood sales volume and S4 fuelwood price. Sales volume was expressed in cubic metres per month, while prices were expressed in PLN/m^3. Since the analysed period included years of elevated inflation and strong changes in household energy costs, nominal prices were deflated using the consumer price index (CPI) published by Statistics Poland and expressed as real prices. Nominal prices were used only for descriptive comparison with real prices, while the econometric analysis was based on real prices. In the econometric part of this study, the term "fuelwood (S4) price" refers to the real S4 fuelwood price, unless otherwise stated.

The analysis was conducted in a panel structure, where tree species represented the cross-sectional dimension and months represented the time dimension. The panel structure was used to control for species-specific heterogeneity, while the main inference relied on monthly time variation. The original variables, sales volume $Q_{i,t}$ and real price $P_{real,i,t}$ were transformed into natural logarithms, $\ln Q_{i,t}$ and $\ln P_{real,i,t}$, and then into first log differences. This transformation was applied to reduce the risk of modelling non-stationary variables and to focus on short-term monthly dynamics rather than on price and sales-volume levels.

To facilitate interpretation, first log differences were multiplied by 100. Therefore, throughout the econometric analysis, $\Delta \ln Q$ and $\Delta \ln P_{real}$ denote log differences multiplied by 100 and can be interpreted as approximate monthly percentage changes in S4 fuelwood sales volume and real S4 fuelwood prices, respectively.

Accordingly, the econometric models were estimated using two transformed variables: $\Delta \ln Q_{i,t}$, representing the approximate monthly percentage change in S4 fuelwood sales volume, and $\Delta \ln P_{real,i,t}$, representing the approximate monthly percentage change in the real S4 fuelwood price. For simplicity, $\Delta \ln P$ may be used in tables to denote $\Delta \ln P_{real}$. In both cases, subscript i denotes the tree species and t denotes the month.

Two period dummy variables were included in the models. The first variable, $D_{2020–2021}$, covered the years 2020–2021 and was introduced to control for a broad period of market disturbance associated with the COVID-19 pandemic and post-pandemic adjustment. The second variable, $ENERGY_{2022–2023}$, covered the years 2022–2023 and was introduced to control for the energy-crisis period, characterised by increased uncertainty in energy markets and growing interest in locally available energy sources. Both variables were treated as broad period controls rather than as direct causal measures of the pandemic or the energy crisis. They were included to reduce the risk that the estimated price–volume relationship would be driven solely by exceptional market conditions in 2020–2023.

3.2. Descriptive Statistics and Seasonal Analysis

The empirical analysis began with descriptive statistics for S4 fuelwood sales volume and real prices. Descriptive statistics were calculated separately for each analysed species. The following measures were reported: mean, median, minimum, maximum, standard deviation, coefficient of variation and total sales volume over the study period.

The coefficient of variation was used to compare the relative variability of prices and sales volume. This was necessary because prices and sales volumes were expressed in different units and differed substantially in scale.

Seasonality was assessed using average monthly values and seasonal indices. For each calendar month, average sales volume and average real price were calculated across the analysed period. These monthly averages were then related to the overall monthly average for the whole period. Values above 100 indicated that the given month was above the long-term monthly average, while values below 100 indicated a below-average level.

The seasonal analysis had two purposes. First, it allowed intra-annual patterns in S4 fuelwood sales volume and real prices to be identified. Second, it provided methodological justification for including monthly effects in the econometric models.

3.3. Preliminary Econometric Diagnostics

The empirical strategy followed approaches used in studies of timber, forest-product and biomass markets, including previous research on timber price dynamics in Poland [34,37,47]. Preliminary econometric diagnostics were conducted to assess the time-series properties of the variables and justify the use of short-term dynamic models.

First, stationarity was tested using the Augmented Dickey–Fuller (ADF) test [48]. The test was applied separately for each tree species to logarithmic levels and first log

differences of sales volume and real prices. Since the econometric variables were defined as first log differences multiplied by 100, the stationarity assessment of the differenced series referred directly to the transformed variables used in the dynamic models.

The ADF regression can be written as (1):

$$\Delta y_t = \alpha + \rho y_{t-1} + \sum_{j=1}^{k} \varphi_j \Delta y_{t-j} + u_t \quad (1)$$

where y_t denotes the analysed time series, Δy_t denotes the first difference of the series, α is the constant term, ρ is the parameter related to the unit-root component, φ_j denotes the coefficient of the j-th lagged first difference, j is the lag index, k is the number of lagged first-difference terms included in the regression and u_t is the error term in period t.

The ADF results were used to verify whether modelling the variables in first log differences was appropriate. Since most logarithmic-level series showed signs of non-stationarity, the main econometric analysis was conducted using differenced variables.

Second, cointegration diagnostics were performed separately for each tree species to assess whether a stable long-run relationship between S4 fuelwood sales volume and real prices could be assumed. Two approaches were used: the Engle–Granger test [49] and the Johansen test [50]. The Engle–Granger procedure was used to examine whether residuals from a long-run relationship between lnQ and $\ln P_{real}$ were stationary. The Johansen test was used as an additional diagnostic tool for identifying possible cointegration between the two variables.

The cointegration analysis was treated only as a preliminary diagnostic stage. Because the results were not fully consistent across species and testing approaches, this study did not estimate a VECM model and did not interpret the price-volume relationship as a stable long-run equilibrium. Instead, the main analysis focused on short-term dynamics in first log differences. Third, Granger-type tests were used to assess whether past changes in one variable helped explain current changes in the other variable, following the predictive interpretation of causality proposed by Granger [51]. The tests were conducted using the transformed variables, defined as first log differences multiplied by 100, and in two directions:

$$\Delta \ln P_{real,i,t} \rightarrow \Delta \ln Q_{i,t} \quad (2)$$

$$\Delta \ln Q_{i,t} \rightarrow \Delta \ln P_{real,i,t} \quad (3)$$

Equation (2) tested whether previous real price changes helped explain later sales-volume changes, whereas Equation (3) tested whether previous sales-volume changes helped explain later real price changes. The Granger-type tests were not interpreted as evidence of strict economic causality, but as a diagnostic tool for identifying predictive and lagged relationships between prices and sales volume. The results were reported using F-statistics, which indicate whether the lagged values of one variable jointly improve the prediction of the current value of the other variable.

3.4. ARDL-Type Fixed-Effects Dynamic Panel Model

Dynamic models with lagged variables are often used in studies of energy and biomass markets because market responses may occur with a delay. Autoregressive Distributed Lag (ARDL)-type approaches help capture short-term adjustments between variables and are often preceded by tests of integration, cointegration and causality [52,53]. In this study, an ARDL-type fixed-effects specification was applied within a dynamic panel framework to analyse short-term price–volume interactions in the S4 fuelwood market.

The main econometric analysis was based on an ARDL-type fixed-effects dynamic panel model estimated using the transformed variables defined above. The term "ARDL-type" refers to the inclusion of lagged dependent and explanatory variables within

a fixed-effects panel framework, rather than to the use of a pooled mean group or mean group panel ARDL estimator. This specification was appropriate for the structure of the dataset, which combined a limited cross-sectional dimension with a long monthly time dimension.

The model was designed to assess whether previous changes in real S4 fuelwood prices were associated with current changes in S4 fuelwood sales volume. The baseline model was specified as (4):

$$\Delta \ln Q_{i,t} = \alpha_i + \beta_1 \Delta \ln Q_{i,t-1} + \beta_2 \Delta \ln P_{real,i,t-1} + \delta_1 D_{2020–2021,t} + \delta_2 ENERGY_{2022–2023,t} + \gamma_m + \varepsilon_{i,t} \quad (4)$$

where $\Delta \ln Q_{i,t}$ is the approximate monthly percentage change in S4 fuelwood sales volume for species i in month t, α_i denotes species fixed effects, $\Delta \ln Q_{i,t-1}$ denotes the lagged approximate monthly percentage change in sales volume, $\Delta \ln P_{real,i,t-1}$ denotes the lagged approximate monthly percentage change in the real S4 fuelwood price, $D_{2020–2021,t}$ denotes the market-disturbance period dummy, $ENERGY_{2022–2023,t}$ denotes the energy-crisis period dummy, γ_m denotes monthly effects controlling for seasonality and $\varepsilon_{i,t}$ is the error term.

Because $\Delta \ln Q$ and $\Delta \ln P_{real}$ denote log differences multiplied by 100, the estimated coefficients can be interpreted in terms of approximate percentage-point changes in monthly dynamics. Coefficients for dummy variables indicate differences in monthly sales-volume dynamics expressed in percentage points. The key coefficient of interest was β_2. A positive and statistically significant value of β_2 indicates that an increase in the real price of S4 fuelwood in the previous month was associated with an increase in current sales-volume dynamics. This effect was interpreted as short-term sales-volume adjustment to price signals within an institutionally managed timber sales system. It was not interpreted as a pure supply response in a fully competitive market. This interpretation is consistent with the institutional character of the Polish primary timber market, where sales volumes may respond to price signals but remain constrained by harvesting plans, assortment structure and the organisation of timber sales.

Species fixed effects were included to control for time-invariant differences between pine, spruce, oak, beech and birch. These differences may include species-specific sales scale, availability, assortment structure and market role. Monthly effects were included to control for recurring seasonal patterns in sales volume and prices. Their inclusion reduced the risk of attributing regular intra-annual fluctuations to price effects.

The model was estimated for three lag specifications: ARDL(1,1), ARDL(2,2) and ARDL(3,3). The lag length was limited to three months because this study focused on short-term market adjustment. A three-month horizon corresponds to a quarterly adjustment period and allows delayed responses to be captured without excessive model parameterisation. This choice also reduced the risk of overlapping price effects with longer seasonal patterns.

For the two- and three-lag specifications, the model can be expressed in a general form as (5):

$$\Delta \ln Q_{i,t} = \alpha_i + \sum_{l=1}^{p} \beta_l \Delta \ln Q_{i,t-l} + \sum_{l=1}^{p} \theta_l \Delta \ln P_{real,i,t-1} + \delta_1 D_{2020–2021,t} + \delta_2 ENERGY_{2022–2023,t} + \gamma_m + \varepsilon_{i,t} \quad (5)$$

where i denotes the tree species, t denotes the month, l denotes the lag index and $p = 1, 2$ or 3 denotes the maximum lag order.

Standard errors were reported in parentheses below the estimated coefficients. Because the dataset consisted of monthly observations, heteroskedasticity- and autocorrelation-consistent HAC/Newey–West standard errors were used in the ARDL-type fixed-effects models. This correction was applied to obtain inference less sensitive to heteroskedasticity and residual serial correlation [54]. The lag window was set to 12 monthly lags to allow for potential within-year dependence in the monthly data. The dynamic specification

with lagged variables and monthly fixed effects additionally accounted for short-term dependence and recurring seasonal patterns. Model fit and model comparison were assessed using adjusted R^2, AIC and BIC. AIC and BIC were used only as supporting criteria for comparing alternative lag specifications [55,56]. The main interpretation was based on the sign, magnitude and statistical significance of the lagged real-price coefficients.

3.5. Robustness Checks

To assess the robustness of the main findings, Wald tests were used to verify whether lagged real price changes were jointly significant in explaining S4 fuelwood sales-volume dynamics across alternative lag specifications [57]. The Wald test was used because, in models with more than one lag, individual lag coefficients may differ in significance, while their combined effect may still be statistically important.

In addition, an auxiliary ARDL-type fixed-effects price equation was estimated to examine whether the opposite direction of the relationship, from sales volume to real prices, was also present. In this specification, the dependent variable was $\Delta \ln P_{real}$, denoting the approximate monthly percentage change in the real S4 fuelwood price, while lagged sales-volume changes, expressed as $\Delta \ln Q$, were included as explanatory variables.

The auxiliary price equation was not treated as the main model of this study. It was used to verify whether the price-volume relationship had a bidirectional dynamic character. The primary interpretation remained focused on the response of S4 fuelwood sales volume to previous real price changes, because the central research question concerned the adjustment of sales volume of a locally available biomass energy resource within a managed timber sales system. The auxiliary specification included the same control structure as the main models, including species fixed effects and monthly effects. Finally, species–price interaction terms were included as an additional robustness check to assess whether the short-term price–volume relationship differed among the five analysed tree species.

4. Results

4.1. Descriptive Statistics

Nominal S4 prices increased markedly, particularly after 2020; however, after adjustment for inflation, the increase in real prices proved to be substantially weaker. The highest real prices were not observed at the end of the study period, but mainly around 2015–2017, indicating that the nominal price increase was largely associated with general inflationary pressure (Figure 4).

Real prices of S4 fuelwood varied clearly across tree species, although their overall variability was moderate. The highest average prices were recorded for oak and beech, at 96.44 and 93.80 PLN/m^3, respectively, whereas the lowest prices were observed for spruce and pine, at 66.83 and 72.22 PLN/m^3, respectively (Table 2). The coefficient of price variation was low, ranging from 8.1% for spruce to 9.9% for beech, indicating relatively stable real prices compared with sales volumes. The widest price ranges were recorded for beech and oak, while the narrowest range was observed for spruce, suggesting that real spruce prices were the most stable among the analysed species.

The sales volume of S4 fuelwood varied substantially across tree species. Pine was the dominant species, accounting for 42.0% of total sales, with an average monthly volume of 81.9 thousand m^3 and a cumulative volume exceeding 19.6 million m^3 in 2005–2024. Oak was the second most important species, with a share of 19.6%, whereas spruce, beech and birch had similar but lower shares, amounting to approximately 12–13%. High coefficients of variation, ranging from 32.7% to 40.2%, indicate considerable variability in monthly sales. For most species, maximum sales volumes occurred in March 2023, indicating a pronounced increase in S4 sales in the final part of the study period (Table 3, Figure 5).

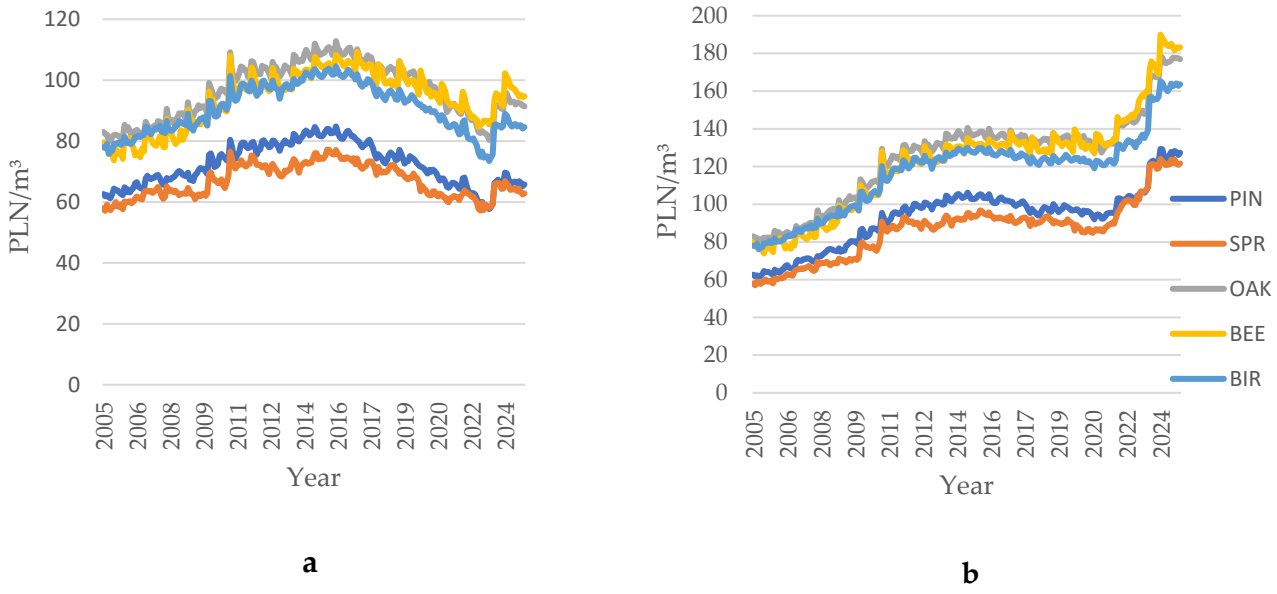


Figure 4. Nominal (**a**) and real (**b**) S4 fuelwood prices by species in Poland in 2005–2024, expressed in PLN/m^3.

Table 2. Descriptive statistics of real S4 fuelwood prices by species.

Species	Mean (PLN/m^3)	Median (PLN/m^3)	Min (PLN/m^3; Date)	Max (PLN/m^3; Date)	Range (PLN/m^3)	SD [1] (PLN/m^3)	CV [2] (%)
Pine	72.22	71.55	57.68; IV 2023	84.84; I 2016	27.16	6.99	9.7
Spruce	66.83	66.14	57.10; II 2005	77.18; IX 2015	20.08	5.45	8.1
Oak	96.44	97.07	80.06; V 2005	112.85; I 2016	32.79	9.31	9.7
Beech	93.80	96.38	73.68; VII 2005	109.35; I 2017	35.66	9.29	9.9
Birch	90.53	90.57	73.47; IV 2023	104.56; I 2016	31.09	8.10	8.9

[1] standard deviation (SD); [2] coefficient of variation (CV).

Table 3. Descriptive statistics of S4 sales volume by species.

Species	Mean (m^3/Month)	Median (m^3/Month)	Min (m^3/Month; Date)	Max (m^3/Month; Date)	SD (m^3/Month)	CV (%)	Total 2005–2024 (m^3)	Share (%)
Pine	81,860	80,889	30,821; XII 2005	188,250; III 2023	28,005	34.2	19,646,435	42.0
Spruce	25,504	26,127	6941; I 2021	63,290; VI 2023	9989	39.2	6,120,930	13.1
Oak	38,327	36,478	14,410; XII 2005	88,220; III 2023	13,328	34.8	9,198,473	19.6
Beech	23,573	23,624	6235; I 2007	54,004; III 2023	9466	40.2	5,657,599	12.1
Birch	25,813	24,766	9085; I 2010	55,728; III 2023	8438	32.7	6,195,034	13.2

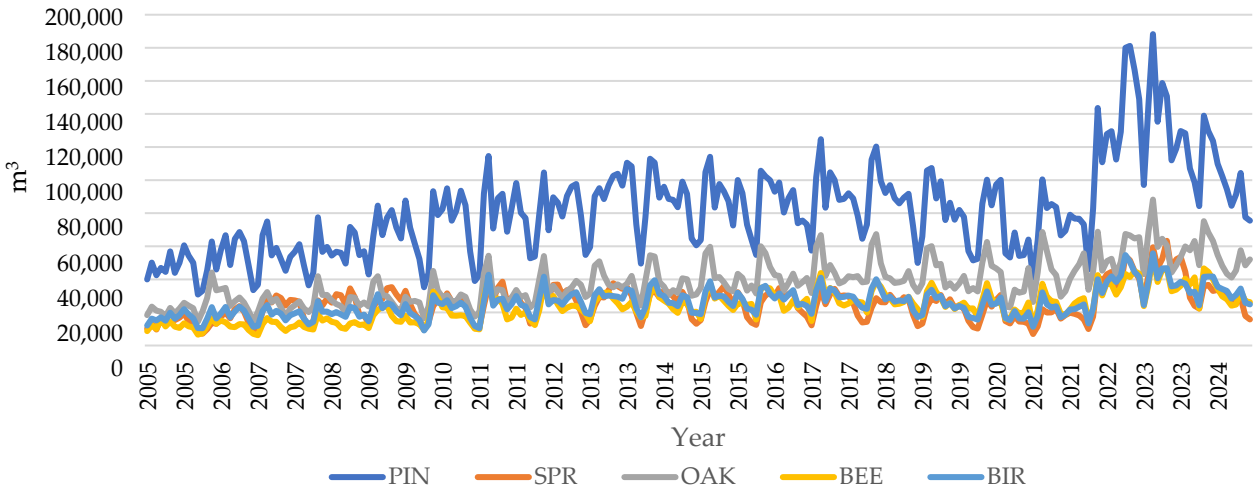


Figure 5. Monthly S4 fuelwood sales volume (m^3) by species in Poland, 2005–2024.

4.2. Seasonal Patterns

The seasonal analysis showed that S4 fuelwood sales volume was strongly seasonal, while real prices remained relatively stable throughout the year. The highest average sales volume was recorded in March, reaching 256.51 thousand m^3/month, whereas the lowest was observed in January, at 128.89 thousand m^3/month. In contrast, the seasonal index of real prices ranged only from 98.7 to 102.7, indicating limited intra-annual price variation (Table 4).

Table 4. Seasonal patterns in S4 fuelwood prices and sales volume.

Month	Average S4 Sales Volume (Thousand m^3/Month)	Sales Volume Seasonal Index (Mean = 100)	Average Real S4 Price (PLN/m^3)	Price Seasonal Index (Mean = 100)
January	128.89	66.1	86.23	102.7
February	212.42	108.9	85.06	101.3
March	256.51	131.5	84.11	100.2
April	206.76	106.0	83.00	98.8
May	216.48	111.0	82.87	98.7
June	214.50	110.0	83.14	99.0
July	180.88	92.7	84.31	100.4
August	183.88	94.3	84.73	100.9
September	213.50	109.4	84.45	100.6
October	203.69	104.4	83.70	99.7
November	171.22	87.8	83.06	98.9
December	152.19	78.0	82.91	98.8

Note: Sales volume is expressed in thousand cubic metres per month. Prices are real prices, expressed in PLN/m^3. Seasonal indices are calculated relative to the annual monthly average, where the mean equals 100.

The results indicate that S4 seasonality was mainly volume-based rather than price-based. The March peak suggests that sales patterns were shaped not only by household heating demand, but also by sales organisation, wood availability and earlier fuelwood stockpiling. These findings justify the inclusion of monthly effects in the econometric models.

4.3. Econometric Diagnostic Results

Preliminary econometric diagnostics were conducted to assess the stationarity of the variables, the appropriateness of modelling them in first logarithmic differences and the direction of short-term relationships between price and sales volume. In the first step, the stationarity of the variables in logarithmic levels and in first logarithmic differences was examined using the ADF test (Table 5).

Table 5. Stationarity diagnostics: ADF test results for log levels and first log differences.

Species	lnQ *p*-Value	$\ln P_{real}$ *p*-Value	ΔlnQ *p*-Value	$\Delta \ln P_{real}$ *p*-Value
Pine	0.1492	0.5583	0.0067	0.0027
Spruce	0.0012	0.4025	0.0579	0.0014
Oak	0.7286	0.4135	<0.001	0.0093
Beech	0.4163	0.2864	0.0019	0.0056
Birch	0.1629	0.4907	0.0054	0.0022

Note: Q denotes S4 fuelwood sales volume, while P_{real} denotes the real S4 fuelwood price. Values below 0.05 indicate stationarity.

The ADF test results generally supported the use of first logarithmic differences in the dynamic models. However, spruce sales volume showed a mixed integration pattern: lnQ was already stationary in levels ($p = 0.0012$), whereas the first-differenced series produced a borderline result at the 5% significance level ($p = 0.0579$). This suggests that the integration properties of spruce differed from those of the remaining species. Because the main models were estimated in first log differences and focused on short-term dynamics rather than long-run levels, spruce was retained in the baseline panel specification. Nevertheless, to verify whether this mixed result affected the main inference, a sensitivity analysis excluding spruce was conducted. The sum of lagged real-price coefficients remained positive and statistically significant in all three specifications, ranging from 0.977 to 2.366, with *p*-values from 0.0166 to 0.00055. Therefore, the baseline specification including all five species was retained. Full results of this sensitivity check are reported in Supplementary Table S1. Subsequently, it was verified whether a stable long-run relationship could be identified between S4 fuelwood sales volume and the real price. For this purpose, the Engle–Granger test and the Johansen test were applied (Table 6).

The Johansen tests were conducted separately for each species using lnQ and $\ln P_{real}$. The specification included a constant and no deterministic trend. The VAR lag order in levels was set to 2, corresponding to one lag in first differences in the Johansen representation. Both trace and maximum-eigenvalue tests were reported for the hypotheses $r = 0$ and $r \leq 1$. Full rank-test results, including trace and maximum-eigenvalue statistics for both rank hypotheses, are presented in Supplementary Table S2.

The cointegration diagnostics did not provide sufficiently consistent evidence for interpreting the relationship between S4 fuelwood sales volume and real prices as a stable long-run equilibrium across all species. The Engle–Granger test supported cointegration only for spruce and only in one specification. The Johansen rank-test results indicated rank = 1 for pine, oak and birch, whereas for spruce and beech they indicated rank = 2, suggesting full rank or mixed integration properties rather than a standard single cointegrating relationship. Therefore, the Johansen results were not interpreted as unequivocal evidence of a stable long-run price–volume equilibrium. Cointegration was treated as an auxiliary diagnostic step, and the main empirical analysis focused on short-term dynamics in first logarithmic differences (Table 7).

Table 6. Cointegration diagnostics between S4 fuelwood sales volume and real price.

Species	Engle–Granger: lnQ on lnP_{real}, *p*-Value	Engle–Granger: lnP_{real} on lnQ, *p*-Value	Johansen Specification	Trace-Test Rank Conclusion at 5%
Pine	0.3481	0.7855	constant, no trend; VAR lag = 2	rank = 1, cointegration indicated
Spruce	0.0070	0.6929	constant, no trend; VAR lag = 2	rank = 2/full rank; mixed integration, not standard cointegration
Oak	0.9124	0.6859	constant, no trend; VAR lag = 2	rank = 1, cointegration indicated
Beech	0.3909	0.3314	constant, no trend; VAR lag = 2	rank = 2/full rank; mixed integration, not standard cointegration
Birch	0.3187	0.7149	constant, no trend; VAR lag = 2	rank = 1, cointegration indicated

Note: Engle–Granger tests were performed in both directions. Johansen tests were estimated separately for each species using lnQ and lnP_{real}, with a constant, no deterministic trend, and VAR lag order = 2.

Table 7. Granger-type predictive tests in first log differences.

Species	Price → Sales Volume, Lag 1	Price → Sales Volume, Lags 1–2	Price → Sales Volume, Lags 1–3	Sales Volume → Price, Lag 1	Sales Volume → Price, Lags 1–2	Sales Volume → Price, Lags 1–3
Pine	34.641	12.291	8.053	49.275	23.629	14.269
Spruce	24.743	9.026	5.733	27.238	14.835	9.004
Oak	51.839	36.835	23.989	19.762	19.433	14.678
Beech	78.782	70.662	53.573	15.802	13.075	9.973
Birch	33.906	17.937	12.536	25.491	17.457	9.893

Note: The table reports F-statistics from Granger-type predictive tests performed on ΔlnQ and ΔlnP_{real}. Lags 1, 1–2 and 1–3 denote joint tests of the corresponding lag orders. The numerator degrees of freedom were 1, 2 and 3, respectively; the denominator degrees of freedom were 235, 232 and 229. All tests were statistically significant at $p < 0.001$.

The results of the Granger tests indicate that significant bidirectional predictive relationships existed between changes in real S4 fuelwood prices and changes in sales volume. For all analysed species, lagged changes in real prices helped explain subsequent changes in sales volume, while lagged changes in sales volume helped explain subsequent changes in real prices.

These results should not be interpreted as evidence of strict economic causality, but rather as an indication of dynamic interdependence between real price and sales-volume changes. The F-statistics should be interpreted only as evidence against the null hypothesis of no predictive content of the lagged variables. They do not provide a direct measure of the magnitude of the economic effect and should not be used to compare the strength of price responses across species. These findings justify the use of a fixed-effects model with an ARDL-type lag structure, including both lagged price changes and lagged changes in sales volume.

4.4. ARDL-Type Fixed-Effects Model for S4 Fuelwood Sales-Volume Dynamics

ARDL-type fixed-effects dynamic panel models were estimated to assess whether lagged changes in real S4 fuelwood prices were associated with current sales-volume dynamics; the results are presented in Table 8.

Table 8. Estimated ARDL-type fixed-effects models for S4 fuelwood sales-volume dynamics.

Variable	ARDL(1,1)	ARDL(2,2)	ARDL(3,3)
$\Delta \ln Q_{t-1}$	−0.237 *** (0.029)	−0.301 *** (0.034)	−0.279 *** (0.032)
$\Delta \ln P_{real,t-1}$	1.053 *** (0.287)	0.835 *** (0.295)	0.758 ** (0.301)
$\Delta \ln Q_{t-2}$	—	−0.169 *** (0.032)	−0.154 *** (0.033)
$\Delta \ln P_{real,t-2}$	—	0.510 (0.394)	0.659 (0.405)
$\Delta \ln Q_{t-3}$	—	—	0.039 * (0.023)
$\Delta \ln P_{real,t-3}$	—	—	0.744 *** (0.244)
$D_{2020–2021}$	2.274 * (1.244)	2.225 * (1.350)	2.822 ** (1.321)
$ENERGY_{2022–2023}$	1.412 (1.413)	1.597 (1.607)	1.590 (1.655)
Observations, baseline estimation	1190	1185	1180
Adjusted R^2, baseline estimation	0.595	0.619	0.626
Observations, common sample	1180	1180	1180
Adjusted R^2, common sample	0.613	0.624	0.626
AIC, common sample	9972.225	9941.596	9937.348
BIC, common sample	10,073.690	10,053.208	10,059.107

Note: The dependent variable is 100 × ΔlnQ. Standard errors in parentheses are HAC/Newey–West standard errors with 12 monthly lags. All models include species and monthly fixed effects. AIC and BIC were calculated on a common sample of 1180 observations. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The first lag of real price changes was positive and statistically significant in all specifications, with coefficients ranging from 0.758 to 1.053. This indicates that increases in real S4 fuelwood prices were associated with higher subsequent sales-volume dynamics in the short term. Lagged sales-volume changes were mostly negative and statistically significant, especially for the first and second lags, suggesting short-term adjustment or mean reversion in monthly sales dynamics. The period controls were included to account for exceptional market conditions in 2020–2023. $D_{2020–2021}$ was positive and statistically significant or weakly significant across the models, whereas $ENERGY_{2022–2023}$ was positive but statistically insignificant after controlling for lagged real price changes, species fixed effects and monthly seasonality. This suggests that the main short-term adjustment was captured primarily by lagged real price changes rather than by the energy-crisis period dummy itself. When the models were re-estimated on a common sample of 1180 observations, ARDL(3,3) had the lowest AIC, whereas ARDL(2,2) had the lowest BIC. Therefore, the information criteria did not point unambiguously to a single best specification. The main conclusion is instead that the positive association between lagged real price changes and sales-volume dynamics remained robust across alternative lag structures.

4.5. Dynamic Panel ARDL Results

To assess the robustness of the main findings, Wald tests were used to verify the joint significance of lagged real price changes. The sum of lagged real-price coefficients was calculated as the sum of lagged $\Delta \ln P_{real}$ coefficients in each ARDL-type specification. In

addition, an auxiliary price equation was estimated to check the opposite direction of the relationship, from sales volume to real prices (Table 9).

Table 9. Sum of lagged real-price coefficients in ARDL-type fixed-effects models.

Model	Sum of Lagged Real-Price Coefficients	95% CI	Wald Statistic	*p*-Value
ARDL(1,1)	1.053	0.487–1.619	13.314	<0.001
ARDL(2,2)	1.345	0.226–2.464	5.565	0.018
ARDL(3,3)	2.162	0.860–3.464	10.619	0.001

Note: The table reports the sum of lagged $\Delta \ln P_{real}$ coefficients from the corresponding baseline ARDL-type model in Table 8. Confidence intervals and Wald statistics were calculated using heteroskedasticity and autocorrelation-consistent HAC/Newey–West standard errors with 12 monthly lags.

The Wald tests indicated that the sum of lagged real-price coefficients was positive and statistically significant in all specifications. This indicates that the relationship between previous real price changes and subsequent sales-volume dynamics was not dependent on a single lag structure. In the ARDL(2,2) and ARDL(3,3) models, the sum of lagged real-price coefficients was more informative than the interpretation of individual lags alone. Full summary results of the auxiliary price equation are reported in Supplementary Table S3. The auxiliary specification indicated a weak negative association between previous sales-volume dynamics and subsequent real price changes. However, this model was treated only as a robustness check and was not used as the main basis for interpretation.

As an additional robustness check, species–price interaction terms were included to test whether the short-term price–volume relationship differed among pine, spruce, oak, beech and birch. Wald tests of the joint significance of the species–price interaction terms did not reject the null hypothesis of homogeneous price slopes across species. The *p*-values were 0.987 for ARDL(1,1), 0.984 for ARDL(2,2) and 0.397 for ARDL(3,3). Therefore, there was no statistically significant evidence that the short-term price response differed across species. On this basis, the common-slope fixed-effects specification was retained as the baseline model, while species fixed effects were used to control for time-invariant differences between species. The results of these slope-heterogeneity tests are reported in Supplementary Table S4.

5. Discussion

The results obtained in this study show that S4 fuelwood in Poland functions as a specific segment of the biomass market: it is simultaneously a forestry assortment, an institutionally managed resource and a locally available biomass energy resource. Between 2005 and 2024, total timber sales in the State Forests National Forest Holding increased by 27.1%, whereas the sales volume of S4 fuelwood increased by 77.0%. This substantial difference indicates that the growing importance of S4 was not simply a consequence of the overall increase in timber sales but reflected a structural increase in the role of fuelwood assortments within the primary timber market. The contribution of this study therefore lies not only in documenting the scale of this segment, but also in showing how real prices and sales volumes of S4 were related in the short term within an institutionally managed sales system.

The most important modelling result is the positive association between lagged changes in real prices and subsequent sales-volume dynamics of S4 fuelwood. The first lag of real price changes was positive and statistically significant in all ARDL-type model specifications, with coefficient values ranging from 0.758 to 1.053. This means that posi-

tive changes in real S4 prices were associated with higher sales-volume dynamics in the following month. The sum of lagged real-price coefficients was also positive and statistically significant in all ARDL-type specifications, ranging from 1.053 to 2.162. This finding was robust across different lag structures, as indicated by Wald tests for the sum of lagged real-price coefficients. When the models were re-estimated on a common sample of 1180 observations, ARDL(3,3) had the lowest AIC, whereas ARDL(2,2) had the lowest BIC. Therefore, the information criteria did not indicate one unambiguously superior specification. The main conclusion is that the positive association between lagged real price changes and subsequent sales-volume dynamics remained stable across alternative lag structures.

This result should be interpreted in the broader context of studies showing that wood and biomass markets are shaped not only by price signals, but also by market organisation, resource availability and supply-chain constraints. Roszkowska and Szubska-Włodarczyk [58] identified institutional and market barriers to biomass-market development in Poland, while Scholz et al. [59] showed that forest-fuel markets may be influenced by spatial and organisational factors. Therefore, the positive lagged price–sales relationship observed in this study may reflect not only market pressure, but also short-term adjustment within the State Forests sales system, including the timing of sales, expectations concerning future availability and local responses to energy-market uncertainty.

This interpretation is also consistent with broader evidence from forest-product markets. Asada et al. [60] showed that roundwood price dynamics in Europe may differ between countries and can be affected by natural disturbances, while Březina et al. [61] demonstrated that disturbances in Central European forests influence timber-market behaviour. Diniz et al. [62], in turn, showed that international markets for energy forest products are shaped by changing market shares and country-specific dynamics. Against this background, the present study indicates that price–volume relationships may also be assortment-specific and visible within a nationally managed primary timber market.

However, this relationship should be interpreted cautiously. The positive sign of the coefficients for lagged changes in real prices should not be treated as direct evidence of an increase in final demand, because the dataset does not observe household consumption behaviour. Rather, the results indicate that previous real price changes contained predictive information about subsequent monthly sales-volume dynamics in the institutionally managed S4 fuelwood market. This relationship may reflect short-term adjustment to changing market conditions, expectations concerning future availability, administrative timing of sales, or local reactions to broader energy-market uncertainty. S4 fuelwood operates within an institutionally managed timber sales system, in which the available volume depends on harvesting plans, forest-resource structure, assortment classification and local supply conditions. In this context, the lagged price–volume relationship indicates short-term adjustment within a managed biomass resource, rather than an unrestricted supply or demand response in a fully competitive market. Recent European studies similarly emphasise that additional wood mobilisation is constrained by resource structure and economic conditions. Lerink et al. [63] assessed near-future wood availability in European forests and pointed to limits resulting from forest resources and mobilisation capacity. Bozzolan et al. [64] showed spatial differences in softwood shortage and hardwood availability across EU regions, while Jonsson and Sotirov [11] linked future wood availability in Europe with climate, energy-policy and geopolitical developments.

The ARDL-type models also indicated short-term adjustment or mean reversion in sales-volume dynamics. The negative and statistically significant coefficients for lagged changes in sales volume mean that a stronger increase in sales in one month was usually associated with weaker sales dynamics in subsequent months. This pattern is consistent with the specific nature of the fuelwood market, where sales volume cannot increase

without constraints because it depends on raw-material availability, harvesting schedules and the organisation of timber sales. Since the cointegration diagnostics did not provide consistent evidence of a stable long-run equilibrium across all species, these negative coefficients should not be interpreted as evidence of a formal error-correction mechanism. They should rather be understood as short-term adjustment in monthly sales dynamics within a managed and resource-constrained market. Similar caution is suggested by studies showing that sustainable wood-fuel potential depends on ecological restrictions, mobilisation costs and competition between material and energy uses of wood [65–67].

The Granger-type test results further supported the dynamic nature of the relationship between real prices and sales volume. For all analysed species, lagged changes in real prices helped explain subsequent changes in sales volume, while lagged changes in sales volume also helped explain subsequent changes in real prices. These relationships are predictive rather than causal in the strict economic sense. Their value lies in showing that price and volume form a short-term information system that may be useful for monitoring changes in the availability and market behaviour of S4 fuelwood.

The S4 market is strongly retail-oriented. In 2007–2024, as much as 99.5% of the volume of this assortment was sold through retail channels, while contract-based sales were marginal. This means that S4 differs from more industrial biomass streams, such as pellets, wood chips, or by-products of wood processing. Nevertheless, retail dominance should be interpreted as evidence of the market channel rather than as a direct measure of final use. The data describe transactions within the State Forests sales system and do not follow the purchased wood beyond the primary market. Previous studies indicate that household fuelwood use depends on income, energy prices, heating technologies and the availability of alternative fuels [14,15]. A similar conclusion was reached by Jaime et al. [68], who showed that household fuel choice is shaped by prices, income and the availability of energy sources and heating technologies. In the context of Poland, the energy potential of fuelwood and wood-processing by-products was also emphasised by Mydlarz and Wieruszewski [16], who at the same time pointed to limitations resulting from resource availability and competition for wood raw material.

Recent European evidence further indicates that wood-fuel use in households may depend on heating habits, pre-season fuel preparation and energy-burden conditions. Petrović [69] linked fuelwood consumption with heating-degree-day conditions in Central and Southeastern Europe, while Szép et al. [70] showed that solid fuels remain important in residential heating in Central and Eastern Europe, especially under conditions of energy burden.

The comparison between S4 fuelwood prices and the prices of electricity, natural gas and hard coal should be interpreted only as a nominal price-context comparison. Between 2005 and 2024, the nominal price of S4 increased by 115.6%, whereas the prices of electricity, natural gas and hard coal increased by 146.3%, 260.7% and 270.6%, respectively. These figures do not compare the cost of useful energy, because the analysed fuels differ in physical units, calorific value, conversion efficiency and heating technologies. They also do not provide direct evidence of household energy behaviour. Rather, they show the broader household energy-price environment in which S4 fuelwood was sold. In this sense, the results are consistent with broader evidence that energy-price shocks and markets for energy forest products may influence biomass price formation, although such effects differ between countries, products and market channels [62]. Combined with the almost exclusively retail character of sales, this suggests that S4 may have served as a locally available supplementary biomass resource, especially during periods of increased energy-price instability.

Seasonality was an important dimension of the S4 market. The results indicated that seasonality primarily concerned sales volume rather than real prices. The highest average sales volume was recorded in March, at 256.51 thousand m^3 per month, whereas the lowest was observed in January, at 128.89 thousand m^3 per month. At the same time, the seasonal index of real prices remained within a narrow range from 98.7 to 102.7. This means that the S4 market was characterised mainly by quantitative seasonality.

This pattern may reflect not only heating-season expectations, but also the timing of timber sales, delivery organisation and fuelwood preparation. Trzciński and Tymendorf [71] showed that the parameters of medium-sized wood deliveries may differ depending on season, moisture content and assortment characteristics, while Petrović [69] confirmed the importance of heating-season conditions for fuelwood consumption. The separation between sales-volume seasonality and relative stability of real prices suggests that monthly S4 sales were shaped by both seasonal energy needs and the institutional timing of timber supply.

The species-level results confirmed that the S4 market was not homogeneous. Pine had the greatest quantitative importance, accounting for 42.0% of total S4 sales in 2005–2024, while oak was the second most important species, with a share of 19.6%. At the same time, the highest average real prices were recorded for oak and beech, at 96.44 and 93.80 PLN/m^3, respectively, whereas the lowest prices were recorded for spruce and pine, at 66.83 and 72.22 PLN/m^3, respectively. This means that the largest sales volume did not concern the most expensive species, but primarily pine, a species characterised by high availability and a lower real price. This finding is consistent with European evidence that wood availability and market use are shaped by species composition, assortment structure and regional resource distribution, rather than by price levels alone [63,64]. The interaction-based robustness test did not provide statistically significant evidence that price slopes differed across species. Therefore, the common-slope fixed-effects specification was retained as the baseline model, while species fixed effects controlled for time-invariant differences between species.

From an interpretative perspective, S4 should be treated as a basket of species with different market and energy functions. Pine forms the quantitative basis of the market and determines the overall availability of fuelwood, whereas oak and beech represent higher-priced broadleaved assortments. High-volume species may stabilise the supply of local fuel. However, the econometric results did not provide statistically significant evidence that the short-term price response differed between species. For this reason, monitoring of S4 should include not only aggregated data, but also the species structure of sales, while avoiding overinterpretation of species-specific differences in predictive test statistics.

The results should be interpreted with caution. S4 fuelwood is a renewable but limited resource. Its availability depends on forest structure, species composition, harvesting conditions, seasonality and the regional distribution of wood resources [12,13]. The use of wood for heating also competes with the material use of wood raw material and should be considered in the context of sustainable forest management. The environmental effects of wood heating also depend on combustion technology, fuel quality, wood moisture content and the length of the supply chain [9,26]. Čermák et al. [72] showed that wood-chip quality parameters and their price linkages are relevant for energy sustainability in Poland, which confirms that biomass-energy assessments should account not only for volume and price, but also for fuel-quality characteristics. Therefore, S4 should not be treated as an unlimited substitute for fossil fuels, but rather as a locally important, managed and supplementary biomass energy resource.

Several limitations should be acknowledged. First, the analysis was based on nationally aggregated monthly sales data and therefore did not capture regional differences in

fuelwood availability, heating practices, transport costs or local market conditions. Second, the dataset did not include weather variables, such as temperature or heating-degree days, which may influence seasonal fuelwood demand. Third, possible endogeneity between prices and sales volume cannot be fully excluded, because both variables may respond simultaneously to unobserved market conditions. Fourth, the analysis did not include data on final fuelwood use after purchase. Finally, the comparison with electricity, natural gas and hard coal was used only as a nominal price-context comparison and did not account for differences in calorific value, energy efficiency or final useful heat costs. Further research should therefore extend the analysis to regional markets, weather-related demand factors, transport conditions and household-level fuelwood use. Such extensions would allow the short-term price–volume relationships identified in this study to be linked more directly with local supply-chain constraints, heating practices and regional fuelwood availability.

In summary, S4 should be monitored not only as a timber-market category, but also as a component potentially relevant to local biomass-energy resilience. Its significance does not result from the possibility of unlimited substitution for fossil fuels, but from its local availability, retail character of sales, relative price stability and short-term association between earlier real price changes and subsequent sales-volume dynamics.

The results indicate that S4 is a measurable but limited component of the local biomass-energy system, whose market behaviour is shaped by both price signals and institutional conditions of timber supply.

6. Conclusions

Real prices of S4 fuelwood in Poland in 2005–2024 were relatively stable but clearly differentiated by tree species. Oak and beech recorded the highest average prices, whereas pine and spruce belonged to the lower-priced assortments. At the same time, pine had the greatest quantitative importance, as it accounted for the largest share of total S4 sales. The highest real prices were observed mainly around 2015–2017, indicating that the increase in nominal prices in recent years did not translate into equally strong real price growth.

Sales volume was considerably more variable than real prices and was also strongly differentiated by tree species. The S4 market was characterised primarily by volume-based rather than price-based seasonality. Sales varied clearly throughout the year, whereas real prices remained relatively stable seasonally. Therefore, the assessment of the S4 fuelwood market as a local biomass energy resource should consider not only price levels, but also species structure, volume variability, seasonality and the timing of wood availability.

Cointegration diagnostics did not provide unequivocal grounds for treating the relationship between real price and sales volume as a stable long-run equilibrium. However, ARDL-type fixed-effects models showed that lagged changes in real S4 prices were positively and statistically significantly associated with subsequent sales-volume dynamics. This result was robust across alternative lag specifications, as indicated by Wald tests for the sum of lagged real-price coefficients.

The positive relationship between earlier changes in real prices and subsequent sales dynamics should not be interpreted as direct evidence of household demand or as a simple supply response in a fully competitive market. Rather, S4 should be interpreted as a managed fuelwood market, in which sales-volume dynamics may respond to earlier price signals, but remain constrained by harvesting plans, forest-resource structure, assortment classification and the organisation of timber sales.

Granger-type tests indicated bidirectional predictive relationships between changes in real prices and changes in sales volume. These results do not imply strict economic causality but indicate that price and volume form a system of short-term signals that may be useful for monitoring the S4 market.

From the Polish perspective, S4 fuelwood can be treated not only as a forestry assortment, but also as a limited local biomass energy resource with a strong retail-market orientation. However, retail sales should not be interpreted as a direct measure of final household fuelwood consumption, and S4 should not be presented as an unlimited or fully flexible substitute for fossil fuels.

From the perspective of forest and energy policy, S4 sales should therefore be monitored not only through price levels, but also through volume availability, seasonality and the species structure of sales, while taking into account the sustainability constraints of forest-resource management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19163774/s1. Table S1: Sensitivity analysis excluding spruce: sum of lagged real-price coefficients; Table S2: Johansen rank-test cointegration diagnostics; Table S3: Auxiliary price equation: sum of lagged sales-volume coefficients; Table S4: Slope heterogeneity tests based on species–price interaction terms.

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