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ORIGINAL PAPER

Analysis of the price relationship between coal and wood chip for the Czech Republic

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ABSTRACT

The article deals with the relation of coal prices to the contractual prices of wood chips within the Czech Republic. Over the last decade, the issue of the wood and coal market has become an important area of interest for producers and consumers. The increasing consumption of wood fuels has opened new research opportunities in the energy market and the declining growth of fossil fuels based on new environmental policies. The origin of the wood chips and its quality parameters are decisive for the market price of wood chips. For elemental analysis, spruce wood samples from three sources are analyzed: white, green, and brown chips, which together form a mixture with an average calorific value of 8 $GJ \cdot t^{-1}$. The Granger causality method and OLS regression for the long-term price relationship are used. Empirical results show that the price relationship between the monitored commodities is not balanced in the long term. Based on the regression analysis, there is no statistically significant relationship between the observed prices. A causal relationship in both directions was also not proven here. There is an independent relationship between both coal and wood chips price due to economic and environmental causalities.

KEY WORDS

bioenergetics, chip, cointegration regression, Granger causality, price relationship

Introduction

Global consumption of firewood and charcoal remains relatively constant, but the use of wood chips and wood pellets for electricity generation (bioenergy) and residential heating has doubled in the past decade and will continue to increase in the future (Jonsson *et al.*, 2013; Lamers *et al.*, 2014; Guo *et al.*, 2015; Deboni *et al.*, 2019; Stolarski *et al.*, 2020). The trade between 2000 and 2010 grew from around 56 to 300 PJ. Wood pellets grew the most, *i.e.*, from 8.5 to 120 PJ. Other relevant flows up to 2010 were wood waste (77 PJ), firewood (76 PJ), wood chips (17 PJ), residues (9 PJ) and logs (2.4 PJ) (Lamers *et al.*, 2012). Trade within the EU covered two thirds of global trade

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by 2010. The issue of intensive use of wood from the forest is already addressed by Mřller *et al.* (2014), which is strongly dependent on specific regional circumstances, soil type and changes in land use and generally related management practices. The main source of wood chips in most EU countries is logging residues, but a shift towards increased use of stumps and logs is expected soon (Díaz-Yáńez *et al.*, 2013).

The results of Kanzian *et al.* (2009) indicate that direct transport of solid firewood as logs and chips to the site is the cheapest supply system with resulting costs of 6.05-7.13 USD×m^{-3} bulk material. At the same time, the lower bulk density of wood chips means that energy requirements for transportation and greenhouse gas emissions are higher compared to logs and chipped wood bales (Whittaker *et al.*, 2011). On the other hand, the economic analysis of Paolotti *et al.* (2017) showed that it is more profitable to produce firewood than wood chips at current market prices. Even at present, the geographical relationship of cumulative sources of wood chips and their average costs for the selected bioenergy power plant can be used to determine sources of wood chips (Möller and Nielsen, 2007).

In a study by Zhu *et al.* (2016) an evaluation of the basic structures and chemical composition of wood and wood materials, which are necessary for a wide range of existing and new technologies, is carried out. One of these technologies is bioenergetics (Akhtar *et al.*, 2018; Malaťáková *et al.*, 2021). Bioenergy has significantly reduced the impact on human health and at the same time increased the quality of the ecosystem compared to burning coal fuel. Weldu *et al.* (2017) reported toxicity reductions of 89-95% for carcinogens, 68-81% for noncarcinogenics, and 66-76% for ecotoxicity impacts compared to coal-fired electricity. The use of wood biomass in the heating and energy industry reduces direct emissions by 4-27% for Northern Europe (Jåstad *et al.*, 2020). Emission savings of 77% can be achieved by co-firing torrefied pellets with fossil coal (Agar *et al.*, 2015). Agbor *et al.* (2016) show that a coal-fired power plant co-firing with forest residues is the most attractive option because it has balanced electricity costs and CO_2 abatement costs. The results of Khorshidi *et al.* (2014) show that increasing the quality of wood chips to wood pellets and torrefied pellets improves plant performance with a slight increase in electricity costs. The levelized cost of electricity (LCOE) of indirect coal-biomass co-firing power generation is significantly higher than that of a pure coal unit, with the LCOE increasing by nearly 8% (Xu *et al.*, 2020). Through sensitivity analysis, LCOE increases by 10.7% when burning 15% biomass and 19.1% when burning 20% biomass (Xu *et al.*, 2020). Currently, wood chips and pellets are the economically and environmentally preferred options for burning in district heating systems and in large co-incineration power plants (Gerssen-Gondelach *et al.*, 2014). The levelized costs of a biomass power plant are mainly influenced by calorific value, equipment efficiency, investment and operating costs (Patel *et al.*, 2011).

The physico-chemical properties of wood chips, as a source of renewable energy, are essential for optimizing their use (Moskalik and Gendek, 2019; Nurek *et al.*, 2019). Moisture content is the most important quality parameter of wood fuels, where its accurate determination (Leoni *et al.*, 2021) but also accurate determination of calorific value (Hnilička *et al.*, 2020) is essential. The technique of storing wood fuels is also essential for the final moisture content (Manzone *et al.*, 2013), but also based on the risk and sensitivity analyses of Bianchini and Simioni (2021), the investment for drying wood chips is viable. Drying during storage is affected by storage organization as well as the environmental conditions (Röser *et al.*, 2011; Manzone, 2018). In some areas, it is justified to partially cover the wood from the effects of weather on the final moisture in the wood, while in others it may be counterproductive (Röser *et al.*, 2011). The moisture content of fresh wood chips reaches high values (Dzurenda *et al.*, 2014), which directly affects the calorific value of this fuel (Černý *et al.*, 2016), because this parameter is the only one that can be reduced by suitable drying technology (Bianchini and Simioni, 2021). The share of individual CHNS has a fundamental influence on the thermal work of the incinerator (Malaťák and Passian, 2011; Jenicek *et al.*, 2021), but also on the resulting emission concentrations during the combustion of wood biomass fuels (Bradna and Malaťák, 2016; Malaťák *et al.*, 2020), as well as on the economics of operating a bioenergy power plant.

Biocoal can be considered as a substitute for coal as a renewable energy source without demanding modifications to the combustion equipment. Biochar is a stabilized, durable organic carbon compound that is produced by heating biomass to temperatures typically between 200 and 1000°C under low (preferably zero) oxygen concentrations (Xie *et al.*, 2015). Biomass torrefaction (Phanphanich and Mani, 2011) clearly showed improved fuel properties and properties closer to coal.

As a commodity, wood chips are subject to evaluation from an economic point of view. The authors' study (Bianchini and Simioni, 2021) is aimed at evaluating the economics and risk of industrial drying of wood chips. Other articles evaluate the physical parameters of wood chips and the achieved bid price within the framework of the economic effect (Gendek and Nurek, 2016). Coal consumption is currently on the verge of returning to the values of 2013. The main factor is the current crisis on the market for energy raw materials. Based on assumptions, it is expected to grow by 0.7% in the current year with a continuing trend in future years. The entire market for energy commodities has recently experienced sharp shocks, resulting in a strong imbalance between producers and consumers (Guénette and Khadan, 2022).

In the Czech Republic, black and brown coal are mined, and coke is produced (Dvořák *et al.*, 2015). In 2010, coal production was 55.2 million tons, and as a result of the gradual decline in mining, 20% less was mined in 2017, *i.e.*, 44.2 million tons of coal and 43.7 million tons the following year (Bufka and Veverková, 2019). Extractable reserves of black coal in 2018 were estimated at 29.2 million tons, and their lifetime with the current depletion of reserves through mining corresponds to 7 years (Bufka and Veverková, 2019). Brown coal reserves in used deposits are estimated at 634.2 million tons with a lifetime of 16 years. Since 2010, the import of thermal coal has increased by 35% to 1,778 thousand. pool. In 2017, imports from Poland accounted for 93% and the rest from other countries (Bufka and Veverková, 2019). Currently, the Czech Republic is considering ending the use of coal for electricity production by 2038 and fully switching to renewable energy sources (Zimmermannova *et al.*, 2023).

Midgley *et al.* (2017) summarized that there should be reliable markets for the whole wood industry. They noted also that the resource risk relates to clear ownership of trees. It is needed to consider different political situation in countries we are focusing on. It faces also the risk of natural shocks, for instance the extreme weather conditions or natural disaster like eruptions. Further it is important to consider the role of the energy crises starting in the year of 2022. The problem of increasing prices is crucial for solid fuels. Especially in the short-run the energy crises had a significant impact on industrial production (Hutter and Weber, 2022). In the long-term the effect on the wood processing should be occur.

The aim of the article is to assess the effect of coal prices on the price of domestic wood chips in the period 2009-2022 for the Czech Republic. Three research questions are related to this main objective:

- Are there positive or negative influences between the price of coal and the contract price of wood chips in the last ten years?
- Is there a long-run equilibrium relationship between the variables coal and wood chips?
- Is there significant information in the coal price time series that helps predict future woodchip contract price values?

Methods and materials

The analysis is focused on the effect of the price of fossil fuels in the form of coal on the price of domestic wood chips. Average coal prices in the Czech Republic are set as a starting point. These prices correspond to the total market value of coal in the world because the coal trade is fundamental to the economic as well as environmental impacts of national and global communities. Coal prices are obtained for trading on the Intercontinental Exchange and the New York Mercantile Exchange. Coal is the main fuel used to generate electricity worldwide. China is the largest producer and consumer of coal. Other major producers include United States, India, Australia, Indonesia, Russia, South Africa, Germany, and Poland. The largest exporters of coal are Indonesia, Australia, Russia, United States of America, Colombia, South Africa, and Kazakhstan. Coal prices shown in Trading Economics (2022) are based on over-the-counter (OTC) financial instruments and contracts for difference (CFDs). Coal prices are tracked from 2009 to the first half of 2022, see Fig. 1.

Wood chips are wood material in Czech conditions mainly made of spruce firewood. Chips are obtained from three possible sources. The first source of wood chips is from debarked wood, usually offcuts from sawmilling. The bark is no longer found on the individual chips, which is why it is usually defined as a white chip (WCh-W). The advantage of this raw material is that it no longer contains a higher proportion of inorganic pollution, therefore it has a higher calorific value (Vusić *et al.*, 2021) and there are no technical problems with ash during its thermochemical use (Malaťák *et al.*, 2020).

The second source of wood chips is residues after logging. It can be found not only parts of small branches, but also leaves, possibly needles – hence the green chip (WCh-G). Because fresh material is processed, the moisture content of this chip is high, immediately after mining it reaches more than 55% by weight. This chip is characterized not only by its high moisture content, but also by its inorganic content, which enters this raw material during mining (Dzurenda *et al.*, 2014).

The problem is not only a reduction in calorific value, but also a high proportion of ash (Dzurenda *et al.*, 2014), which can be the cause of technical problems during combustion (Malaťák *et al.*, 2020).

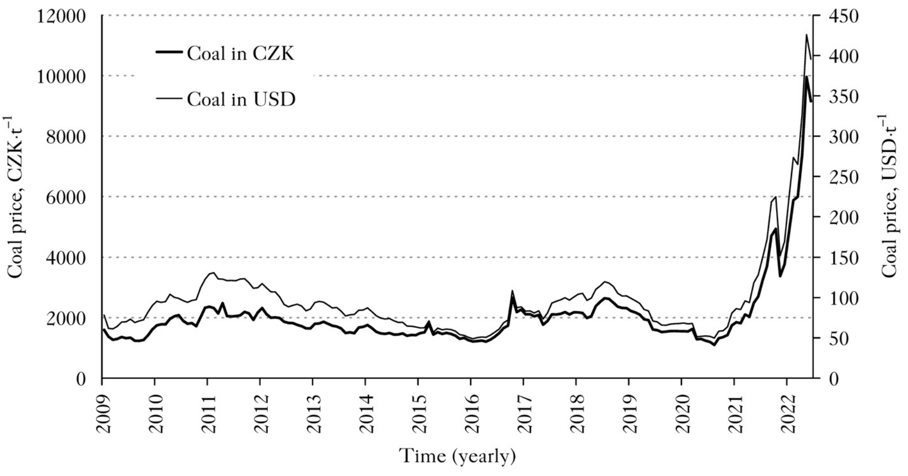

Fig. 1.
Coal prices 2009-2022 (Trading Economics, 2022)

The last chip is obtained from the remaining parts of trunks, sawmill cuttings, *etc*. The common element of this wood raw material is the bark content – brown wood chip (WCh-B). The wood raw material was not debarked before processing, so parts of the bark can be recognized on the individual chips. The bark as the raw material itself contains phellogen tissue, which is located between the phloem and bark (Vusić *et al.*, 2021). Towards the center of the stem, it produces phelloderm cells that contain chloroplasts. It produces cork outwards (Nurek *et al.*, 2019). A problem can arise with an increased content of inorganic substances that can enter the bark during mining and transport (Bożym *et al.*, 2021).

Default quality parameters are determined on three selected samples of white, green, and brown wood chips. This involves the determination of moisture, ash, combustion heat, calorific value, and elemental composition (C, H, N, S). The heat of combustion of the samples is analyzed in a semi-automatic calorimeter LECO AC-600. A LECO AC600 bomb calorimeter (LECO Corporation, USA) was used for the determination of gross calorific values, while net calorific values were calculated according to ISO 18125:2017.

The content of carbon, hydrogen, nitrogen, and sulfur was determined on the LECO CHN628+S analyzer (LECO Corporation, USA). The oxygen content was subsequently calculated. Analysis results were converted to dry state according to ISO 16993:2016. All analyzes for each sample were repeated at least three times to avoid measurement error. These parameters determine the suitability of the material for energy use and influence all thermo-technical determinations. The total moisture content and ash content of all samples are determined on the thermogravimetric analyzer LECO TGA-701 (LECO Corporation, USA). The methods used corresponded to ISO 18134-3:2015 for moisture and ISO 18122:2015 for ash content.

An energy company that processes an average mixture of these three sources of wood chips with an average calorific value of 8 $GJ \cdot t^{-1}$ is selected for its own analysis. The prices of wood chips correspond to the wholesale price in the conditions of the Czech Republic and are given by the contract price for the energy company, which corresponds to the average price of wood chips for wholesale customers for the period from 2009 to the first half of 2022 in the conditions of the Czech Republic, see Fig. 2.

Table 1 shows the basic descriptive statistics for both woodchip price and coal price variables. During the observed period, the average price of wood chips was 800 $CZK \cdot t^{-1}$ (37.53 $USD \cdot t^{-1}$), the price of coal 2061 $CZK \cdot t^{-1}$ (97.05 $USD \cdot t^{-1}$). The largest price variability is represented by the coal variable, as there has been significant growth here, especially in the last year. Therefore, even the maximum value for coal is significantly skewed. The contract price of wood chips does not tend to fluctuate over time. The quoted prices are based on the main commodity exchange with daily frequency. The data of the Intercontinental Exchange and CME exchange are included for research. Both commodities are traded among producers and consumers.

Both price trajectories are affected by external shocks in the commodity markets in the last decade. The charts show the start of energy crisis in the end of 2021. The coal price was more sensitive than wood chip with more stable prices. The ongoing problem with carbon emission has significant impact on the price movements. The German energy policy have been influenced the whole financial market within Europe.

The method of time series analysis is used for the own evaluation of the data. As part of the assessment of raw material prices, an analysis of the stationarity of time series will be carried out. Stationarity of time series describes behavior that can be clearly described by a mathematical formula. The goal of time series analysis is to determine the model according to which the monitored data is generated. Knowledge of this model makes it possible to predict the future development of the system and, to a certain extent, to control and optimize the behavior of the system by an appropriate choice of input parameters and initial conditions. The stationarity of time series is an important prerequisite for further testing, as it is necessary to ensure a stable mean and variance within the given period.

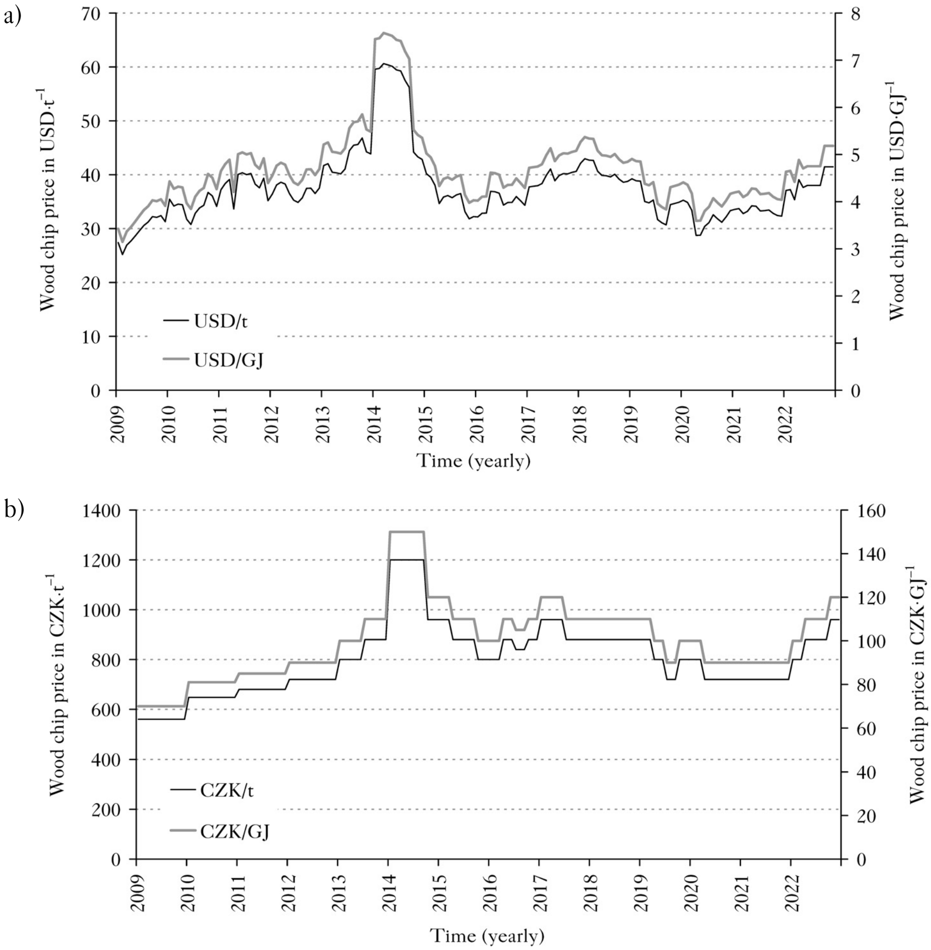

Fig. 2.
Contract price 2009-2022: a) in CZK, b) in USD

Table 1.
Descriptive statistics of wood chips and coal variables in CZK·t^{-1} and USD·t^{-1}, 2009-2022

Variable	Mean	Median	S.D.	Min	Max
Wood chip					
CZK·t^{-1}	800	800	144	560	1200
USD·t^{-1}	37.53	36.51	6.61	25.18	60.62
Coal					
CZK·t^{-1}	2061	1795	1205	1099	9958
USD·t^{-1}	97.05	87.15	53.42	48.78	425.89

For the time series transformation the logarithmic returns are used:

$$r_t = \left(\ln \frac{P_t}{P_{t-1}} \right) \tag{1}$$

where:

P_t is closing price of commodity and P_{t-1} is one lagged (prior day).

The Augmented Dickey-Fuller test method was used at the á=0.05 significance level to determine the presence of a unit root (a positive occurrence detects non-stationarity of the time series) in the contract prices of wood chips and coal prices. In statistics and econometrics, the augmented Dickey-Fuller (ADF) test tests the null hypothesis that a unit root is present in a time series sample. The alternative hypothesis varies depending on the version of the test used but is usually stationary or trending. This is an extended version of the Dickey-Fuller test for a larger and more complicated set of time series models. The Augmented Dickey-Fuller (ADF) statistic used in the test is a negative number. The more negative it is, the stronger the rejection of the hypothesis that a unit root exists at a given confidence level (Fuller, 1976).

The result of the ADF test statistic is therefore a number that is found in negative values. For comparison with other values, the smallest value of the test statistic is significant. In this case, this is the strongest confirmation of the rejection of the hypothesis of the presence of a unit root at the given level of significance.

By including lags of order p, the ADF formulation allows higher-order autoregressive processes. This means that the delay length p must be determined when applying the test. One possible approach is to test from high orders and examine the t-values on the coefficients.

OLS regression analysis of differentiated time series is used for the time series of contract prices of wood chips and coal prices. This method is intended to clarify the relationship between the dependent variable quantity Y and time t. For a simple analysis of the relationship between the two variables, the linear regression method is used:

$$y_t = \alpha + \beta x_t + \epsilon_t \tag{2}$$

where the coefficient α is a constant, x_t is then the independent variable, y_t is the dependent variable and ϵ_t is the residual. The relationship is conceived as two-way: the price of coal = the price of wood chips and the price of wood chips = the price of coal.

As part of further cointegration testing using the Engle-Granger test, the following unit root regression is performed. The Engle Granger test is a cointegration test. Constructs residuals (errors) based on static regression. The test uses the residuals to determine whether unit roots are present, using the Augmented Dickey-Fuller test or another similar test. If the time series is cointegrated, the residuals will be virtually stationary (Armstrong, 2001). Cointegration analysis using the Engle-Granger test is performed based on the non-stationarity of the time series of coal prices Xt and wood chip prices Yt with the assumption of integration in order 1, d(1). Their linear combination is then stationary (Engle and Granger, 2015).

The following hypotheses are established:

H_0 = no cointegration

H_1 = cointegration

The Granger causality method (Granger, 1969) will be used as part of the analysis of the improvement of time series prediction within the monitored commodities. The development of the coal price provides information regarding the development of the contract prices of wood chips and vice versa. Granger causality is a statistical concept of causality that is based on prediction. According to Granger causality, if signal X_1 'Grangers' (or 'G-causes') signal X_2, then past values of X_1 should contain information to help predict X_2 over and above the information contained in past values of X_2 itself. Its mathematical formulation is based on linear regression modeling of stochastic processes (Boudjellaba *et al.*, 1992).

$$
\begin{aligned}
X_t &= \alpha_0 + \sum_{i=1}^{m} \mu_i X_{t-1} + \sum_{j=1}^{m} \delta_j Y_{t-1} + u_{1t} \\
Y_t &= \alpha_1 + \sum_{i=1}^{m} \beta_i X_{t-1} + \sum_{j=1}^{m} \varepsilon_j Y_{t-j} + u_{2t}
\end{aligned}
\tag{3}
$$

where the time series X represents the average prices of coal and Y the wood chips of the stationary time series, m is then the length of the lag and u_{1t} and u_{t2} are uncorrelated residual components.

For the own testing of the Granger-causal relationship, the hypothesis is formulated:

$$H_0 = \beta_1 = \beta_2 = \ldots = 0 \tag{4}$$

For the null hypothesis, the time series of coal prices does not Granger-causally affect the time series of wood chip prices and vice versa.

Results

The resulting average value of the elemental analyzes is shown in Table 2. The results of the quality parameters show relatively balanced elemental parameters in the dry matter of individual samples compared to another woody biomass (Vassilev *et al.*, 2010). A high amount of ash is determined for green wood chip samples, where the amount of ash corresponds to herbaceous biomass (Tao *et al.*, 2012). A large amount of ash has a significant effect on the reduction of combustion heat, but also on the course of thermochemical processing such as direct application (Malaťák *et al.*, 2020), but also on other thermochemical processes such as gasification (Malaťáková *et al.*, 2021). The most limiting element that fundamentally reduces the calorific value is the high amount of water in the original sample (Moskalik and Gendek, 2019; Nurek *et al.*,

Table 2.

Composition of white wood chips (WCh-W), green wood chips (WCh-G), and brown wood chips (WCh-B), (o.s. – original sample, d.b. – on dry basis)

Sample	Water Content	Ash	Carbon	Hydrogen	Sulphur	Nitrogen	Oxygen	Gross Calorific Value	Net Calorific Value
	[% wt.]	[% wt.]	[% wt.]	[wt.]	[% wt.]	[% wt.]	[% wt.]	[MJ kg^{-1}]	[MJ kg^{-1}]
	W	*A*	*C*	*H*	*S*	*N*	*O*	Q_s	Q_i
WCh-W. o.s.	28.47	0.19	36.80	4.31	0.00	0.16	30.07	15.25	13.61
WCh-W. d.b.		0.26	51.44	6.03	0.00	0.22	42.05	20.15	18.83
WCh-G. o.s.	50.31	5.17	24.71	2.76	0.01	0.27	16.77	9.25	7.42
WCh-G. d.b.		10.40	49.72	5.55	0.03	0.54	33.76	18.81	17.59
WCh-B. o.s.	40.87	1.57	31.10	3.45	0.00	0.20	22.81	13.89	12.14
WCh-B. d.b.		2.65	52.60	5.84	0.00	0.33	38.58	21.13	19.85

Note: o.s. – original sample, d.b.– dry basis, WCh-W – white wood chips, WCh-G – green wood chips, WCh-B – brown wood chips, wt. – weight

2019), which is why the final mixture of these samples reaches an average required calorific value of 8 GJ·t^{-1}.

The following qualitative parameters are established for coal: ash content 12% wt. (Wt.=weight), water, sulfur content 1.7% wt. by average calorific value 22 MJ·kg^{-1} in comparison with chip in 90% wt. with green usage (average calorific value 8 MJ·kg^{-1} in original state (S&P Global Patts, 2022).

The resulting analyzes address three research questions:

– Are there causal positive or negative effects between the price of coal and the contract price of wood chips in the last ten years?
– Is there a long-run equilibrium relationship between the variables coal and wood chips?
– Is there significant information in the coal price time series that helps predict future woodchip contract price values?

Based on the analysis of time series, an analysis of the stationarity of time series is performed. The Augmented Dickey-Fuller test method at the α=0.05 significance level is used to determine the presence of a unit root in the contract prices of wood chips and coal prices. The resulting values under the null hypothesis of a unit root: a=1 are shown in Table 3.

Based on the ADF tests, it is found that the presence of a unit root is detected for both time series. Both time series are non-stationary. As part of the transformation of both time series, the first differences are made for further calculations based on formula 1.

OLS regression analysis of differentiated time series is used for the time series of contract prices of wood chips and coal prices, see formula 2. The resulting values are shown in Table 4.

The relationship between the dependent variable (coal price) and the independent variable of the contract price of wood chips is statistically insignificant. The coefficient of determination is 0.004, where it can be stated that no relationship is detected between the variables within the linear model. Therefore, further, more advanced analysis can be performed to verify significant relationship.

As part of cointegration testing using the Engle-Granger test, a regression is performed, where in the first step the unit root of coal is tested, followed by wood chips. Furthermore, cointegration regression is determined. The resulting values are shown in Table 5. For the analysis of the cointegration relationship, the formula 2 is used to express the dependence of the variable x on y and vice versa.

Using the p-value, the null hypothesis of non-stationary cointegration regression residuals cannot be rejected, therefore both time series are not in a long-term equilibrium relationship. The p-value of 0.9144 is greater than the chosen significance level. (α=0.05)

Table 3.
ADF test of wood chips and coal prices

	Coal	Wood chip
	testing down from 13 lags, criterion AIC	
	Observations: 152	Observations: 161
	Test with constant	
Test statistic:	tau_c(1)=0.430332	tau_c(1)=–1.93806
Asymptotic p-value:	0.9843	0.3142
		0.008
	With constant and trend	
Test statistic:	tau_ct(1)=0.19137	tau_ct(1)=–2.00595
Asymptotic p-value:	0.998	0.5975

Table 4.
Results of the OLS regression analysis

Model OLS Dependent: d_coal				
	Coefficient	Stand. Deviation	t-rate	p-value
Const	48.0902	27.2248	1.766	0.0792*
d_chip	–0.543805	0.663060	–0.8201	0.4134

Mean value of dependent variable	46.92832	Sd. Independent regression	344.6225
Residual sum squares	18922302	Sd. Error regression	344.9756
Coefficient of det.	0.004213	Adj. Coefficient of determination	–0.002050
F(1, 159)	0.672637	P-value(F)	0.413361
Logarithmic likelihood	–1168.242	AIC	2340.484
Schwarz criterio	2346.647	Hannah-Quinn criterion	2342.987
Rho (autocorrelation coeff.)	0.139807	Durbin-Watson statistic	1.688728

Table 5.
Cointegration regression of wood chips and coal variables, (T=162)

Cointegration regression – OLS, (T=162) Dependent variable: coal price				
	Coefficient	Stand. Error	t-rate	p-value
Const	1159.41	407.492	2.845	0.0050***
Wood chip	1.19122	0.523518	2.275	0.0242**

Mean value of dependent variable	2061.737	Sd. Independent regression	1208.932
Residual sum squares	2.28e+08	Sd. Error regression	1193.546
Coefficient of det.	0.031345	Adj. Coefficient of determination	0.025291
F(1, 159)	–1376.581	P-value(F)	2757.161
Logarithmic likelihood	2763.337	AIC	2759.669
Schwarz criterio	0.958643	Hannah-Quinn criterion	0.087985

The Granger causality method is used in the analysis of the improvement of time series prediction within the monitored commodities. The development of the coal price provides information regarding the development of the contract prices of wood chips and vice versa. The resulting values are shown in Table No. 6. Formulas 3 and 4 are used to test the Granger-causal relationship.

As part of the analysis of the improvement of the prediction of one time series against the other, it is found that there is no improvement of any kind for both time series. Woodchip contract prices do not help predict the time series of coal prices and vice versa. The null hypotheses of no Granger-causal relationship are rejected for both variables in both directions. In other words, the Granger causal relationship was not proven for both commodities, so it can be stated that there are no positive or negative shocks to the given price relationship for both commodities.

Table 6.
Granger causality tests of wood chips and coal variables

Equation 1: coal				
	Coefficient	Stand. error	t-rate	p-value
Const	–40.4458	179.387	–0.2255	0.8220
Coal_1	1.10829	0.0919276	12.06	<0.0001***
Coal_2	–0.250753	0.148308	–1.691	0.0934*
Coal_3	0.158216	0.151498	1.044	0.2983
Coal_4	0.244618	0.156314	1.565	0.1201
Mean value of dependent variable	2117.867	Sd. Independent regression		1239.034
Residual sum squares	10967303	Sd. Error regression		296.2067
Coefficient of det.	0.952055	Adj. Coefficient of determination		0.942849
F(1. 159)	103.4222	P-value(F)		0.875614
Logarithmic likelihood	0.009714	AIC		1.958102
F-test for 0 restriction:				
Lagged values coal AF(12. 125)=89.1 [0.0000]				
Lagged values chip(12. 125)=0.65511 [0.7910]				
All lagged variables(2. 125)=1.3345 [0.2670]				
Equation 2: wood chip				
	Coefficient	Stand. error	t-rate	p-value
Const	79.3128	24.4109	3.249	0.0015***
Wood chip_1	0.00765622	0.0125095	0.6120	0.5416
Wood chip_2	–0.0332564	0.0201817	–1.648	0.1019
Wood chip_3	0.0534317	0.0206157	2.592	0.0107**
Wood chip_4	–0.0427286	0.0212712	–2.009	0.0467**
Mean value of dependent variable	781.6000	Sd. Independent regression		164.2516
Residual sum squares	203088.6	Sd. Error regression		40.30768
Coefficient of det.	0.949478	Adj. Coefficient of determination		0.939778
F(1. 159)	97.88212	P-value(F)		0.921130
Logarithmic likelihood	0.050411	AIC		1.730700
F-test for 0 restriction:				
Lagged values coalAF(12. 125)=1.7153 [0.0710]				
Lagged values chip (12. 125)=83.43 [0.0000]				
All lagged variables 12F(2. 125)=1.54 [0.2184]				

Discussion

The energy value of wood chips determines the selling price of this renewable energy source. The share of moisture significantly affects the calorific value of wood chips, as shown by other authors (Bożym *et al.*, 2021), fresh green wood chips can reach a high share of moisture even over 50% by weight. (Gürdil *et al.*, 2009; Vassilev *et al.*, 2010), unlike white wood chips, where moisture is determined by storage conditions (Manzone, 2018). High humidity in incinerators significantly affects the dynamics of combustion processes (Ragland *et al.*, 1991). Another part of the fuel that significantly reduces the calorific value is the share of ash in the fuel (Stolarski *et al.*, 2019). The high proportion of ash in green wood chips is equal to herbal biomass, where the amount of ash in wheat straw is also around 5% by weight (Vassilev *et al.*, 2010). The high concentration of ash found in green wood chips makes this fuel a technically more complex fuel intended especially for larger combustion devices, such as heating plants or power plants (Malaťák *et al.*, 2009). Therefore, wood chips with a high proportion of moisture and ash can also meet the requirement for a minimum calorific value of 8 GJ/t for these large sources.

Wood chips with a qualitatively higher ash content and higher moisture content have a 3 times lower calorific value compared to coal (Stolarski *et al.*, 2019). One of the solutions to better use the energy from wood chips is its torrefaction, which on the one hand will reduce the moisture and the amount of oxygen in the fuel (Jenicek *et al.*, 2021) and on the other hand the material will become more stable (Aniszewska *et al.*, 2020) and above all the calorific value of this material in the form of biochar will increase (Tamelová *et al.*, 2022). On the other hand, transportation costs will increase (Stolarski *et al.*, 2021), due to the globalization of these raw materials. For the use of this biochar, its total price compared to local wood chips and the global price of coal is essential.

Global coal supply investment is expected to grow by 10% in 2022 as tight supply continues to attract investment in new projects, particularly in Europe, as leading consumers step up efforts to diversify their energy sources (Trading Economics, 2022). The war in Eastern Europe caused a global energy crisis and deepened concerns about coal supplies in an already tight market (Bianchini and Simioni, 2021). Coal prices rose as high as USD 430 at the end of May, and further upward pressure can be expected soon, which is inherently related to the duration of the conflict and the severity of the disruption to commodity flows (Trading Economics, 2022). At the same time, an further increase in the use of wood chips is expected in 2022, which is the first candidate to replace coal (Jåstad *et al.*, 2020; Xu *et al.*, 2020). This influence will already have a fundamental effect on the price formation of wood chips, which has not been confirmed in this article until the end of 2021. The overall price impact to wood chip commodity has also the interest of European Union policy in the field of environmental sustainability. In December 2019 the EU introduced the strategic plan called "European Green Deal" helping the economy and society in Europe with transformation on sustainable path (Schunz, 2022).

From economic point of view, woodchips are cheaper to produce than wood pellets and wood cords. The harvest process is more automated and faster. The whole tree can be processed into wood chips. For efficient burning the cord wood is needed to be dry. In the case of wood pellets there are additional costs covering of trucking or storing the wood. It relates to the need of greater physical volume, as well (Visser *et al.*, 2020).

As a result of the calamity of unplanned logging in the Czech Republic, spruce production increased from the planned 15.5 million to almost 36.8 million trees, this calamity wood is mostly intended for energy purposes (Maitah *et al.*, 2022). Currently, there is also a significant increase in average prices for all conifer assortments in forestry for the year 2021. Compared to 2020, the average prices thus approached the level of 2015 before the bark beetle disaster (Hlásný *et al.*, 2021). Currently, the average price of coniferous fuel increased by 14.1% year-on-year to 503 CZK m^{-3}. In particular, climate change has a negative effect on the state of forestry and thus threatens the timber industry in the Czech Republic (Šafařík *et al.*, 2022). These reasons have raised many questions on how to ensure the sustainability of wood processing enterprises (Michal *et al.*, 2021).

From the point of view of Europe, the trade in wood chips for energy production is largely limited to wood waste (Nurek *et al.*, 2019) and small volumes of trade in primary wood chips (Moskalik and Gendek, 2019). Wood biomass trade is mainly regional or cross-border (Kanzian *et al.*, 2009; Díaz-Yáñez *et al.*, 2013; Lamers *et al.*, 2014). Market factors and regional policies defined wood biomass trade volumes, while policy changes did not have as dramatic an impact on trade developments as in the fossil fuel sector (Trading Economics, 2022). Among the aspects of using wood biomass for energy production there are environmental, social, economic, and technological types (Gołos and Kaliszewski, 2015).

Conclusion

This article deals with the analysis of the price relationship between wood chips and fossil fuel – coal. One of the quality requirements that affects the market price of wood chips is the calorific value of the average mixture, which is basically determined by the moisture value of the three sources of spruce wood. The most problematic is the green wood mass, where a large increase in ash is also recorded.

Empirical findings are found for all formulated research questions in the form of partial time series analyses. The research results show that the Granger-causal relationship for both variables is not proven. Price changes in one time series do not affect price changes in the other time series. The analysis did not prove a causal negative or positive relationship. A long-term equilibrium relationship leading to equilibrium is not proven for both monitored variables. Their price development is not within the mean value of the stationary generating process.

To understand the empirical findings of the article, it is necessary to consider the influence of European Union policies in the areas of the environment. The economic cause of the possible independent relationship between coal and wood chips is emission allowances and their trading. In general, the wood chip is renewable in contrary to coal. The coal mining will be eliminated in the future according to the framework of green deal, especially in Europe. Precipitous price growth has a significant impact on the situation on the energy market, or on the fossil fuel market. The gradual pressure on producers and the use of ecologically objectionable raw materials will have a significant impact in the future. As a topic for further research in this area, an analysis of the prediction of the development of the market of energy commodities and their price spillover into various sectors of the economy could be used. For financial practitioners and investors, risk analysis in relation to quality sensitivity is appropriate.

Author's contributions

Conceptualization and design of the study – Ji.M., Ja.M. , M.J. and J.V.; implementation of the study – J.V., B.T., Ja.M., Ji.M., and M.J.; analysis of the data – Ja.M., M.J., J.V., A.G. and M.A.; writing-original draft preparation – Ja.M., Ji.M., M.J., J.V., B.T., A.G. and M.A.; writing-review and editing – Ji.M., Ja.M., J.V., M.J., A.G. and M.A.; supervision – Ja.M., Ji.M., and M.J.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the deci-sion to publish the results. The work is an original research carried out by the authors. All authors agree with the contents of the manuscript and its submission to the journal. All Authors listed have contributed significantly to the work and agree to be in the author list.

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References

Agar, D., Gil, J., Sanchez, D., Echeverria, I., Wihersaari, M., 2015. Torrefied versus conventional pellet production – A comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria. *Applied Energy*, 138: 621-630. DOI: https://doi.org/10.1016/j.apenergy.2014.08.017.

Agbor, E., Oyedun, A.O., Zhang, X., Kumar, A., 2016. Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. *Applied Energy*, 169: 433-449. DOI: https://doi.org/10.1016/j.apenergy.2016.02.018.

Akhtar, A., Krepl, V., Ivanova, T., 2018. A Combined Overview of Combustion, Pyrolysis, and Gasification of Biomass. *Energy and Fuels*, 32 (7): 7294-7318. DOI: https://doi.org/10.1021/acs.energyfuels.8b01678.

Aniszewska, M., Gendek, A., Hýsek, Š., Malaťák, J., Velebil, J., Tamelová, B., 2020. Changes in the composition and surface properties of torrefied conifer cones. *Materials*, 13 (24): 1-14. DOI: https://doi.org/10.3390/ma13245660.

Armstrong, S.J., 2001. Principles of Forecasting: A Handbook for Researchers and Practitioners (International Series in Operations Research & Management Science, 30) 2001st Edition. New York: Springer, 862 pp.

Bianchini, D.C., Simioni, F.J., 2021. Economic and risk assessment of industrial wood chip drying. *Sustainable Energy Technologies and Assessments*, 44: 101016. DOI: https://doi.org/10.1016/j.seta.2021.101016.

Boudjellaba, H., Dufour, J., Roy, R., 1992. Testing causality between two vectors in multivariate autoregressive moving average models. *Journal of the American Statistical Association*, 87: 1082-90. DOI: https://doi.org/10.1080/01621459.1992.10476263.

Bożym, M., Gendek, A., Siemiątkowski, G., Aniszewska, M., Malaťák, J., 2021. Assessment of the composition of forest waste in terms of its further use. *Materials*, 14 (4), 1-17, 973. DOI: https://doi.org/10.3390/ma14040973.

Bradna, J., Malaťák, J., 2016. Flue gases thermal emission concentration during waste biomass combustion in small combustion device with manual fuel supply. *Research in Agricultural Engineering*, 62 (1): 1-7. DOI: https://doi.org/10.17221/36/2014-RAE.

Bufka, A., Veverková, J., 2019. Uhlí v České Republice. TZB-info. Available from https://energetika.tzb-info.cz/19810-uhli-v-ceske-republice [accessed: 25.01.2023].

Černý, D., Malaťák, J., Bradna, J., 2016. Influence of biofuel moisture content on combustion and emission characteristics of stove. *Agronomy Research*, 14 (3), 725-732.

Deboni, T.L., Simioni, F.J., Brand, M.A., Lopes, G.P., 2019. Evolution of the quality of forest biomass for energy generation in a cogeneration plant. *Renewable Energy*, 135: 1291-1302. DOI: https://doi.org/10.1016/j.renene.2018.09.039.

Díaz-Yáñez, O., Mola-Yudego, B., Anttila, P., Röser, D., Asikainen, A., 2013. Forest chips for energy in Europe: Current procurement methods and potentials. *Renewable and Sustainable Energy Reviews*, 21: 562-571. DOI: https://doi.org/10.1016/j.rser.2012.12.016.

Dvořák, J., Wittlingerová, Z., Bicanová, K., 2015. Energy consumption for coal and lignite mining and treatment in the Czech republic. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, SGEM, 2 (5), pp. 549-556.

Dzurenda, L., Banski, A., Dzurenda, M., 2014. Energetic properties of green wood chips from Salix Viminalis grown on plantations. *Scientia Agriculturae Bohemica*, 2014 (1), 44-49. DOI: https://doi.org/10.7160/sab.2014.450106

Dzurenda, L., Bartko, M., Ridzik, L., 2012. Energetic characteristics green chips made of branches of wood species Populus x euroamericana clone Koltay grown on plantations. *Acta Facultatis Xylologiae*, 54 (2), 115-122.

Engle, R.F., Granger, C.W.J., 2015. Co-Integration and Error Correction: Representation, Estimation, and Testing. *Applied Econometrics*, 39 (3): 107-135.

Fuller, W.A., 1976. Introduction to Statistical Time Series. New York: John Wiley and Sons, 720 p.

Gendek, A., Nurek, T., 2016. Variability of energy woodchips and their economic effects. *Folia Forestalia Polonica*, 58 (2): 62-71. DOI: https://doi.org/10.1515/ffp-2016-0007.

Gerssen-Gondelach, S.J., Saygin, D., Wicke, B., Patel, M.K., Faaij, A.P.C., 2014. Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. *Renewable and Sustainable Energy Reviews*, 40, 964-998. DOI: https://doi.org/10.1016/j.rser.2014.07.197.

Gołos, P., Kaliszewski, A., 2015. Aspects of using wood biomass for energy production. *Forest Research Papers*, 76 (1), 78-87. DOI: https://doi.org/10.1515/frp-2015-0009.

Granger, C.W.J., 1969. Investigating Causal Relations by Econometric Models and Cross-Spectral Methods. *Econometrica*, 37, 424-438.

Guénette, J.D., Khadan, J., 2022. World Bank. WorldBank. Available from: https://blogs.worldbank.org/developmenttalk/energy-shock-could-sap-global-growth-years [accessed 7.10.2022].

Guo, M., Song, W., Buhain, J., 2015. Bioenergy and biofuels: History, status, and perspective. *Renewable and Sustainable Energy Reviews*, 42: 712-725. DOI: https://doi.org/10.1016/j.rser.2014.10.013.

Gürdil, G.A.K., Selvi, K.C., Malaták, J., Pinar, Y., 2009. Biomass utilization for thermal energy. AMA, *Agricultural Mechanization in Asia, Africa and Latin America*, 40 (2): 80-85.

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., Turčáni, M., 2021. Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. *Forest Ecology and Management*, 490: 119075. DOI: https://doi.org/10.1016/j.foreco.2021.119075.

Hnilička, F., Hniličková, H., Kudrna, J., Kraus, K., Kukla, J., Kuklová, M., 2020. Combustion calorimetry and its application in the assessment of ecosystems. *Journal of Thermal Analysis and Calorimetry*, 142 (2): 771-781. DOI: https://doi.org/10.1007/s10973-020-09961-9.

Hutter, Ch., Weber, E., 2022. Russia-Ukraine War: Short-run production and labour markets effects of the energy crisis. IAB-Discussion paper. Nürnberg: Institut für Arbeitsmarkt- und Berufsforschung (IAB) [Nuremberg, Germany Institute for Employment Research,]. DOI: https://doi.org/10.48720/IAB.DP.2210.

ISO, 18134-3:2015, 2015. Solid Biofuels – Determination of Moisture Content. Geneva, Switzerland: International Organization for Standardization.

ISO 18122:2015, 2015. Solid Biofuels – Determination of Ash Content. Geneva, Switzerland: International Organization for Standardization.

ISO 16993:2016, 2016. Solid Biofuels – Conversion of Analytical Results from One Basis to Another. Geneva, Switzerland: International Organization for Standardization.

ISO 18125:2017, 2017 Solid Biofuels – Determination of CalorificValue; Geneva, Switzerland: International Organization for Standardization.

Jåstad, E.O., Bolkesjø, T.F., Trømborg, E., Rørstad, P.K., 2020. The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. *Applied Energy*, 274: 115360. DOI: https://doi.org/10.1016/j.apenergy.2020.115360.

Jenicek, L., Neskudla, M., Malatak, J., Velebil, J., Passian, L., 2021. Spruce and Barley Elemental and Stochiometric Analysis Affected by the Impact of Pellet Production and Torrefaction. *Acta Technologica Agriculturae*, 24 (4): 166-172. DOI: https://doi.org/10.2478/ata-2021-0028.

Jonsson, R., Mustonen, M., Lundmark, T., Nordin, A., Gerasimov, Y., Granhus, A., Hendrick, E., Hynynen, J., Kvist Johannsen, V., Kaliszewski, A., Miksys, V., Nord-Larsen, T., Polley, H., Sadauskiene, L., Snowdon, P., Solberg, B., Sollander, E., Snorrason, A., Valgepea, M., Ward, S., Zalitis, T., 2013. Conditions and prospects for increasing forest yield in Northern Europe. Vantaa: Finnish Forest Research Institute, 41 pp.

Kanzian, C., Holzleitner, F., Stampfer, K., Ashton, S., 2009. Regional energy wood logistics – Optimizing local fuel supply. *Silva Fennica*, 43 (1): 113-128. DOI: https://doi.org/10.14214/sf.464.

Khorshidi, Z., Ho, M.T., Wiley, D.E., 2014. The impact of biomass quality and quantity on the performance and economics of co-firing plants with and without CO2 capture. *International Journal of Greenhouse Gas Control*, 21: 191-202. DOI: https://doi.org/10.1016/j.ijggc.2013.12.011.

Lamers, P., Junginger, M., Hamelinck, C., Faaij, A., 2012. Developments in international solid biofuel trade – An analysis of volumes, policies, and market factors. *Renewable and Sustainable Energy Reviews*, 16 (5): 3176-3199. DOI: https://doi.org/10.1016/j.rser.2012.02.027.

Lamers, P., Marchal, D., Heinimö, J., Steierer, F., 2014. Global woody biomass trade for energy. *Lecture Notes in Energy*, 17 (1): 41-63. DOI: https://doi.org/10.1007/978-94-007-6982-3_3.

Leoni, E., Mancini, M., Aminti, G., Picchi, G., 2021. Wood fuel procurement to bioenergy facilities: Analysis of moisture content variability and optimal sampling stratégy. *Processes*, 9 (2): 1-14. DOI: https://doi.org/10.3390/pr9020359.

Maitah, M., Toth, D., Malec, K., Appiah-Kubi, S.N.K., Maitah, K., Pańka, D., Prus, P., Janků, J., Romanowski, R., 2022. The impacts of calamity logging on the sustainable development of spruce fuel biomass prices and spruce pulp prices in the Czech Republic. *Forests*, 13 (1): 97. DOI: https://doi.org/10.3390/f13010097.

Malaťák, J., Gendek, A., Aniszewska, M., Velebil, J., 2020. Emissions from combustion of renewable solid biofuels from coniferous tree cones. *Fuel*, 276: 118001. DOI: https://doi.org/10.1016/j.fuel.2020.118001.

Malaták, J., Jevic, P., Gürdil, G.A.K., Selvi, K.C., 2009. Biomass heat-emission characteristics of energy plants. *AMA, Agricultural Mechanization in Asia, Africa and Latin America*, 39 (4): 9-13.

Malaťák, J., Passian, L., 2011. Heat-emission analysis of small combustion equipments for biomass. *Research in Agricultural Engineering*, 57 (2): 37-50. DOI: https://doi.org/10.17221/28/2010-rae.

Malaták, J., Velebil, J., Bradna, J., Gendek, A., Tamelová, B., 2020. Evaluation of CO and NOx emissions in real-life operating conditions of herbaceous biomass briquettes combustion. *Acta Technologica Agriculturae*, 23 (2): 53-59. DOI: https://doi.org/10.2478/ata-2020-0009.

Malat'áková, J., Jankovský, M., Malat'ák, J., Velebil, J., Tamelová, B., Gendek, A., Aniszewska, M., 2021. Evaluation of small-scale gasification for chp for wood from salvage logging in the czech republic. *Forests*, 12 (11): 1448. DOI: https://doi.org/10.3390/f12111448.

Manzone, M., 2018. Performance evaluation of different techniques for firewood storage in Southern Europe. *Biomass and Bioenergy*, 119: 22-30. DOI: https://doi.org/10.1016/j.biombioe.2018.09.004.

Manzone, M., Balsari, P., Spinelli, R., 2013. Small-scale storage techniques for fuel chips from short rotation forestry. *Fuel*, 109: 687-692. DOI: https://doi.org/10.1016/j.fuel.2013.03.006.

Midgley, S.J., Stevens, P.R, Arnold, R.J., 2017. Hidden assets: Asia's smallholder wood resources and their contribution to supply chains of commercial wood. *Australian Forestry* 80, (1): 10-25. DOI: https://doi.org/10.1080/00049158.2017.1280750.

Michal, J., Březina, D., Šafařík, D., Babuka, R., 2021. Sustainable development model of performance of woodworking enterprises in the czech republic. *Forests*, 12 (6), 672. DOI: https://doi.org/10.3390/f12060672.

Möller, B., Nielsen, P.S., 2007. Analysing transport costs of Danish forest wood chip resources by means of continuous cost surfaces. *Biomass and Bioenergy*, 31 (5): 291-298. DOI: https://doi.org/10.1016/j.biombioe.2007.01.018.

Møller, F., Slentø, E., Frederiksen, P., 2014. Integrated well-to-wheel assessment of biofuels combining energy and emission LCA and welfare economic Cost Benefit Analysis. *Biomass and Bioenergy*, 60: 41-49. DOI: https://doi.org/10.1016/j.biombioe.2013.11.001.

Moskalik, T., Gendek, A., 2019. Production of chips from logging residues and their quality for energy: A review of European literature. *Forests*, 10 (3): 262. DOI: https://doi.org/10.3390/f10030262.

Nurek, T., Gendek, A., Roman, K., 2019. Forest residues as a renewable source of energy: Elemental composition and physical properties. *BioResources*, 14 (1): 6-20. DOI: https://doi.org/10.15376/biores.14.1.6-20.

Paolotti, L., Martino, G., Marchini, A., Boggia, A., 2017. Economic and environmental assessment of agro-energy wood biomass supply chains. *Biomass and Bioenergy*, 97: 172-185. DOI: https://doi.org/10.1016/j.biombioe.2016.12.020.

Patel, C., Lettieri, P., Simons, S.J.R., Germanà, A., 2011. Techno-economic performance analysis of energy production from biomass at different scales in the UK context. *Chemical Engineering Journal*, 171 (3): 986-996. DOI: https://doi.org/10.1016/j.cej.2011.04.049.

Phanphanich, M., Mani, S., 2011. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource Technology*, 102 (2): 1246-1253. DOI: https://doi.org/10.1016/j.biortech.2010.08.028.

Ragland, K.W., Aerts, D.J., Baker, A.J., 1991. Properties of wood for combustion analysis. *Bioresource Technology*, 37 (2): 161-168. DOI: https://doi.org/10.1016/0960-8524(91)90205-X.

Röser, D., Mola-Yudego, B., Sikanen, L., Prinz, R., Gritten, D., Emer, B., Väätäinen, K., Erkkilä, A., 2011. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass Bioenergy*, 35: 4238-4247. DOI: https://doi.org/10.1016/j.biombioe.2011.07.011.

Schunz, S., 2022. The „European Green Deal" – a paradigm shift? Transformations in the European Union's sustainability metadiscourse. *Political Research Excahnge*, 4 (1): 2085121. DOI: https://doi.org/10.1080/2474736X.2022.2085121.

Specifications Guide Global Coal, 2020. S&P Global Platts, a division of S&P Global Inc. Available from: https://www.spglobal.com/commodityinsights/plattscontent/_assets/_files/en/our-methodology/methodology-specifications/coalmethodology.pdf [accessed: 12.10.2022].

Stolarski, M.J., Rybczyńska, B., Krzyżaniak, M., Krzyżaniak, M., Lajszner, W., Graban, Ł., Peni, D., Bordiean, A., 2019. Thermophysical properties and elemental composition of agricultural and forest solid biofuels versus fossil fuels. *Journal of Elementology*, 24 (4): 1215-1228. DOI: https://doi.org/10.5601/jelem.2019.24.1.1819.

Stolarski, M.J., Stachowicz, P., Sieniawski, W., Krzyżaniak, M., Olba-Zięty, E., 2021. Quality and delivery costs of wood chips by railway vs. Road transport. *Energies*, 14 (21): 6877. DOI: https://doi.org/10.3390/en14216877.

Stolarski, M.J., Warmiński, K., Krzyżaniak, M., Olba-Zięty, E., Akincza, M., 2020. Bioenergy technologies and biomass potential vary in Northern European countries. *Renewable and Sustainable Energy Reviews*, 133: 110238. DOI: https://doi.org/10.1016/j.rser.2020.110238.

Šafařík, D., Březina, D., Michal, J., Hlaváčková, P., 2022. State of the raw wood growing stocks and prediction of further development of cutting in the context of coniferous stands calamity in the Czech Republic. *Journal of Forest Science*, 68 (10), 423-435. DOI: https://doi.org/10.17221/76/2022-JFS.

Tamelová, B., Malaťák, J., Velebil, J., Gendek, A., Aniszewska, M., 2022. Impact of Torrefaction on Fuel Properties of Aspiration Cleaning Residues. *Materials*, 15 (19): 6949. DOI: https://doi.org/10.3390/ma15196949.

Tao, G., Lestander, T.A., Geladi, P., Xiong, S., 2012. Biomass properties in association with plant species and assortments I: A synthesis based on literature data of energy properties. *Renewable and Sustainable Energy Reviews*, 16 (5): 3481-3506. DOI: https://doi.org/10.1016/j.rser.2012.02.039.

Trading Economics, 2022. Coal. Trading Economics. Available from: https://tradingeconomics.com/commodity/coal [accessed 6.6.2022].

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G., 2010. An overview of the chemical composition of biomass. *Fuel*, 89 (5): 913-933. DOI: https://doi.org/10.1016/j.fuel.2009.10.022.

Visser, L., Hoefnagels, R., Junginger, M., 2019. Wood pellet supply chain costs – A review and cost optimization analysis. *Renewable and Sustainable Energy Reviews*, 118: 109506. DOI: https://doi.org/10.1016/j.rser.2019.109506.

Vusić, D., Vujanić, F., Pešić, K., Branimir, Š., Jurišić, V., Zečić, Ž., 2021. Variability of normative properties of wood chips and implications to quality control. *Energies*, 14 (13), 3789. DOI: https://doi.org/10.3390/en14133789.

Weldu, Y.W., Assefa, G., Jolliet, O., 2017. Life cycle human health and ecotoxicological impacts assessment of electricity production from wood biomass compared to coal fuel. *Applied Energy*, 187: 564-574. DOI: https://doi.org/10.1016/j.apenergy.2016.11.101.

Whittaker, C., Mortimer, N., Murphy, R., Matthews, R., 2011. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass and Bioenergy*, 35 (11): 4581-4594. DOI: https://doi.org/10.1016/j.biombioe.2011.07.001.

Xie, T., Reddy, K.R., Wang, C., Yargicoglu, E., Spokas, K., 2015. Characteristics and applications of biochar for environmental remediation: A review. Critical Reviews in *Environmental Science and Technology*, 45 (9): 939-969. DOI: https://doi.org/10.1080/10643389.2014.924180.

Xu, Y., Yang, K., Zhou, J., Zhao, G., 2020. Coal-biomass co-firing power generation technology: Current status, challenges and policy implications. *Sustainability*, 12 (9): 3692. DOI: https://doi.org/10.3390/su12093692.

Zhu, H., Luo, W., Ciesielski, P.N., Fang, Z., Zhu J.Y., Henriksson, G., Himmel, M.E., Hu, L., 2016. Wood-derived materials for green electronics, biological devices, and energy applications. *Chemical Reviews*, 116 (16): 9305-9374. DOI: https://doi.org/10.1021/acs.chemrev.6b00225.

Zimmermannova, J., Smilnak, R., Perunova, M., Ameir, O., 2023. Coal or biomass? case study of consumption behaviour of households in the Czech Republic. *Energies*, 16 (1): 192. DOI: https://doi.org/10.3390/en16010192.

STRESZCZENIE

Zależność ceny węgla i zrębków energetycznych w Republice Czeskiej

W skali globalnej zużycie węgla i drewna opałowego utrzymuje się na stałym poziomie, natomiast wykorzystanie zrębków drzewnych, peletu i brykietu do produkcji energii, w tym ogrzewania mieszkań, podwoiło się w ostatnich 10 latach i będzie rosło w przyszłości. Analiza rynku węgla i drewna opałowego stała się zatem ważnym obszarem zainteresowania producentów i konsumentów. Rosnące w oparciu o nową politykę środowiskową zużycie paliw drzewnych otworzyło nowe możliwości badawcze na rynku energetycznym, spowodowane m.in. zmniejszającym się użyciem paliw kopalnych. Obecnie zrębki drzewne i pelety są ekonomicznie oraz środowiskowo preferowanymi opcjami spalania w systemach ciepłowniczych i dużych elektrowniach współspalających. Na koszty spalania biomasy wpływają głównie wilgotność materiału, wartość opałowa, sprawność urządzeń oraz koszty inwestycyjne i operacyjne. Właściwości fizykochemiczne zrębków drzewnych jako źródła energii odnawialnej są niezbędne do optymalizacji ich wykorzystania.

Przeprowadzone badania dotyczą relacji cen węgla do umownych cen za zrębki energetyczne w Republice Czeskiej w latach 2009-2022. Podjęto się odpowiedzi na pytania: czy istnieje pozytywna bądź negatywna relacja pomiędzy ceną węgla i zrębków, czy zachodzi długookresowy związek między nimi oraz czy na podstawie cen węgla można przewidzieć przyszłe kontraktowe ceny zrębki drzewnej.

Do analizy wykorzystano rozdrobnione drewno świerkowe pochodzące z pozbawionych kory odpadów tartacznych (zrębki białe), z leśnych pozostałości pozrębowych (zrębki zielone) oraz z nieokorowanych odpadów tartacznych i pozostałości drewna okrągłego (zrębki brązowe). Parametry jakościowe zrębków obejmowały określenie wilgotności, zawartości popiołu, ciepła spalania, wartości opałowej oraz składu pierwiastkowego (C, H, N, S) przy użyciu aparatury firmy LECO (LECO AC600, LECO CHN+S, LECO TGA 701). Na podstawie uzyskanych danych obliczono zawartość tlenu. Parametry te określają przydatność materiału do wykorzystania energetycznego i wpływają na wszystkie oznaczenia termotechniczne. Pomiary wykonywane były w minimum 3 powtórzeniach. Do analizy wybrano przedsiębiorstwo energetyczne, które przetwarza mieszankę zrębków pochodzących z 3 źródeł o średniej wartości opałowej 8 $GJ \cdot t^{-1}$. Jako punkt wyjścia przyjęto średnie ceny węgla w Republice Czeskiej (ryc. 1). Ceny zrębków odpowiadają cenie hurtowej i są podane jako cena kontraktowa dla przedsiębiorstwa energetycznego (ryc. 2). Analizowano okres od 2009 r. do połowy 2022 r. W tabeli 1 podano podstawowe wartości statystyczne dla ceny węgla i zrębków drzewnych.

Do oceny danych zastosowano metodę analizy szeregów czasowych z wykorzystaniem wzoru 1, metodę testu Augmented Dickey-Fuller w celu określenia obecności pierwiastka jednostko-

wego, test Dickeya-Fullera (ADF) dla badanych hipotez (Fuller 1976) oraz test Engle'a--Grangera (wzory 3, 4 i 5).

Oczekuje się, że globalne inwestycje w dostawy węgla wzrosną o 10% w 2022 r., ponieważ napięta podaż nadal przyciąga inwestycje w nowe projekty. Wojna w Ukrainie spowodowała globalny kryzys energetyczny i pogłębiła obawy o dostawy węgla. Jednocześnie w 2022 r. spodziewany jest zwiększony wzrost wykorzystania zrębków drzewnych, które są pierwszym kandydatem do zastąpienia węgla. Zrębki drzewne o wyższej zawartości popiołu i wyższej wilgotności mają jednak 3-krotnie mniejszą wartość opałową w porównaniu do węgla.

W tabeli 2 przedstawiono wyniki analiz wilgotności, ilości popiołu, składu pierwiastkowego, ciepła spalania i wartości opałowej badanych zrębków w stanie wilgotnym i suchym. Najwyższą wilgotność i ilość popiołu wykazywały zrębki zielone, a najwyższą wartość opałową zrębki brunatne. W tabeli 3 podano wyniki testu ADS, w tabeli 4 wyniki analizy OLS, w tabeli 5 parametry równania regresji, a w tabeli 6 wyniki testu Grangera związku cen węgla oraz zrębków. Wyniki empiryczne pokazują, że relacja cenowa pomiędzy monitorowanymi towarami nie jest zrównoważona w długim okresie. Na podstawie analizy regresji nie stwierdzono statystycznie istotnej zależności między obserwowanymi cenami. Nie udowodniono również związku przyczynowego w obu kierunkach. W ramach analizy stwierdzono, że ceny kontraktów na drewno nie pomagają w przewidywaniu szeregu czasowego cen węgla i odwrotnie. Hipotezy zerowe o braku związku przyczynowego Grangera odrzucono dla obu zmiennych w obu kierunkach. Związek przyczynowy Grangera nie został więc udowodniony dla obu towarów: można stwierdzić, że nie ma pozytywnych ani negatywnych efektów dla danej relacji cenowej dla obu towarów. Dla obu monitorowanych zmiennych nie udowodniono długookresowej relacji prowadzącej do równowagi. Kształtowanie się ich cen nie mieści się w średniej wartości stacjonarnego procesu generującego.