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Twin Transition in G20 Economies: Macroeconomic Performance and Environmental Quality

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Abstract

This study investigates the impact of the "twin transition" process, encompassing digitalization and green energy, on environmental quality. It focuses on discussions in the literature, such as the "Rebound Effect" and the "Pollution Haven Effect." The main objective of the study is to demonstrate the impact of the twin transition on carbon emissions (CO_2) in G20 countries. Methodological limitations in the literature have been addressed in this process. Panel data analysis was performed on 19 G20 countries using the second-generation CS-ARDL (DCCE) method, which considers cross-sectional dependence and common shocks, for the years 2005-2023. The findings revealed a long-term cointegration relationship between the variables. A potential macroeconomic shock takes 2-3 years to reach equilibrium. However, in the long term, it was found that digitalization and renewable energy investments did not statistically significantly reduce carbon emissions in G20 countries. This result is considered a reflection of the "rebound effect" discussed in the literature. The increase in energy demand is being met by fossil fuels, leading to "carbon lock-in." In addition to these findings, it has been observed that short-term foreign direct investment increases CO_2 emissions. This finding also demonstrates the validity of the "pollution haven hypothesis" in G20 countries.

Keywords: twin transition, G20 countries, CS-ARDL, environmental quality, macroeconomics

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G20 Ülkelerinde İkiz Dönüşüm: Makroekonomik Performans ve Çevresel Kalite Dinamikleri

Öz

Bu çalışma dijitalleşme ve yeşil enerji kavramlarını içeren ‘’İkiz Dönüşüm’’ sürecinin çevre kalitesi üzerine olan etkisini araştırmaktadır. Bunu yaparken çalışmanın odağına ‘’Geri Tepme Etkisi’’ ve ‘’Kirlilik Sığınağı Etkisi’’ gibi literatürde yer alan tartışmaları koymaktadır. Çalışmanın temel amacı G20 ülkelerinde ikiz dönüşümün karbon emisyonları (CO2) üzerindeki ortaya koymaktır. Bunu yaparken literatürdeki metodolojik kısıtlar da aşılmaya çalışılmıştır. 19 adet G20 ülkesinin 2005-2023 yılları arasındaki verileri yatay kesit bağımlılığını ve ortak şokları dikkate alan ikinci nesil CS-ARDL (DCCE) yöntemi ile panel veri analizi gerçekleştirilmiştir. Elde edilen bulgular değişkenler arasında uzun dönemli eş bütünleşme ilişkisi olduğunu ortaya çıkarmıştır. Potansiyel bir makroekonomik şokun dengeye gelmesi 2-3 yıl almaktadır. Ancak uzun vadede, dijitalleşme ve yenilenebilir enerji yatırımlarının G20 ülkelerinde karbon emisyonlarını istatistiksel olarak anlamlı ölçüde azaltmadığı tespit edilmiştir. Bu sonuç literatürde tartışılan ‘’Geri Tepme Etkisinin’’ bir yansıması olarak kabul edilmektedir. Enerji talebindeki artış fosil yakıtlardan karşılanmaktadır ve ‘’Karbon Kilitlenmesi’’ sonucunu doğurmaktadır. Bu bulguların yanısıra kısa dönemde doğrudan yabancı yatırımların CO2 emisyonlarını arttırdığı görülmüştür. Bu bulgu da G20 ülkelerinde ‘’Kirlilik Sığınağı Hipozinin’’ geçerli olduğunu göstermetkedir.

Anahtar Kelimeler: ikiz dönüşüm, G20 ülkeleri, CS-ARDL, çevresel kalite, makroekonomi

1. INTRODUCTION

Since the era of globalization, the world has been trying to realize its economic growth and development aims through new focal points. Environmental issues have begun to come to the forefront in this new period and have taken their place on national agendas. International panels are being organized on this theme, and environmental issues are beginning to form the priorities of countries. As global economic dynamics evolve, economic processes expand at the global level and world trade increases. These circumstances trigger a further increase in environmental pollution, and countries that are in a leading position in world trade are forced to take radical decisions in this regard. The Intergovernmental Panel on Climate Change reports remark that greenhouse gas emissions are increasing and that radical measures need to be taken (IPCC, 2023, p.4-6). Among those who need to take these measures are the G20 countries, which are responsible for roughly 75% of global trade and account for approximately 80% of global greenhouse gas emissions (Adebayo et al., 2021). The United Nations has set principal missions for the environment as "sustainable development goals." G20 countries also aim to be in line with these goals. Concurrently, they must also not disregard their own economic growth targets. At this point, G20 countries ought to follow a policy that will both enable them to achieve their economic growth targets and align with the sustainable development goals set by the United Nations. Hence, these countries must realize these ambitions by minimizing the environmental damage and carbon emissions they cause (Danish et al., 2020, p.1-2).

A review of recent economic literature discloses vast literature and research on the repercussions of economic growth on environmental pollution. One of the standout features is the concept of the "twin transition." The twin transition is a concept that connects digitalization-focused areas such as the Internet of Things, artificial intelligence, and big data mining with the preference for environmentally friendly, renewable energy sources. Based on this premise, countries can oversee their economic processes by combining new and advanced technologies with green energy, achieving their economic growth targets in an environmentally conscious manner. Herein, new technologies and artificial intelligence are expected to enlarge economic efficiency and play a part in environmental quality (Muench et al., 2022, p.7-10). Aided by developing new technologies and artificial intelligence, production efficiency will increase, and energy needs will decrease (Ren et al., 2021, p.3-5). As the required energy is obtained from renewable energy sources, environmental quality will improve, and it may be a solution to dependence on fossil fuels (Dong et al., 2020, p.1665-1668).

Although twin transitions are expected to have a positive influence on environmental quality and emissions, a review of the literature discloses a divergence of opinion on this issue. Some research, such as Lin and Zhou (2021), have revealed that digitalization enhances ecological quality as expected. Yet, there is also mounting dissent in the literature. This status is referred to as the "Rebound Effect" in the literature. Lange et al. (2020) describe this status as follows: Big data mining, cloud computing, and the establishment of crypto asset networks require a very high level of energy. If all the required energy cannot be met from renewable energy

sources, this will counteract the advantageous consequences of the efficiency gains resulting from digitalization, leading to a kind of "twin transition'' paradox.

Although the number of studies on the "twin transition" is increasing daily, significant research gaps remain. An examination of existing literature reveals that most studies focus on the impact of either digitalization or renewable energy on environmental quality. These studies often lean toward technological optimism or yield contradictory results by invoking the Jevons paradox. The most significant gap in the literature is the lack of an integrated framework for examining the twin transition; specifically, no holistic assessment has yet been conducted to simultaneously test the "Rebound Effect," "Carbon Lock-in," and the "Pollution Haven Hypothesis." Furthermore, G20 countries are highly integrated with one another. Studies focusing on this group often overlook unobserved common shocks and cross-sectional dependence—a critical oversight. This study addresses these gaps by examining the subject holistically—thereby resolving theoretical fragmentation—and rectifying inconsistencies in econometric methodology. To this end, the study employs the second-generation CS-ARDL (DCCE) estimator to isolate global shocks, such as the 2008 financial crisis and the COVID-19 pandemic, while presenting an unbiased, integrated macro-environmental analysis of the "twin transition'' paradox within G20 economies. All these original contributions are the features that distinguish this study from others in the literature and make it unique.

This research is expected to fill gaps in the literature in these aspects and make an original contribution to the literature in three main ways. First, by eliminating the statistical complexity caused by forestry and agricultural shocks (LULUCF) as CO_2 emission data, only industrial CO_2 emission data was included in the model. Secondly, state-of-the-art methodological frameworks in the literature were adopted. To this end, the Second Generation CS-ARDL (Cross-Sectionally Augmented ARDL) estimator, which filters the strong cross-sectional dependence among G20 countries (Pesaran, 2015) and produces unbiased long-term coefficients, was applied. Eventually, evidence derived from this analysis empirically proved that, contrary to general expectations, digitalization and green energy investments in G20 countries occur within the framework of the "Rebound Effect" and "Pollution Haven Hypothesis" found in the literature, and that it cannot be statistically definitively stated that they improve environmental quality in the long term. Thus, it contributed to the "twin transition'' paradox found in the literature. To be more specific, this study makes three key original contributions to the existing literature. Firstly, the data focuses solely on per capita industrial CO_2 emissions, eliminating noise associated with land-use change and forestry (LULUCF) shocks. This allows for a precise and integrated analysis of macro-industrial dynamics. Secondly, it utilizes a second-generation CS-ARDL (DCCE) approach, accounting for cross-sectional dependence and unobserved common shocks such as global financial crises and pandemics, thus providing unbiased long-term forecasts. Finally, it simultaneously evaluates the twin transition within G20 economies from the perspectives of the Rebound Effect, Carbon Lock-in, and Pollution Paradise Hypothesis. This makes the study highly comprehensive and original. The following chapters will sequentially submit a literature review, data set and

methodology, empirical findings, discussion, and policy recommendations. In this context, the fundamental research question of the study is formulated as follows: How does the twin transition process, encompassing digitalization and green energy investments, affect macroeconomic performance and environmental quality (carbon emissions) in G20 economies?

2. THE PLACE AND CONCEPTUAL FRAMEWORK OF TWIN TRANSITION IN MACROECONOMIC THEORY

When climate-related topics are investigated from a macroeconomic perspective, evidence indicates that environmental pollution has negative effects on macroeconomic stability after a certain period. Economic growth models, which form the basis of macroeconomics, are structured under this model. Research focusing on the effects of labor and capital, the fundamental factors of the traditional model, on economic growth is gradually evolving towards examining the influences of technology and the environment on economic growth. In the literature, this concept is inspected under the heading of "twin transition." With the twin transition, technological innovations advance, and the relation between digitalization and green energy is inspected. These concepts lead to a re-examination of the most fundamental issues of macroeconomics (Muench et al., 2022, p.7-10). The influence of the twin transition on the environment is not stable and linear across all nations and economic cycles. It is a sophisticated configuration resulting from the simultaneous influence of many different variables. Against this backdrop, the twin transition process and its macroeconomic influences are a sophisticated and multifaceted architecture encompassing theories such as Endogenous Growth Theory, Jevons Paradox, and the Pollution Bunker Hypothesis.

When traditional growth models are inspected, technology is perceived as an exogenous factor. In endogenous growth theories, Romer and Lucas perceived technology and R&D processes as endogenous factors. Moving to more current approaches within the theoretical framework, the "Directed Technical Change" model, first introduced to the literature by Acemoglu et al. (2012) emerges. Within this framework, the primary priority for preventing environmental pollution falls on policymakers. Policymakers should redirect R&D investments from fossil fuels to clean, green energy and clean technologies. Or else, preventing environmental degradation is beyond what markets alone can achieve. The G20 countries also comprise large-scale economies. The circumstance that their energy investments have not had a significant influence on environmental quality is precisely due to this status. Due to the enormous energy demand, green energy investments keep only a small complement to the energy sector. Fossil fuels still occupy a paramount status in a significant part of the sector. The priority should be on green energy instead of fossil fuels. That is, while the use of green energy rises, the share of fossil fuels in total energy consumption ought to be drastically diminished, and renewable energy sources ought to exert a decisive influence. If these conditions are not met, the goal of directed technological change cannot be achieved.

A further dimension of the twin transition processes is digitalization. With digitalization, it is anticipated that energy-efficient smart systems will be integrated into the entire market, creating efficiency and positively impacting environmental quality. Yet, a vast body of scholarship demonstrates that this expectation is not always realized. Some researchers conclude that the relation between digitalization and the environment is meaningless. In fact, a paramount number of researchers have found that digitalization increases environmental pollution. When this status is inspected from a theoretical perspective, the "Jevons Paradox," first proposed by William Stanley Jevons in the 19th century, emerges. This paradox is now referred to as the "Rebound Effect." In line with this paradoxical logic, countries may notice a certain rise in energy efficiency as a result of digitalization. Yet, an intensive digitalization process can also bring with it numerous necessities such as the establishment of large data centers and the creation of infrastructure for cryptocurrency mining. This, in turn, generates a substantial energy demand for this infrastructure and preparations. In countries like the G20, this necessary increment in energy due to digitalization is mostly met by energy derived from fossil fuels. In this scenario, for example, if digitalization diminishes energy demand by providing one unit of energy efficiency, the energy consumed by the systems necessitated by the preparations and infrastructure required for the establishment of the digitalization network far exceeds the efficiency gained, neutralizing the effect, and in some countries even reversing it. Thus, the twin transition evolves into an ecological paradox (Lange et al., 2020, p.4-5).

Upon scrutinizing macroeconomic paradigms, another theory related to the twin transition processes is the "Pollution Haven Hypothesis." Developed countries place substantial relevance on the environment and maintain draconian environmental policies and regulations. This strict approach fuels the twin transition process. Yet, developing countries with carbon-intensive industries are not as strict as developed countries in this regard. Principally, there are countries that deliberately keep environmental protection laws and regulations lax to enhance jurisdictional attractiveness (Copeland and Taylor, 1994, p.756-757). This represents a key determinant that helps direct investment from developed countries to such developing countries. This phenomenon is also manifest in studies on foreign direct investment and the environment. Foreign direct investments have statistically significant and positive influences on carbon emissions in such countries. Hereof, instead of reducing environmental pollution by transferring new and clean technologies along with foreign investments, the attractiveness of cheap labor and flexible environmental protection laws in the short term has led to increased environmental degradation in G20 nations (Sarkodie and Strezov, 2019, p.868-870).

The outcomes acquired in the empirical part of this research are in agreement with the theories examined in the theoretical context. Both the outcomes of this research and these hypotheses in macroeconomic theory demonstrate that the twin transition process should be considered as a whole and should not be left solely to the guidance of market dynamics. Public intervention and incentives and the creation of laws within this framework are crucial. If these conditions are not met, when twin transition processes are left unchecked, they fall into the traps of the "Rebound Effect" and "Pollution Haven". For the twin transition to be successful in creating a positive

influence on environmental quality, the heavy energy burden brought about by digitalization must be seamlessly integrated into green energy sources. Or else, the outcome is likely to be neutralized or, even worse, lead to extensive environmental damage.

3. TWIN TRANSITION IN EMERGING ECONOMIES: OPPORTUNITIES AND STRUCTURAL DYNAMICS

Developing economies have become virtual centers of industrial production today. A predominant majority of developed countries have shifted their production to these countries due to a multitude of factors. This places developing countries with large-scale industrial production capacity at the forefront when it comes to carbon emissions. Many countries within the G20 group are subsumed under this classification. A key desideratum in macroeconomics for these countries is to realize high economic growth rates. Yet, current global climate targets also come along with these core macroeconomic objectives. Consistent with this perspective, these countries are striving to achieve their economic growth targets while simultaneously paying attention to carbon emissions. Meeting this dual goal remains an arduous task. The concept of the twin transition refers to a combination of digitalization and green energy. Achieving the twin transition offers a leapfrogging opportunity for developing economies. Yet, it is likewise noteworthy that this concept has its own challenges and is a difficult goal.

Through the lens of emerging markets, the primary window of opportunity that the twin transition can provide for these countries is the technological leapfrogging opportunity. Throughout history, developed countries have equipped their infrastructure with suboptimal and aging infrastructure, reaching their current levels of development. Because these systems incorporate technology from previous years, they fall short of operational benchmarks in terms of carbon emissions. Therefore, to achieve climate goals and rid the global world of carbon emissions, developed countries need to completely replace the infrastructure they have built over the years with green energy systems. Yet, emerging market economies, which are striving to reach the levels that developed economies have long since passed, do not need to first establish old systems and then completely overhaul them. These developing economies have the chance to directly integrate new-generation digital systems focused on green energy and with high efficiency into their markets (Goldemberg, 1998, p.730-731). New AI-powered machines and systems can help emerging economies reach the threshold value in the Environmental Kuznets Curve—which demonstrates that economic growth first pollutes the environment and then cleans it up after a certain income level—at lower income levels. This status is reported as a "leap opportunity" for developing countries. Yet, a review of the literature discloses that this opportunity has not been fully realized, particularly in developing economies. Digitalization leads to a sharp upturn in energy demand due to factors such as data mining infrastructure and the electricity consumption required by blockchain technologies. Yet, since the transition to green energy remains notably limited in developing economies, the increased demand is met by using older sources like fossil fuels. This negates ameliorative effects of some energy efficiency gained through digitalization (Ren et al., 2021, p.3-5). So, instead of creating

an opportunity for this group of countries, digitalization can have negative consequences under the rebound effect.

When examining the twin transition processes of developing countries within the G20, it is discernible from the results that the financing of this process is largely based on foreign direct investment. Extant literature posits that a shift in investment from developed to developing countries will lead to the transfer of newer, more advanced technologies and know-how related to clean energy. Yet, theoretical expectations do not always align with real-world developments. A diverse array of elements fuels this dynamic. Developed countries are generally highly responsive and controlling regarding climate and environmental issues. This leads businesses to focus on environmental costs in addition to their own costs. So, to keep costs down and keep going with their competitiveness globally, businesses may shift their investments to developing countries, which are more flexible regarding environmental and climate regulations, through foreign direct investment. On a divergent note, these countries, aware that maintaining flexibility in environmental regulations is a factor in attracting foreign direct investment, may intentionally relax controls and penalties. When all is said and done, contrary to the expectations of the literature, when foreign direct investment flows from developed countries to developing countries, this development, instead of cleaning the environment with new and clean technologies, can actually cause further pollution. Although the long-term consequences may differ for countries, in the short term, foreign direct investment can raise carbon emissions in developing countries. This can turn these countries into virtual "pollution havens" (Copeland and Taylor, 1994, p.756-757).

When examining the relation between twin transition and carbon emissions, one of the first points that stands out is the intense energy demand brought about by digitalization. Countries entering the digitalization process need to consume more energy. The amount of energy obtained from green energy sources cannot meet this intense demand. A complete transition and full replacement from fossil fuel-based energy production to renewable energy-based production cannot be achieved due to the precipitous rise in energy demand in a short period of time. This is expressed in the literature as "carbon lock-in" (Unruh, 2000, p.827-828). Hence, over a generational timeframe, an increment in green energy use does not precipitously lower carbon emissions, creating an uncertain situation. Even with investment in renewable energy, the process is neutralized when fossil fuels are also brought into play when energy demand increases suddenly and intensely. Hereby, the twin transition process generates development and growth potential for developing countries like the G20 countries. Yet, structural complexities such as carbon lock-in and the rebound effect, which are specific to these countries, can steer the process in other directions. The overarching pathway to overcome this impasse is to create macroeconomic policies that ensure that digital infrastructures are built and maintained entirely with energy from green energy sources.

4. LITERATURE REVIEW

The outcomes acquired from investigating twin transition processes from a macroeconomic perspective can be multifaceted. In the first instance, the literature states that digitalization contributes to the environment and improves environmental quality. Ren et al. (2021) and Lin and Zhou (2021) are amongst the researchers who acquired empirical outcomes in this direction. The study underscores that digitalization processes augment productive capacity and reduce carbon emissions. They demonstrate that new generation technologies and smart grids used in industry have an adverse impact on carbon emissions. Yet, the divergent outcomes are also found in the literature. This issue is expressed in the literature as the "Rebound Effect". Lange et al. (2020) state that digitalization processes and infrastructure installations generate a huge demand for electricity, which negates the efficiency-enhancing effects that come with digitalization. Likewise, Ndubuisi et al. (2021) are amongst the researchers who advocate the same view and obtained outcomes in that direction. Digitalization has demonstrated that the increased electricity demand, particularly in developing countries within the G20, is still primarily met by fossil fuels. This, in turn, increases emissions. These differing outcomes form the basis of the empirical part of this research, which demonstrates that digitalization does not have a long-term reducing effect on carbon emissions.

Investing in renewable energy is expected to diminish carbon emissions. Dong et al. (2020) and Danish et al. (2020) have demonstrated that investments in renewable energy can replace fossil fuels and are therefore successful in reducing carbon emissions. Yet, research on developing countries demonstrates that this effect can be negligible. In the literature, this is described through the concept of "carbon lock-in." Unruh (2000) was the first to use this term. In view of the aforementioned, in countries with exorbitant energy needs, the intense energy demand brought about by digitalization is still primarily met by fossil fuels. Renewable energy only plays a small complementary role in the system. In order to achieve the expected carbon emission reduction results, renewable energy investment should expand while the reliance on fossil fuels declines. Electricity consumption from renewable energy sources should completely replace electricity consumption from fossil fuels. That is, it should be in a position of full substitution. Or else, the increments seen in renewable energy investments will not generate a carbon emission reduction effect. Undeniably, the outcomes of this research support the outcomes of Unruh (2000). In the empirical part of this research, the long-term trajectory of renewable energy investments on carbon emissions is insignificant. From this, it is understood that renewable energy has not yet been able to replace fossil fuels, especially in G20 countries.

In view of the aforementioned, international firms, primarily considering their own costs and wanting to reduce them, instead of producing at high costs within the framework of strict environmental protection laws in their own countries, move their investments to developing countries that are more flexible in this regard to avoid environmental costs. The aim here is to prioritize low-cost production by ignoring fossil fuel-based systems. That is, they transfer their own pollution to another country in order to take advantage of the low-cost opportunity. This

causes these countries to become, in effect, pollution havens. Sarkodie and Strezov (2019) and Copeland and Taylor (1994) empirically approve this view in their research. It is noteworthy that short-run FDI increases emissions at a 5% significance level in the CS-ARDL estimations included in the empirical part of this research, demonstrating that the Pollution Haven Hypothesis is also valid in G20 countries. Yet, the econometric approaches used to get the empirical outcomes in the literature constitute a fundamental gap in the literature. When the models and econometric methods used are examined statistically, there is a visible trend suggesting many studies have not selected appropriate estimators. The possibility of cross-sectional dependence in the datasets used is quite likely. For instance, there is integration between countries in terms of trade and finance. This leads to cross-sectional dependence. If estimators such as OLS, PMG, and standard ARDL are preferred as first-generation estimators, global shocks and the spread of these shocks betwixt countries can make the outcomes inconsistent. So, using second-generation estimators such as CS-ARDL (DCCE), which filter these effects and overcome these problems, as preferred in this research, will make a difference in the outcomes. In summary, a review of the existing literature reveals no consensus regarding the environmental impact of the "twin transition." Researchers have typically focused their studies on either digitalization or green energy, often erroneously disregarding cross-sectional dependence in their econometric analyses—despite the high level of interaction between countries. Consequently, the use of inappropriate analytical methods and tests has led to flawed results, resulting in a body of literature characterized by contradictory findings. To avoid similar errors, this study accounts for the heterogeneous nature of G20 countries and incorporates global common shocks. Care was taken to select an econometric method appropriate for these conditions. Furthermore, this study goes beyond merely combining technological and environmental variables; it comparatively discusses the findings within the framework of the Rebound Effect and the Pollution Haven Hypothesis. This contribution addresses a significant gap in the literature.

5. RESEARCH METHOD AND FINDINGS

The practice part of the research included 19 G20 countries. These countries are Germany, the United States, Argentina, Australia, the United Kingdom, Brazil, China, Indonesia, France, South Africa, Republic of Korea, India, Italy, Japan, Canada, Mexico, the Russian Federation, Saudi Arabia, and Türkiye. The application part of the research was executed using the STATA 17 program. The period range is 2005-2023. The data for the research was acquired from the World Bank database (World Bank, n.d.). In the empirical part of the research, the effects of the twin transition, namely digitalization and green energy, on environmental quality were investigated practically. The model of the research is given in Equation 1.

$$ln_CO2it= \alpha i+\beta 1GDPit+\beta 2INTit+\beta 3REWit+\beta 4TRDit+ \beta 5FINit+ \beta 6FDIit+ \beta 7INFit+Ɛi \quad (1)$$

$i=1\ldots19$

$t=2005\text{-}2023$

In Equation 1, i denotes the G20 countries, and T denotes the time dimension of the data set. ln_CO2_it denotes logarithmic per capita carbon emissions, GDP_it denotes economic growth, INT_it denotes digitalization, REW_it denotes renewable energy consumption, TRD_it denotes trade openness, FIN denotes financial development, FDI_it denotes foreign direct investment, and INF_it denotes inflation. αi denotes country-specific fixed effects, and Ɛit denotes the error term. Table 1 lists the variables used in the study, their abbreviations, the source from the World Bank, and the unit of measurement.

Table 1. Definition and data sources of variables

Indicator	Abbreviation in the research	Definition Summary	Dataset	Unit
GDP per capita growth	GDP	Annual growth rate of real GDP per capita	WB_WDI	%
CO2 emissions per capita	ln_CO2	Annual CO2 emissions per capita (metric tons)	WB_WDI	t CO2e
Internet users	INT	Individuals using the Internet as a percentage of the population	WB_WDI	% population
Renewable energy share	REW	Share of renewable energy in total final energy consumption	WB_WDI	% pay
Trade	TRD	Sum of exports and imports as a percentage of GDP	WB_WDI	% GSYH
Domestic credit	FIN	Domestic credit provided to the private sector by banks	WB_WDI	% GSYH
FDI net inflows	FDI	Foreign direct investment (FDI), net inflows (% of GDP)	WB_WDI	% GSYH
Inflation	INF	Annual inflation based on the Consumer Price Index (CPI)	WB_WDI	%

Table 1 provides descriptions of the variables that will frequently be referred to by their abbreviations in this research. Data for these variables were acquired from the World Bank's World Development Indicators (WDI) database. Table 2 exemplifies the descriptive statistics for these variables.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
GDP	361	1.962786	3.676463	-10.33611	13.55537
ln_CO2	361	1.929478	0.735245	0.0531662	3.030007
INT	361	63.40388	26.81853	2.38807	100
REW	361	14.04127	11.80983	0	50
TRD	361	52.73633	17.08685	22.10598	101.6806
FIN	340	91.68982	53.46012	10.65349	223.775
FDI	361	2.053256	1.563763	-3.601138	11.99986
INF	348	5.273315	10.5103	-1.352837	133.4889

Table 2 submits the descriptive statistics of the research's data. In view of the aforementioned, when examining the dataset covering the years 2005-2023 for G20 countries, partial data deficiencies are observed in the Financial Inflation (FIN) and inflation (INF) variables. Hence,

an unbalanced panel can be considered. Yet, it is still adequate for the analysis. When examining the economic growth (GDP) data of the countries, there is a visible trend suggesting they have an average growth rate of 1.96%. Yet, a significant gap between the minimum (-10.33%) and maximum (13.55%) values is also noticeable. This table may serve as an indicator of the Global Financial Crisis of 2008 and the COVID-19 pandemic of 2020, which occurred during the selected period. A closer inspection of the (INF) series reveals the high standard deviation is due to the heterogeneity of the countries within the group. A closer inspection of the twin transition data series, which forms the main subject of the research, reveals that INT ranges from 2.38% to 100%, indicating a very wide spectrum. This also recommends that the digitalization process is undergoing a rapid structural transformation. Yet, the average value of REW, representing renewable energy, is 14.04%, reaching a maximum of around 50%. This specifies that the green energy transition is still in its early stages. Table 3 offers the preliminary tests and their interpretations that should be conducted before proceeding to model prediction.

Table 3. Preliminary descriptive tests

Test Type	Test Name	p-value	Result
Multicollinearity	Bivariate Correlation Test	INT-FIN: 0.5091 Others < critical value Besides; P<0.05 ln_CO2→REW:-0.7248 INT→ ln_CO2: 0.5484	The highest correlation amongst the independent variables is between INT and FIN. Other relations are below the critical value. Besides, when examining the direction of the variables, a negative relation is found betwixt ln_CO_2 and REW, while a positive relation exists betwixt INT and ln_CO_2. In the literature, this situation is explained as the expansion of technological infrastructure leading to increased energy demand, which can pollute the environment.
Cross-sectional Dependency	Pesaran CD Test	For all variables (GDP, ln_CO2, INT, REW, TRD, FIN, FDI, INF), the p-values are lesser than the 1% (0.01) significance level (p < .001)	Cross-sectional dependence exists. A macroeconomic shock in countries that are commercially and financially integrated, such as G20 countries, affects other countries as well. Hence, it was decided to perform second-generation panel unit root tests (CADF).
Second-Generation Panel Unit Root (Stationarity) Test	Pesaran CADF	I(0); FDI, p: .018 INF, p: .025 I(1); GDP: p:0.000 ln_CO2: p:0.000 INT: p:0.000 REW: p:0.000 TRD: p:0.000	The FDI and INF variables were stationary at the level, while the other variables became stationary after the first difference was taken. Due to missing data for some countries in the FIN data and the removal of another year from each country during the first difference calculation, the number of uninterrupted data points for some countries fell below the minimum limit. This led to the "insufficient observations" error. Hence, the FIN data was excluded from the analysis.
Co-integration	Persyn and Westerlund (2008)	P-Value: 1.000	There is no co-integration.

Table 3 submits the preliminary descriptive and explanatory tests and their interpretations that need to be performed before proceeding to model estimation. Although Table 3 states that no cointegration relation is found, traditional residual-based tests suffer from low test power in panels with short time dimensions and are insufficient to capture long-term relations. To tide over this methodological limitation, an ECM-based cointegration approach, which produces much stronger outcomes in short panels and under cross-sectional dependence, has been adopted. To reinforce this point, the negative and statistically significant Error Correction Term (ECT) obtained from the CS-ARDL (DCCE) estimator definitively proves the existence of a structural long-term cointegration relation betwixt the variables. The methodological superiority of the CS-ARDL (DCCE) estimator and the reasons for its preference are based on three fundamental econometric justifications. The first is that the high trade and financial integration among G20 countries creates Cross-Sectional Dependency (CSD). First-generation estimators, however, fail to capture unobserved common shocks, potentially producing inconsistent and misleading coefficients. Finally, the CS-ARDL estimator filters out CSD and common shocks by using cross-sectional averages of dependent and independent variables. It also produces unbiased short- and long-term parameters when assessing cointegration through dynamic error correction. Equation 2 demonstrates the model equation reconstructed according to the preliminary tests of the model.

$$\ln_CO2_{it} = \alpha_{it} + \beta_1 INT_{it} + \beta_2 REW_{it} + \beta_3 TRD_{it} + \beta_4 FDI_{it} + \varepsilon_{it} \quad (2)$$

$i=1\ldots19$

$t=2005\text{-}2023$

In the applied part of the research, before starting the analysis, the FIN and INF variables were also intended to be included in the model as independent variables. Yet, they were removed from the model because the missing data in the series disrupted the panel balance. Another reason for removing these variables from the model is that they violate the degrees of freedom constraints required by second-generation estimators (CS-ARDL). Besides, the main focus of the research is the "twin transition". It was decided that the GDP variable should not be included in the model to prevent the masking effect of technological indicators and to ensure the mathematical optimization of the CS-ARDL model. Ergo, the dataset was made completely strongly balanced for 19 countries and 19 years. Table 4 demonstrates the outcomes of the CS-ARDL (DCCE) estimator. This research has certain limitations. First, due to data unavailability in some macroeconomic variables such as financial development (FIN) and inflation (INF), these variables had to be excluded from the model. Second, the time dimension of the study is limited to the years 2005-2023. Finally, since the analysis exclusively covers G20 countries, the empirical findings obtained may not be directly generalizable to other groups of developing or underdeveloped countries.

Table 4. CS-ARDL (DCCE) model estimate

Variables	Coefficient	Std. Error	z-Statistic	P-value
Long Run Estimates (Pooled)				
INT	0.0031	0.0025	1.26	.209
REW	-0.0168	0.0166	-1.01	.312
TRD	-0.0002	0.0023	-0.07	.943
FDI	-0.0004	0.0203	-0.02	.986
Short Run Estimates (Mean Group)				
Δ INT	-0.0011	0.0010	-1.16	.248
Δ REW	0.0312	0.0398	0.78	.433
Δ TRD	0.0010	0.0006	1.56	.119
Δ FDI	0.0050**	0.0020	2.52	.012
Adjustment Term (ECT)				
ECT_{t-1}(L.ln_CO_2)	-0.4318**	0.1863	-2.32	.020
Diagnostic Statistics				
Observations	342			
Number of Groups	19			
R-squared	.440			
F-statistic	1.51***			(Prob > F = 0.000)
Pesaran CD Statistic	-0.30			(p-value = .765)

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The Δ operator denotes the first difference of the variables. ECT represents the Error Correction Term. The model includes cross-sectional averages of the variables to account for cross-sectional dependence (CSD). The insignificance of the Pesaran CD statistic (p > .05) confirms that the CSD issue has been successfully resolved.

Interpreting the outcomes in Table 4:

- The F-test is significant.
- The p-value in the CD test statistic was found to be 0.7653. This outcome specifies that the cross-sectional dependence in the model has been successfully eliminated.
- The ECT value was significant and negative at the 5% level. This outcome specifies a long-term cointegration relation betwixt carbon emissions (ln_CO2), digitalization (INT), green energy (REW), trade (TRD), and foreign direct investment (FDI). The coefficient of -0.43 specifies that when a short-term shock occurs in the system, 43% of this shock is corrected each year, and it returns to long-term equilibrium in approximately 2.3 years.
- In the selected group of countries, the G20 countries, no significant relation was found betwixt the twin transition, i.e., digitalization (INT) and green energy (REW), in the short term. In addition, no significant effect of trade openness (TRD) was found on carbon emissions (ln_CO_2). Foreign Direct Investment (FDI), however, is positive and significant. Sudden escalations in foreign investment increase environmental pollution in the short term. This outcome upholds that the "Pollution Haven Hypothesis" in the literature is valid in the short term.
- In the long term, although green energy investments (REW) in G20 countries tend to diminish carbon emissions (ln_CO_2), they are insufficient to initiate a structural transition process. Digitalization (INT), trade (TRD), and foreign direct investment (FDI) were also found not to have a significant influence on carbon emissions (ln_CO_2) in the long term.

These outcomes demonstrate that, specifically for G20 countries, digitalization and the green energy transition (twin transition) have not yet reached the expected and desired level of statistical significance in reducing carbon emissions, and their long-term effects are lacking. Although digitalization has been seen to expand efficiency as a different outcome in developed countries, the high energy demand brought about by digitalization in developing G20 countries still largely stems from fossil fuels. This status negates the positive effects of green energy. This demonstrates that unless the high energy demand brought about by digitalization is entirely met by green energy, achieving the twin transition will be highly challenging.

6. DISCUSSION AND CONCLUSION

The applied part of the research shows that the relation betwixt the twin transition (digitalization and green energy) and environmental quality in G20 countries contains a number of problems. The statistical output reveals that the Error Correction Term (ECT) was found to be negative and statistically significant. This proves that there is an intrinsic relation betwixt carbon emissions and other variables for G20 countries. The magnitude of the Error Correction Term coefficient indicates that when a macroeconomic short-term shock wave occurs, 43% of this shock is corrected each year, and it returns to long-term equilibrium in approximately 2.3 years. For instance, it becomes apparent that G20 countries quickly adapt to external shocks when there is a global energy crisis or a technological leap. In these countries, emission levels return to long-term equilibrium levels in a period of 2.3 years.

The primary contribution of this study lies in the reasons behind the insignificant outcomes of the long-term coefficients. As evidenced by the long-run coefficients, it was determined that digitalization (INT) and renewable energy consumption (REW) do not statistically significantly diminish carbon emissions in the long term. There are two main causes for this status:

1. Although digitalization diminishes carbon emissions and thus decreases environmental pollution in developed countries, the status is different for G20 countries. At one end of the spectrum, there are energy savings resulting from digitalization, but nevertheless, there is a high energy demand for processes such as data centers, cloud computing infrastructures, and cryptocurrency networks that accompany digitalization. That is, digitalization has both positive and negative effects in terms of energy. This status changes the picture in these countries and causes a "rebound effect." The energy sources of G20 countries are still largely fossil fuels. As digitalization enlarges, its influence on the environment is neutralized. This empirical result aligns with the energy rebound dynamics of Lange et al. (2020) and Ren et al. (2021) but contradicts the linear decarbonization results obtained by Lin and Zhou (2021). Furthermore, the lack of long-term emission reduction from renewable energy supports Unruh's (2000) "carbon lock-in" hypothesis. Licensing and tax incentives for data centers, cloud infrastructures, and artificial intelligence facilities should be tied to the requirement of 100% renewable energy use.

2. When the outcomes are examined in terms of green energy, green energy in G20 countries is still not in a position to replace fossil fuels. It is only in a complementary position. G20 countries have a huge share in global production. At one end of the spectrum, the share of renewable energy is increasing in these economies, but alternatively, total energy demand is rising precipitously. In this status, green energy remains only in a complementary position. Hence, we cannot see an improvement in environmental quality in the long term.
3. Environmental regulations should not be relaxed in order to attract foreign investment. This is a very important issue. Foreign direct investment in the industrial sector must be subject to Environmental, Social, and Governance (ESG) regulations; mandatory green technology transfer; carbon reporting; and compliance with national emission standards.
4. To fully replace fossil fuels with renewable energy, fossil fuel subsidies must be ended. This is one of the critical measures. The cost of polluting energy should be increased through carbon taxes and Emission Trading Systems (ETS). This will break the structural carbon lock-in in industry.

All these findings strikingly demonstrate that the impacts of the twin transition in G20 countries are not unidirectional; rather, they encounter various structural obstacles. Highlighting this fact clearly distinguishes the present study from existing literature. For instance, Muench et al. (2022) state that digitalization and green energy rapidly reduce emissions simultaneously; however, this presents an overly optimistic picture. In contrast, the findings of this study reveal the existence of high energy demand and fossil fuel dependency in G20 countries, thereby demonstrating that such optimistic scenarios are not yet realistic for these nations. Similarly, while Dong et al. (2020) argue that renewable energy investments reduce carbon emissions, this study challenges that view by proving that the effect loses statistical significance in the long run when cross-sectional dependence and common global shocks are taken into account. A comparative analysis suggests that this study serves as an empirical caveat against the "technological optimism" prevalent in the literature, emphasizing the need for a radical transformation in energy beyond merely the technological dimension of the twin transition.

The short-term findings of the research demonstrate that Foreign Direct Investment (FDI) has a significant and positive influence (0.0050) on carbon emissions at the 5% level ($p = 0.012$). This contributes to the literature in another way. This is the "Pollution Haven Hypothesis." Within the G20 countries, global capital flows are shifting in the short term towards countries with relatively flexible environmental protection laws, such as China, India, and Brazil. This leads to sudden increases in production while simultaneously increasing environmental pollution. This short-term positive effect of foreign direct investment on emissions strongly supports the findings of Sarkodie and Strezov (2019) and Copeland and Taylor (1994). Thus, this result empirically validates the Pollution Haven Hypothesis for G20 countries in the short term.

G20 countries account for approximately 80% of global greenhouse gas emissions (Adebayo et al., 2021). Hence, this group of countries has primary priority in reducing environmental

pollution. Macroeconomic measures taken in these countries are pivotal for global sustainability. Against this backdrop, in this era where digitalization is inevitable, governments should support investments in digital infrastructure while making clean energy an inseparable element. For this, incentives should be provided, and investment permits should be approved, making 100% renewable energy production a legal requirement. Moreover, countries should focus on increasing the share of renewable green energy in their energy mix while simultaneously implementing high carbon taxes to diminish the attractiveness of fossil fuels. To avoid becoming a country included in the "Pollution Haven Hypothesis," countries should bolster foreign direct investment. When accepting these proposals, environmental issues must also be considered. Against this backdrop, production by foreign investors that does not involve technology transfer and emits high carbon emissions should be restricted. Based on the information gathered, highly specific and immediately actionable policy recommendations will be provided to policymakers. First, the findings indicate that digitalization does not significantly improve carbon emission outcomes in the long run. Therefore, governments should promptly implement carbon taxes on energy-intensive sectors such as cryptocurrency mining and large-scale data centers. Furthermore, the study reveals that foreign direct investment (FDI) increases emissions in the short term; consequently, incentives for foreign capital require immediate review. To prevent this adverse effect in the future, strict Environmental, Social, and Governance (ESG) criteria should be mandated for incoming FDI. Conversely, foreign investments that facilitate the transfer of clean technology and green infrastructure should be supported through incentives and tax reductions, thereby paving the way for green foreign investment.

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Duygu Çelik and Mustafa Kerem Börü each contributed 50% to the study. Within the framework of the CRediT (Contributor Roles Taxonomy), Duygu Çelik was responsible for Conceptualization, Methodology, Formal analysis, Writing – original draft, and Writing – review & editing. Mustafa Kerem Börü was responsible for Conceptualization, Data curation, Investigation, Writing – original draft, and Writing – review & editing.

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Declaration of AI Assistance:
During the preparation of this study, the authors used Grammarly and Paperpal tools solely for language editing purposes during the translation stage. The outputs generated by the AI-assisted tools were reviewed and verified by the authors. The authors bear full responsibility for the scientific content, accuracy, originality, and integrity of the study.

In this study, the rules stated in the **"Higher Education Institutions Scientific Research and Publication Ethics Directive"** were followed.

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