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## Article

# Decarbonization of the Romanian economy: An ARDL and KRLS approach of ecological footprint

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**DECARBONIZATION OF THE ROMANIAN ECONOMY:  
AN ARDL AND KRLS APPROACH OF ECOLOGICAL FOOTPRINT****Dan Ioan Topor<sup>1</sup>**, **Andreea Marin-Pantelescu<sup>2</sup>**, **Adela Socol<sup>3</sup>**  
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**Abstract**

The mechanisms developed at the European level through the Green Deal, to achieve the assumed decarbonization process, are facing major challenges to reach climate neutrality of the EU in a clean and circular economy by 2050. The purpose of this study is to investigate the hypothesis of the Environmental Kuznets Curve (EKC), based on the causal relationship between the ecological footprint as an indicator of sustainable development, and several variables, namely the gross domestic product per capita (GDP per capita) to capture the growth of the economy, globalisation (KOF Globalisation Index), and two environmental variables: fossil fuel energy and CO<sub>2</sub> emissions. The study was developed for Romania, for the period 1990 to 2018, and used Autoregressive Distributed Lag (ARDL), dynamic ARDL, and Kernel Regularised Least Squares (KRLS) models.

The results indicate the existence of a relationship between variables, both in the long and short term and, also coexistence between the U-shaped and inverted U-shaped EKC graphs, which confirm the empirical results found in the literature. The originality of the research consists in analysing the decarbonization of the Romanian economy by studying the influence of economic growth, globalisation, and energy from fossil fuels and CO<sub>2</sub> emissions on the ecological footprint. From the perspective of public policies, the results highlight the need to configure appropriate instruments aimed at climate neutrality according to the objectives assumed by Romania through the Green Deal of the European Union.

**Keywords:** ARDL, decarbonization, ecological footprint, Environmental Kuznets Curve (EKC), GDP per capita, KOF Globalisation Index, KRLS.

**JEL Classification:** C58, P18, O44

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## **Introduction**

One of the main targets of the European Union's policies to achieve climate neutrality by 2050, contained in the European Union's Green Deal (European Commission, 2019), aims to protect the environment as well as improve the health and quality of life of citizens through a sustainable approach to the economy and society. This study was developed from the perspective of the Triple Bottom Line (TBL) theory, which circumscribes the success of a system/entity through the prism of economic, social, and environmental factors.

The main objective of this study is to explore the impact of economic growth, globalisation, CO<sub>2</sub> emissions, and fossil fuel energy on Romania's ecological footprint. Numerous studies have investigated through various methods the effect on the ecological footprint of different proxies in both developed and emerging economies (Ghita et al., 2019; Alper et al., 2022; Rustemoglu, 2022; Zakari et al., 2022), but none have analysed the effect of economic growth, globalisation, CO<sub>2</sub> emissions and fossil fuel energy on the ecological footprint in Romania. Thus, the need for research to address this gap in the literature has been identified. Romania's ecological footprint over the period of 1990 to 2018 was analysed using Autoregressive Distributed Lag (ARDL), dynamic ARDL and Kernel Regularised Least Squares (KRLS) models.

The originality of the work is first distinguished by the research model. This is the first study that addresses the case of post-socialist Romania and that brings together three categories of studied indicators (economic, social, and environmental) by testing the Environmental Kuznets Curve (EKC) hypothesis and using econometric methods such as ARDL, dynamic ARDL, and KRLS. Another dimension of originality derives from the contribution of the study to practice, which has the potential to provoke the interest of regulatory authorities in the configuration of public policies for the decarbonization of the Romanian economy.

The paper begins with a literature analysis, and the subsequent sections present the research methodology, results, discussions, and conclusions.

## **1. Literature review**

### **1.1. Ecological footprint, an important proxy of climate neutrality**

Reducing the ecological footprint, the main proxy of the climate neutrality associated with the European Union's Green Deal, may help achieve the global objectives of sustainability and maintaining an unpolluted environment. The ecological footprint is a composite index of anthropogenic pressure on the environment (Solarin, 2019) and defines the ecological impact on land and water areas, determined by human activities such as agriculture, fisheries, industry, infrastructure development, etc. (Zambrano-Monserrate et al., 2020). A high value of the ecological footprint indicator is associated with environmental degradation and denotes the increasing pressure on environmental resources. Thus, 1.75 multiplied by the Earth's surface would be needed to provide sufficient resources to absorb waste, which means that the planet needs one year and eight months to regenerate what it uses in a year (Zambrano-Monserrate et al., 2020).

A considerable number of specialised studies have captured environmental degradation exclusively with the help of CO<sub>2</sub> emissions; however, such an approach treats asymmetrically the ratio of the necessary natural resources, i.e., through the exclusive reference to air quality

(Charfeddine, 2017; Destek and Okumus, 2019; Altıntaş and Kassouri, 2020; Abbas et al., 2021; Nathaniel et. al., 2021; Ahmed et al., 2021; Adai et al., 2022), while the ecological footprint is considered to be a comprehensive variable in illustrating the quality of the environment by establishing the impact of environmental degradation (Mancini et. al., 2016; Global Footprint Network, 2022). Thus, a new trend identified in the literature is that of using the ecological footprint as an indicator of sustainable development to show the surface area of land and water needed to absorb the waste generated by the economy, society, and individuals (Ghita et al., 2019; Alper et al., 2022; Rustemoglu, 2022; Zakari et al., 2022).

### 1.2. Analysis of the environmental impact of economic growth

According to the EKC hypothesis, there is a negative relationship between a low level of gross domestic product (GDP) per capita and environmental quality in the early stages of economic development, as well as a positive relationship between higher levels of growth or higher GDP per capita and the quality of the environment in the coming years (Kuznets, 1955). A study of relevant research that tests the relations between economic growth and environmental deterioration using the EKC reveals mixed results at the level of different countries or regions, depending on the type of environmental degradation variables analysed (e.g. CO<sub>2</sub> emissions, other greenhouse gas emissions, ecological footprint, etc.), control variables (renewable energy, fossil fuel energy, various human development indicators, trade opening indicators, etc.) and chosen econometric techniques (Al-Mulali et al., 2015; Brad et al., 2016; Chen and Chang, 2016; Uddin et al., 2016; Zortuk and Çeken, 2016; Alkhars, et al., 2022).

Research indicates either the confirmation of the EKC hypothesis of the negative effect of economic growth on the quality of the environment (in the form of an inverted U-type graph) or six other types of relations between economic growth and environmental deterioration: an N-shaped graph, N-shaped inverted graph, no relationship, U-shaped graph, monotonic positive or monotonic negative (Mrabet and Alsamara, 2017; Alkhars et al., 2022). Economic growth accelerates environmental degradation, as GDP growth stimulates economic activities through production, consumption, and a high level of investment, which in turn increases environmental deterioration. This cycle demonstrates that economies that move from middle incomes to high incomes face environmental problems, which arise due to economic progress at the expense of environmental sustainability (Shahbaz et al., 2017; Yang, et al., 2021). The early stages of economic growth are associated with activities that generate pollution and degrade the environment; however, as economic growth becomes sustainable and of high value, it becomes associated with green technologies, which compensate for the deterioration of the environment (Szigeti et al., 2017).

Thus, the following hypothesis was developed based on the EKC in which the deterioration of the environment was analysed from the perspective of the ecological footprint:

$H_1$ : Economic growth influences the ecological footprint.

### 1.3. Analysis of the impact of globalisation on the ecological footprint

Globalisation is associated with a complex of manifestations of interactive coevolution of millions of technological, cultural, economic, social, and environmental trends at all

imaginable space-time scales (Rennen and Martins, 2003). Globalisation has reached a stage of development in which the international dispersion of economic activities has recently become unimaginable (Postelnicu et al., 2015). While globalisation contributes to economic growth by expanding trade and investment flows, it can negatively affect the environment, in particular through the use of resources and air pollution specific to the industrial sector (Pata and Yilanci, 2020).

As various indices of globalisation have been developed to capture this phenomenon, interest in analysing the impact of globalisation on environmental quality has increased in the literature in recent years. One of the commonly used indices in the analysis of globalisation is the KOF Swiss Economic Institute Index, a composite index that involves three subindices that measure economic, social, and political dimensions of globalisation. The KOF Globalisation Index scores range from 0 to 100, with high scores indicating a degree of increased globalisation (Kollias and Paleologou, 2017).

The positive influence of globalisation (quantified using the KOF Globalisation Index) on the ecological footprint, in the sense of increasing the latter, is attributed to the deterioration of natural resources with the aims of increasing exports, the transfer of polluting industries, and the inability to attract green technologies (Sabir and Gorus, 2019; Bilgili et al., 2020) or attract foreign investment, including by relaxing environmental regulations (Hussain et al., 2021). In developed countries with high income levels, globalisation reduces environmental degradation in the background of increased efficiency, modernisation of technologies (with a focus on green ones), and citizens' expectations to reduce the intensity of environmental degradation (You and Lv, 2018).

The many dimensions of globalisation have different effects on the ecological footprint: social globalisation negatively influences the ecological footprint and contributes to the preservation of the environment; economic globalisation, *ceteris paribus*, determines a greater ecological footprint; and political globalisation does not influence the ecological footprint. In a broad sense, globalisation increases the ecological footprint (Rudolph and Figge, 2017); however, recent evidence indicates no link between globalisation and the ecological footprint (Apaydin et al., 2021).

The following hypothesis shall be considered:

$H_2$ : The degree of globalisation influences the ecological footprint.

#### 1.4. Analysis of the impact of environmental factors on the ecological footprint

The increased use of fossil fuels and coal is considered the main cause of a worldwide increase of more than 2 billion tonnes (6%) in global energy-related CO<sub>2</sub> emissions (the total value of energy-related CO<sub>2</sub> emissions stood at 36.3 billion tonnes in 2021), the largest absolute annual growth in history according to the International Energy Agency – IEA, (International Energy Agency, 2022). According to data provided by the IEA in 2021, CO<sub>2</sub> emissions increased to the highest level in history after lower emission levels were recorded during the COVID-19 pandemic (International Energy Agency, 2022). More than 40% of the increase in CO<sub>2</sub> emissions is attributed to fossil fuels and coal (International Energy Agency, 2022). The link between ecological footprint and CO<sub>2</sub> emissions is mainly determined by fossil energy sources, since when fossil fuels are burned, carbon accumulates in the

atmosphere if there is not enough biocapacity to absorb these emissions (Charfeddine, 2017; Akalin et al., 2021; Global Footprint Network, 2022).

The ecological footprint was developed based on six major areas, of which the carbon footprint fraction (Global Footprint Network, 2022) has been shown to be directly influenced by CO<sub>2</sub> emissions, which was established *a priori* based on the calculation of the carbon footprint fraction (McBain et al., 2018; Abbas et al., 2021; Rustemoglu, 2022). The carbon footprint is defined as the regenerative capacity of wooded areas needed to capture anthropogenic CO<sub>2</sub> emissions that are not absorbed by the oceans (Mancini et. al., 2016). The carbon footprint is conceptually related to CO<sub>2</sub> emissions because both indicators show the influence of carbon either on the air (through the CO<sub>2</sub> emissions indicator) or on the Earth's surface (through the carbon footprint fraction of the ecological footprint) (Solarin, 2019).

The following assumptions have been formulated to study the influence of two environmental factors—CO<sub>2</sub> emissions and energy from fossil fuels—on the ecological footprint:

*H*<sub>3</sub>: Fossil fuel energy influences the ecological footprint.

*H*<sub>4</sub>: CO<sub>2</sub> emissions influence the ecological footprint.

The effects of applying positive or negative future shocks in developments on explanatory variables of the ecological footprint (e.g., CO<sub>2</sub> emissions) using dynamic analysis models such as dynamic ARDL (Sarkodie and Owusu, 2020; Zhang et al., 2021) allow simulating and predicting the behaviour of the variation of the ecological footprint. From the perspective of the measures to reduce CO<sub>2</sub> emissions provided for in the European Union's Green Deal, in order to achieve climate neutrality by 2050 and reduce emissions by 2030 by 55% relative to emissions in 1990 (European Commission, 2019), the influence of applying a shock to reduce CO<sub>2</sub> emissions on the sustainable development indicator, represented by the ecological footprint. No literature has been identified to address the subject of the analysis of the influence of CO<sub>2</sub> emissions on the ecological footprint in the dynamic ARDL approach.

The following hypothesis shall be considered:

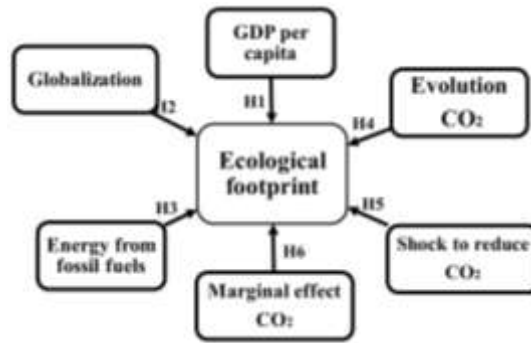
*H*<sub>5</sub>: The application of a shock to reduce CO<sub>2</sub> emissions in the coming period will influence the environmental footprint.

Machine learning methodologies (e.g., KRLS) can be applied to assess and establish causal relationships between variables in an optimised approach (Hainmueller and Hazlett, 2014; Ferwerda et al., 2017). Previous research has demonstrated marginal effects of specific variables (e.g., nuclear energy) on economic growth (Sarkodie and Owusu, 2020) but without addressing the analysis of the marginal effects of CO<sub>2</sub> emissions on the ecological footprint.

The following hypothesis is formulated:

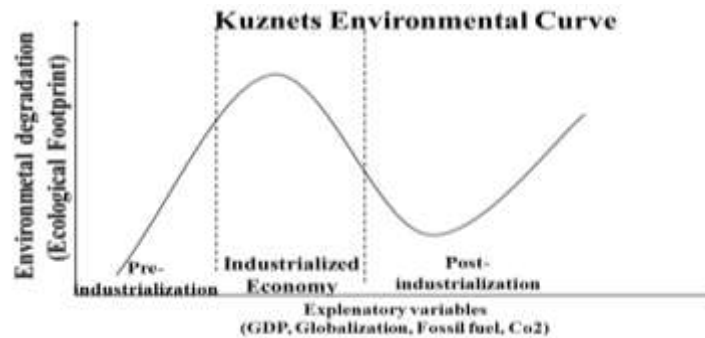
*H*<sub>6</sub>: CO<sub>2</sub> emissions have a marginal effect on the ecological footprint.

Based on the results of the previous research presented, a research model is proposed (Figure no. 1 and Figure no. 2), which captures the influence that economic factors (measured as the GDP per capita indicator – *GDP\_pp*), globalisation (measured as the KOF Globalisation Index), and two environmental factors (measured as energy from fossil fuels – *Energy\_fossil\_pp* and carbon dioxide emissions – CO<sub>2</sub>) have on sustainable development, captured by the ecological footprint (*Ecol\_footprint*) variable.



**Figure no. 1. Theoretical model of research**  
*Source: authors' own projection*

In close connection with the theoretical model of the research, the graphic representation of the expected evolution of environmental degradation (Figure no. 2) is developed in the research undertaken based on the Environmental Kuznets Curve (EKC) hypothesis.



**Figure no. 2. Evolution of Environmental Degradation – Kuznets Environmental Curve**  
*Source: author processing from Alkhars et al. (2022)*

**2. Research methodology**

According to the literature on state-of-the-art decarbonization, the ARDL, dynamic ARDL, and KRLS models were developed to determine whether there are both short-term and long-term relationships between the ecological footprint and the variables related to economic growth, globalisation, fossil fuel energy and CO<sub>2</sub> emissions. Our empirical research (see Figure no. 3) is based on an annual series covering the period 1990 – 2018 in Romania. The data set involved the following variables:

- Ecological footprint, measured in global hectares per capita (gha) and provided by the Global Footprint Network database (Global Footprint Network, 2022). As presented by the issuing entity, the ecological footprint of consumption measures the area of biologically productive land and water that a person, population or activity requires to produce all the

resources it consumes and to absorb the waste it generates, using the prevailing technology and resource management practices.

- GDP per capita (*GDP\_pp*), measured at current prices in US dollars and provided by the United Nations database (United Nations, 2022).
- The Globalisation Index (*Glob*), which measures the economic, social, and political dimensions of globalisation and was provided by the KOF Swiss Economic Institute database (Dreher, 2006; Savina, et al., 2019; KOF Swiss Economic Institute, 2022).
- Fossil fuel energy (*Energy\_fossil\_pp*), measured in fossil fuels per capita (kWh) and provided by the Our World in Data (Our World in Data, 2022).
- CO<sub>2</sub> emissions (CO<sub>2</sub>), measured in metric tonnes per capita and provided by the World Bank database (World Bank, 2022).

The conceptual development of the ARDL, dynamic ARDL and KRLS models in this study is based on the approach of the authors Sarkodie and Owusu (Sarkodie and Owusu, 2020).

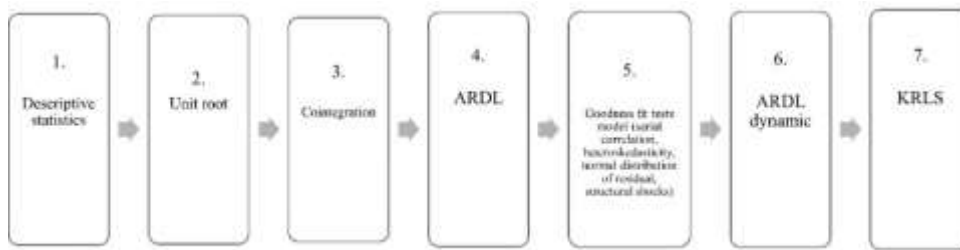


Figure no. 3. Stages of research

The ARDL-type econometric model, considered one of the greatest discoveries of the 20th century, is an appropriate cointegration technique to generate long-term and short-term evaluations and analyse series with a single cointegration vector (Hainmueller and Hazlett, 2014; Nkoro and Uko, 2016; Soren and Philips, 2018; Kripfganz and Schneider, 2020). To estimate the relationships between the dependent and independent variables, the following model was built:

$$Ecological\ footprint = f(GDP\ per\ capita, Globalisation, Fossil\ fuel\ energy, CO_2\ emissions) \quad (1)$$

All the variables in equation (1) were considered at the natural logarithm value, since the variables are used for investigation in their logarithmic form when homoscedasticity occurs (Akadiri, et al., 2020). The estimated model is as follows:

$$\Delta \ln Ecological\ footprint_t = \alpha_0 + \sum_{k=1}^n \theta_k \Delta \ln Ecological\ footprint_{t-k} + \sum_{j=0}^p \theta_j \Delta \ln GDP_{pp\ t-j} + \sum_{l=0}^r \theta_l \Delta \ln Glob_{t-l} + \sum_{m=0}^s \theta_m \Delta \ln EnergyFossil_{t-m} + \sum_{q=1}^v \theta_q \Delta \ln CO_2_{t-q} + \theta_1 \ln GDP_{pp\ t-1} + \theta_2 \ln Glob_{t-1} + \theta_3 \ln EnergyFossil_{t-1} + \theta_4 \ln CO_2_{t-1} + \epsilon_t \quad (2)$$



where  $\alpha_0$  is the constant,  $\theta$  represents the variable coefficients,  $\Delta$  denotes first difference operator and  $\epsilon_t$  is the residual term (white noise).

The study targets Romania because it is an important emerging south-eastern European economy that faces major challenges in maintaining and increasing environmental protection. In the context of the sharp volatility of the energy market in 2021 and the humanitarian and political crisis in Ukraine in the first half of 2022 and given the persistent effects of the COVID-19 pandemic, Romania is forced to prepare to face volatility and risk in the energy sector and, at the same time, to overcome the challenges in meeting the objectives set by the European Union through the Green Deal (European Commission, 2019). Since 1990, Romania has had a democratic socioeconomic reality, which is the reason for choosing this period in the study.

The second section of econometric processing, based on dynamic ARDL modelling (Sarkodie and Owusu, 2020), aims to study future shocks of economic and environmental indicators and estimates a dynamic ARDL model for the ecological footprint should a CO<sub>2</sub> emissions shock be applied.

The last part of the modelling process refers to a new machine learning algorithm, the KRLS method, which provides closed-form estimates for predicted values, variations, and partial pointwise derivatives that characterize the marginal effects of each independent variable at each data point in the covariated space (Hainmueller and Hazlett, 2014; Ferwerda et al., 2017).

The econometric data processing was carried out using STATA 17 (Stata/SE Prof+Plan (dl) 17).

### 3. Results and discussions

#### 3.1. ARDL model

The basic presumption of the ARDL model is that the variables are integrated at order I(0) or I(1) but never at order I(2) or above, and this prerequisite requires testing the stationarity of the data. Another very important condition is that the properties of the time series must be integrated in the same order, since the link between variables would be meaningless in the absence of co-integration.

The first part of the empirical approach is to test the stationarity of variables and their cointegration, based on the estimated ARDL model, to determine whether there is statistical evidence of a long-term cointegration relationship between variables.

The description of the variables and the descriptive statistics of the data are given in Table no. 1.

**Table no. 1. Description and summary statistics of the variables**

| Variable         | Mean      | Standard deviation | Minimum   | Maximum   |
|------------------|-----------|--------------------|-----------|-----------|
| Ecol_footprint   | 3.080     | 0.400              | 2.343     | 4.364     |
| GDP_pp           | 5189.416  | 3865.590           | 883.639   | 12378.500 |
| Glob             | 66.758    | 11.089             | 43.000    | 79.000    |
| Energy_fossil_pp | 18083.310 | 3643.352           | 13901.080 | 29863.670 |
| CO <sub>2</sub>  | 4.539     | 0.870              | 3.868     | 7.440     |

To verify that the data do not lead to potentially spurious regression, stationarity was tested both at the level and at the first difference to determine if the time series contains unit roots (Kripfganz and Schneider, 2018). The results of the variable stationary testing, based on the Phillips-Perron and Augmented Dickey-Fuller tests, show stationarity at the first difference.

The ARDL estimation model was developed, based on the optimal lags, based on the Akaike test of information on the ideal lags, respectively, ARDL (4, 3, 4, 3, 4), parametrized with the Error Correction technique (EC) (Kripfganz and Schneider, 2018). The results are presented in Table no. 2.

**Table no. 2. ARDL estimation model**

| Model = (lnEcol_footprint/lnGDP_pp, lnGlob, lnEnergy_fossil_pp, lnCO <sub>2</sub> )<br>ARDL (4, 3, 4, 3, 4) |              |                |                     |                     |                    |
|---|--------------|----------------|---------------------|---------------------|--------------------|
| Parameters  | Coefficients | Standard error | P-value probability | Min 95 Minimum 95 % | Max 95 Maximum 95% |
| <b>Adjustment</b>   |              |                |                     |                     |                    |
| lnEcol_footprint <sub>t-1</sub>   | 14.033       | 2.797          | 0.038**             | 1.998               | 26.069             |
| <b>Long-term</b>  |              |                |                     |                     |                    |
| lnGDP_pp  | 0.302        | 0.005          | 0.000***            | 0.277               | 0.328              |
| lnGlob  | -1.236       | 0.036          | 0.001***            | -1.394              | -1.077             |
| lnEnergy_fossil_pp  | 2.762        | 0.097          | 0.001***            | 2.344               | 3.180              |
| lnCO <sub>2</sub>   | -2.230       | 0.103          | 0.002***            | -2.673              | -1.789             |
| <b>Short-term</b>   |              |                |                     |                     |                    |
| Δ lnEcol_footprint <sub>t-1</sub>   | -15.960      | 3.004          | 0.034**             | -28.888             | -3.032             |
| Δ lnEcol_footprint <sub>t-2</sub>   | -13.385      | 2.530          | 0.034**             | -24.274             | -2.496             |
| Δ lnEcol_footprint <sub>t-3</sub>   | -5.296       | 1.089          | 0.040**             | -9.982              | -0.061             |
| Δ lnGDP_pp  | 2.281        | 0.489          | 0.043**             | 0.174               | 4.387              |
| Δ lnGDP_pp <sub>t-1</sub>   | 1.262        | 0.251          | 0.038**             | 0.178               | 2.345              |
| Δ lnGDP_pp <sub>t-2</sub>   | 1.731        | 0.377          | 0.044**             | 0.108               | 3.354              |
| Δ lnGlob  | -20.015      | 4.032          | 0.038**             | -37.366             | -2.664             |
| Δ lnGlob <sub>t-1</sub>   | -3.304       | 1.716          | 0.194               | -10.691             | 4.082              |
| Δ lnGlob <sub>t-2</sub>   | 6.579        | 1.779          | 0.066*              | -1.078              | 14.237             |
| Δ lnGlob <sub>t-3</sub>   | -5.892       | 1.869          | 0.088*              | -13.935             | 2.150              |
| Δ lnEnergy_fossil_pp  | 37.312       | 6.794          | 0.032**             | 8.076               | 66.548             |
| Δ lnEnergy_fossil_pp <sub>t-1</sub>   | 32.638       | 6.359          | 0.036**             | 5.277               | 59.999             |
| Δ lnEnergy_fossil_pp <sub>t-2</sub>   | 11.849       | 2.581          | 0.044**             | 0.743               | 22.955             |
| Δ lnCO <sub>2</sub>   | -27.707      | 5.133          | 0.033**             | -49.796             | -5.618             |
| Δ lnCO <sub>2</sub> <sub>t-1</sub>  | -24.364      | 5.128          | 0.042**             | -43.431             | -2.297             |
| Δ lnCO <sub>2</sub> <sub>t-2</sub>  | -3.737       | 1.211          | 0.091*              | -8.951              | 1.476              |
| Δ lnCO <sub>2</sub> <sub>t-3</sub>  | 1.539        | 0.316          | 0.040**             | 0.179               | 2.900              |
| <b>Note 25; R<sup>2</sup> = 0.916; MSE root (square root of the quadratic mean error) = 0.024</b>           |              |                |                     |                     |                    |
| <i>Notes: ***, ** or * denotes statistical significance at the level of 1%, 5% or 10%, respectively.</i>    |              |                |                     |                     |                    |

To test the cointegration according to the estimation of the ARDL model, testing of the limits of the cointegration results (Table no. 3) was carried out following the model of Pesaran, Shin and Smith (Pesaran et al., 2001; Nkoro and Uko, 2016). The short-term coefficient was

12.789, and the *t* statistic was 5.017 above the upper critical values of all I(1) variables at the significance levels of 1%, 5%, and 10%.

**Table no. 3. Pesaran, Shin and Smith Cointegration Test**

| Model = (lnEcol_footprint/lnGDP_pp, lnGlob, lnEnergy_fossil_pp, lnCO <sub>2</sub> )<br>ARDL (4, 3, 4, 3, 4)               |        |                        |        |                       |        |                       |        |               |
|---|--------|------------------------|--------|-----------------------|--------|-----------------------|--------|---------------|
|   | Coef.  | Significance level 10% |        | Significance level 5% |        | Significance level 1% |        | Result        |
|   |        | I(0)                   | I(1)   | I(0)                  | I(1)   | I(0)                  | I(1)   |               |
| <b>F</b>  | 12.789 | 2.450                  | 3.507  | 2.865                 | 3.994  | 3.748                 | 5.012  | Cointegration |
| <b>t</b>  | 5.017  | -2.569                 | -3.654 | -2.864                | -3.975 | -3.434                | -4.573 |               |
| Notes: I(0) and I(1) denote the critical values in the lower and upper bands at the significance level of 10%, 5%, or 1%. |        |                        |        |                       |        |                       |        |               |

Based on the ARDL model, regression post-estimation tests were performed to test serial correlation, heteroskedasticity and normality, as well as structural breaks. The purpose of conducting these robustness tests was to determine whether the ARDL model and its assumptions were validated and whether it was necessary to re-fit the model and use modified assumptions.

The general hypothesis is that variables in the ARDL models are not strictly exogenous (Kripfganz and Schneider, 2018). Indeed, in conditional models such as ARDL, the variables of the model are weak exogeneity (Nyomo, 2011). However, despite economic evidence that suggests that some of the variables in the model could be correlated (e.g., CO<sub>2</sub> emissions and energy from fossil fuels, GDP per capita, and the globalisation index), we obtained statistical significance for the Durbin test for self-correlation and accepted the null hypothesis of no serial correlation. Even under the conditions in which serial correlation would remain present in the model, the ARDL technique comes with a courageous solution to use the ARDL instrumental variable and overcome the problem of serial correlation (Adekoya and Razak, 2018).

To test the heteroskedasticity in the residuals, the test proposed by Cameron and Tivedi (Sarkodie and Owusu, 2020) was conducted, and based on the results, the null hypothesis of homoskedasticity cannot be rejected at a significance level of 5%, which indicates that the residuals are homoskedastic.

To test normality and explain the independence of residuals, the Skewness/Kurtosis test (Sarkodie and Owusu, 2020) was used, and the null hypothesis of the normal distribution was confirmed at the 5% significance level.

For the *H*<sub>1</sub> assumption, the results of the ARDL model indicate a positive correlation between economic growth (GDP per capita) and the ecological footprint, with robust and reliable results both in the short-term and long-term ARDL models. The results are consistent with relevant literature results (Shahbaz et al., 2017; Yang et al., 2021), so *H*<sub>1</sub> can be accepted. The coefficients of GDP per capita are positive (0.302 in the long term, and for the current, first, and second lags of the variable GDP per capita, the coefficients are 2.281, 1.262 and 1.731, respectively). Thus, these results provide evidence of an EKC Environmental Kuznets Curve in the form of an inverted U of EKC type, in line with those found in the literature

(Alkhars et al., 2022) and specific to the period of preindustrialisation and transition to an industrialised economy (Figure no. 1 and Figure no. 2).

The relationship between the GDP per capita and the ecological footprint is in the first ascending part of the inverted U form, and considering the fact that Romania is an emerging economy, the results are justified given that economic growth after the 1990s was based on partially sustainable or environmentally friendly technologies that have exacerbated environmental degradation. As higher levels of GDP per capita are recorded, the relationship between economic growth and the ecological footprint is expected to follow the downward curve of the inverted U-shaped relationship (after reaching the peak of an industrialised economy); according to research in the literature, as the economy grows, a decrease in the ecological footprint is expected amid sustainable green technologies and sustainability concerns (Szigeti et al., 2017).

Based on the negative coefficients in the long-term (-1.236) and short-term (except for the third globalisation index gap) ARDL models, the results suggest evidence of a non-EKC-type U-shaped relationship between globalisation and the ecological footprint. The results are in line with previous research (You and Lv, 2018), which validates the  $H_2$  hypothesis. An increase in the KOF Globalisation Index in Romania during the period of 1990 to 2018 contributed to the decrease in the ecological footprint. The *de jure* and *de facto* mechanisms of globalisation, calculated in a globalisation index that captures complex economic, social, and political problems, contributed to the mitigation of the environmental aspects in Romania during 1990 to 2018, even if the development phase of the economy was one of transition from a preindustrialized to an industrialised economy, inverse to the expectations established in the conceptual model of the work developed in Figure no. 1 and Figure no. 2.

With regard to fossil fuel energy, a positive relationship with the ecological footprint has been identified (coefficient of 2.76 in the long-term ARDL model and a positive series of short-term coefficients), in line with previous results (Akalin et al., 2021; Charfeddine, 2017), which leads to the acceptance of the  $H_3$  hypothesis. Fossil fuel energy has contributed to environmental degradation and led to an increase in the ecological footprint in Romania, even if progress was made in terms of national and European policies to reduce dependence on fossil fuels during the period studied. Thus, an EKC-type evolution between fossil fuel energy and the ecological footprint is outlined, in line with the conceptual model developed in Figure no. 1 and Figure no. 2.

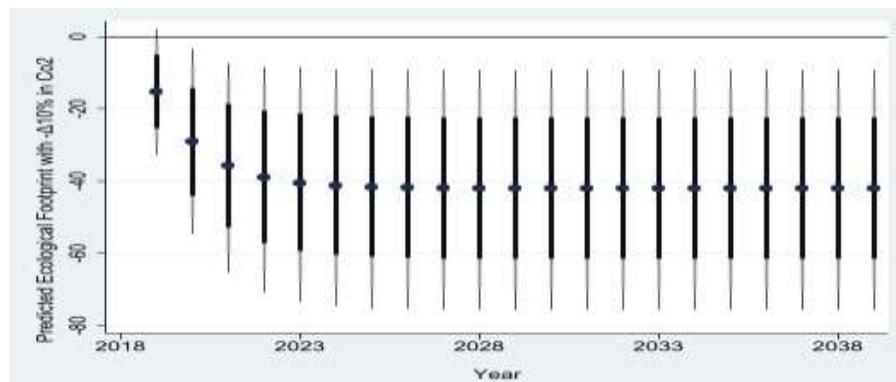
The ARDL model demonstrated the existence of a mixed relationship between CO<sub>2</sub> emissions and the ecological footprint, i.e., a negative coefficient of 2.230 in the long-term ARDL model; for the short-term model, a gap of order 3 (lag 3) for CO<sub>2</sub> emissions led to a positive coefficient for the CO<sub>2</sub> emissions variable under the ARDL model, while the first two lags (1 and 2) had negative CO<sub>2</sub> emission coefficients. The negative influence of CO<sub>2</sub> emissions on the ecological footprint shows an early U-shaped downward relationship found in the conceptual model of the study (Figure no. 1 and Figure no. 2) as specific to the final stage of industrialisation of the economy and the nascent stage of postindustrialisation.

Considering, however, that the analysed period characterises a Romanian economy in preindustrialisation and initial industrialisation phases, the negative relationship between CO<sub>2</sub> emissions and the ecological footprint is explained by the fact that CO<sub>2</sub> emissions in a period of time  $t$  do not influence the ecological footprint instantly. Rather, CO<sub>2</sub> emissions require time to be captured by wooded land areas, i.e., oceans, as the retention of CO<sub>2</sub> in soil

and waters is influenced by the type of vegetation, climatic conditions, soil properties, etc. (Mancini et al., 2016). Thus, the positive coefficient between CO<sub>2</sub> emissions in the  $t-3$  period and the ecological footprint shows the influence that carbon degradation has on the ecological footprint, and the results are in line with previous studies (McBain et al., 2018; Abbas et al., 2021; Rustemoglu, 2022). This influence of CO<sub>2</sub> emissions on the ecological footprint is based on Romania's situation, which at the beginning of the analysed time interval closed many polluting industries and thus decreased the level of CO<sub>2</sub> emissions. In addition, the European ecological policies with which Romania aligns itself contribute significantly to the reduction of CO<sub>2</sub> emissions. Thus, the  $H_4$  hypothesis of the influence of CO<sub>2</sub> emissions on the ecological footprint is validated.

### 3.2. Dynamic ARDL model

The purpose of developing a dynamic ARDL model was to capture the variables future evolution of the studied variables given the hypothesis of a 10% decrease in CO<sub>2</sub> emissions from 2018 to 2038. The choice to apply a shock to this variable was based on the results of the ARDL model, in which CO<sub>2</sub> emissions demonstrated an unexpected negative correlation with the dependent variable, i.e., the ecological footprint. In accordance with the responsibilities assumed by the European Union's Green Deal, Romania aims to reduce its CO<sub>2</sub> emissions. As novelty in a vanguardist approach, we consider the effect of a decrease in marginal CO<sub>2</sub> yields on the ecological footprint; counterfactual shocks were assessed by decreasing CO<sub>2</sub> by 10% over 20 years. The empirical results are presented in Figure no. 4 and Table no. 4.



**Figure no. 4. Counterfactual shock under the assumption of -10% CO<sub>2</sub> emissions over 20 years in a dynamic ARDL model**

*Notes: The black dot represents the predicted environmental footprint of -10% shock in CO<sub>2</sub> emissions, and the segments (from inside to outside) represent the confidence intervals of 75%, 90% and 95%.*

Table no. 4. Estimates of the dynamically simulated ARDL model  
(-10% CO<sub>2</sub> emissions)

| Parameters<br>ΔlnEcol_footprint   | Estimate | Standard error | P-value probability | Min 95 Minimum 95% | Max 95 Maximum 95% |
|-----------------------------------|----------|----------------|---------------------|--------------------|--------------------|
| lnEcol_footprint <sub>t-1</sub>   | -0.511   | 0.251          | 0.056*              | -1.037             | 0.015              |
| ΔlnCO <sub>2</sub>                | 1.533    | 0.874          | 0.096*              | -0.303             | 3.369              |
| lnCO <sub>2</sub> <sub>t-1</sub>  | 2.160    | 1.184          | 0.085*              | -0.327             | 4.647              |
| Δ lnGDP_pp                        | 0.209    | 0.115          | 0.086*              | -0.033             | 0.450              |
| Δ lnEnergy_fossil_pp              | -0.878   | 0.956          | 0.371               | -2.887             | 1.131              |
| ΔlnGlob                           | -0.766   | 0.965          | 0.437               | -2.793             | 1.260              |
| lnGDP_pp <sub>t-1</sub>           | 0.069    | 0.075          | 0.374               | -0.089             | 0.226              |
| lnEnergy_fossil_pp <sub>t-1</sub> | -1.951   | 1.232          | 0.131               | -4.539             | 0.636              |
| lnGlob <sub>t-1</sub>             | -0.480   | 0.420          | 0.268               | -1.361             | 0.402              |
| Prob > F                          | 0.005*** | R <sup>2</sup> | 0.510               | MSE Root           | 0.066              |

Notes: \*\*\*, \*\* or \* denotes statistical significance at the level of 1%, 5% or 10%, respectively.  
MSE root (the square root of the quadratic mean error)

In the first period, the shock of -10% applied to the future evolution of CO<sub>2</sub> emissions will affect the ecological footprint, which is constant thereafter (Figure no. 4). Therefore, the decarbonization of the economy will not have a lasting impact on the ecological footprint. Based on the dynamic ARDL model (Zhang et al., 2021; Sarkodie and Owusu, 2020), the H<sub>5</sub> hypothesis is validated.

### 3.3. KRLS Model

To examine the marginal derivatives pointwise, a KRLS model was applied (Table no. 5). Changes in the ecological footprint have been studied using point marginal effect and 25th, 50th, and 75th percentile estimation and with national and European policies to reduce dependence on fossil fuels and CO<sub>2</sub> emissions taken into account.

Table no. 5. Pointwise derivatives using KRLS

| lnEcol_footprint   | Marginal effect mean | Standard error | t     | P > t          | P-25   | P-50  | P-75  |
|--------------------|----------------------|----------------|-------|----------------|--------|-------|-------|
| lnGDP_pp           | 0.132                | 0.030          | 4.413 | 0.000          | 0.048  | 0.072 | 0.270 |
| lnGlob             | 0.306                | 0.142          | 2.151 | 0.041          | 0.165  | 0.260 | 0.498 |
| lnEnergy_fossil_pp | 0.406                | 0.142          | 2.865 | 0.008          | 0.247  | 0.481 | 0.536 |
| lnCO <sub>2</sub>  | 0.182                | 0.172          | 1.056 | 0.301          | -0.150 | 0.046 | 0.659 |
| <b>Diagnostics</b> |                      |                |       |                |        |       |       |
| Lambda             | 0.053                | Sigma          | 4     | R <sup>2</sup> | 0.867  |       |       |
| Tolerance          | 0.029                | Eff. Df        | 11.75 | Looloss        | 1.399  | Obs   | 29    |

Notes: P-25, P-50 and P-75 are the 25th, 50th, and 75th percentiles, respectively.

A model with a 1% significance level was obtained for the following variables: GDP per capita, the KOF Globalisation Index, and energy from fossil fuels. The model explains the 86.74% variation in the ecological footprint, and the average marginal effects of the variable were 0.132% (GDP per capita), 0.306% (KOF Globalisation Index) and 0.406% (fossil fuel

energy). The KRLS results underline the importance of the independent variables chosen and, for a better understanding of the fourth variable that was not significant in the model (CO<sub>2</sub> emissions), from the graphical analysis of the marginal pointwise derivatives of CO<sub>2</sub> emissions on the ecological footprint, it resulted that higher CO<sub>2</sub> emission levels are associated with a high marginal effect on the ecological footprint and, as CO<sub>2</sub> emissions begin to decrease, the marginal influence remains positive but at lower levels and leads to an increase in the ecological footprint. With the help of the KRLS model (Sarkodie and Owusu, 2020), the  $H_6$  hypothesis was validated.

## Conclusions

From a theoretical perspective, the present study makes an original contribution to the expansion of research based on Triple Bottom Line (TBL) theory, achieving a balance between the pursuit of economic value, social objectives, and environmental protection without ignoring profitability as an economic benefit. The analysis in this paper of the three elements of TBL theory, namely economy (GDP per capita), social factors (KOF Globalisation Index) and the environment (fossil fuel energy and CO<sub>2</sub> emissions), as well as the characterisation of sustainable development through the ecological footprint, represents an innovative approach that addresses identified gaps in the literature. So far, no study has captured these elements for the situation in Romania. The results obtained highlight the role of economic growth in the decarbonization of the Romanian economy and identify the peculiarities of the last approximately 30 years (1990–2018) from the perspective of the effects of globalisation and environmental degradation on sustainable development and Romania's ecological footprint. Based on the ARDL, dynamic ARDL and KRLS models, and the study tests the behaviour of the variables of TBL theory, enrolls the acquisitions in the lines of the previous literature, and addresses a need to analyse the determinants of the sustainable development of Romania and their economic effects. This approach scientifically supports future instruments for the development and implementation of policies that will meet the goals of the European Union's Green Deal.

The general theoretical perspective of the Kuznets Hypothesis is specifically approached by the Environmental Kuznets Curve (EKC) hypothesis, which is confirmed by the research conducted on Romania that considered the period 1990 to 2018. In the early stages of economic growth, pollution emissions increase, and the quality of the environment decreases, but beyond a certain level of per capita income, the trend is expected to reverse so that, at high levels of income, economic growth will lead to an improvement in the environment. This implies that the impact on the ecological footprint is represented by an EKC-type function, an inverted U-shaped GDP per capita. Meanwhile, the ARDL model shows the existence of a possible incipient U-shaped relationship of a non-EKC type between globalisation and the ecological footprint as well as the positive link between fossil fuel energy and the ecological footprint (EKC link, U reversed). Moreover, a contribution of the research is the identification of the specificity of the Romanian economy, namely the existence of a mixed relationship between CO<sub>2</sub> emissions and the ecological footprint (negative in the short term and positive in the long term). Considering the particularities of Romania's industrial evolution for the analysed period, especially the period of decrease in the number of large industrial facilities that generate CO<sub>2</sub>, the negative relationship obtained between CO<sub>2</sub> emissions and the ecological footprint is explained by the fact that CO<sub>2</sub> emissions over a period of time  $t$  do not influence the ecological footprint instantly, but the

impact on land or water, i.e., the capture of CO<sub>2</sub> emissions, occurs over time. The results obtained are consistent with previous research identified in the specialised literature.

From a managerial perspective, with respect to public policies, the paper highlights the need for a systemic approach to the sustainable development of Romania based not only on the punctual approach of reducing CO<sub>2</sub> emissions or decreasing the dependence on energy from fossil fuels but also on the adoption of complex stimuli for economic development. Using the dynamic ARDL approach, this study highlighted that a reduction in CO<sub>2</sub> emissions is likely to contribute for a short period of time to a reduction in the ecological footprint, although this trend will not be maintained. These results were achieved by simulating a decarbonization process based on the European Union's Green Deal, namely, the reduction of CO<sub>2</sub> by 10%, over a period of 20 years (2018–2038). To consolidate the econometric results, the study used an artificial learning algorithm to examine point derivatives obtained from the KRLS method, which demonstrated that higher CO<sub>2</sub> emission levels are associated with a high marginal effect on the ecological footprint. Furthermore, as CO<sub>2</sub> emissions begin to decrease, the marginal influence remains positive but at lower levels, which leads to a further increase in the ecological footprint.

We have identified an important limit of the research, taking into consideration a single country, namely Romania, for the evaluation of sustainable development through the ecological footprint. A future direction of research is to analyse different clusters of countries that present industrial developments of a similar nature (such as, for example, post-socialist economies), as well as developed countries, in the context of the application of European Union Green Deal measures. An index that captures economic complexity (e.g., the Economic Complexity Index) could help increase the relevance of future research.

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