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The Impact of Digital Economies on Carbon Emissions and Economic Growth in Türkiye: Evidence from the FA-ARDL

Türkiye'de Dijital Ekonomilerin Karbon Emisyonu ve Ekonomik Büyüme Üzerine Etkisi: FA-ARDL Yönteminden Kanıtlar

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ÖZ

Bu çalışma dijital ekonomilerin ekonomik büyüme ve karbon emisyonu üzerine etkilerini araştırmaktadır. Dijital ekonomilerin karbon emisyon salınımını azaltmaya ve sürdürülebilir büyümeyi gerçekleştirmeye yönelik politikalara etkisi son dönemlerde literatürde tartışılan bir konudur. Ancak bu tartışmaların sınırlı ülkeler üzerinde gerçekleştirildiği görülmektedir. Bu nedenle çalışmada dijital ekonomilerin ekonomik büyüme ve karbon emisyon salınımları üzerine etkilerinin Türkiye ekonomisi özelinde araştırılması literatüre katkı sağlamaktadır. Bu motivasyon ile çalışmada dijital ekonomilerin karbon emisyon salınımları ve ekonomik büyüme üzerine etkilerini araştırmak için iki farklı model tercih edilmiştir. Modellerde karbon emisyon salınımı ve ekonomik büyüme verileri bağımlı değişken olarak yer almaktadır. Bağımlı değişkenleri açıklamak üzere dijital ekonomiler verisi ile birlikte enerji yapısı, hükümet harcamaları, kentleşme ve dışa açıklık verileri kullanılmıştır. Verilerin birim kök sürecini ve yapısal kırılma olup olmadığını tespit etmek amacı ile yapısal kırılmalı ADF birim kök testi kullanılmıştır. Veriler arasındaki uzun dönemli ilişkiyi araştırmak için AARDL yöntemi tercih edilmiştir. Ancak verilerde yapısal kırılmaların varlığından dolayı AARDL yöntemine Fourier terimleri eklenerek FA-ARDL yönteminden faydalanılmıştır. Çalışmadan elde edilen bulgulara bakıldığında dijital ekonomilerin ekonomik büyümeyi artırıcı etkilerinin yanı sıra karbon emisyon salınımını azaltıcı etkileri olduğu belirlenmiştir.
Anahtar Kelimeler: Dijital Ekonomi, Karbon Emisyonu, Ekonomik Büyüme, Zaman Serisi Analizi

ABSTRACT

This study investigates the effects of digital economies on economic growth and carbon emissions. The impact of digital economies on policies to reduce carbon emissions and realise sustainable growth has recently been discussed in the literature. However, it is seen that these discussions have been carried out on limited countries. For this reason, this study contributes to the literature by investigating the effects of digital economies on economic growth and carbon emissions in the Turkish economy. With this motivation, two different models were preferred to investigate the effects of digital economies on carbon emissions and economic growth. In the models, carbon emissions and economic growth data are included as dependent variables. Energy structure, government expenditures, urbanisation, and openness to internationalisation data are used together with the data on digital economies to explain the dependent variables. In order to determine the unit root process of the data and whether there is a structural break, ADF unit root test with a structural break is used. AARDL method was preferred to investigate the long-run relationship between the data. However, due to the presence of structural breaks in the data, the FA-ARDL method was utilised by adding Fourier terms to the AARDL method. When the findings from the study are analyzed, it is determined that digital economies have the effect of increasing economic growth as well as reducing carbon emissions.

Keywords: Digital Economy, Carbon Emission, Economic Growth, Time Series Analysis

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1. Introduction

The concept of the digital economy first attracted attention in Don (1996) and has been the subject of research in many studies in the following periods (Zhang et al., 2022: 1-2). These studies reveal diverse interpretations and evaluations of the digital economy concept. For instance, Mesenbourg (2001) assessed digital economies in the context of the Internet, describing them as the infrastructure and processes of e-commerce, which includes online sales of goods and services (Mesenbourg, 2001: 2). Carlsson (2004) defined the digital economy as a set of economic activities created by the clustering of complementary techniques (Carlsson, 2004: 247-248). Eisenman et al. (2006) defined digitalisation as an integration between trade and electronic information technology (Eisenman et al., 2006: 2-3). Knickrehm et al. (2016) defined the digital economy as a share of the total economic output obtained from the activity inputs within the scope of the digital economy. As part of their study, Knickrehm et al. (2016) also said that digital skills, digital equipment (such as hardware, software, and communication equipment), and intermediate digital goods and services used in production are all things that support the digital economy. In light of the definitions above, it is possible to define digital economies as a series of economic activities that have become widespread in the production, consumption, and service sectors with the development of technology, thus increasing their place in economic and social life day by day.

Digital economies are one of the most recent and intensively developing areas of economic science. This is because digital transformations in economies affect all businesses, the labour market, and people's lifestyles (Novikova and Strogonova, 2020, p. 76; Zhang et al., 2022). Therefore, it is predicted that digital economies will significantly affect productivity and employment and will have a significant multiplier effect on economies in the coming years (Arsić, 2020: 432; Novikova and Strogonova, 2020: 76). Therefore, promoting digitalisation is expected to contribute significantly to the realisation of sustainable development goals along with economic growth (Mura and Donath, 2023: 1-2). In this context, digitalisation is an important topic of discussion in both developed and developing countries. Figure 1 presents internet usage and the population using it in Türkiye, one of the developing countries.

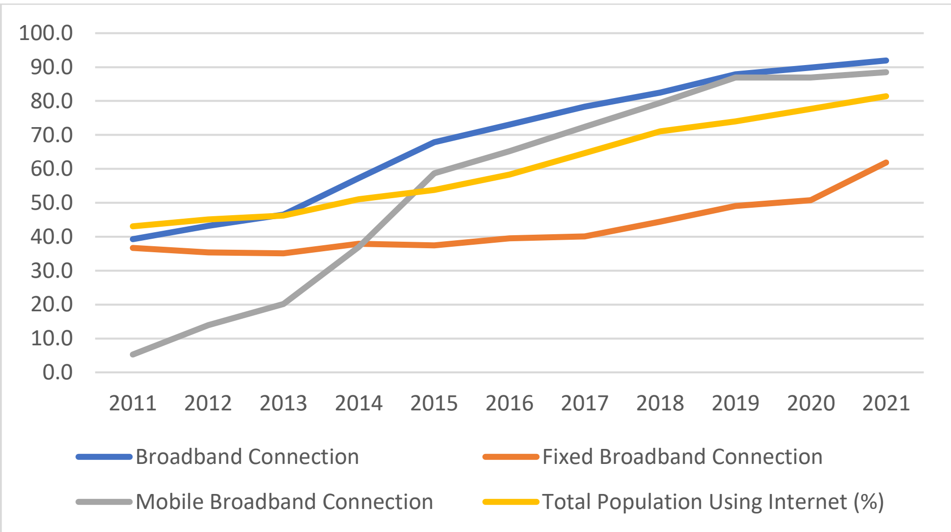


Figure 1. Internet Usage Option and Population Using Internet (%)
Source: TURKSTAT, 2024. World Bank Database, 2024.

In addition to the effects of digital economies on national economies, their effects on energy efficiency are also discussed. According to the 'Digital Carbon Neutrality' bulletin published by the Chinese Academy of Information and Communication, digital technologies will reduce total carbon emissions by 12-22% for societies and 10-40% for industries (Zheng, 2023: 2). Using digitalisation to cut down on carbon emissions and boost energy efficiency can be done by regulating the energy supply by the government, making production faster, and shifting production factors to more energy-efficient areas. This means that digitalisation not only lowers carbon emissions, but it also makes resource allocation more efficient and boosts economic growth (Yang et al. 2022: 2-3). On the other hand, the spread of digital economies creates advantages in renewable energy costs. Therefore, increased renewable energy production together with cost advantages provides mitigating effects on carbon emissions (Moyer and Hughes, 2012: 919:920).

Digital economies have carbon emission reducing effects as well as carbon emission increasing effects (Moyer and Hughes, 2012: 921; Yang et al., 2022: 2-3). Energy consumption increases due to the positive effects of digitalisation on economic growth. More digital equipment means more energy use, which means more carbon emissions (Truby, 2018; Nguyen et al., 2020; Coyne and Denny, 2021; Su et al., 2021). Because of this, more carbon emissions will happen (Moyer and Hughes, 2012: 919–920; Yang et al., 2022). In this context, the question of the source of increasing energy demand is important for environmental pollution and environmental health (Li et al., 2020; Nguyen et al., 2020; Coyne and Denny, 2021; Su et al., 2021). However, in the first stage of digitalisation, it increases carbon emissions due to the construction of digital infrastructure, but in the following periods, it decreases carbon emissions with the new competitive advantages brought by digitalisation (Wang and Zhong, 2023: 51750). Therefore, digitalisation's effects on carbon emissions are an important topic of discussion in the literature, and studies on the subject contribute to the current debate.

This study examines the effects of digitalisation on carbon emissions and economic growth. This provides an opportunity to critically evaluate the role of digitalisation in achieving sustainable development goals. Therefore, it is intended to present a perspective on the potential of digitalisation, discuss environmental policies within the scope of sustainable development, and create a sustainable economic growth model that takes environmental health into account. In addition, when the studies investigating the relationship between digitalisation and carbon emissions in the literature are examined, it is seen that the studies are mostly on China. This study aims to investigate the effects of digitalisation on economic growth and carbon emissions in Türkiye, the 13th country with the highest carbon emissions in the world in 2022. In this regard researching the study with current methods specific to Türkiye contributes to the originality and motivation of the study. This situation contributes to the literature. In this context, the continuation of the study is planned as follows. In the second section, a summary of the literature on the subject is presented. The third section presents the methodology and the findings obtained. The fourth section plans to complete the study by providing a conclusion and evaluation.

2. Literature Review

Since digital economies are a rapidly growing area in today's world, their effects on economic growth and carbon emissions are a matter of curiosity. This section scrutinises the literature for studies that explore the impacts of digitalisation on economic growth and carbon emissions. Two subheadings present the literature in this context. The first subheading includes the relationship between digitalisation and economic growth, while the second subheading includes studies investigating digitalisation and carbon emissions.

2.1. Relationship between Digital Economies and Economic Growth

Solow and Swan (1956) highlighted the importance of technological development and population growth in the process of economic growth. Thus, the effects of technology on economic growth have become a prominent research topic in the literature (Aydın, 2022: 22; Magoustas et al., 2024: 2). In recent years, the use of digital economies has spread rapidly, and many studies have investigated the impact of digital economies on economic growth. Among the research done in this area, Asoy (2024) used the Driscoll-Kraay method to look into the link between 41 countries' economic growth and indicators of their digital economies from 2015 to 2018. The study determined that digital economy indicators have a positive impact on economic growth. Sheikh et al. (2021) investigated the effects of digitalisation on economic growth and corruption in Asian countries between 1990 and 2019. They concluded that digital transformation has a positive impact on economic growth and is an effective factor in combating corruption. Cheng and Huang (2022) determined that digitisation positively affects economic growth in five provinces in China. Hosan et al. (2022) investigated the effect of digitalisation on economic growth using panel data analysis methods for 30 developing countries between 1995 and 2018. They determined that digitalisation promotes economic growth across all quantiles. In 2023, Patra and Sethi used the Driscoll-Kraay estimator to look at how digital payments affected economic growth in 25 CPMI member countries from 2012 to 2020. They looked at institutional quality, consumer spending, and bank credit. According to the results, they found that the increase in digital payments positively affects economic growth.

Pradhan et al. (2019) stated that the development of the digital economy in Europe increases the productivity and economic performance of firms and thus will promote economic growth. Cheng et al. (2021) investigated the issue in 72 countries between 2000 and 2015 and concluded that the diffusion of information and communication technologies will positively affect economic growth in high-income countries. Wang et al. (2022) investigated the effects of globalisation and digital economies on sustainable development. Their findings demonstrate that globalisation and the digital economy have a significant impact on sustainable growth. A study by Moskalyk and Balashova (2024) used panel EKK methods to look into the link between the digital economy and society index and economic growth in EU member states from 2017 to 2022. They concluded that a 1% increase in the digitalisation index has a 0.2% growth effect on economic growth. Similar results were found in Kurniawati (2022), Ibrahimi and Fetai (2022), Wang et al. (2022), Khan and Xiemei (2022), Wu and Yu (2022), Varlamova and Kadochnikova (2023), Hegde and Guruprasad (2024), Latief and Javeed (2024), Magoutas et al. (2024), Török (2024), and Zhang et al. (2024). On the other hand, some studies in the literature indicate that digital economies will cause a negative impact on economic growth or will not cause any impact. For example, Ishida (2015) finds that developments in information and communication technology in Japan will not contribute to economic growth. Yousefi (2011) investigated the effects of information and communication technologies on economic growth for 62 countries between 2000 and 2006. Accordingly, he concluded that while developments in information and communication technologies are an important factor in economic growth in upper-middle-income group countries, they do not contribute to economic growth in lower-middle-income group countries. Varlamova and Kadochnikova (2023) investigated the relationship between the digital economy and economic growth for 85 regions in Russia between 2016 and 2021 with SAR, SEM, and SAC methods. They found that the digital data economy has a negative effect on economic growth in the short run and a positive effect in the long run.

2.2. Relationship between Digital Economies and Carbon Emissions

In the coming years, especially in developing countries, energy use is expected to increase as industrial production increases. Therefore, the importance of digitalisation in increasing energy efficiency is expected to increase (Hosan et al., 2022: 4). Examining the literature in this context reveals the potential of digital economies to mitigate carbon emissions. In addition, most of the studies have been conducted in China, which has the highest carbon emissions in the world and, on the other hand, is a country where digitalisation is developing rapidly (Mohsin et al., 2021). For example, Wang and Li (2023) investigated the impact of digital economies on carbon emissions for 30 provinces of China between 2011 and 2021 using panel data methods. The study reveals that the digital economy significantly contributes to the reduction of carbon emissions. They stated that carbon emissions decreased, especially in regions where digital economies are more developed. Wang et al. (2022) investigated the effect of the digital economy on CO2 emissions for 30 provinces of China between 2006 and 2017 with the Panel GMM method. They found that digital economies reduce CO2 emissions. They also stated that digital economies encourage green technology innovation by reducing the rate of coal consumption. Zhang et al. (2023) investigated the issue in China between 2014 and 2020 and found that digital economies can significantly prevent environmental pollution. Wang and Zhong (2023) examined the impact of digital economies and smart city projects on carbon emissions for 253 provinces of China between 2000 and 2019. They found that digital economies and smart city projects play an important role in reducing carbon emissions. Li and Tang (2024), in their study on China, found that digital economies are effective in reducing carbon emissions, and the successful implementation of this strategy increases environmental sustainability. Hao et al. (2022) found that the development of digital economies reduces carbon emissions. Yi et al. (2022), Ma et al. (2022), Chang et al. (2022), Zhou et al. (2022), Cui et al. (2023), and Yang et al. (2023) found similar results.

The spatial Durbin and mediation effect model was used by Wang et al. (2023) to look at how digital economies affected carbon emissions in China from 2011 to 2019. The findings indicate that digital economies are actively contributing to the reduction of carbon emissions, particularly in Eastern China. Bai et al. (2023) used a spatial panel data analysis method to look at 271 provinces in China from 2011 to 2019 and found that there is a relationship between digital economies and carbon emission intensity that looks like an upside-down "U." Luo et al. (2023) used a panel data analysis method to look at 251 provinces of China from 2011 to 2019 and found that digital economies make a big difference in how efficiently carbon emissions are used. They also found that this effect changes depending on the region and the size of the city. Yu and Liu (2024) found that digitisation reduces carbon emissions by using fixed effects and mediation models for 136 countries between 2000 and 2020. Li and Nadeem (2024) found that the only factor that positively affects environmental sustainability is the transition to green energy for 18 countries in South America. Luo et al. (2022) reported that technological innovation positively affects green productivity through the accumulation of human capital and the improvement of industrial structures.

In addition to studies indicating that digital economies have a positive impact on economic growth, there are also studies indicating that they have no impact on the environment or have a negative impact on the environment. Wang et al. (2024), for example, found that the effect of digital economies on carbon emissions for 97 countries from 2003 to 2019 looks like U when looking at natural resource rent. They also found that digital economies as a whole cause carbon emissions to rise. Zhao et al. (2024) concluded that the digital economy negatively affects the ecological footprint in their study for OECD countries between 2002 and 2020. Chen et al. (2024) used the dynamic ARDL model and the KRLS algorithm to analyse the impacts of digital economies on carbon emissions in India. They examined the short- and long-run effects of combining digital technology and economic growth with women entrepreneurship on environmental quality. Accordingly, they found that women entrepreneurship is effective in reducing carbon dioxide emissions. However, economic growth and industrial technology developments increased carbon emissions. Zhang et al. (2022) conducted a study on 30 provinces of China based on the panel data method between 2012 and 2019 and concluded that developments in the digital economy did not increase energy efficiency and thus increased carbon emissions. Tao et al. (2023) found that digital economies negatively affect carbon emissions, and the relationship between the two variables is non-linear for 67 countries between 2010 and 2019. Li et al. (2024) investigated the effects of digital economies on green innovation for 278 provinces of China between 2011 and 2019 using panel methods. According to the findings, the digital economy has a negative impact on the environment and hinders the growth of green innovation. Huang and Wu (2024) determined that digital economies reduce carbon emissions in their study on China's provinces between 2011 and 2021. They found that the positive effects of digitalisation on carbon emissions are effective in eastern and central China but insignificant in western China.

Analysing the literature summary, it appears that most studies endorse the digital economy's potential to decrease carbon emissions. However, the fact that there is no link between the digital economy and pollution or that it is assumed that digital economies cause more pollution shows that there isn't agreement in the research on this topic. Therefore, the study is expected to contribute to the ongoing debate in the literature. Furthermore, the majority of the literature concentrates on the relationship between digitalisation and other factors. This study contributes to the literature as it is specific to Türkiye and tests the hypotheses by taking into account the possible structural breaks in the model.

3. Econometric Method

This study investigates the effects of digitisation on carbon emissions and economic growth using annual time series data covering the period between 1996 and 2021. The digital economies data used in the study is obtained by taking into account the share of internet users in the total population (Dong, et al., 2022). The study uses dollar-based economic growth data sourced from the World Bank database and carbon emission data sourced from the https://ourworldindata.org/ database. The study used energy structure (es), government expenditure (gov), openness level (trd), and urbanisation (urb) data in its models to explain both carbon emissions and economic growth (Dong et al., 2022). With the idea that the use of renewable energy can correct environmental negativities (Yu et al., 2022: 2990), energy structure data was obtained by calculating the ratio of renewable energy consumption to total energy consumption. Among the other control data used in the study, government expenditures data is calculated as the total amount of government expenditures in GDP and included in the model. The openness data is obtained by calculating the ratio of the sum of exported and imported goods and services to GDP. Urbanisation data, which is another control variable, represents the urban population. In this context, all of the data included in the models used in the study are presented in Table 1.

Table 1. Definitions of Variables

Variables	Symbols	Definition of Variables	Sources
Carbon Emissions	lnco2	Logarithmic transformation of annual carbon emission output	https://ourworldindata.org/
GDP	lngdp	Logarithmically transformed GDP (in US Dollars)	World Bank
Digitalisation	lndig	Logarithmic transformation of the number of individuals using the internet within the total population	World Bank
Energy Structure	es	Ratio of renewable energy usage to overall energy consumption	World Bank
Government Expenditures	lngov	Total logarithmically converted government spending as a percentage of GDP (in USD)	World Bank
Urbanization	lnurb	Logarithmically modified urban populace	World Bank
External Openness	trd	Proportion of total exports and imports of goods and services to GDP (measured in USD)	World Bank

The model utilised in the study is presented in equations (1) and (2), based on the work of Dong et al. (2022).

$$lnco2_t = \beta_0 + \beta_1 lndig_t + \beta_2 es_t + \beta_3 lngov_t + \beta_4 lnurb_t + \beta_5 trd_t + \mu_t \quad (1)$$

$$lngdp_t = \varphi_0 + \varphi_1 lndig_t + \varphi_2 es_t + \varphi_3 lngov_t + \varphi_4 lnurb_t + \varphi_5 trd_t + \varepsilon_t \quad (2)$$

The first step in examining the relationship between the study's variables is to determine their stationarity levels. To determine the stationarity levels of the variables, we used the single-break Augmented Dickey Fuller (ADF) test, which considers the structural breaks in the variables.

The augmented autoregressive distributed lag (FA-ARDL) method combined with Fourier terms is used to look into how the variables are related to each other in the rest of the study. Pesaran et al. (2001) developed the ARDL method, which forms the basis of the A-ARDL method. In the ARDL method, the dependent variable follows an I(1) process, while the independent variables follow I(0) and I(1) processes. However, Sam et al. (2019) developed the A-ARDL model, which permits the dependent variable to be stationary at I(0) and I(1) levels alongside the independent variables. We present the A-ARDL model below (Sam et al., 2019):

$$\begin{aligned}\Delta lnco2_t = {} & \theta_0 + \sum_{i=1}^{n} \theta_{1i}\, \Delta lnco2_{t-1} \\ & + \sum_{i=1}^{m} \theta_{2i}\, \Delta lndig_{t-1} + \sum_{i=1}^{e} \theta_{3i}\, \Delta es_{t-1} + \sum_{i=1}^{r} \theta_{4i}\, \Delta lngov_{t-1} + \sum_{i=1}^{p} \theta_{5i}\, \Delta lnurb_{t-1} \\ & + \sum_{i=1}^{m} \theta_{6i}\, \Delta trd_{t-1} + \beta_1 lnco2_{t-1} + \beta_2 lndig_{t-1} + \beta_3 es_{t-1} + \beta_4 lngov_{t-1} + \beta_5 lnurb_{t-1} \\ & + \beta_6 trd_{t-1} + \mu_t \ldots \quad (3)\end{aligned}$$

$$\begin{aligned}\Delta lngdp_t = {} & \gamma_0 + \sum_{i=1}^{c} \gamma_{1i}\, \Delta lngdp_{t-1} \\ & + \sum_{i=1}^{v} \gamma_{2i}\, \Delta lndig_{t-1} + \sum_{i=1}^{b} \gamma_{3i}\, \Delta es_{t-1} + \sum_{i=1}^{k} \gamma_{4i}\, \Delta lngov_{t-1} + \sum_{i=1}^{l} \gamma_{5i}\, \Delta lnurb_{t-1} \\ & + \sum_{i=1}^{m} \gamma_{6i}\, \Delta trd_{t-1} + \delta_1 lngdp_{t-1} + \delta_2 lndig_{t-1} + \delta_3 es_{t-1} + \delta_4 lngov_{t-1} + \delta_5 lnurb_{t-1} \\ & + \delta_6 trd_{t-1} + \varepsilon_t \ldots \quad (4)\end{aligned}$$

In Equations 3 and 4, three different tests are applied to investigate the existence of a cointegrated relationship based on the A-ARDL method. The restrictions and hypotheses of these tests are as follows (Sam et al., 2019):

$F_{overall;}$ $H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$
$H_0: \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6 = 0$ ....(5)

$t_{DV;}$ $H_0: \beta_1 = 0$
$H_0: \delta_1 = 0$ ....(6)

$F_{IDV;}$ $H_0: \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$
$H_0: \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6 = 0$ ....(7)

The main hypotheses investigated in the study are:

Model 1:
H_0: there is no relationship between digitalization and carbon emissions.
Model 2:
H_0: there is no relationship between digitalization and economic growth.

The $F_{overall}$ test used to test the hypotheses in Equations 5, 6, and 7 is based on the table critical values in Narayan (2005), while the t_{DV} test is based on the table critical values in Pesaran et al. (2001). Finally, the table critical values of Sam et al. (2019) were used for the F_{IDV} test. If the test statistic for cointegration falls between the lower and upper limits of the relevant table critical value, the existence of cointegration is questionable. The A-ARDL method accepts cases where both the dependent and independent variables are I(0). Therefore, if all variables are I(0), we use I(0) as the critical value for the test statistic value, which calculates the presence of cointegration. If all variables are I(1), then the upper limit, i.e., I(1), is appropriate as the critical value (Sam et al., 2019: 137). There are two different degenerates in the AARDL model. The first one is when the statistical value of the lagged dependent variable is statistically significant, and the lagged independent variables are statistically insignificant. The second one is when the lagged independent variables are significant, but the independent variable with the lagged dependent variable is insignificant (Çağlar, 2022: 920-921; Solarin, 2019: 2877). In the AARDL model, it is necessary to investigate the date, frequency, and exact shape of structural breaks. However, it is not necessary to investigate the presence of existing breaks in the model by adding Fourier terms to the AARDL model. In this context, the FA-ARDL model is obtained by adding Fourier terms to Equations 3 and 4 expressing the AARDL model (Solarin, 2019: 2877).

$$\begin{aligned}\Delta lnco2_t = \ & \theta_0 + \sum_{i=1}^{n} \theta_{1i}\,\Delta lnco2_{t-1} \\ & + \sum_{i=1}^{m} \theta_{2i}\,\Delta lndig_{t-1} + \sum_{i=1}^{e} \theta_{3i}\,\Delta es_{t-1} + \sum_{i=1}^{r} \theta_{4i}\,\Delta lngov_{t-1} + \sum_{i=1}^{p} \theta_{5i}\,\Delta lnurb_{t-1} \\ & + \sum_{i=1}^{o} \theta_{6i}\,\Delta trd_{t-1} + \beta_1 lnco2_{t-1} + \beta_2 lndig_{t-1} + \beta_3 es_{t-1} + \beta_4 lngov_{t-1} + \beta_5 lnurb_{t-1} \\ & + \beta_6 trd_{t-1} + \beta_7 \sin\left(\frac{2\pi kt}{T}\right) + \beta_8 \cos\left(\frac{2\pi kt}{T}\right) \\ & + \mu_t \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (8)\end{aligned}$$

$$\begin{aligned}\Delta lngdp_t = \ & \gamma_0 + \sum_{i=1}^{c} \gamma_{1i}\,\Delta lngdp_{t-1} \\ & + \sum_{i=1}^{v} \gamma_{2i}\,\Delta lndig_{t-1} + \sum_{i=1}^{b} \gamma_{3i}\,\Delta es_{t-1} + \sum_{i=1}^{k} \gamma_{4i}\,\Delta lngov_{t-1} + \sum_{i=1}^{l} \gamma_{5i}\,\Delta lnurb_{t-1} \\ & + \sum_{i=1}^{s} \gamma_{6i}\,\Delta trd_{t-1} + \delta_1 lngdp_{t-1} + \delta_2 lndig_{t-1} + \delta_3 es_{t-1} + \delta_4 lngov_{t-1} + \delta_5 lnurb_{t-1} \\ & + \delta_6 trd_{t-1} + \delta_7 \sin\left(\frac{2\pi kt}{T}\right) + \delta_8 \cos\left(\frac{2\pi kt}{T}\right) \\ & + \varepsilon_t \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (9)\end{aligned}$$

In Equations 8 and 9, β_7, β_8, δ_7 and δ_8 are the coefficients of the trigonometric terms, k is the Fourier frequency, t is the trend, π =3.14 and T is the sample size. Moreover, θ_0 and γ_0 are the constant term, $\theta_{1,\ldots,6}$ and $\gamma_{1,\ldots,6}$ are the short-run coefficients, $\beta_{1,\ldots,6}$ and $\delta_{1,\ldots,6}$ are the long-run coefficients, μ_t and ε_t are the error terms, and n, m, e, r, p, o, c, v, b, k, I and s are the lag lengths.

4. Empirical Findings

4.1. Unit Root Test Results

Determining the presence of the unit root and structural break in the variables is crucial for obtaining consistent results in the study's model estimation. Table 3 presents the results of the ADF test with a structural break, which determines the stationarity properties of the study's variables and whether a structural break exists. The ADF test with structural breaks shows that the variables lnco2, es, and trd are stable in the first difference. On the other hand, the variables lngdp, lndig, lngov, and lnurb are stable at their level values. Additionally, the study identifies breaks in the series at various dates. Since the series are stationary at different levels and there are structural breaks, it was decided to use the FA-ARDL method in the study.

Table 2. ADF Break Unit Root Test

Variables	Level	First Difference Level	Break Date
lnco2	-2.517(3)	-5.399***(0)	2003
lngdp	-4.226*(0)	-	2001
lndig	-6.529***(0)	-	2020
es	-2.913(0)	-7.790***(1)	2010
lngov	-5.802***(0)	-	2001
lnurb	-5.640***(0)	-	2008
trd	-2.983(0)	-5.493***(0)	2008

Note: ***, * denote significance at the 1% and 10% level, respectively.
The symbol ( ) denotes the lag length.

4.2. FA-ARDL Test Results

The ADF single-break unit root helps determine the stationarity properties of the study's variables. Then, we will use the AARDL model with Fourier term to determine the cointegrated relationship between the variables. Firstly, the AARDL method assumes that the variables are stationary at the I(0) and I(1) levels. Subsequently, the existence of cointegrated relationship is determined. On the other hand, the single-break ADF unit root test revealed that the variables are in a structural break process. For this reason, the FA-ARDL method, which is the result of adding a Fourier term to the AARDL model, is preferred. When the results obtained using the FA-ARDL method are analysed, it is determined that the error term in Model 1 is statistically significant and the coefficient takes a negative value. Moreover, at least one of the trigonometric terms used in Model 1 is statistically significant. Finally, despite using the Fourier function to achieve consistent results against structural breaks, Model 1's CUSUM and CUSUMQ test results indicate its stability.

Table 3. FA-ARDL Cointegration Test Results for Model 1

Model	k	Tests	Test Statistics	Critical Values		
				%1	%5	%10
(1,0,0,0,1,0)	5	$F_{overall}$	13.841***	6.370	4.608	2.457
		$t_{depentent}$	-5.049***	-4.79	-4.19	-3.86
		$F_{independent}$	16.317***	6.48	4.54	3.76

Diagnostic Tests	Test Statistics	Probability Values
Autocorrelation (LM Test)	1.739	0.187
Heteroscedasticity (BPG Test)	10.046	0.346
Normality	1.294	0.523
Ramsey RESET	0.368	0.553
CUSUM	Stabil	
CUSUMQ	Stabil	

Note: *** represents significance at the 1% level.

The cointegration test results for Model 1 in Table 3 indicate that there is a cointegrated relationship from the independent variables to the dependent variable. Moreover, the diagnostic test results in Model 1 indicate that the long-run coefficients obtained from the cointegration test are consistent and reliable. Table 4 presents the long-run results from Model 1 using the FA-ARDL method.

Table 4. Model 1 Long Run Estimation Results

Variables	Coefficients	t-statistic Values	Probability Values
lndig	-0.103	-5.271	0.001***
es	-0.038	-3.477	0.003***
trd	-0.291	-2.151	0.048**
lngov	0.152	2.846	0.012**
lnurb	1.608	10.915	0.000***
Error Correction Model			
$\Delta\cos$	0.012	2.365	0.031**
$\Delta\sin$	0.011	2.335	0.033**
ect	-0.793	-10.522	0.000***

Note: ***, ** represent significance at the 1% and 5% level, respectively.

According to the FA-ARDL long-run results for Model 1 in Table 4, lndig, es and trd variables have statistically significant and negative coefficients. Accordingly, a 1% increase in lndig, es and trd variables decreases lnco2 by 0.0103%, 0.038% and 0.291%, respectively. On the other hand, lngove and lnurb variables were found to have a statistically significant and positive coefficient. Accordingly, it is concluded that a 1 percent increase in lngove and lnurb variables increases lnco2 by 0.152% and 1.608%, respectively. According to other results obtained from the FA-ARDL (1,0,0,0,1,0) model, the coefficients of the trigonometric terms of the model are 0.012 and 0.011, respectively, and both terms are statistically significant at the 5% level. Finally, the coefficient of the error term of the model is -0.793 and statistically significant at the 1% level.

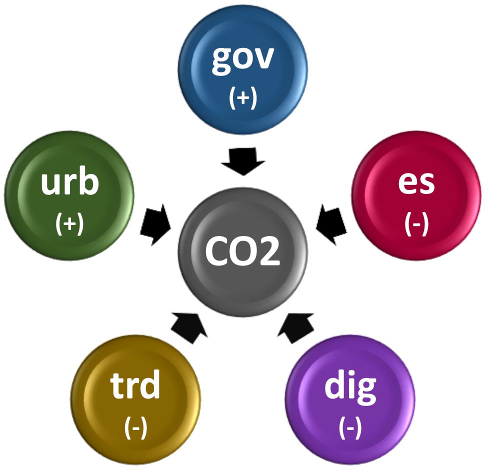
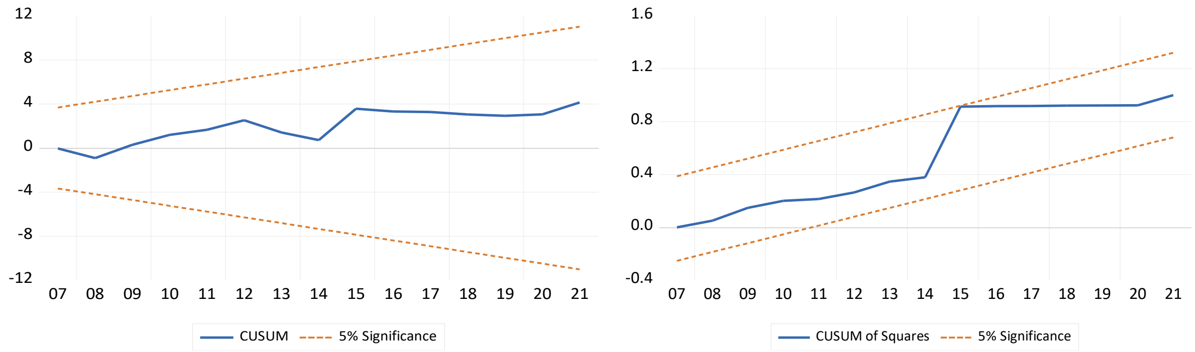


Figure 2. Model 1 Estimation Results



Graph 1. CUSUM and CUSUMQ Tests for Model 1

The rest of the study investigates the diagnostic test results for Model 2. According to the diagnostic test results in Table 5, Model 2 does not suffer from autocorrelation and heteroscedasticity, and the normality assumption is satisfied. Moreover, the error term of Model 2 is statistically significant, and the coefficient takes a negative value, while at least one of the trigonometric terms used is statistically significant. Finally, despite using the Fourier function to achieve consistent results against structural breaks, Model 2's CUSUM and CUSUMQ test results demonstrate its stability.

Table 5. FA-ARDL Cointegration Test Results for Model 2

Model	k	Tests	Test Statistics	Critical Values		
				%1	%5	%10
(1,1,1,0,0,0)	3	$F_{overall}$	55.397***	6.370	4.608	2.457
		$t_{dependent}$	-15.803***	-4.79	-4.19	-3.86
		$F_{independent}$	50.911***	6.48	4.54	3.76

Diagnostic Tests	Test Statistics	Probability Values
Autocorrelation (LM Test)	1.192	0.294
Heteroscedasticity (BPG Test)	13.742	0.185
Normality	1.62	0.444
Ramsey RESET	2.887	0.113
CUSUM	Stabil	
CUSUMQ	Stabil	

Note: *** represents significance at the 1% level.

The cointegration test results for Model 2 in Table 5 indicate that there is a cointegrated relationship from the independent variables to the dependent variable. Moreover, the diagnostic test results in Model 2 indicate that the long-run coefficients obtained from the cointegration test are consistent and reliable. Table 6 presents the findings from Model 2 using the FA-ARDL method.

Table 6. Model 2 Long Run Estimation Results

Variables	Coefficients	t-statistic Values	Probability Values
lndig	0.053	1.865	0.083*
es	0.041	2.616	0.02**
trd	0.979	3.314	0.005***
lngov	0.586	6.001	0000***
lnurb	0.57	2.919	0.011**
	Error Correction Model		
$\Delta\cos$	-0.055	-5.082	0.002***
$\Delta\sin$	0.054	6.173	0.000***
ect	-1.132	-21.239	0.000***

Note: ***, ** represent significance at the 1% and 5% level, respectively.

The long-term FA-ARDL results for Model 2 can be seen in Table 6. The lndig, es, trd, lngov, and lnurb variables all have statistically significant and positive coefficients. Accordingly, a 1% increase in lndig, es, trd, lngov, and lnurb variables increases lngdp by 0.053%, 0.041%, 0.979%, 0.586%, and 0.57%, respectively. According to other results obtained from the FA-ARDL (1,1,1,0,0,0) model, the coefficients of the trigonometric terms are -0.055 and 0.054, respectively, and both terms are significant at the 1% level. Finally, the coefficient of the error term of the model is -1.132 and statistically significant at the 1% level.

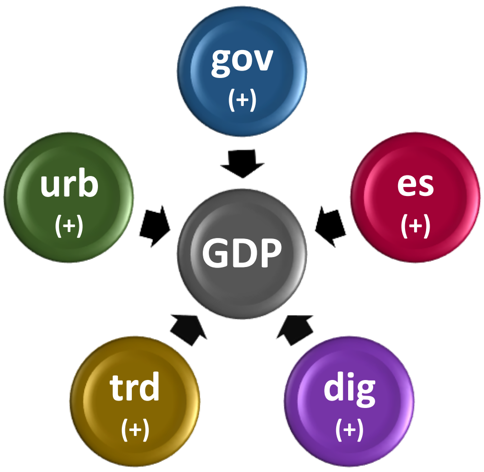
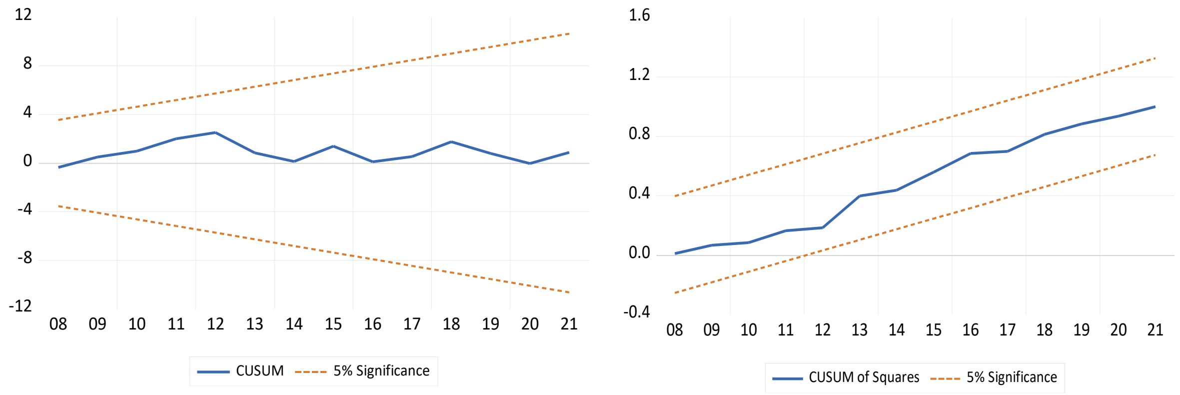


Figure 3. Model 2 Estimation Results



Graph 2. CUSUM and CUSUMQ Tests for Model 2

Conclusion and Assessment

This study investigates the effects of digital economies on carbon emissions and economic growth between 1996 and 2021. The study uses data on the ratio of internet users to the total population as a digital economy indicator, Türkiye's annual total carbon emission data as a carbon emission indicator, and dollar-based GDP data as an economic growth indicator. In addition, the ratio of renewable energy consumption to total energy consumption, the share of public expenditures in GDP, urban population data, and finally trade openness data representing the ratio of exported and imported goods and services to GDP were used as control variables. In order to determine whether the data of the study contain both unit root and structural break, ADF unit root test with structural break is preferred. Since the data are stationary at different levels (I(0) and I(1)) and contain structural breaks at different dates, it was decided to use the FA-ARDL method, which adds Fourier terms to the AARDL method. In this context, the validity of two different hypotheses was investigated in the models created. Considering the hypotheses; the null hypothesis (H_0) used in Model 1 states that there is no relationship between digitalisation and carbon emissions, while the null hypothesis (H_0) used in Model 2 states that there is no relationship between digitalisation and economic growth. In addition, at least one of the terms in the Fourier functions used in the FA-ARDL method was found to be statistically significant in both models. The error terms, on the other hand, are also statistically significant and have a negative coefficient. Therefore, it is concluded that both models have a cointegrated relationship.

Examining the long-run results from the study reveals a negative and statistically significant relationship between digitalisation and carbon emissions in Model 1, leading to the rejection of the H_0 hypothesis. This result is similar to Chang et al. (2022), Hao et al. (2022), Ma et al. (2022), Yi et al. (2022), Zhou et al. (2022), Wang et al. (2022), Cui et al. (2023), Wang et al. (2023), Wang and Li (2023), Wang and Zhong (2023), Zhang et al. (2023), Yang et al. (2023) and Li and Tang (2024). Moreover, Model 1 revealed a negative, long-term relationship between energy intensity and trade openness, as well as a positive relationship between government expenditures and urbanization. When examining the results from Model 2, it reveals a positive and statistically significant relationship between digitalisation and economic growth, leading to the rejection of the H_0 hypothesis. This result is supported by Pradhan et al. (2019), Cheng et al. (2021), Sheikh et al. (2021), Cheng and Huang (2022), Ibrahimi and Fetai (2022), Hosan et al. (2022), Kurniawati (2022), Varlamova and Kadochnikova (2023), Patra and Sethi (2024), Asoy (2024), Hegde and Guruprasad (2024), Latief and Javeed (2024), Moskalyk and Balashova (2024), Török (2024) and Zhang et al. (2024). On the other hand, Model 2 shows that energy intensity, trade openness, government expenditures, and urbanization all positively affect economic growth. The study's results indicate that digitalisation contributes positively to economic growth and negatively to carbon emissions.

The results of the study show that digitalisation contributes positively to economic growth and negatively to carbon emissions. Therefore, it is concluded that the development of digital economies in the Turkish economy will lead to both economic growth and a reduction in carbon emissions. These results coincide with the objectives of sustainable development. Because policies towards human health, nature and national welfare are among the objectives of sustainable development. Therefore, in the light of the findings obtained from the study, the widespread use of digital economies in Türkiye can be considered as a correct policy to achieve the objectives of sustainable development. In this context, it can be expected that the digitalisation process in Türkiye will contribute to the welfare of the country and the policies developed to reduce carbon emissions. For this reason, policy makers should support and encourage policies for the spread of digitalisation to help achieve the relevant objectives of sustainable development. Finally, the study has an important limitation. The study focuses on carbon emission emissions calculated for Türkiye in general. Therefore, the empirical findings of the study are considered to cover all sectors of the Turkish economy. Therefore, in the next research, it is aimed to investigate the impact of digitalisation on carbon emissions in Türkiye on a sectoral basis.

Compliance with Ethical Standard

Conflict of Interests: *The author(s) declare that they do not have a conflict of interest with themselves and/or other third parties and institutions, or if so, how this conflict of interest arose and will be resolved, and author contribution declaration forms are added to the article process files with wet signatures.*

Ethics Committee Approval: *There is no need for ethics committee approval in this article, the wet signed consent form stating that the ethics committee decision is not required has been added to the article process files on the system.*

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