The Impact of Economic Growth on the Dynamics of Carbon Emissions in the United States: Spline Analysis

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Abstract. The relationship between trends in energy consumption, carbon emissions and economic growth is of increasing interest to researchers in connection with climate change. Currently, the provisions of several international climate agreements are being implemented – the United Nations Framework Convention on Climate Change, the Kyoto Protocol and the Paris Agreement. At the same time, the implementation of each of the agreements requires maintaining a balance between striving for carbon neutrality and ensuring economic growth. The article attempts to identify the relationship between trends in carbon emissions and GDP production - the main indicator of economic growth. In this sense, the example of the USA turned out to be interesting, where economic growth in recent years has occurred with a permanent reduction in carbon emissions. To identify mutual reactions, taking into account inertia and weak volatility in the dynamics of GDP production and carbon emissions, the article compares the growth rates of indicators against the background of the impact of “event components” of dynamics. To achieve maximum accuracy in comparing the oscillation rate of the studied indicators, it is proposed to model the dynamics of empirical data by splines.

1 Introduction

Currently, attempts are being made to study the relationship between carbon emissions and economic growth using various methods. A review of numerous studies leads, at first glance, to contradictory conclusions. Firstly, part of the research has led to the conclusion that economic growth trends and energy consumption are the main sources of carbon emissions in many countries. Some researchers came to the conclusion that carbon emissions in developed countries correlate slightly with economic development indicators. The strongest dependence of economic development on energy consumption is characteristic of developing countries, which leads to a strong correlation between economic growth trends and carbon emissions [1]. Despite the growing amount of scientific research, there is still not enough understanding of how to find a balance between the flows of energy consumption and carbon emissions, while ensuring economic growth. Researchers still find contradictions, some of which consider economic development to be

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the main factor in increasing carbon emissions, while others consider economic development not as a source of environmental problems, but rather as a potential opportunity to achieve carbon neutrality [2, 3]. The desire for carbon neutrality for emerging economies still remains a deterrent. Countries with poorly developed economies do not consider it fair to demand that carbon emissions be reduced by limiting energy consumption, which limits economic growth opportunities. It is the developed countries with the largest economies that are perceived to be responsible for a significant share of carbon emissions for many years, therefore, responsible for the ongoing climate change. It is in the context of the perception of responsibility of countries with developed economies that the analysis of trends in economic growth and carbon emissions in the United States is interesting and relevant. It should be informative to compare the dynamics of carbon emissions from energy and the main indicator of economic growth – the volume of GDP production.

2 Materials and Methods

Analysis of BP data shows that China accounted for the largest amounts of carbon emissions from energy in 2021, followed by the United States and Russia [4]. The US accounted for 13.3% of all carbon emissions in 2021, while China accounted for 30.9%. This imposes on the states with the largest economies the greatest historical responsibility for climate pollution [5]. Carbon dioxide can remain in the atmosphere for many years, which is already evident in the dynamics of global warming. Hydrocarbon energy resources currently continue to be the main sources of energy that ensure GDP growth in many countries. It seems relevant to analyze the correlation between the dynamics of GDP production and carbon emissions on the example of the United States – the world's leading economy. An interesting fact is that from 2010 to 2021, with a close positive correlation between global GDP production and carbon emissions (r = 0.842), the dynamics of these indicators in the United States demonstrates a close inverse relationship (r = - 0.791). This suggests that the United States has generally managed to free itself from the direct relationship between economic growth and carbon emissions. However, "latent" correlations are interesting, which can manifest themselves between fluctuations in the instantaneous growth rate of GDP production and carbon emissions.

Table 1. Dynamics of GDP production by PPP and carbon dioxide emissions from energy in the United States.

<table>
<thead>
<tr>
<th>Year</th>
<th>GDP, current prices (Purchasing power parity; billions of international dollars)</th>
<th>Carbon Dioxide Emissions from Energy, Million tonnes of carbon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>15049.0</td>
<td>5485.7</td>
</tr>
<tr>
<td>2015</td>
<td>18206.0</td>
<td>5137.5</td>
</tr>
<tr>
<td>2018</td>
<td>20527.2</td>
<td>5132.7</td>
</tr>
<tr>
<td>2019</td>
<td>21372.6</td>
<td>4980.9</td>
</tr>
<tr>
<td>2020</td>
<td>20893.8</td>
<td>4420.6</td>
</tr>
<tr>
<td>2021</td>
<td>22996.1</td>
<td>4701.1</td>
</tr>
</tbody>
</table>

The dynamics of GDP production in the United States in recent years has shown growth, increasing in 2021 compared to 2010 by $7947.1 billion in absolute terms or by 50% in relative terms. At the same time, the United States managed to reduce CO2 emissions from fossil energy consumption in 2021 by 10.4% relative to 2010 (Table 1). The existing antagonism of economic development factors and the desire for carbon neutrality leads to instability of carbon emission trends within some time intervals [6, 7]. Despite the positive results achieved, it is important to assess the consistent changes in the dynamics of
carbon emissions and GDP production, including studying the local reactions of processes to the "event components" of dynamics. Significant "event components" in the dynamics of GDP production and carbon emissions in recent years include the 2014 energy crisis, the conclusion of the Paris Climate Agreement in 2015 and the beginning of the COVID-19 pandemic in 2020.

3 Results and Discussion

The impact of "event components" can change the correlation between the flows of GDP production and carbon emissions within some time intervals. Often, mutual reactions of processes may not be detected in absolute changes in indicators, manifesting themselves only in accelerations or decelerations of growth within short time intervals. One of the methods of detecting "latent" changes in the dynamics of indicators is to study the behavior of not the indicator itself, but the rate of its change [8]. The impact of event components leads to variability in the structure of the dynamics under study, when the correlation between indicators within different time intervals can noticeably increase or, on the contrary, take on a "latent" character. For the analytical writing of structural-variable dynamics, traditional methods are ineffective. To study fluctuations in the rate of development, taking into account the impact of "event components" of dynamics, it is necessary to model processes with piecewise continuous functions, avoiding smoothing of empirical data at nodal points. Classical smoothing methods of data modeling turn out to be limited for describing the continuous dynamics of flows – the accuracy of empirical data in the dynamics models under construction is lost, the sequence of changes over time in regression models is disrupted. The exact coincidence of model and empirical data, the preservation of the sequence of changes are crucial for the formal description and study of structural-variable dynamics.

![Dynamics of GDP production by PPP and Carbon dioxide emissions from energy in the USA](image)

Fig. 1. Spline models of GDP production dynamics by purchasing power parity and carbon emissions in the USA

It is proposed to implement the existing problem of accounting for structural changes in economic analysis by modeling dynamics with cubic spline functions (Fig. 1). The
constructed spline model can be transformed into a mathematical model of the growth rate by differentiation [9, 10]. The first derivative of the analytical model of the dynamics under study is the instantaneous growth rate of the indicator. The simulation of dynamics by cubic splines preserves the real statistics of the indicator at the nodal points with absolute accuracy. Differentiability and the property of minimal curvature of cubic splines allow us to proceed to a more accurate analysis and control "by derivative".

A significant share of carbon emissions is currently associated with the consumption of hydrocarbon energy resources – the burning of oil, gas, and coal. The analysis of spline models makes it possible to single out the USA as a country demonstrating a decrease in carbon emissions (by an average of 1.3% annually from 2010 to 2021) with a noticeable increase in GDP production. At the same time, in the dynamics of absolute indicators, there was a significant synchronous drop in carbon emissions and GDP production during the spread of COVID-19 in 2020. The subsequent recovery of economic activity in 2021 and the growth of GDP production in the United States required an increase in energy consumption – this led the dynamics of carbon emissions to a growth trajectory. The manifestation of the variability of mutual reactions of the studied processes over time requires the determination of regression switching points. This can be done by quantitative methods by calculating the values of the correlation function. The points of possible regression switches will be determined qualitatively by the ratio with the beginning of the "event components" of dynamics critical for the global economic system [11]. It is known that the relevance of the results to the research tasks depends on the conceptual approach to the analytical description of the data – acceptance or rejection of smoothing the data, taking into account or abstracting from the impact of "event components" of dynamics, comparing sets of discrete empirical data or continuous sequential changes.

Fig. 2. Spline models of the instantaneous growth rate of GDP production at purchasing power parity and carbon emissions from energy in the United States

Splines are widely used in solving problems of computational mathematics, in engineering calculations, and in recent years have found effective use in modeling economic dynamics. The effectiveness of splines is explained, firstly, by their flexibility and accuracy in solving problems of approximation of functions. Secondly, the growing popularity of splines in modeling structural-variable dynamics is due to the ease of computer implementation of computational algorithms based on spline functions. Splines in
modeling dynamics with weakly expressed trends allow us to obtain analysis results at a higher quality level, revealing greater accuracy compared to the methods of classical econometrics. First of all, this is achieved by abstracting from the smoothing of real data in the dynamics of emissions. A well-known feature of spline modeling, which consists in an absolutely exact coincidence of empirical and model data at the nodal points, becomes the basis of the new approach proposed in the study to identify "latent" correlations. The transition to the analysis of fluctuations in the growth rate of GDP production and carbon emissions can be accomplished by differentiating the constructed spline models of empirical dynamics (Fig. 2). The mathematical accuracy of the apparatus of spline functions and methods of differential calculus, coupled with the visibility of the solutions obtained, are relevant, they are in demand for flow control tasks in complex dynamic systems.

The obtained curves of the first derivative describe the instantaneous rate of fluctuations in the dynamics of GDP production and carbon emissions. The interpretation of the derivative as the speed and acceleration of economic flows, by analogy with physical movement, deepens and expands the possibilities of studying dynamics. Instantaneous velocity curves allow us to identify reactions in the dynamics of emissions to "event components", presenting even small changes more clearly. Cubic splines, due to their accuracy, adaptability and differentiability, become an effective tool for "fine" data analysis. The "subtlety" of the proposed method should be understood as the use of derivatives in the analysis of the dynamics of flows, ensuring the accuracy of the data of the indicator itself, which, when switching to derivatives of analytical models of dynamics, preserves all local characteristics of the rate of change, allows identifying temporary areas and points of structural changes.

A comparison of the instantaneous growth rate curves allows us to move on to a more meaningful analysis of changes in the dependence of carbon emissions on economic growth trends. The factors of the "transformation" of the studied relationship could be the "event components" of dynamics. In the analyzed time interval, several events can be identified that could have a global impact on the dynamics of economic activity, and as a result, on the dynamics of carbon emissions in the United States. Firstly, it is the crisis of 2014 caused by the rapid fall in world energy prices. This has led to a decline in economic activity in many countries of the world, including the United States. The curve of the first derivative since 2014 shows a noticeable decrease, remaining in the region of positive values, which indicates the continuation of GDP production growth, but only with a slowdown. At the same time, the curve of the instantaneous growth rate of carbon emissions goes into the region of negative values of the first derivative, which indicates a decrease in carbon emissions. The analysis of instantaneous velocity curves reveals "latent" features of communication for classical econometric methods. If there is a close negative correlation in the dynamics of the initial data, then since 2014, the slowdown in GDP growth has led to a decrease in carbon emissions in the United States. The example of achieving economic growth in the United States proves the possibility of getting rid of the dependence between GDP growth and the dynamics of carbon emissions for technologically advanced countries.

Another event that was supposed to lead to a noticeable reduction in carbon emissions in the world was the signing of the Paris Agreement in 2015. Currently, about 200 countries have declared their commitment to the goals of the Paris Agreement. The parties to the agreement declared their desire to reduce emissions and efforts to adapt to climate change, which are not limited to national borders. At the same time, the need for assistance from developed economies to developing countries on the way to achieving global goals in climate conservation is recognized. Despite the fact that the implementation of the goals of the Paris Agreement is planned for several decades, some trends in reducing carbon
emissions should have already manifested themselves in the next few years. As the curves of the first derivatives show, the instantaneous growth rate of carbon emissions in the United States remained in the negative zone until 2016 against the background of a slight acceleration in GDP growth. The increase in the rate of GDP growth in 2017 and 2018 led to an increase in carbon emissions, which suggests a permanent dependence of carbon emissions in the United States on economic growth trends.

4 Conclusions

The onset of the global crisis in the context of the spread of Covid-19 has become a global factor in reducing carbon emissions worldwide – during this period, the trajectories of the GDP growth rate curves and carbon emissions in the United States turned out to be synchronous, demonstrating an unprecedented drop. The lifting of most restrictions in 2021 has led to increased economic activity and a sharp increase in carbon emissions in the United States. This indicates that economic growth factors are beginning to dominate efforts to achieve carbon neutrality in crisis conditions, including in developed economies.

The spline modeling proposed in the study develops the theoretical basis for the use of differential calculus methods in relation to the study of dynamics. The introduction of new analytical description approaches that allow modeling dynamics in transforming dynamic systems without losing information about the real values of the process will allow studying climate change with high accuracy. The apparatus of mathematical and instrumental methods of studying processes in dynamical systems is noticeably expanded by the involvement of spline functions, methods of differential calculus, interdisciplinary methods of studying dynamics.

"Latent" trends, as the analysis showed, can be detected within short time periods, not being manifestations of long-term trends. When quantifying correlations between economic growth trends and carbon emissions within short time intervals, the property of splines to restore missing values in the source data or to interpolate additional points of the empirical process may be useful. If necessary, the use of data "condensation" in quantitative analysis will remove the limitations of classical econometrics methods to the length of the time series under study. As the analysis showed, modeling by splines allowed us to investigate the transformation of the relationship between the trends of GDP production and carbon emissions, manifested in crisis conditions or as a result of the impact of "event components" of dynamics. The most important conclusion of the study is that at the global level, GDP production and carbon emissions in the world maintain a close positive relationship. The direct link between the dynamics of carbon emissions and economic growth in emerging economies is explained by the fact that accelerating economic growth also requires more energy consumption. Countries with developed economies are characterized by higher energy efficiency of production, which allows, as can be seen from the example of the United States, to ensure economic growth while reducing carbon emissions.

References


