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An analysis of coal consumption, CO_2 emissions and economic growth in Slovenia

Analiza porabe premoga, izpustov CO_2 in gospodarske rasti v Sloveniji

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Abstract in English

The common characteristics and possible correlations between coal consumption, CO_2 emissions, emission productivity and economic growth in Slovenia are discussed in this article. The correlation between these variables was analysed by using the Pearson correlation coefficient, and we used linear regression and the least squares method to develop predictive mathematical models that can be used to estimate trends in coal consumption and CO_2 emissions in the future. The link between coal consumption, emissions, and emission productivity is significant, while the correlation between coal consumption and economic growth is minimal. Therefore, coal consumption and the resulting emissions do not have a significant impact on economic growth. Mathematical models show a good fit, which is a condition for the reliability of the prediction. Possible scenarios of the transition to carbon neutrality and the related problems of future electricity supply as a consequence of the cessation of coal mining and use are also discussed below.

Keywords: coal, emissions, correlation, forecasting

Abstract in Slovene

Obravnavane so skupne značilnosti in možne korelacije med porabo premoga, emisijami CO_2, emisijsko produktivnostjo in gospodarsko rastjo v Sloveniji. S Pearsonovim koeficientom korelacije se je analizirala povezanost med navedenimi spremenljivkami ter se s pomočjo linearne regresije in metode najmanjših kvadratov izdelalo napovedne matematične modele, s katerimi se lahko ocenijo trendi porabe premoga in emisij CO_2 v prihodnosti. Povezanost med porabo premoga, emisijami in emisijsko produktivnostjo je znatna, medtem ko je korelacija med porabo premoga in gospodarsko rastjo minimalna, zato poraba premoga in s tem emisije nimajo pomembnega vpliva na gospodarsko rast. Matematični modeli kažejo dobro prileganje, kar je pogoj za zanesljivost napovedi. V nadaljevanju so obdelani tudi možni scenariji prehoda na ogljično nevtralnost in s tem povezano problematiko prihodnje oskrbe z električno energijo kot posledico prenehanja pridobivanja in uporabe premoga.

Ključne besede: premog, emisije, povezanost, napovedovanje

Introduction

The main challenge facing many countries is the development of energy and environmental policies for the production of sustainable energy, while reducing greenhouse gas (GHG) emissions. As global energy demand continues to increase, energy security issues have become even more important.

Researching emission trends and predicting their further values is therefore an important part of adapting energy strategies, especially those involving low carbon. Understanding the dynamic link between coal consumption, CO_2 emissions and economic growth is therefore crucial in shaping energy strategies.

We would like to present the common characteristics and possible correlations between

coal consumption, CO_2 emissions, and economic growth in Slovenia, as well as develop predictive mathematical models that will assess the trend of coal consumption and CO_2 emissions in the future.

Materials and methods

Coal

Among fossil fuels, coal is the only source that will have the longest presence in the energy market due to the enormous number of reserves worldwide. As an energy source, it represents a quarter of the world share. In Europe, its consumption is declining while in the fast-growing Asian markets its consumption is quickly rising (Figure 1) [1]. However, the combustion of fossil fuels releases a lot of CO_2 into the atmosphere, which contributes to the greenhouse effect.

It is necessary to handle coal reserves and their exploitation in Slovenia as rationally as possible, because of all the fossil energy sources, Slovenia disposes only of coal. Energy obtained from coal represents a quarter of all electricity consumed in Slovenia. On the one hand, this represents a great burden on the environment, and on the other hand, it is a strong economic and social factor for both the region and the country [2].

After the cessation of excavation in the Trbovlje-Hrastnik Mine and the closure of the Trbovlje Power Station, Termoelektrarna Trbovlje (TET), the only two major consumers of coal for the production of electricity or heat (which is collectively called transmission) that remained in Slovenia are Termoelektrarna Šoštanj (TEŠ), which uses lignite from Premogovnik Velenje (PV), and the Ljubljana Power Station, Termoelektrarna-toplarna Ljubljana (TE-TOL)) which already replaces imported coal with wood chips and gas [3].

Coal consumption in Slovenia has been in decline for some time (Figure 2), and harmful emissions from the transmission sector have also decreased by about a quarter owing to more modern procedures and improvements [2].

CO_2 emissions

CO_2 is one of the most dangerous pollutants, which has a great impact on the environment and consequently on humans and all living things on Earth. The combustion of fossil fuels is the largest source of atmospheric CO_2.

Nowadays, production and consumption of CO_2 are out of balance; therefore, the CO_2 content in the atmosphere is increasing. The consequences of an increased concentration of CO_2 in the atmosphere are also called the 'greenhouse effect'.

The share of CO_2 emissions from coal combustion in Slovenia in the period observed is around 30% and is declining, mainly owing to reduced coal consumption but also to the replacement of fossil fuels, changes in the amount of carbon in coal, improved efficiency, and changes in the share of renewable sources and nuclear energy [5].

The National Energy and Climate Plan of Slovenia anticipates the phasing out of the use of domestic and imported coal for energy

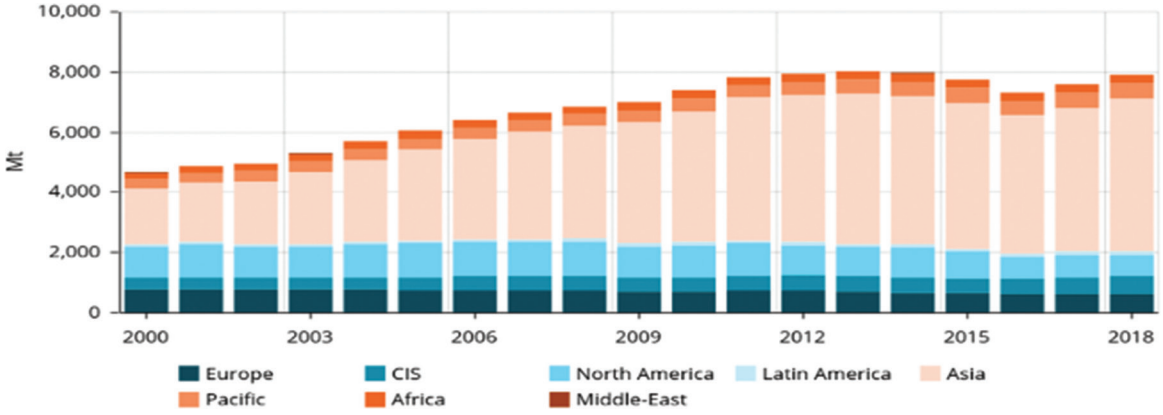


Figure 1: *Worldwide coal consumption [1].*

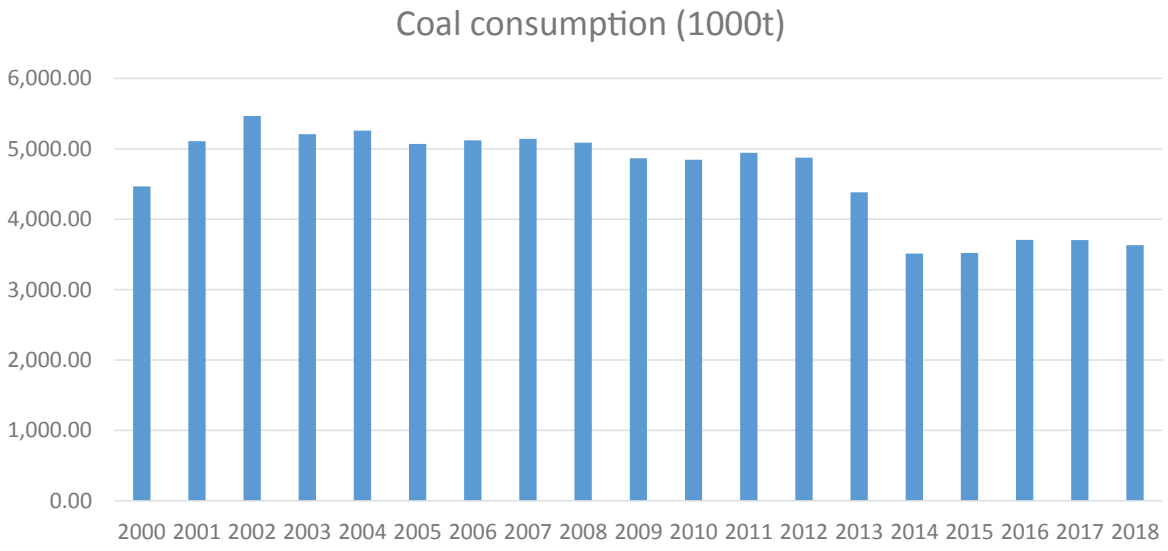


Figure 2: *Coal consumption in Slovenia [7].*

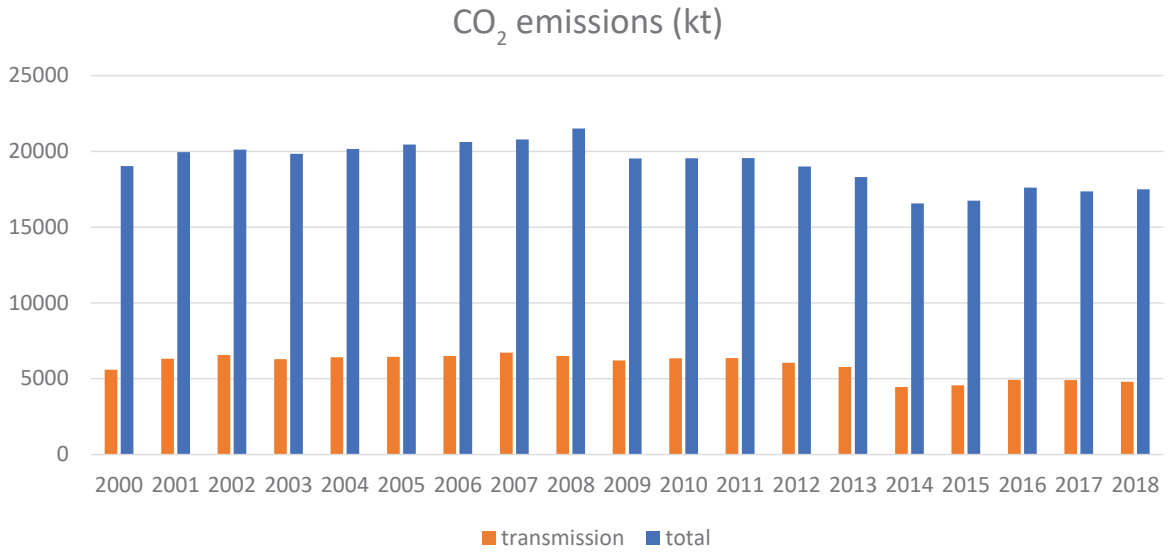


Figure 3: *Amount of CO_2 emissions [3].*

purposes or a reduction of at least 30% by 2030, as well as the reduction of total GHG emissions by up to 36% compared with 2005 [6].

Although the energy sector has great potential to reduce emissions, it must be acknowledged that it has already made a significant contribution to reducing them. In Slovenia, for example, emissions from the energy sector decreased by about 24 percent between 2005 and 2017, while such a decline has not been seen in any other sector; for example, transport emissions increased by 25 percent [2].

The largest sources of energy emissions (in 2015) are transportation (40%) and electricity and heat production (37%), while manufacturing contributes to 12% of the energy emissions, and households and the service sector together contribute to 11% of the energy emissions (Figure 3) [3].

The largest share in greenhouse gas emissions is CO_2 (96 %).

CO_2 is the equivalent of all greenhouse gases expressed in weight rates of CO_2.

Economic growth

Positive economic growth is one of the most important goals of any economy. Economic growth is measured by the growth rate of the gross domestic product (GDP) [8].

The share of transmission of the electricity produced is about one third, and the share of GDP is between 0.56 and 0.86 percent.

A comparison of the movement of GHG emissions from energy sources with the movement of the gross domestic product and energy supply shows whether the breakdown of GDP growth and emissions was achieved and what influenced the breakdown. The analysis showed that the breakdown was achieved mainly in the period 2002–2007 because of structural changes and more efficient energy use and in 2012–2014 because of a reduction in the share of fossil fuels in energy supply and greater energy efficiency (Figure 4) [3].

Emission productivity

Emission productivity is calculated as the quotient of the gross domestic product at constant prices and total greenhouse gas emissions (Figure 5). The key objective of the emission productivity indicator is to monitor the environmental performance of the economy.

Emission productivity in Slovenia is steadily growing and approaching the EU average.

In the future, it will be important that the indicator improves and ensures a breakdown between GDP and GHG growth. The goal is to significantly reduce GHG emissions while at the same time growing economically [3].

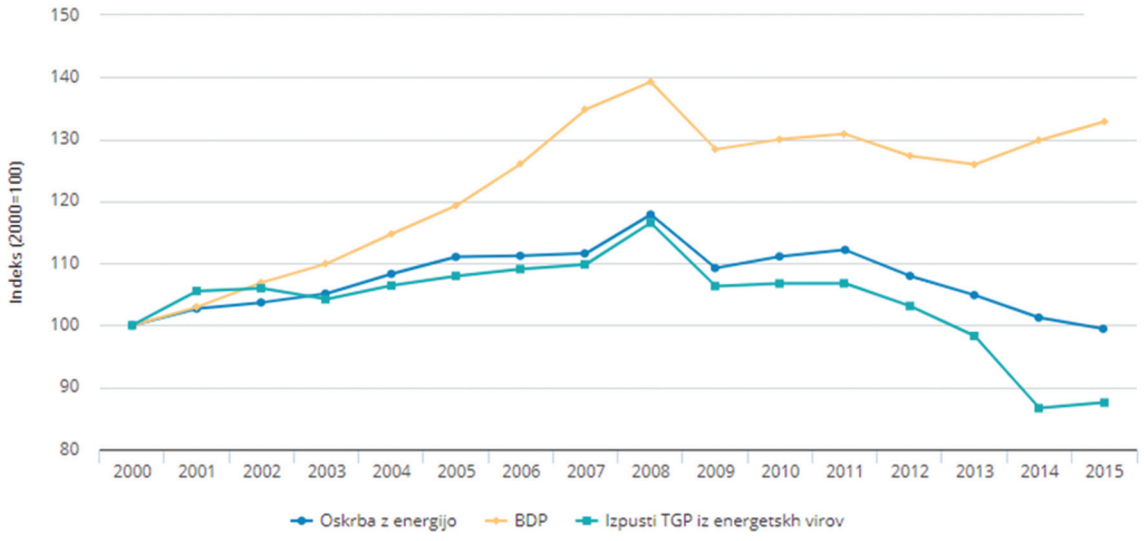


Figure 4: *Trends in GHG emissions from energy sources, gross domestic product and energy supply in the period 2000–2015 [3].*

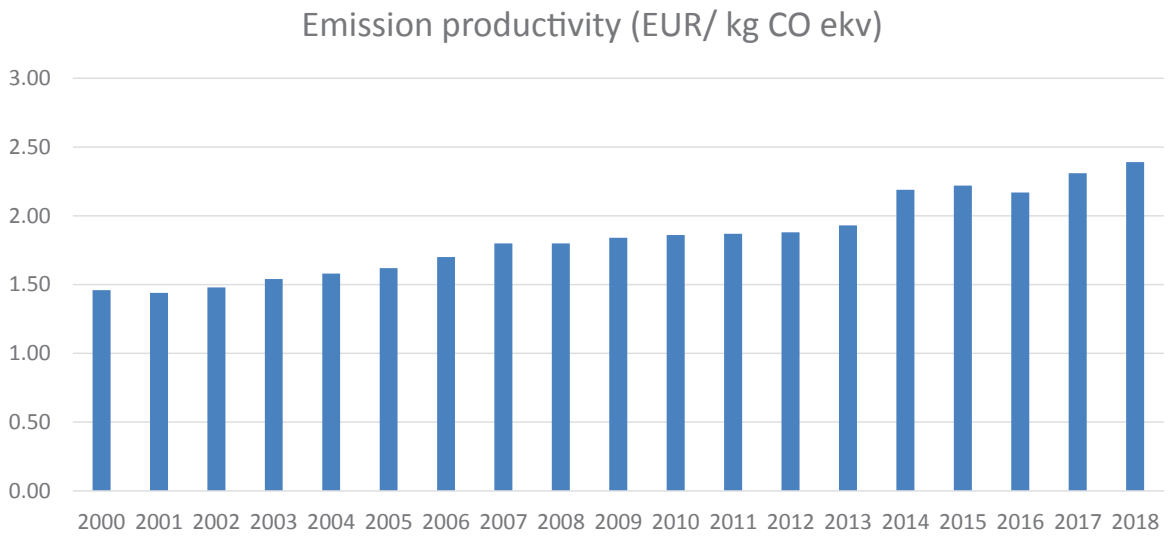


Figure 5: *Emission productivity in Slovenia [3].*

Pearson correlation coefficient

Correlation or the correlation coefficient is a numerical measure that represents the strength of the linear relationship of two variables.

The Pearson correlation coefficient is the most commonly used measure of the linear correlation of two numerical variables, calculated on the basis of the covariance and standard deviations of the set of both variables [9].

$$\rho = \frac{K(x;y)}{\sigma(x)\sigma(y)} = \frac{\sum_{i-1:N}(xi-\bar{x})(yi-\bar{y})}{\sqrt{\sum_{i-1:N}(xi-\bar{x})^2\left(\sum_{i-1:N}yi-\bar{y}\right)^2}} \quad (1)$$

K(x;y) represents the covariance, and the σ values represent the standard deviation for the variables *x* and *y* [9].

Pearson correlation values are called the correlation index or strength, which can assume a value between -1 and 1 (Figure 6).

An is some extreme value relative to other data and that does not match the general data trend. One method of determining outliers is the visual perception of the extreme value in the graph itself (Figure 7) [11].

Simple linear regression

The fit of an appropriate mathematical model to data is called regression, which can be simple or complex. We are looking for relations between the independent and dependent variable.

Simple linear regression is the simplest and most commonly used form of linear regression, where a regression line is used to study the effect of only one independent variable *X* on *Y*.

The goal of the regression is to calculate the values of the parameters so that the model will best describe the data or fit them optimally. This means that the vertical deviations of the actual points from the model must be as small as possible (Figure 8) [10].

$$e_i = \hat{y}_i - y_i = min \quad (2)$$

Because some deviations are positive and some are negative, we square them. The criterion for minimising the sum of the squared deviations is called the Ordinary Least Squares method (OLS) [12].

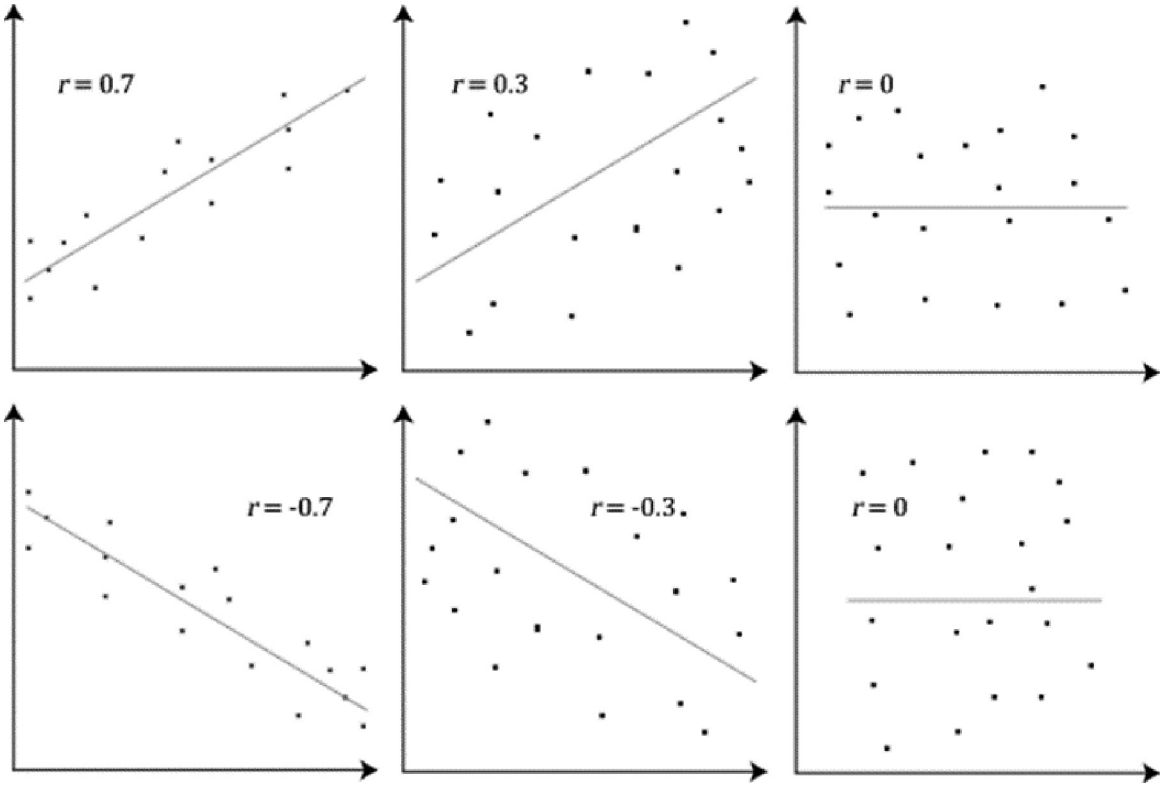


Figure 6: *Correlation coefficient strength [10].*

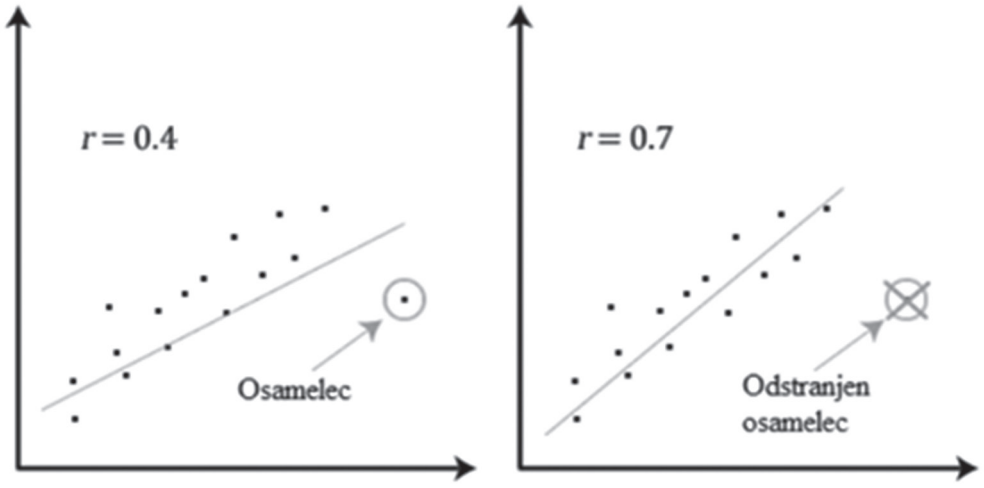


Figure 7: *Removing the outlier [11].*

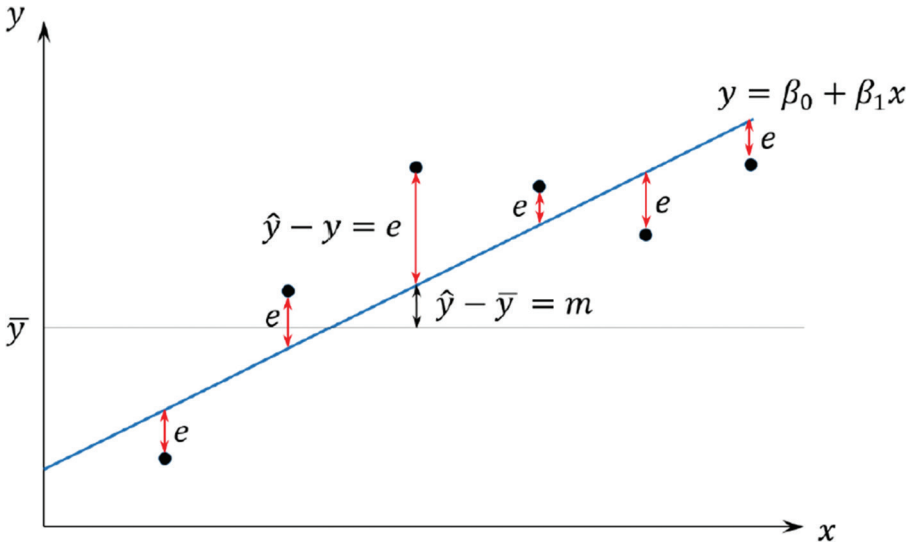


Figure 8: *Deviations of points from the line and deviation of the line from the mean [10].*

In the case of an *n*th degree polynomial, we look for *n* + 1 parameters, with which we try to best approximate the measurements (Figure 9).

$$\hat{d}(t) = \hat{a}t + \hat{b} \rightarrow \begin{cases} \hat{d}(1) = \hat{a} * 1 + \hat{b} \\ \dots \\ \hat{d}(N) = \hat{a} * N + \hat{b} \end{cases} \rightarrow \begin{bmatrix} \hat{d}(1) \\ \dots \\ \hat{d}(N) \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 1 \\ 2 & 1 \\ 3 & 1 \\ \dots & 1 \\ N & 1 \end{bmatrix} = \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} \quad (3)$$

$$\hat{d}(t) = \hat{a}t^2 + \hat{b}t + \hat{c} \rightarrow\rightarrow$$

$$\begin{cases} \hat{d}(1) = \hat{a} * 1^2 + \hat{b} * 1 + \hat{c} \\ \dots \\ \hat{d}(N) = \hat{a} * N^2 + \hat{b} * N + \hat{c} \end{cases}$$

$$\rightarrow \begin{bmatrix} \hat{d}(1) \\ \dots \\ \hat{d}(N) \end{bmatrix} = \begin{bmatrix} 1^2 & 1 & 1 \\ 2^2 & 2 & 1 \\ 3^2 & 3 & 1 \\ \dots & \dots & 1 \\ N^2 & N & 1 \end{bmatrix} = \begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} \quad (4)$$

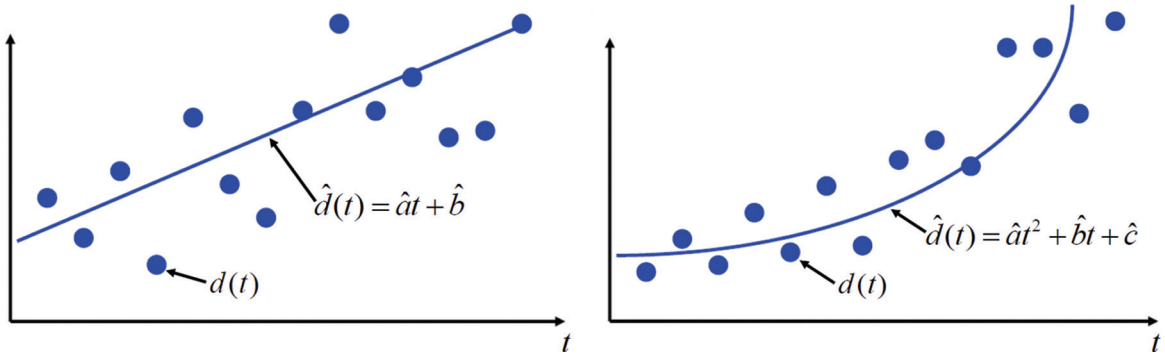


Figure 9: *1st- and 2nd-order linear regressions [10].*

The regression model can be better or worse, and the quality of the model can be evaluated in different ways. One of the simplest measures to evaluate the quality of a regression model is the coefficient of determination [12].

$$\Sigma(y_i - \bar{y})^2 = \Sigma(\hat{y}_i - \bar{y})^2 + \Sigma(\hat{y}_i - y_i)^2 \quad (5)$$

or

$$SST = SSR + SSE \quad (6)$$

The coefficient of determination R^2 is the ratio between SSR and SST.

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \quad (7)$$

SST: sum of squared deviations,
SSR: total correction of the sum of squares and
SSE: model sum error.

The values of the coefficient of determination range from $0 \leq R^2 \leq 1$. The closer to the value of 1, the smaller the deviation between the actual points and the model [10].

Another indicator of the reasonableness of fit is the presentation of residues compared with the independent variable. Residues must be randomly distributed and contained in a relatively small band, which is proportional to the accuracy of the data [4].

The relationship between coal consumption and transmission of CO_2

The correlation between coal consumption and CO_2 emissions generated directly by transmission is a very high positive relationship: *r = 0.98*.

The correlation between CO_2 emissions and economic growth and between coal consumption and economic growth is small and negative (-0,23274 or –0,36466), which means that the impact of coal consumption – and thus also transformational emissions – on economic growth is minimal, that is, coal consumption does not have a large impact on economic growth, which is typical for developed countries, where the 'black industry' is no longer a driver of development. The minus sign, however, means inverse connectivity, ie that by reducing coal consumption and CO_2 emissions, gross domestic product grows.

We calculate the linear regression equation (Figure 10), which in this case is a 1st-order equation, or a linear line in which *y* represents CO_2 emissions and *x* represents coal consumption.

$$y = 1{,}110555x + 745{,}027 \quad (8)$$

In this case, the fitting of the mathematical model is $R^2 = 0.96$. Since the value of the coefficient of determination is very close to 1, the suitability of the model is very high. The residue graph does not show a visible trend.

The relationship between coal consumption and total CO_2 emissions

The correlation between coal consumption and total CO_2 emissions, which are defined as the sum of emissions from transport, energy, industrial processes, fuels in manufacturing, agriculture, waste, other sectors, fugitive emissions from fuels, and others, also indicates a high positive relationship *r* = 0.93 between coal consumption and total CO_2 emissions, as the transmission sector accounts for almost a third of the total emissions.

The calculation gives the linear regression equation (Figure 11), which in this case is an equation of the 1st order, or a linear line with the equation:

$$y = 2{,}002699x + 9908{,}849 \quad (9)$$

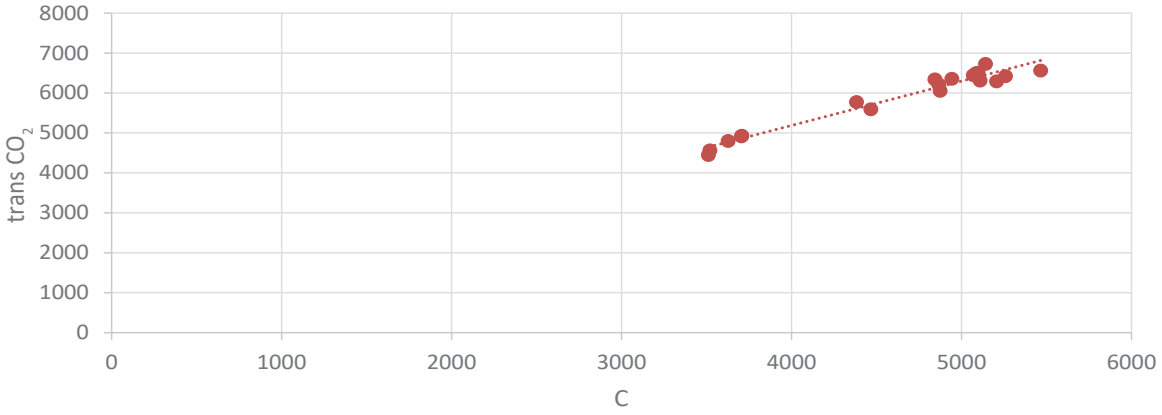


Figure 10: *Emissions of transmission depending on the use of coal.*

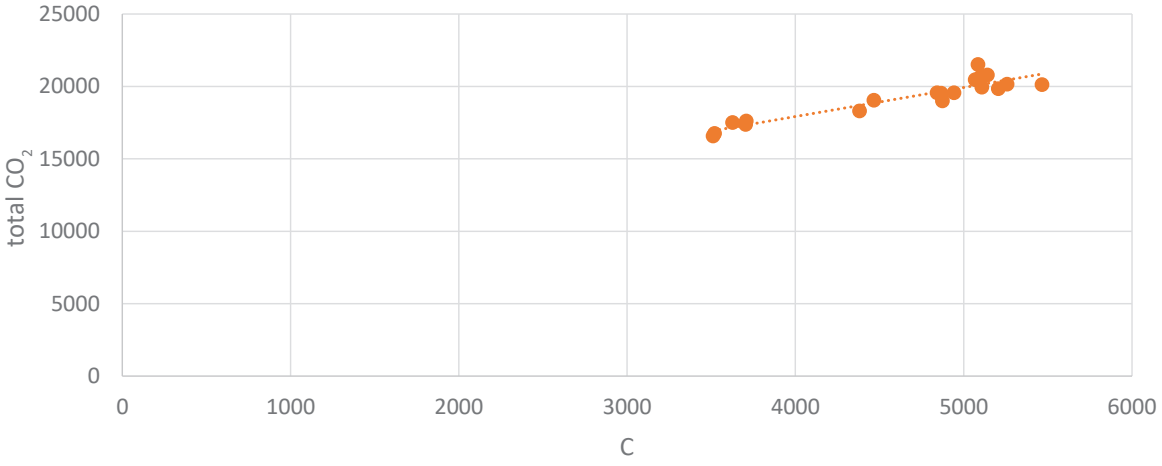


Figure 11: *Total emissions depending on coal consumption.*

where y represents the total emissions and x represents coal consumption.

The fit of the mathematical model is defined by the coefficient of determination R^2, which in our case is $R^2 = 0.87$. The value of the coefficient of determination is quite close to 1, which means that the suitability of the model is high to very high.

Another indicator of the reasonableness of fit is the display of residues compared with the independent variable. The residual graph shows a random distribution without a visible trend, which is also a condition for the suitability of the model.

The relationship between coal consumption and emission productivity

Emission productivity is calculated as the ratio between the gross domestic product at constant prices and all greenhouse gas emissions expressed in eq. CO_2.

In the analysis of the graph, a point that stands out from the trend of the model, which we call the outlier (year 2000), is noticed. We eliminate this point and start with 2001 and continue with the calculations (Figure 12).

The correlation coefficient increased from –0.86145 to -0.92875, that is, the connectedness of the data is now just under 7% better.

The calculation of the Pearson correlation coefficient shows a very high negative correlation, $r = -0.93$, between coal consumption and emission productivity. The strength of the connection is high and inversely proportional, which means that coal consumption has a strong impact on emission productivity in the sense that the lower the coal consumption, the higher the emission productivity.

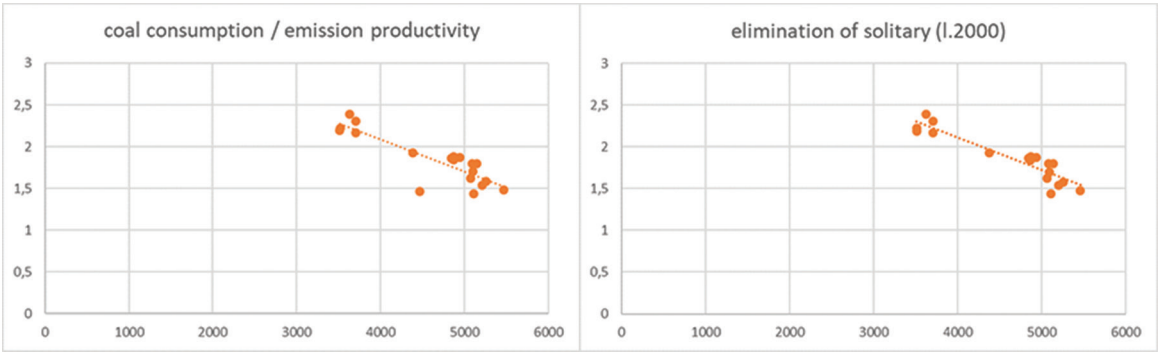


Figure 12: *Elimination of the outlier.*

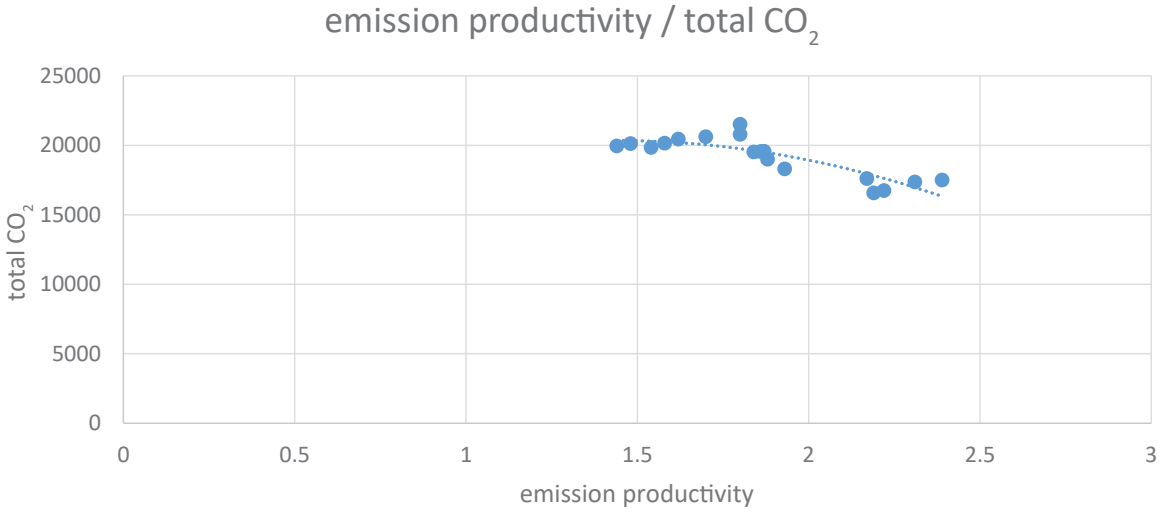


Figure 13: *Emission productivity in relation to total emissions.*

The calculation gives the linear regression equation, where y is the emission productivity and x is the coal consumption, which in this case is a first-order equation or linear line with the following equation:

$$y = -0.00039x + 3.671887 \qquad (10)$$

The fit of the mathematical model is defined by the coefficient of determination R^2, which in our case is $R^2 = 0.86$. The display of residues compared with the independent variable also shows the degree of relevance of the model.

The relationship between productivity and the emission of total CO_2 emissions

The correlation between emission productivity and total CO_2 emissions shows a high negative correlation, which leads us to the fact that with increasing emission productivity, total CO_2 emissions fall. The Pearson correlation coefficient is $r = -0.82$.

A connectedness in the form of an inverse U curve is noticeable, so we set the mathematical model as a linear regression of the second order, or a quadratic regression.

The calculation gives a mathematical model in functional form:

$$y = -4,402.5x2 + 12615.56x + 11,320.67 \qquad (11)$$

In this model, y represents total emissions and x represents emission productivity.

The fit of the mathematical model is defined by the coefficient of determination R^2, which in our case is $R^2 = 0.73$. The residual graph does not show a visible trend, which is also a condition for the suitability of the model.

Withdrawal from coal

The strategy of withdrawing from coal or the closure of the Velenje Mine and thus the cessation of TEŠ's operation, as well as the work

of various restructuring groups and presentations of various studies, both on the governmental and non-governmental side, imply that 2033 or 2050 would be possible years to completely end coal consumption, where 2033 is a governmental prediction and 2050 is a prediction made by employee representatives and the energy professionals. The following two reasons were crucial for such a decision: changing external circumstances, especially the increase in emission coupon prices (and price projections until 2030), together with the increase in climate targets at the EU level, which significantly increase the risk of uneconomical operation of TEŠ; and that such a scenario has the most positive effects on climate, local environment, nature, and human health. Such a decision is also influenced by the possibility of drawing funds from the European Fund for a Fair Transition.

However, such a rapid and uncontrolled withdrawal from coal would also be problematic from the point of view of a reliable supply of electricity produced in Slovenia, as it would be difficult to plan replacement capacities in time, as well as from the point of view of employees and the closure process of Premogovnik Velenje.

The share of electricity that would be lost in this way cannot be replaced with renewable sources in a short time, especially because TEŠ is also the most important domestic source, which can adapt to most unpredictable situations in the electricity system and provide a range of system services. At the same time, it also produces thermal energy for the needs of consumers in the Šalek Valley and thus supplies the second largest hot water system in the country. It should also not be forgotten that in the event of the imminent shutdown of TEŠ, import dependence would also increase sharply, averaging around 17 percent of electricity in recent years, in view of forecasts of growing demand for electricity in the future.

Among several possible energy sources that would be an energy alternative to fossil fuels and would continue to use the energy location at TEŠ, one is gas, whilst others may be some alternative sources for which it would be difficult to compensate for the lack of electricity in a short time. Gas and alternative fuels, where we have Solid Recovered Fuel, have a half lower emission factor (the ratio between CO_2 emissions and net calorific value expressed in kg CO_2/GJ), which means that when we burn these, half as many CO_2 emissions are produced as with coal combustion. The use of gas is not economically justifiable for now, and the local community opposes the incineration of Solid Recovered Fuel. Even the reserves in hydropower, which are supposed to mitigate the outage in the beginning, would not be sufficient in the long run.

The solution proposed by employees for closing the mine as late as possible is also to redirect the funds paid by TEŠ through CO_2 coupons to the Climate Change Fund, whose funds are intended for climate change mitigation, to solve the problem of closing the Velenje Coal Mine and the region. The funds raised in this way would be used to improve and reduce the environmental footprint by capturing carbon, new technologies, environmental policies and for the needs of regional development policies.

We will have to take care of our self-sufficiency, and we will need another major conventional source in the long run, so the decision on long-term use of nuclear energy is also important, which some decision makers believe is the only real solution to replace energy production from thermal power plants. There are several obstacles with this as well, including the fact that the construction of a nuclear power plant is expensive and time-consuming, so it may be that we would have to wait a very long time for electricity from this source.

In shaping Slovenia's energy future, we will need an appropriate mix of energy sources that will provide us with a safe and reliable supply of low-carbon energy at affordable prices.

In addition to the benefits, the withdrawal from coal consumption also brings problems that need to be solved. Not only is it necessary to compensate for the loss of electricity production with other sources, but it is also necessary to take care of areas that have so far lived off the coal industry. The problem is not only the renewed employment of the people who have worked in this industry, but the economic restructuring of the entire economy of these areas. Finally, we must also invest in the rehabilitation of the environment left behind by the coal industry.

Conclusion

Coal consumption in Slovenia has been on a declining trend for quite some time, harmful emissions from the transmission sector have also decreased by about a quarter due to more modern procedures and improvements. On the other hand, total GHG emissions are not decreasing; rather, they are increasing slightly, mainly owing to a large increase in transport emissions. Emission productivity is growing steadily and is approaching the EU average. If in the last century coal was still a driver of development in Slovenia and its impact on economic growth was significant, nowadays there is a noticeable gap between GDP and coal consumption, which is a characteristic of developed countries.

Using mathematical modelling and setting up mathematical models to predict the behaviour of certain dependent parameters in the future, we can predict how the parameters observed will react to changes. In general, models can only approximate behaviour in the real world.

The National Energy and Climate Plan of Slovenia anticipates the phasing out of the use of domestic and imported coal for energy purposes, which means that we will have to develop an appropriate energy strategy in the future that will ensure a safe and reliable supply of low-carbon energy.

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