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An investigation of the effects of moderator variables on the lower heating value estimation of lignite deposits in Turkey

Introduction

The use of coal in meeting the energy needs of the world became important after 1900 and has remained important in the twenty-first century. Although the share of renewable energy sources continues to increase in electricity and heating energy production today, its share in total energy production remains at the level of 5%. In other words, most of the electricity in the world is still produced from fossil fuels (coal, natural gas and petroleum).

Electricity in Turkey is produced from natural gas, hydropower, domestic coal and lignite, imported coal, wind, petroleum products, and geothermal, biogas and solar energy. In 2019, the total amount of electricity produced in Turkey was approximately 304 TWh, and the share of the different energy sources in this production is presented in Figure 1 (Enerji Atlası 2020). The natural gas and petroleum products used in these power plants are fully

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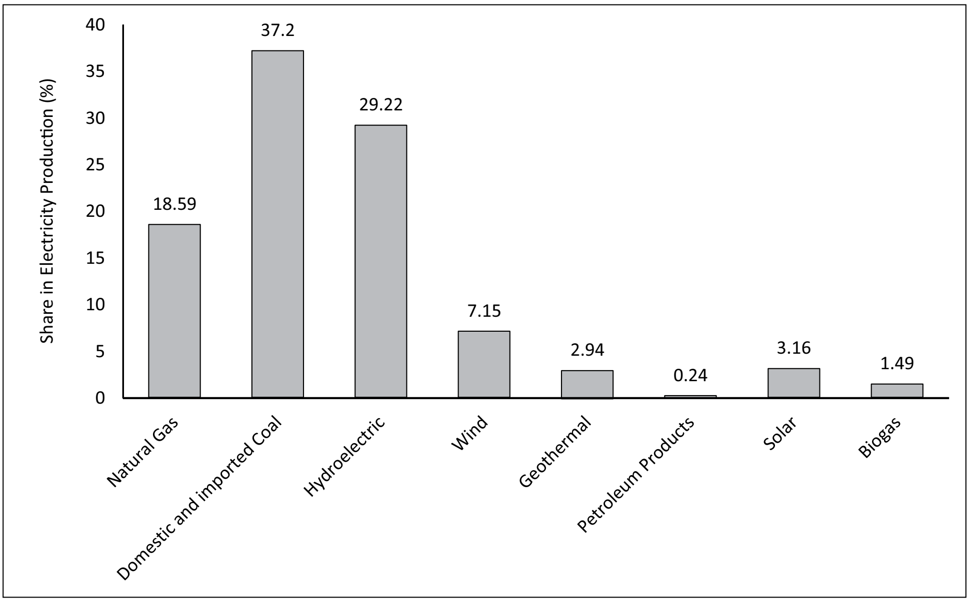

Fig. 1. Distribution of Turkey's electricity production sources
(prepared from the data derived from Enerji Atlası 2020)

Rys. 1. Rozmieszczenie źródeł produkcji energii elektrycznej w Turcji

imported due to Turkey being not a major producer of these products, and the percentage share of imported coal used is 19.86% despite Turkey having large coal reserves. The percentage of import-based electricity production in the total electricity production is 38.69%. For this reason, Turkey has put extensive incentive plans into action for the establishment of new power plants that use renewable energy sources (wind and solar) in order to secure electricity production, and these incentive plans are also valid for the establishment of new thermal power plants that use domestic lignite.

Turkey has 1.3 billion tons of hard coal and 19.3 billion tons of lignite reserves (MENR 2020). Its hard coal and lignite reserves can be classified into low and moderate levels of reserves compared to other countries in the world. Pliocene, Miocene, Oligocene, and Eocene lignite basins make up 51%, 41%, 6%, and 2% of Turkey's lignite basins, respectively (Ediger et al. 2014). Most of these lignite basins are of low calorific values, and these low values make them preferable to be used in thermal power plants. The calorific value of lignite coal used in thermal power plants for electricity generation is important because it represents the useful energy content and its value as a fuel. The lower and higher heating values (LHV and HHV) of coal can be estimated by using data from the proximate and ultimate analyses of coal. However, the use of proximate analysis data is generally preferred for both heating values in the literature. This is due to the ultimate analysis for lignite being time consuming and expensive because it requires very expensive equipment and highly trained analysis staff

(Özdemir and Sarici 2020; Akkaya 2009; Majumder et al. 2008; Parikh et al. 2005). In proximate coal analysis, moisture, ash, volatile matter, fix carbon and heating value properties are generally determined. The determination of these parameters is critical for the following reasons: fixed carbon helps to predict roughly heating value; volatile matter indicates the presence of gaseous fuels; ash indicates the non-combustible part of the coal structure and explains the formation of clinker and slag during and after combustion; moisture decreases the heating value of the coal (Boylu and Karaagaclıoglu 2018).

In the literature, many prediction models have been developed by using methods such as support vector regression (Parikh et al. 2005), linear and nonlinear multiple regression (Akkaya 2013; Boylu and Karaagaclıoglu 2018; Demirbas et al. 2008) and artificial neural networks (Demirbas 2008) in order to estimate heating values (lower and higher) and gross calorific values of solid fuels, biomass and coal with proximate analysis data. There are also some studies related with the prediction of heating values of lignite basins in Turkey (Özdemir and Sarici 2020; Akkaya 2013, 2009; Demirbas 2008; Demirbas et al. 2008).

As a result of this literature research, it can be said that multiple regression models (MRM) are widely used to estimate the LHV of coal and lignite, and although the coefficients of the obtained multiple linear regression models are generally statistically insignificant, these models continue to be used to predict heating values because of the meaningful correlation coefficient. For this reason, it is thought that these MRM models can give incorrect estimations, and this might be caused by some proximate analysis variables being moderator variables.

Important studies have been conducted in the fields of social science as there may be moderator variables that affect the direction and/or strength of the relationship between the independent variable or variables and the dependent variable. In the study by Baron and Kenny, in which the effect of moderator variables in social psychology research was investigated, the test procedures to be followed were explained to determine whether an independent variable is a moderator variable or not (Baron and Kenny 1986). Fairchild and McQuillin described statistical methods to evaluate the effects of the moderator variable on the prediction model (Fairchild and Mcquillin 2010). In the field of psychology, the effects of mediation and moderation on the dependent variable were evaluated by different researchers (Çelik et al. 2015; Nima et al. 2013). One of studies in mediation and moderation analysis is the study by Jacoby and Sassenberg which shows that an independent variable cannot be a mediator and a moderator variable at the same time (Jacoby and Sassonberg 2011). Hypothesis testing of moderated multiple regression models in management research was discussed by Aguinis (Aguinis 1995). Koç et al. used multiple regression analysis and the test method of Baron and Kenny to analyze the moderated effect in their studies in which they investigated whether there was a moderated effect of replacement cost on the relationship between service errors and perceived quality (Koç et al. 2014). Erciş and Türk showed that the moderator effect could be tested with hierarchical regression in their studies investigating the effect of ecological literacy on ethical consumption in their studies (Ercis and Turk 2016).

The goal of this study is to determine whether moderator variables are effective on LHV estimation using proximate analysis data of samples as received basis from forty one lignite deposits in different regions of Turkey, as well as to develop a model as a result of moderator variable analysis (MVA) to be used for LHV prediction.

1. Materials and method

1.1. Materials

The proximate analysis and LHV data of the forty-one lignite basins in different regions of Turkey that are used in this study are collected from the studies of Bağlıoğlu (Bağlıoğlu 2019), EÜAŞ (EÜAŞ 2017), Cebeci (Cebeci 2016), Erdogan (Erdogan 2014), Sensogut et al. (Sensogut et al. 2008), Temel (Temel 2007) and Tuncalı et al. (Tuncalı et al. 2002). The sampling locations of this collected data are shown as a Google Earth map in Figure 2. Of the proximate analysis data gathered by these researchers, only the proximate analysis data of the samples as received basis are taken into account and used in this study.

Fig. 2. The sampling locations of the collected data

Rys. 2. Miejsca poboru próbek dla gromadzonych danych

Moisture (MO), ash (A), volatile matter (VM) and fix carbon (FC) parameters obtained from proximate analysis are defined as weight percent, and LHV of lignite samples indicates energy content (kcal/kg) measured by a bomb calorimeter. Proximate analysis and LHV data used in this study are given in Table 1. The values of LHV are converted into MJ/kg.

Table 1. Proximate and LHV analysis data of lignite basins of Turkey

Tabela 1. Analiza techniczna i wartość opałowa węgla brunatnego w zagłębiach w Turcji

Lignite Basin	Moisture (MO, %)	Ash (A, %)	Volatile Matter (VM, %)	Fix Carbon (FC, %)	LHV (MJ/kg)
Adana-Tufanbeyli	38.90	28.00	22.00	11.30	5.33
Adıyaman-Gölbaşı	48.66	15.13	23.69	12.52	6.91
Afyon-Dinar	41.00	19.50	31.00	8.50	7.14
Amasya-Merzifon	7.00	45.00	24.00	23.00	14.03
Ankara-Çayırhan	25.00	30.00	25.00	20.00	11.18
Aydın-Söke	22.20	12.10	32.90	32.90	17.03
Aydin	21.80	10.20	34.00	34.00	18.53
Balıkesir-Dursunbey	17.70	6.60	34.60	41.10	19.77
Bingöl-Karlıova	30.00	31.00	24.00	15.00	8.42
Bolu-Göynük	31.00	12.00	28.00	29.00	13.32
Bolu-Seben	4.00	31.00	45.40	19.50	18.33
Bursa-Keles	38.00	20.00	23.00	19.00	9.87
Bursa-Orhaneli	26.00	8.00	34.00	32.00	16.11
Çanakkale-Çan	21.00	17.00	29.00	33.00	16.86
Çorum-Dodurga	16.50	15.00	33.50	35.00	17.08
Denizli-Çardak	15.00	43.00	22.00	20.00	9.33
Eskişehir-Alpu	34.00	32.00	21.00	13.00	9.99
Eskişehir-Mihalıççık	28.50	17.50	28.60	25.50	13.39
Isparta-Şarkikaraağaç	30.00	23.00	33.00	14.00	9.78
İstanbul-Yeniköy	29.50	6.20	33.50	30.80	15.11
K.Maraş-Afşin Elbistan	50.00	17.00	21.00	12.00	6.41
Karaman-Ermenek	18.00	13.30	33.10	35.60	16.95
Kırklareli-Vize	45.00	14.00	23.00	18.00	8.99
Kirsehir-Çiçekdağ	18.80	14.60	32.50	34.10	15.53
Konya-Beyşehir	53.83	17.36	20.36	8.45	5.93
Konya-Ilgın	40.00	18.00	21.00	21.00	9.19
Konya-Karapınar	47.00	20.00	23.00	10.00	5.63
Kütahya-Seyitömer	36.00	25.00	21.00	18.00	8.47
Kütahya-Tunçbilek	20.00	20.00	27.00	33.00	15.68
Malatya-Arguvan	20.33	34.58	23.02	19.08	10.66
Manisa-Soma	14.00	13.00	33.00	40.00	20.65
Muğla-Milas	38.00	13.00	28.00	21.00	10.94
Muğla-Yatağan	39.00	14.00	27.00	20.00	10.71
Sivas-Gemerek	24.20	12.50	31.80	31.50	14.28
Sivas-Kangal	52.00	16.00	21.00	11.00	5.78
Tekirdag-Batkın	32.80	11.30	28.80	27.00	13.70
Tekirdağ-Çerkezköy	33.00	25.00	22.00	20.00	8.69
Tekirdağ-Damlarca	21.60	24.70	28.20	25.50	12.25
Tekirdağ-Ibribey	25.70	19.10	31.50	23.70	12.64
Tekirdağ-Maymundere	14.00	45.80	22.90	17.20	8.40
Tekirdağ-Saray	44.00	14.00	23.00	19.00	8.79

Descriptive statistics of the dataset retrieved from the proximate analysis data (Table 1) are given in Table 2. Plots of LHV versus predictor variables are shown in Figure 3.

Table 2. Descriptive statistics of the dataset

Tabela 2. Statystyki opisowe dla zbioru danych

Parameters	Number of samples	Minimum	Maximum	Mean	Median	SD
LHV	41	5.33	20.63	11.896	10.936	4.271
Fix carbon (FC)	41	8.45	41.10	22.787	20.000	9.047
Moisture (MO)	41	4.00	53.83	29.586	29.500	12.446
Ash (A)	41	6.20	45.80	20.107	17.360	9.892
Volatile matter (VM)	41	20.36	45.40	27.424	27.000	5.583

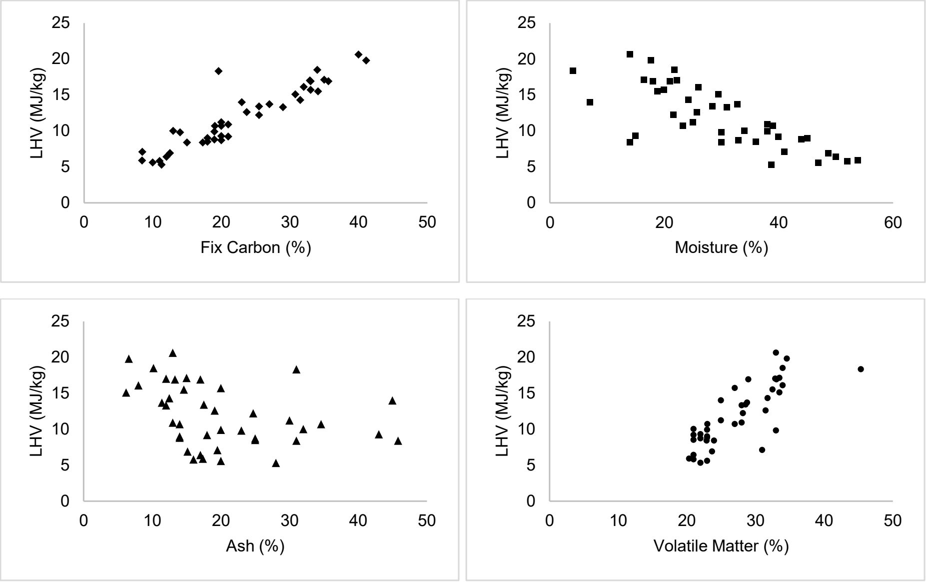

Fig. 3. Plots of LHV versus predictor variables

Rys. 3. Wykresy wartości opałowej w funkcji zmiennych predykcyjnych

1.2. Method

MINITAB (version 14) statistical analysis software was used for the statistical analyses performed in this study.

1.2.1. Multiple Regression Analysis (MRA)

A modeling study for the prediction of a dependent variable by more than one independent variable is known as multiple regression analysis. Independent variables associated with the dependent variable are expected to be included in the MRA model. The least squares method is generally used in the calculation of the MRA model parameters.

The determination coefficient (R^2) is usually used to determine whether there is a significant relationship between the dependent variable and independent variables. Hypothesis tests (F and t tests) were performed to determine the overall model and the significance of each parameter.

The coefficient of determination reveals what percentage of the variance in the dependent variable is explained by independent variables, and this is calculated with the following equation:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{Y}_i - \mathrm{Y}'_i\right)^2}{\sum_{i=1}^{n} \left(\mathrm{Y}_i - \bar{\mathrm{Y}}\right)^2} \tag{1}$$

↳ Y – measured dependent variable,
Y′ – estimated dependent variable,
Ȳ – mean of measured dependent variable,
n – number of samples.

In this study, the formation of regression equations with standardized coefficients (β_i) for multiple regression analysis for LHV estimation is preferable thanks to all variables given as percentage by weight. In this way, the variable with the highest β value obtained in the analysis can be decided as a more important estimator. In testing the significance of β coefficients, the following hypothesis was formed.

Hypothesis test:

- $H_0 - \beta_1 = \beta_2 = \ldots = \beta_n = 0$ (Regression coefficients are meaningless),
- H_1 – at least one β value is nonzero.

The F statistic is calculated to determine whether the whole model is meaningful, and the t statistic is calculated to determine whether the model coefficients (β_i) are significant. If p is less than 0.05, which is calculated as the level of significance, the model or coefficients are determined to be significant.

1.2.2. Moderator Variable Analysis (MVA) and Hypothesis Testing

In the moderator variable models, it is tested whether an independent variable (variable X that affects Y the most) changes according to the values of M (other independent variables with lower effect) in the estimation of the dependent variable Y (Figure 4). If the M variable strengthens the prediction of the dependent Y variable with the X variable, this M variable is known as the moderator variable. If an independent variable is not a moderator variable, it should be ensured that this variable is included in the multiple regression model.

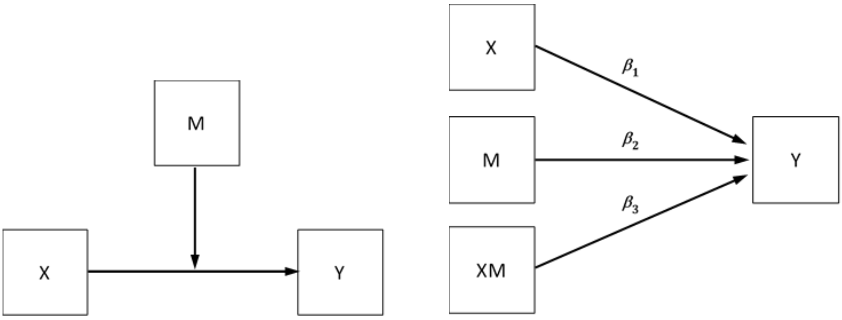

Fig. 4. Path diagram of the moderator variable

Rys. 4. Wykres ścieżki zmiennej moderatora

The multiple regression equation, including the moderator variable, is created with the standardized values of the variables as given in Equation 2.

$$Y = \beta_0 + \beta_1 \cdot ZX + \beta_2 \cdot ZM + \beta_3 \cdot ZXM + e \tag{2}$$

↳ β_i – coefficients of MRM,
e – prediction error.

In order to calculate the coefficients of the multiple regression equation, firstly, the standardized values of the dependent, independent and moderator variables are calculated from Equation 3.

$$ZX = \frac{\left(X_i - \bar{X}\right)}{S_x} \quad ZY = \frac{\left(Y_i - \bar{Y}\right)}{S_y} \quad ZM = \frac{\left(M_i - \bar{M}\right)}{S_m} \quad ZXM = \frac{\left(XM_i - \overline{XM}\right)}{S_{xm}} \tag{3}$$

↳ ZX, ZY, ZM and ZXM – standardized values of variables,
$\bar{X}$, $\bar{Y}$, $\bar{M}$, $\bar{X}$, $\bar{M}$ – mean of variables,
S_x, S_y, S_m, S_{xm} – standard deviations of variables.

In order to determine whether an independent variable is a moderator variable, it is necessary to test the significance of the coefficients of the multiple regression model in which the moderator variable is included. The t statistic is also used to test the significance of the standardized coefficient (β_3) of the moderator variable (XM) in the regression model, and the hypothesis is formed as follows:

Hypothesis test:

- $H_0 - \beta_3 = 0$ (Related variable is not a moderator variable),
- $H_1 - \beta_3 \neq 0$ (Related variable is moderator variable).

If p is less than 0.05, which is calculated as the level of significance, it is determined that the coefficient of β_3 is significant, and the relevant variable is a moderator variable.

2. Results and discussion

Prior to regression analysis, the Kolmogorov-Smirnov (KS) test, which is widely used in single samples, was used to determine whether the variables showed a normal distribution. The results of the KS test are given in Table 3, and it was determined that the A and VM values did not show a normal distribution.

Table 3. The results of the KS test

Tabela 3. Wyniki testu KS (Kołmorogowa-Smirnowa)

Parameters	Number of samples	KS Value	P Value	Result
LHV	41	0.111	>0.150	normal
Fix carbon (FC)	41	0.127	0.093	normal
Moisture (MO)	41	0.089	>0.150	normal
Ash (A)	41	0.163	<0.010	non normal
Volatile matter (VM)	41	0.157	0.014	non normal

A linear multiple regression analysis is performed by using Equation 3. In this equation, the parameters of proximate analysis data (fix carbon, moisture, ash and volatile matter) are accepted as independent variables, whereas LHV is accepted as a dependent variable. As a result of this analysis, the model given in Equation 4 and *F*-test and *t*-test results for standardized coefficients given in Table 4 were obtained.

$$LHV = \beta_0 + \beta_1 \cdot FC + \beta_2 \cdot MO + \beta_3 \cdot A + \beta_4 \cdot VM + e \tag{4}$$

$$LHV = 37.18648 - 0.07947 \cdot FC - 0.42477 \cdot MO - 0.37509 \cdot A - 0.12291 \cdot VM$$

As it can be seen from Table 4 that there is a significant relationship between the proximate analysis data and LHV according to the *F*-test result (since $p < 0.05$). However, according to the *t*-test results in which the coefficients of the MRA model were tested, none of the proximate analysis variables (since $p > 0.05$) were significant. In addition, when the signs of the non-standardized parameters of the model are examined, a result is found such that LHV decreases as all parameters increase, which is against the tendency of the distribution graph of proximate analysis data versus LHV given in Figure 1. In other words, LHV is expected to increase with increasing FC and VM, while LHV decreases with increasing MO and A. Whereas, in the model, LHV also decreases with increasing FC and VM with the effect of MO and A. Moreover, all of the variance inflation factor (VIF) values are greater than 10, there is a level of multicollinearity between the variables. In this case, the results of multiple regression analysis with normal values will be misleading.

Table 4. *F*-test and *t*-test results for standardized coefficients

Tabela 4. Wyniki testów *F* i *t* dla współczynników standaryzowanych

	Adjusted R^2	Std. error of the estimate	*F*-test		Unstandardized coefficients B	Standardized coefficients β	*t*-test		VIF
			F	Sig. (*p*)			*t*	Sig. (*p*)	
MRM	0.944	1.0136	168.520	0.000*	37.18648	0	1.048	0.302**	
					–0.07947	–0.16835	–0.222	0.826**	408.3
					–0.42477	–1.23789	–1.201	0.238**	754.5
					–0.37509	–0.86878	–1.038	0.306**	497.2
					–0.12291	–0.16069	–0.348	0.730**	151.1

* The relationship between the variables is significant since $p < 0.05$ according to the *F*-test,

** The standardized coefficient β is not significant since $p > 0.05$ according to the *t*-test.

In the study of Huda, a MRA was conducted between the four proximate analysis parameters and gross calorific value (GCV) for Indonesian coals, and it was found that GCV increases with increasing MO and A (Huda 2014). In the study of Akhtar et al., where the higher heating value (HHV) of Pakistan lignite is predicted by MRA, it is stated that HHV increases while A increases (Akhtar et al. 2017). Similarly, in both studies, the parameters of the obtained MRA model were not tested. However, in the study of Özdemir and Sarici where MRA was used to predict the calorific value (CV) of some Turkish lignite, it was found that CV decreases while MO and A increase, and the parameters of the obtained MRA model was also tested (Özdemir and Sarici 2020). However, it should be noted that the finding of the decrease in CV with the increase in VM is open to discussion.

Both this study and other studies in the literature show that although the parameters of the models obtained from the linear MRA studies for the calorific value estimates of the coals have passed the test, the obtained models are said to be meaningless. It is thought that this is due to the predominance of some proximate values over others, and the linear MRA models cannot solve this problem. For this reason, calorific value estimates with MRA may give misleading results. To eliminate the possible misleading results of MRA, in this study, moderator variable analysis (MVA) was selected to predict the LHV of Turkish lignite with proximate analysis data. In this analysis, in order to determine the independent variable, a correlation analysis was first conducted between all variables, and the obtained correlation values are given in Table 5.

Table 5. Correlations between LHV and proximate analysis data

Tabela 5. Korelacje między wartością opałową a danymi z analizy proksymalnej

	MO	A	VM	FC	LHV
LHV	–0.757	–0.340	0.796	0.922	1

As can be seen from Table 5, the variables that affect LHV the most are found to be FC ($r = 0.922$) and VM ($r = 0.796$). In this case, it is determined that the first independent and the second variable in the MVA model could be FC and VM, respectively. After this, it was decided to create alternative MVA models with standardized values of independent and moderator variables as given in Table 6. In this table, the last variables of MVA consist of the multiplication product of the independent variable and the moderator variable.

Table 6. Model equations of MVA alternatives created with standardized variables

Tabela 6. Modelowe równania alternatyw MVA utworzone ze zmiennymi standaryzowanymi

MVA model	Equation
Moderator 1	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZMO} + \beta_3 \cdot \mathrm{ZFC} \cdot \mathrm{ZMO} + e$
Moderator 2	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZA} + \beta_3 \cdot \mathrm{ZFC} \cdot \mathrm{ZA} + e$
Moderator 3	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZVO} + \beta_3 \cdot \mathrm{ZFC} \cdot \mathrm{ZVO} + e$
Moderator 4	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZVO} + \beta_3 \cdot \mathrm{ZMO} + \beta_4 \cdot \mathrm{ZFC} \cdot \mathrm{ZMO} + e$
Moderator 5	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZVO} + \beta_3 \cdot \mathrm{ZMO} + \beta_4 \cdot \mathrm{ZVM} \cdot \mathrm{ZMO} + e$
Moderator 6	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZVO} + \beta_3 \cdot \mathrm{ZA} + \beta_4 \cdot \mathrm{ZFC} \cdot \mathrm{ZA} + e$
Moderator 7	$\mathrm{LHV} = \beta_0 + \beta_1 \cdot \mathrm{ZFC} + \beta_2 \cdot \mathrm{ZVO} + \beta_3 \cdot \mathrm{ZA} + \beta_4 \cdot \mathrm{ZVM} \cdot \mathrm{ZA} + e$

Test results of MVA models, which also include moderator variables, are as provided in Table 7. As it can be seen from Table 7, all MVA model alternatives are generally meaningful according to F-test results ($p < 0.05$). However, the coefficient is only significant in the Moderator 5 equation ($p = 0.012 < 0.05$) according to the results of the t-test for the

Table 7. *F*- and *t*-test analysis results for alternative MVA models

Tabela 7. Wyniki analizy testów *F* i *t* dla alternatywnych modeli MVA

MVM	Adjusted R^2	*F*-test		Unstandardized coefficients B	Standardized	*t*-test	
		F	Sig. (*p*)		coefficients β	*t*	Sig. (*p*)
Moderator 1	0.888	106.700	0.000	11.6723 3.0427 –1.3916 –0.3537	0 0.7122 –0.3257 –0.0739	39.77 9.55 –3.95 –1.18	$p < 0.05$ $p < 0.05$ $p < 0.05$ 0.247*
Moderator 2	0.844	73.206	0.000	11.8020 3.9931 0.3186 –0.2208	0 0.9347 0.0746 –0.0358	35.05 10.65 1.02 –0.45	$p < 0.05$ $p < 0.05$ 0.313 0.652*
Moderator 3	0.928	172.190	0.000	11.9491 3.0074 1.5384 –0.0865	0 0.7039 0.3602 –0.0167	50.42 11.58 6.17 –0.34	$p < 0.05$ $p < 0.05$ $p < 0.05$ 0.739*
Moderator 4	0.944	169.900	0.000	11.7337 2.5489 1.3270 –0.8858 –0.2489	0 0.5966 0.3107 –0.2074 –0.0520	56.55 10.67 6.18 –3.38 –1.17	$p < 0.05$ $p < 0.05$ $p < 0.05$ $p < 0.05$ 0.250*
Moderator 5	0.951	197.060	0.000	11.6760 2.8011 0.9974 –0.8549 –0.3816	0 0.6556 0.2336 –0.2001 –0.1111	69.17 12.70 4.17 –4.02 –2.65	$p < 0.05$ $p < 0.05$ $p < 0.05$ $p < 0.05$ 0.012**
Moderator 6	0.942	162.680	0.000	11.9569 3.2193 1.6815 0.6041 0.1381	0 0.7336 0.3938 0.1415 0.0224	57.83 12.93 7.94 3.12 0.46	$p < 0.05$ $p < 0.05$ $p < 0.05$ $p < 0.05$ 0.648*
Moderator 7	0.946	175.420	0.000	12.0306 3.4358 1.4681 0.6844 0.3623	 0.8042 0.3438 0.1603 0.0813	69.1534 13.0488 6.2910 3.6335 1.7022	$p < 0.05$ $p < 0.05$ $p < 0.05$ $p < 0.05$ 0.097*

* The moderator variable is meaningless since $p > 0.05$.

** The moderator variable is meaningful since $p < 0.05$.

variability parameters (standardized), which is the product of the moderator variable and the independent variable.

According to the Moderator 5 equation, the independent variables FC and VM moderated by variable MO significantly affect the LHV. As a result of the regression analysis, Equation 5 is obtained. The standard errors of the estimates, test results and coefficients of determination are given in Table 8.

$$\mathrm{LHV} = 11.676 + 2.8011 \cdot \mathrm{ZFC} + 0.9974 \cdot \mathrm{ZVM} - 0.8549 \cdot \mathrm{ZMO} - 0.3816 \cdot \mathrm{ZMO} \cdot \mathrm{ZVM} \quad (5)$$

Table 8. Regression and hypothesis testing results of the best MVA model

Tabela 8. Wyniki regresji i testowania hipotez najlepszego modelu MVA

	Adjusted R^2	Std. error of the estimate	*F*-test		Unstandardized coefficients B	Standardized coefficients β	*t*-test	
			F	Sig. (*p*)			*t*	Sig. (*p*)
MVA Model	0.951	0.9408	197.061	0.000*	11.6760	0	69.17	0.000**
					2.8011	0.6556	12.70	0.000**
					0.9974	0.2336	4.17	0.000**
					–0.8549	–0.2001	–4.02	0.000**
					–0.3816	–0.1111	–2.65	0.012**

* Regression relationship is significant since $p < 0.05$ according to the *F*-test

** The standardized coefficient of β is significant since $p < 0.05$ according to the *t*-test

In this study, two models are developed in order to predict the LHV of Turkish lignite basins by means of linear MRA (Equation 4) and MVA (Equation 5) with proximate analysis data. Coefficients of determination, absolute and standard errors are calculated by considering the predicted values of two models and experimental values. Calculated values and a scatter plot of experimental versus predicted values are given in Table 9 and Figure 5.

Table 9. R^2, MAE and SEE values calculated with predicted and experimental values of MVA and MRA models

Tabela 9. Wartości R^2, MAE i SEE obliczone na podstawie przewidywanych i eksperymentalnych wartości modeli MVA i MRA

Model	Absolute error MAE (MJ/kg)	Standard error SEE (MJ/kg)	R^2
MRA	0.747	1.013	0.944
MVA	0.682	0.940	0.951

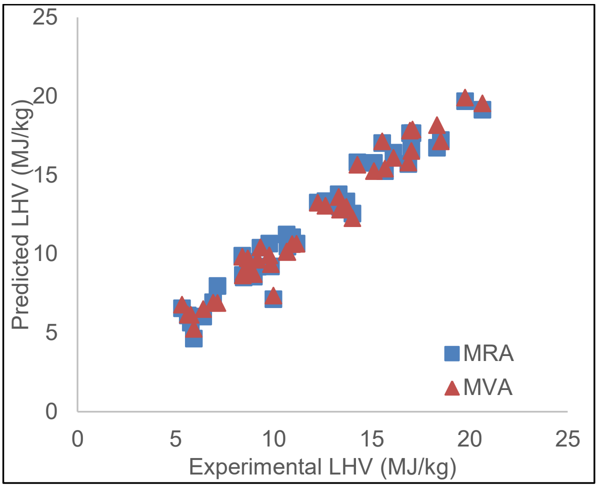

Fig. 5. Predicted LHV values with both models versus experimental LHV values

Rys. 5. Przewidywane wartości wartości opałowej dla obu modeli w porównaniu z eksperymentalnymi wartościami wartości opałowej

In Table 9, the value of the coefficient of determination of the MVA model is higher than that of the MRA model by 0.7%, and absolute and standard error values of the MVA model are found to be less than those of the MRA model by 0.065 and 0.073 MJ/kg, respectively. Therefore, it can be stated that LHV for lignite can be predicted with the equation obtained from MVA in which FC and VM moderated by MO are independent variables. Furthermore, this prediction is more in accordance with the experimental data and gives a lower prediction error.

Conclusions

The main focus of this study is to highlight the statistically problematic usage of MRA models in order to estimate the LHV of coal and lignite, and to use an MVA model instead of a MRA model to obtain statistically correct estimations. Therefore, both MRA and MVA analyses were performed for LHV predictions of lignite.

In the MRA analysis, the MRA model is found to be statistically significant according to the *F*-test result ($p < 0.05$), and there is a meaningful relationship between LHV and FC, MO, A and VM. However, other regression coefficients, except for the constant coefficient, are meaningless according to the *t*-test results where the coefficients are tested. In addition, when one-to-one relationships between dependent variable LHV and independent variables are examined, LHV increases as FC and VM values increase and LHV decreases as MO and A increase. However, according to the MRA model, LHV decreases even with the increase in the FC and VM content. In this case, when the meaninglessness of all regression coefficients according to the t-test results and coefficients of FC and VM which are incompatible with the theory are taken into consideration, it is possible to say that a reliable estimate of LHV based on proximate analysis data for lignite deposits cannot be made by using the MRA model.

In the MVA analysis, the selected MVA model and all the regression coefficients are found to be statistically significant and meaningful according to the F-test ($p < 0.05$) and the t-test ($p <0.05$). In addition, the sign of the one-to-one relationships between FC, VM, MO and LHV is the same with the sign of multiple regression coefficients between the standardized FC, VM, moderator variable MO and LHV in the MVA model. In other words, the MVA model can be used for more realistic predictions of the LHV of lignite deposits in Turkey.

When the determination coefficients (R^2), absolute errors (MAE) and standard errors (SEE) of both models are compared, it turns out that the MVA model has a higher determination coefficient ($R^2 = 0.951$) than that of the MRA model ($R^2 = 0.944$), and the MVA model has lower error absolute and standard values (MAE = 0.682 MJ/kg and SEE = 0.940 MJ/kg) than those of MRA model (MAE = 0.747 MJ/kg and SEE = 1.013 MJ/kg).

As a result of this study, it is determined that the LHV of lignite deposits in Turkey mainly depends on the fix carbon (FC) and volatile matter (VM) content, and moisture (MO) has a moderate effect on the VM. Finally, it can be stated that the prediction errors will be small if the MVA model (Equation 5) is used to predict LHV from the data of the basis of the proximate analysis of lignite as received.

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AN INVESTIGATION OF THE EFFECTS OF MODERATOR VARIABLES ON THE LOWER HEATING VALUE ESTIMATION OF LIGNITE DEPOSITS IN TURKEY

Keywords

lignite, lower heating value, multiple linear regression, moderator analysis, proximate analysis

Abstract

Turkey has 19.3 billion tons of lignite reserves and the vast majority of these Neogene lignite deposits are preferred for use in thermal power plants due to their low calorific value. The calorific value of lignite used in thermal power plants for electricity generation must be kept under constant control. In the control of calorific value, the estimation of the lower and higher heating values (LHV and HHV) of lignite is of great importance. In the literature, there are many studies that establish a relationship between the heating values of coal and proximate and ultimate analysis variables. In the studies dealing with proximate analysis data, it is observed that although the coefficients of the obtained multiple linear regression models (MRM) are statistically insignificant, these models are used to predict heating values because of the meaningful correlation coefficient. In this study, it is investigated whether moderator variables are effective on LHV estimation with proximate analysis data collected from forty-one lignite basins in different regions of Turkey, and a moderator variable analysis (MVA) model is developed to be used for the prediction of LHV. As a result of the study, it is found that the proposed MVA model is in accordance with observation values (coefficient of determination $R^2 = 0.951$), and absolute and standard errors are also small. Therefore, it is concluded that the use of MVA to estimate the LHV of Turkey's lignite is found to be more statistically meaningful.

BADANIE WPŁYWU ZMIENNYCH MODERATORA NA SZACOWANIE WARTOŚCI OPAŁOWEJ ZŁÓŻ WĘGLA BRUNATNEGO W TURCJI

Słowa kluczowe

węgiel brunatny, wartość opałowa, wielokrotna regresja liniowa,
analiza moderatora, analiza techniczna

Streszczenie

Turcja posiada 19,3 mld ton zasobów węgla brunatnego, a zdecydowana większość tych neogeńskich złóż węgla brunatnego jest preferowana do wykorzystania w elektrowniach cieplnych ze względu na ich niską wartość opałową. Wartość opałowa węgla brunatnego wykorzystywanego w elektrowniach ciepłowniczych do produkcji energii elektrycznej musi być stale kontrolowana. W procesie kontroli wartości opałowej bardzo ważne jest oszacowanie wartości opałowej i ciepła spalania węgla brunatnego. W literaturze istnieje wiele badań, które ustalają związek między wartościami opałowymi węgla a zmiennymi analizy przybliżonej (technicznej) i końcowej. W badaniach dotyczących danych analizy technicznej zaobserwowano, że chociaż współczynniki uzyskanych modeli wielokrotnej regresji liniowej (MRM) są statystycznie nieistotne, modele te są wykorzystywane do przewidywania wartości opałowych ze względu na znaczący współczynnik korelacji. W niniejszym artykule zbadano, czy zmienne moderatora są skuteczne w szacowaniu wartości opałowej (LHV) na podstawie danych z analizy technicznej zebranych z czterdziestu jeden zagłębi węgla brunatnego w różnych regionach Turcji, a także opracowano model analizy zmiennych moderatora (MVA), który ma być wykorzystywany do przewidywania LHV. W wyniku badań stwierdzono, że proponowany model MVA jest zgodny z wartościami obserwacji (współczynnik determinacji R^2 = 0,951), a błędy bezwzględne i standardowe są również niewielkie. W związku z tym stwierdzono, że wykorzystanie MVA do oszacowania LHV tureckiego węgla brunatnego jest statystycznie uzasadnione.