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The relationship between digitalization, CO 2 emissions, and financial development

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Abstract:

This paper first examines the relationship between digitalization and CO_2 emissions to test the inverted U-shaped relationship predicted by the Environmental Kuznets Hypothesis. The results using the fixed effects, two-stage least squares, and generalized method of moments estimation coincide with this inverted U-shaped relationship suggesting that increases in digitalization increase CO_2 emissions up to a certain threshold of digitalization and then decrease it. An interaction term with financial development was then included in the model to determine the role that it plays in this inverted U-shaped relationship. Overall, results indicated that there is no strong evidence that financial development plays a role in the relationship between digitalization and CO_2 emissions. Since the nature of the relationship depends on the level of digital development of a country, this suggests that countries should have different policies when attempting to reduce emissions as they continue to digitalize.

I. Introduction:

Climate change has become a major issue facing the entire world population, with many devastating and irreversible effects to the environment. For example, Parry et al. (2004) found that climate change reduces global food production as a whole and has a particularly negative impact in developing countries, leading to increased starvation. Singh and Singh (2012) also found that climate change leads to rising sea levels and increases in disasters such as earthquakes and hurricanes. These environmental consequences associated with climate change lead to many health and economic issues. Paavola (2017) determined the negative health implications associated with climate change in the UK, finding that exposure to extreme heat or cold, pollution, pollen, and food safety risks are a few among the many health consequences associated with climate change. Hsiang et al. (2017) also found that climate change furthered existing economic inequalities present within the United States as poorer populations do not have access to insurance or health care to combat the adverse effects of climate change.

The leading cause of climate change is greenhouse gas emissions, such as carbon dioxide, CO_2, due to their contribution to the greenhouse gas effect. According to the Environmental Protection Agency, EPA, (2022), greenhouse gases absorb energy in Earth's atmosphere and slow down the transfer of heat from Earth to space. Although this phenomenon is completely natural and necessary, the increased amount of greenhouse gasses present in the atmosphere due to human activities has caused Earth's temperature to rise and the climate to change. According to the EPA (2022) the primary greenhouse gas contributing to climate change is carbon dioxide, CO_2, which can enter the atmosphere through the burning of fossil fuels in manufacturing. Thus, to reduce greenhouse gas emissions and prevent the expansion and continuation of climate change, CO_2 emissions must be reduced. Many countries have taken steps to reduce CO_2 emissions by switching to renewable energy sources such as solar or wind, but few have considered the impact that digitalization can have in curbing CO_2 emissions. In this paper, we consider such an impact.

Digitalization is defined as "the transformation of objects from physical to digital state, enabling communication and interaction between them" (Noussan & Tagliapietra, 2020). Barrutiabengoa et al. (2022), Thanh et al. (2022), Kopp and Lange (2019), and Yang et al. (2022) demonstrated a link between the level of digitalization and countries' CO_2 emissions, suggesting that increasing digitalization could be a potential solution to reduce climate change. This is especially important for developing countries that do not have the available resources to implement other changes such as switching to renewable energy sources.

According to theories proposed by Kopp and Lange (2019), Yang et al. (2022), and Ma et al. (2022), the net effect of digitalization on CO_2 emissions is ambiguous as digitalization could potentially impact emissions in two opposing ways. Digitalization could increase emissions due to the required Information Technology, ICT, to support it or could reduce emissions due to increased environmental awareness through Internet usage and the phasing out of coal consumption. Kuznets (1955) proposed an inverted U-shaped relationship between CO_2 emissions and level of economic development. Chen (2021) and Li et al. (2021) used digitalization to serve as a measurement of economic development. When considering this in terms of the model proposed by Kuznets, then CO_2 emissions initially increase as countries digitize. From a certain threshold, further digitalization reduces CO_2 emissions.

The objective of this study is to investigate the relationship between digitalization and CO2 emissions in light of the environmental Kuznets hypothesis. Obviously, not all countries are at the same level of financial development. Advanced countries have much deeper financial systems compared to poor countries. Hence, in the second part, we consider how the level of financial development affects the relationship between digitalization and CO2 emissions.

This study contributes to the literature by analyzing the effect of digitalization on CO_2 emissions in a broad range of countries. The literature has mainly focused solely on developed countries, particularly China (Yu and Zhu, 2022), (Cai and Song, 2022), and (Zhou, 2022). Additionally, countries who are members of the European Union (Liu et al., 2019), (Kuzior, 2013), and (Thanh et al., 2022) or BRICS countries (Yang et al., 2021) have been analyzed, all of which are countries with relatively high levels of digital development. The only studies that have analyzed the impact on the level of development have looked at different areas within one country, such as in China (Wu, Luo, and Luo, 2021), but have not analyzed such an impact using a wide range of different countries. If the Environmental Kuznets relationship is an accurate measurement of the relationship between digitalization and CO_2 emissions, only studying more developed countries can provide an incomplete picture of the true relationship.

This study also contributes to the literature by utilizing multiple measurements of digitalization rather than one single indicator as others have done. Since there is no comprehensive index to measure digitalization, most researchers have chosen one variable to represent the role of digitalization such as percentage of Internet users in the population (Chen, 2021) or ICT goods exports (Li, Liu, and Ni, 2021). To fully encompass all the aspects of digitalization in an economy, this study will use multiple indicators to proxy for the level of digitalization of a given country. Additionally, no authors have analyzed the role that the level of financial development plays in the relationship between digitalization and CO_2 emissions. This study fills the gap by analyzing such an impact.

Overall, we found the inverted U-shaped relationship between digitalization and CO_2 emissions to hold true when analyzing both developed and developing countries. Additionally, we found no strong evidence that the level of financial development of a country plays a significant role in this relationship.

Section II provides a summary of the existing literature surrounding this topic, including both the theory and how this study will fill gaps in the existing literature. Section III provides a summary of the data and methodology used to conduct the empirical analysis and section IV presents the results of the empirical analysis and a discussion of these results. Section V presents a conclusion with recommendations for policy and future research as well as limitations of the analysis.

I. Literature Review:

The Environmental Kuznets Curve suggests an inverted U-shaped relationship between environmental degradation and economic development (Kuznets, 1955). With CO_2 emissions serving as a proxy for environmental degradation and digitalization serving as a proxy for economic development, this relationship seems to hold up in the findings of Yang et al. (2022), Cai and Song (2022), and Barrutiabengoa et al. (2022), who found in their empirical studies that carbon emissions dropped after reaching a peak at a certain level of digitalization. This relationship is supported by Li et al. (2021), who studied a wide range of countries and found that digitalization initially had an ambiguous relationship with CO_2 emissions, but that once a certain threshold was reached by each country, the relationship was statistically significant and negative. Additionally, Lee et al. (2022) found that digitalization in the transportation sector increased carbon emissions at low levels of urbanization but decreased emissions at a high level of urbanization. Since urbanization is likely to be related to digitalization, this also supports the U-shaped relationship predicted by the Environmental Kuznets hypothesis.

Thus, depending on a country's level of digitalization, increasing digitalization levels could either reduce or increase CO_2 emissions. Digitalization could lead to an increase in emissions due to the increased energy required to implement infrastructure required to support increased digitalization levels or due to the rebound effect, but it could also reduce emissions by improving energy efficiency, encouraging more environmentally friendly policies, and increasing knowledge sharing and innovation. Thus, the degree of each of these effects of digitalization will influence the net impact of digitalization on each country's CO_2 emissions.

Barrutiabengoa et al. (2022) found in their empirical study that digitalization reduces carbon emissions through optimizing energy use and making production more efficient. The Association of German Engineers reported that digitalization increases the efficiency of resources up to 25%

(Kopp and Lange, 2019). In their empirical analysis, Yang et al. (2022) found that this increase in resource efficiency leads to an increase in energy efficiency, contributing to the reduction in carbon emissions that is associated with increased levels of digitalization.

The empirical study conducted by Ma et al. (2022) suggested that another mechanism through which digitalization can reduce CO_2 emissions is by improving the efficiency of coal consumption. This study found a statistically significant negative relationship between digitalization and CO_2 emissions in China. Since China relies heavily upon coal consumption as an energy source, the negative relationship observed is likely due to the improved efficiency of its consumption as a result of increased digitalization.

Ma et al. (2022) also suggested that the implementation of the Internet and technology encourages people to become more active in pursuing environmentally friendly policies. This may be because the Internet has made people more aware of environmental concerns and methods to address these concerns, pushing them to become more concerned with maintaining a healthy environment. Specifically, Thanh et al. (2022) found that digitalization led to an increase in non-fossil and renewable energy consumption. This indicates that one mechanism for the reduction in carbon emissions associated with digitalization is through increased popularity of policies and fuel sources that have a better environmental impact. Zhu et al. (2022) reported that digitalization improves the ability to share knowledge and information which can lead to increased innovation, lowering CO_2 emissions. Similarly, Ordieres-Mére et al. (2020) found a statistically significant negative relationship between digitalization and CO_2 emissions in European Union member countries, citing intra-organizational knowledge sharing, which is supported by the digitalization of the work environment, as the source behind this relationship. Alternatively, Barrutiabengoa et al. (2022) reported a shift in consumer preferences towards dematerialization as a result of increased digitalization. This dematerialization can lead to a decrease in consumer demand and result in decreased production, contributing to reduced carbon emissions.

Digitalization can lead to a reduction in CO_2 emissions by increasing energy and resource efficiency, encouraging people to pursue more environmentally friendly policies, and increasing knowledge sharing and innovation. Alternatively, digitalization could also have an adverse effect on emissions due to the rebound effect and the energy expansion often required to accompany digitalization. For example, digitalization requires the development and operation of infrastructure that requires a lot of energy and thus results in increases in CO_2 emissions (Yang et al., 2022). This is especially true in countries with low levels of digitalization that do not already have the necessary infrastructure to support increases in digitalization. Likewise, Thanh et al. (2022) found that emissions tend to rise dramatically in the first stages of digitalization which they attribute to the development of new infrastructure that is required to foster digitalization. Yu and Zhu (2022) found that digitalization generally fosters economic expansion which leads to increases in emissions associated with increases in production. Kopp and Lange (2019) found that ICTs represent about 8% of global energy use and expect this number to continue to rise as countries adopt policies of digitalization. The increased productivity that accompanies increased digitalization can also lead to a “rebound effect” in which consumer prices are lowered because of this improved efficiency which causes higher demand and an increase in total production which leads to an increase in emissions (Kopp and Lange, 2019). Additionally, Yu and Zhu (2022) found that an improvement in energy efficiency due to digitalization will lead to an increase in energy consumption which will produce more carbon emissions. Thus, digitalization can lead to an overall increase in CO_2 emissions due to increases in energy consumption whether it be to accompany the new infrastructure required to implement digital technologies or due to the rebound effect.

As a result of these opposing effects of digitalization on CO_2 emissions, the literature has overall produced relatively inconclusive results surrounding the net impact of digitalization on emissions. Chen (2021) found that the direction of the relationship between digitalization and CO_2 emissions depends on the country being studied, with some countries yielding a negative relationship and others yielding a positive one. The inverted U-shaped relationship suggested by the Environmental Kuznets Curve may help to provide closure to these inconclusive results and will be tested in this study.

Since the level of digitalization is highly correlated with a country's level of economic development, the relationship between digitalization and CO_2 emissions likely depends on the level of economic development of a country. Wu et al. (2021) found that digitalization has a statistically significant positive effect on the environment in China's developed regions, but a statistically significant negative one in the underdeveloped regions, again suggesting a U-shaped relationship between emissions and digitalization. Likewise, Yang et al. (2022) found that digitalization had a larger and statistically significant negative impact on CO_2 emissions in the central and western regions of China which are more digitally developed.

This study contributes to the literature by determining the relationship between digitalization and CO_2 emissions in a wide range of developed and developing countries. Other research in this area has mainly focused on one country or group of countries with similar levels of digitalization, particularly more digitally developed countries. However, it is important to consider countries at all levels of development to fully capture the Environmental Kuznets Curve and mitigate sample selection bias. This study also uses multiple measurements of digitalization rather than a single indicator as others have done and considers how the level of financial development of each country impacts the relationship between digitalization and CO_2 emissions.

II. Methodology and Data:

Our empirical model is based on the endogenous growth theory as developed by Chen (2021). According to Chen (2021), digitalization helps improve the efficiency of labor and optimize the allocation of resources, leading to economic growth which can increase standards of living. Since the standard of living has an inverted U-shaped relationship with CO_2 emissions according to the Environmental Kuznets Hypothesis, the direct relationship between digitalization and the standard of living demonstrated by Chen (2021) suggests that there should also be an inverted U-shaped relationship between digitalization and CO_2 emissions. The functional form of the model is:

$$CO_{2it} = f(Dig_{it}, GDP_{it}, FDI_{it}, FD_{it})$$

where CO_{2it} is CO_2 emissions, Dig_{it} is the level of digitalization, GDP_{it} is per capita gross domestic product (GDP), FDI_{it} is net foreign direct investment, and FD_{it} is the level of financial development. Based on the work of Chen (2021), Li, Liu, and Ni (2021), and Kopp and Lange (2019), the functional form can be rewritten in econometric form as:

$$lnCO_{2it} = \alpha_{it} + \alpha_0 + \alpha_1 lnDig_{it} + \alpha_2 (lnDig_{it})^2 + \alpha_3 lnGDP_{it} + \alpha_4 FDI_{it} + \alpha_5 FD_{it} + \mu_{it}$$

A quadratic term is included in the model because of the nonlinear relationship between CO_2 emissions and digitalization predicted by the Environmental Kuznets Curve, EKC, and verified by other research (Wu, Luo, and Luo, 2021) and (Yang et al., 2022). This is also consistent with Li et al. (2021) who found that the relationship between the air quality index and economic growth exhibits the EKC phenomenon. Since panel data will be used, α_{it} represents the country and/or time fixed effects and helps to control for omitted variable bias for those variables that vary between countries but not over time or those that vary over time but not between countries. μ_{it} represents the random error term. α_i (i=1, 2, and 3) is the elasticity, showing the percent change in the dependent variable, CO_2 emissions, associated with a one percent change in the independent variable associated with that coefficient. α_i (i=4 and 5) is the marginal effects, showing how a one unit change in foreign direct investment or financial development impacts CO_2 emissions.

After testing the Environmental Kuznets Hypothesis using the first model, a second model is constructed using an interaction term with the financial development variable. This will test whether the level of financial development has an impact on the relationship between digitalization and emissions. The econometric form of this model is specified as:

$$lnCO_{2it} = \alpha_{it} + \alpha_0 + \alpha_1 lnDig_{it} + \alpha_2 (lnDig)^2 + \alpha_3 lnGDP_{it} + \alpha_4 FDI_{it} + \alpha_5 FD_{it} + \alpha_6 (lnDig_{it} * FD_{it}) + \alpha_7 (\ln (Dig_{it}))^2 * FD_{it} + \mu_{it}$$

The control variables utilized in this model are per capita GDP, net foreign direct investment, and financial development. Chen (2021), Li et al. (2021), and Kopp and Lange (2019) used per capita GDP as a control variable when analyzing this relationship. Based on their findings, a positive, statistically significant relationship is expected between per capita GDP and CO_2 emissions. Other studies in this area including Chen (2021), Li et al. (2021), and Zhu et al. (2022) have also included capital as a control variable which is why net foreign direct investment, FDI, is included in this model. Per capita GDP will already account for domestic capital, so including net foreign direct investment as a control will account for foreign capital as well. A positive, statistically significant relationship between CO_2 emissions and FDI is expected based on the findings of these studies. Financial development, measured as domestic credit as a percentage of GDP, is also included as a control variable within the model because countries with higher levels of financial development tend to digitize and also tend to have higher levels of emissions. Thus, a positive relationship between financial development and CO_2 emissions is expected.

The independent variable, digitalization, is expected to exhibit a nonlinear, inverted U-shaped relationship with CO_2 emissions based on the EKC and its application to these variables. The EKC demonstrates this inverted U-shaped relationship between environmental degradation and economic development. Li et al. (2021) and Chen (2021) used CO_2 emissions to proxy for environmental degradation and digitalization to proxy for economic development so this inverted U-shaped relationship is expected to hold true for these variables as well.

The coefficients of the model are first estimated using the OLS regression with panel data. Three different models of the regression are developed: the country fixed effects, the time fixed effects, and the combined country and time fixed effects. The country fixed effects model controls for those omitted variables that vary between countries but are constant over time, the time fixed effects model controls for those omitted variables that vary over time but are constant between countries, and the combined entity and time fixed effects model controls for both types of omitted variables. This helps to control for the omitted variable bias that could stem from failing to include control variables in the model that are correlated with both digitalization and CO_2 emissions. In each of these three specifications of the model, clustered standard errors are used. This controls for any bias in the analysis due to heteroskedasticity, when the independent variable is correlated with the error term, and autocorrelation, when the error terms are correlated with each other.

While the fixed effects techniques control for the omitted variable bias, they do not control for the reverse causality between CO_2 emissions and digitalization. Hence, a Two Stage

Least Squares, 2SLS, analysis is also performed. Yang et al. (2022) used digital application, or a measurement of the application of the digitalized services for use by consumers as their instrumental variable. The number of mobile prescriptions per 100 people is used to identify the application of the digital services for daily use by consumers and is used as an instrument. Wu et al. (2021) used the first and second lag of the digitalization and digitalization squared terms as instruments for their analysis. Combining these instrumental variables, when using individuals using the Internet to measure digitalization, we use the first lag of the digitalization term, the first lag of the digitalization squared term, and mobile prescriptions per 100 people as instruments. When using fixed broadband prescriptions to measure digitalization, we use the first two lags of the digitalization and the digitalization squared term as instruments. Both forms of the model, with and without the interaction terms, are estimated using this technique and are also estimated using the GMM analysis with the same instrumental variables as a robustness check.

Panel data from 82 countries over the time periods of 2000 through 2019 gathered from the World Development Indicators was used for the analysis. The countries used for the analysis are included in Appendix 1. The independent variable, CO_2 emissions, was measured as the total CO_2 emissions of each country in kt with an average of 263, 943.4 kt. Since there is no comprehensive index or evaluation indicators to measure digitalization, measurement of this variable was accomplished based on the measurements of other research in this area. The percentage of the population using the Internet (Chen, 2021) and fixed broadband prescriptions per 100 people were used to estimate the independent variable, digitalization with average values of 301.299% and 8.920 prescriptions respectively. Foreign direct investment was measured using net inflows of foreign direct investment as a percentage of GDP with an average of 4.077%. The control variable GDP was measured using per capita GDP in current US dollars like (see, for instance, (Chen, 2021), (Li et al., 2021), and (Yang et al., 2022) with an average of 12358.81 dollars and financial development was measured using domestic credit to private the private sector as a percentage of GDP with an average of 55.740%. Mobile cellular prescriptions per 100 people was used as an instrumental variable for the analysis with an average of 78.752 prescriptions. Table 1 includes the descriptive statistics for each of these variables. Table 2 includes the correlation coefficients between the variables utilized in the model. Since the variables *internet* and *broadband* are both measurements of digitalization, a higher correlation between these variables is expected and is present in the analysis. The other measured correlation coefficients are relatively low, signaling that multicollinearity, or correlation between two of the regressors, is not an issue.

Table 1. Summary Statistics

Variable:	Obs:	Mean:	Standard Deviation:	Min:	Max:	Units:
CO_2 emissions *(co2)*	1660	263943.4	1058698	120	1.07e+07	Kilotons (kt)
Individuals using the internet *(internet)*	1635	301.297	10739.82	0.0362613	434300	% of population
Fixed broadband prescriptions *(broadband)*	1454	8.920	11.084	0	46.907	Number per 100 people
Per capita GDP *(gdp)*	1660	12358.81	17762.48	113.567	113218.7	Current US dollars
Net foreign direct investment *(fdi)*	1660	4.077	41.836	6.556	260.618	% of GDP
Domestic credit *(dom)*	1449	55.740	45.773	3.113	304.575	% of GDP
Mobile cellular prescription	1655	78.752	47.226	0.018	205.910	Prescriptions per 100 people

s *(mobile)*

Table 2. Correlation Coefficients for variables of interest

	CO_2	internet	broadband	gdp	fdi	broadband	mobile
CO_2	1						
internet	0.188	1					
broadband	0.181	0.840	1				
gdp	0.241	0.719	0.755	1			
fdi	-0.092	0.003	0.020	0.011	1		
dom	0.356	0.633	0.616	0.721	0.053	1	
mobile	0.056	0.712	0.522	0.348	0.022	0.343	1

III. Empirical Results and Discussion:

This section contains the results from several regressions to measure the relationship between digitalization and CO_2 emissions and then determine the role that financial development plays in this relationship. We measure digitalization using both individuals using the Internet (Table 3) and fixed broadband prescriptions (Table 4). We then included an interaction term in the model to determine the role that financial development plays in this relationship which is modeled using both individuals using the Internet (Table 5) and fixed broadband prescriptions (Table 6). Finally, we conducted a 2SLS analysis for both specifications of the model using both individuals using the Internet (Tables 7 and 8) and fixed broadband prescriptions (Tables 9 and 10) to measure digitalization.

Relationship between individuals using the Internet and emissions

Table 3 shows the results of the three different fixed effects specifications using individuals using the Internet as a measurement of digitalization. The coefficients associated with *lndig* and *lndig2* are consistent with the quadratic, inverted U-shaped relationship predicted by the EKC and are statistically significant at the 1% level with the time fixed effects specification with only the squared term significant at the 10% level using the country fixed effects specification. The coefficient on the control variable *lngdp* is positive and significant at the 1% level across all specifications.

Table 3. OLS regression results with individuals using the internet as measurement of digitalization

Variables	Entity fixed effects lnco2	Time fixed effects lnco2	Entity and time fixed effects lnco2
lndig	0.183	0.394***	0.394***
	(0.120)	(0.070)	(0.091)
$lndig^2$	-0.040*	-0.049***	-0.049**
	(0.021)	(0.013)	(0.019)
dom	-0.001	0.001	0.001
	(0.002)	(0.001)	(0.002)
lngdp	0.694***	0.696***	0.696***
	(0.142)	(0.041)	(0.135)
fdi	0.003	0.003	0.003
	(0.003)	(0.003)	(0.003)
constant	4.053***	3.392***	3.392***
	(0.999)	(0.341)	(1.141)
observations	1433	1433	1433
Number of countries	82	82	82
R-squared	0.342	0.383	0.383

Note: All regressions are based on OLS regression analysis. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

Relationship between fixed broadband prescriptions and emissions

The results in Table 4 show the relationship between fixed broadband prescriptions and CO_2 emissions using the three different fixed effects specifications. The coefficients associated with *lndig* and *lndig2* coincide with the predicted inverted U-shaped relationship between digitalization and emissions based on the EKC. The squared term of digitalization is significant at the 5% level across all specifications. The control variable *lngdp* exhibits a positive relationship with CO_2 emissions and is statistically significant at the 5% level with the inclusion of time fixed effects.

Table 4. OLS regression results using fixed broadband prescriptions as a measurement of digitalization

Variables	Entity fixed effects lnco2	Time fixed effects lnco2	Entity and time fixed effects lnco2
lndig	0.021	0.024	0.024
	(0.054)	(0.018)	(0.037)
$lndig^2$	-0.009**	-0.011***	-0.011***
	(0.004)	(0.002)	(0.003)
dom	-0.002	-0.0004	-0.0004
	(0.002)	(0.001)	(0.002)
lngdp	0.344	0.454***	0.454**
	(0.209)	(0.044)	(0.222)
fdi	0.002	0.005**	0.005
	(0.002)	(0.002)	(0.003)
constant	7.269***	5.736***	5.736***
	(1.718)	(0.379)	(1.589)
observations	1289	1289	1289
Number of countries	82	82	82
R-squared	0.224	0.297	0.297

Note: All regressions are based on OLS regression analysis. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

Relationship between individuals using the Internet, emissions, and financial development

Table 5 shows the relationship between individuals using the internet and CO_2 emissions including the interaction term with financial development using an OLS estimation. The coefficients associated with the digitalization terms again demonstrate the expected inverted U-shaped relationship with the inclusion of the time fixed effects specification. The digitalization term is statistically significant at the 1% level with this specification. The coefficients associated with the interaction terms are not statistically significant.

Table 5. OLS regression results using individuals using the internet as measurement of digitalization for model with interaction terms

Variables	Entity fixed effects lnco2	Time fixed effects lnco2	Entity and time fixed effects lnco2
lndig	-0.001	0.351***	0.351***
	(0.167)	(0.106)	(0.159)
$lndig^2$	0.012	-0.031*	-0.031
	(0.034)	(0.018)	(0.032)
dom	0.005	0.008*	0.008*
	(0.005)	(0.003)	(0.006)
$lnDig_{it} * dom_{it}$	0.002	-0.003	-0.003
	(0.003)	(0.003)	(0.003)
$(\ln(Dig_{it})^2 * dom_{it}$	-0.001	0.0001	0.0001
	(0.001)	(0.001)	(0.001)
lngdp	0.664***	0.675***	0.675***
	(0.142)	(0.043)	(0.137)
fdi	0.003	0.003	0.003
	(0.003)	(0.003)	(0.003)
constant	4.216***	3.461***	3.461***
	(0.982)	(0.349)	(1.136)
observations	1433	1433	1433
Number of countries	82	82	82
R-squared	0.353	0.385	0.385

Note: All regressions are based on OLS regression analysis. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

Relationship between fixed broadband prescriptions, emissions, and financial development

Table 6 reports the OLS regression results for the relationship between fixed broadband prescriptions and CO_2 emissions including an interaction term with financial development to determine the role that this plays in their relationship. The coefficients associated with the digitalization terms exhibit the inverted U-shaped relationship that is consistent with the EKC and the squared term is statistically significant at the 5% level across all specifications. The coefficients associated with the interaction terms are not statistically significant.

Table 6. OLS regression results using fixed broadband prescriptions as measurement of digitalization for model with interaction terms

Variables	Entity fixed effects lnco2	Time fixed effects lnco2	Entity and time fixed effects lnco2
lndig	0.010	0.026	0.026
	(0.068)	(0.020)	(0.045)
lndig^2	-0.012**	-0.012***	-0.012***
	(0.005)	(0.002)	(0.005)
dom	-0.001	-0.001	-0.001
	(0.004)	(0.001)	(0.004)
$lnDig_{it} * dom_{it}$	0.0002	0.0002	0.0002
	(0.001)	(0.0002)	(0.001)
$(\ln(Dig_{it})^2 * dom_{it}$	0.0001	0.0001	0.0001
	(0.0001)	(0.0001)	(0.0001)
lngdp	0.341	0.452***	0.452**
	(0.211)	(0.044)	(0.215)
fdi	0.002	0.005**	0.005
	(0.002)	(0.002)	(0.003)
constant	7.339***	5.870***	5.870***
	(1.713)	(0.389)	(1.340)
observations	1289	1289	1289
Number of countries	82	82	82
R-squared	0.226	0.299	0.299

Note: All regressions are based on OLS regression analysis. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

2SLS results for individuals using the Internet

The 2SLS regression results when individuals using the Internet served as a measurement of digitalization for both models are reported in Table 7. The digitalization variables in both models exhibit the inverted U-shaped relationship that coincides with the EKC hypothesis and are statistically significant at the 1% level besides the squared term in the second model. The linear interaction term is statistically significant at the 1% level and indicates that a high level of financial development influences the relationship between digitalization and CO_2 emissions.

The diagnostic tests indicate that both models have strong instruments that are exogenous. The first-stage F-test for weak instruments indicates that both F-statistics are greater than 10 and the J-test of overidentifying restrictions has p-values that are greater than 10% meaning that the instruments are both strong and exogenous.

Table 7. Two Stage Least Squares Regression analysis results, J-test p-value, and first-stage F-statistic using individuals using the internet to measure digitalization

	$lnCO_2$	$lnCO_2$
lndig	0.411***	0.389***
	(0.035)	(0.120)
$lndig^2$	-0.039***	-0.021
	(0.006)	(0.020)
dom	0.001***	0.011***
	(0.0004)	(0.003)
$lnDig_{it} * dom_{it}$		-0.003***
		(0.002)
$(\ln(Dig_{it})^2 * dom_{it}$		0.0002
		(0.0004)
lngdp	0.016	-0.008
	(0.035)	(0.042)
fdi	0.002**	0.003**
	(0.001)	(0.001)
observations	1369	1369
R-squared	0.499	0.483
J-test p-value	0.698	0.928
First-stage F-statistic	235.493	148.535

Note: All regressions are based on two-stage least squares estimator. Mobile cellular prescriptions per 100 people, the first lag of individuals using the internet, and the first lag of individuals using the internet squared are used as the instruments. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

2SLS results for fixed broadband prescriptions

Table 8 shows the 2SLS results when fixed broadband prescriptions were used to measure digitalization for both models. The coefficients associated with the digitalization terms are consistent with the EKC hypothesis and exhibit the inverted U-shaped relationship between digitalization and CO_2 emissions. These coefficients are significant at the 5% level or higher in both models. The squared interaction term is statistically significant at the 1% level and indicates that at much higher levels of digitalization, higher financial development affects the relationship between digitalization and CO_2 emissions.

The diagnostic tests suggest that both models have strong, exogenous instruments. The first-stage F-statistic is greater than 10 in both models suggesting that the instruments are strong and the J-test for overidentifying restrictions rejects the null hypothesis and suggests that the instruments are exogenous at the 10% level. Thus, the instruments are valid as they are both strong and exogenous.

Table 8. Two Stage Least Squares Regression Analysis results, J-test p-value, and first-stage F-statistic using fixed broadband prescriptions to measure digitalization

	$lnCO_2$	$lnCO_2$
lndig	0.044***	0.056**
	(0.009)	(0.012)
lndig2	-0.020***	-0.014***
	(0.002)	(0.003)
dom	0.003***	0.005***
	(0.001)	(0.001)
$lnDig_{it} * dom_{it}$		-0.002
		(0.0002)
$(\ln(Dig_{it})^2 * dom_{it}$		-0.0001***
		(0.0001)
	(0.030)	(0.030)
fdi	-0.001	-0.001
	(0.001)	(0.001)
observations	1148	1148
R-squared	0.486	0.508
J-test p-value	0.984	0.347
First-stage F-statistic	934.254	650.561

Note: All regressions are based on two-stage least squares estimator. The first two lags of the natural log of fixed broadband prescriptions and the first two lags of the natural log of fixed broadband prescriptions squared are used as the instruments. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

IV. Robustness Check

In this section, we run a robustness check to validate the results associated with the 2SLS regressions. We use the Generalized Method of Moments, GMM, estimator as an alternative to the 2SLS estimator to compare the results. While 2SLS is a limited information estimator, the

GMM is a full information estimator meaning that GMM simultaneously estimates all of the equations together while 2SLS estimates each individually.

GMM robustness check for individuals using the Internet

The GMM results associated with the two models when individuals using the Internet is used to measure digitalization are reported in Table 9. These results provide strong qualitative and quantitative support for the results obtained from 2SLS, confirming the inverted U-shaped relationship between digitalization and CO_2 emissions associated with the EKC hypothesis. Since the interaction terms are not statistically significant, the results also imply that the level of financial development has no impact on the relationship between digitalization and CO_2 emissions. The diagnostic tests also indicate that the instruments are valid as they are both strong and exogenous. The first-stage F-statistic is greater than 10 for both models, indicating the instruments are strong, and the p-values associated with the J-test of overidentifying restrictions are greater than 10% indicating that the instruments are exogenous. Thus, the results obtained through the GMM estimation coincide with the results of the 2SLS regressions and indicate that the instruments used are valid.

Table 9. GMM regression analysis results, J-test p-value, and first-stage F-statistic using individuals using the internet to measure digitalization

	$lnCO_2$	$lnCO_2$
lndig	0.410***	0.364***
	(0.035)	(0.117)
$lndig^2$	-0.040***	-0.017
	(0.006)	(0.020)
dom	0.001***	0.011***
	(0.0004)	(0.003)
$lnDig_{it} * dom_{it}$		-0.003
		(0.002)
$(\ln(Dig_{it})^2 * dom_{it}$		0.0001
		(0.0004)
lngdp	0.021	-0.004
	(0.033)	(0.042)
fdi	0.002**	0.003**

	(0.001)	(0.001)
observations	1369	1369
R-squared	0.500	0.483
J-test p-value	0.698	0.928
First-stage F-statistic	235.493	148.535

Note: All regressions are based on GMM estimator. Mobile cellular prescriptions per 100 people, the first lag of individuals using the internet, and the first lag of individuals using the internet squared are used as the instruments. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

GMM robustness check for fixed broadband prescriptions

Table 10 reports the results obtained through the GMM estimation when fixed broadband prescriptions were used to measure digitalization. These results coincide with those obtained from the 2SLS regression, again providing strong qualitative and quantitative support for those results. These results also verify the inverted U-shaped relationship between digitalization and CO_2 emissions associated with the EKC hypothesis. The statistical significance of the squared interaction term at the 1% level suggests that at higher levels of digitalization, the level of financial development does impact the relationship between digitalization and CO_2 emissions.

Table 10. GMM regression analysis results, J-test p-value, and first-stage F-statistic using fixed broadband prescriptions to measure digitalization

	$lnCO_2$	$lnCO_2$
lndig	0.044***	0.057**
	(0.009)	(0.012)
lndig2	-0.021***	-0.013***
	(0.002)	(0.003)
dom	0.003***	0.005***
	(0.001)	(0.001)
$lnDig_{it} * dom_{it}$		-0.0001
		(0.0002)
$(\ln(Dig_{it})^2 * dom_{it}$		-0.0002***
		(0.0001)
lngdp	0.190***	0.182***
	(0.030)	(0.030)
fdi	-0.001	-0.001
	(0.001)	(0.001)

observations	1148	1148
R-squared	0.486	0.509
J-test p-value	0.984	0.347
First-stage F-statistic	934.254	650.561

Note: All regressions are based on GMM estimator. The first two lags of the natural log of fixed broadband prescriptions and the first two lags of the natural log of fixed broadband prescriptions squared are used as the instruments. Robust standard errors are included in parentheses below each variable's coefficient with ***p<0.01, **p<0.05, and *p<0.1

V. Transmission Channels

Relationship between digitalization and CO_2 emissions

The inverted U-shaped relationship between digitalization and CO_2 emissions predicted by the EKC hypothesis is supported by the results of the study. This indicates that digitization initially leads to increases in CO_2 emissions until a certain threshold of digitalization has been reached. Once this threshold has been reached and surpassed, additional increases in digitalization lead to a reduction in CO_2 emissions.

This inverted U-shaped relationship is likely because more energy will be needed to implement the infrastructure required to support increases in digitalization at lower levels of digitalization. Yang et al. (2021) found a positive relationship between digitalization and CO_2 emissions due to the increase in energy demand resulting from digitalization. Energy demand increases in response to increased digitalization because of the construction or updating of infrastructure required to implement higher levels of digitalization. According to Yang et al. (2022), developing and operating digital infrastructure requires large amounts of energy, especially in countries with low levels of digitalization and little experience with such infrastructure. This increased energy demand will be more prevalent at lower levels of digitalization because the country will not already have the infrastructure necessary to support digitalization. At higher levels of digitalization, the country will already have much of the infrastructure required to support increases in digitalization, so the environmental benefits associated with increasing digitalization such as increased efficiency and knowledge sharing overwhelm the increased energy demand, resulting in the negative relationship with emissions that is observed.

Another explanation for this inverted U-shaped relationship is that at higher levels of digitalization, countries will likely have larger amounts of innovations and knowledge sharing accompanying their increases in digitalization since they are more experienced with digital technologies. Ordieres-Mère et al. (2020) report that digitalization increases intra-organizational knowledge sharing which can lead to innovation. This innovation leads to reductions in CO_2 emissions when it is focused on leading to more environmentally friendly production processes as cited by Ma and Fenglan (2023) who found that digitalization fostered increased green patent innovation. This innovation of technologies to promote environmental sustainability is more likely to occur at higher levels of digitalization when a country has more experience with digitalization and innovations surrounding it.

Role of financial development

Altogether, there is not strong evidence that financial development influences the relationship between digitalization and CO_2 emissions. This means that the level of financial development may not matter for the impact that digitalization has on CO_2 emissions. One reason for this is that the existence of mobile financial services in a particular country does not necessarily mean that the country and its members have fully adopted and are using these mobile services. For financial development to play a role in the relationship between digitalization and CO_2 emissions, these mobile services would have to be adopted and used by members of each country. Additionally, the existence of such mobile financial services is recent, meaning that the data might not have fully captured their development and integration within each country that was studied.

VI. Conclusion

In this paper, we investigate the relationship between digitalization and CO_2 emissions in a range of developing and developed countries to test the EKC hypothesis and determine the role that financial development plays in this relationship. The entity fixed effects, time fixed effects, 2SLS, and GMM estimation methods were applied to panel data from 82 countries over the time period of 2000 to 2019. The results support the inverted U-shaped relationship between digitalization and CO_2 emissions specified by the EKC hypothesis. Additionally, the results suggest that there is no strong evidence that financial development influences the relationship between digitalization and CO_2 emissions.

The results of this study also provide support for some policy implications. Specifically, countries should have different policy goals as they continue to digitalize based on their levels of digitalization. First, all countries, but specifically those with lower levels of digitalization should focus on implementing environmentally friendly innovations as they continue to digitalize. This is especially true for those countries with lower levels of digitalization which can help them to combat the increase in emissions that is associated with increases in their digitalization. Specifically, the International Telecommunication Union (2019) suggests that countries focus research on the use of technology to improve the energy efficiency of buildings, use more renewable resources, and reduce traffic congestion. Such research and innovations can help to minimize CO_2 emissions as the use of digital technology increases.

Additionally, countries, specifically those with lower levels of digitalization, should attempt to find more energy efficient methods to implement the infrastructure required to support increased levels of digitalization. The results suggest that this increased energy required to implement digitalization infrastructure, particularly at lower levels of digitalization where such infrastructure is not already in place, results in the increases in emissions that are observed with increases in digitalization. Thus, finding more energy efficient methods to increase digitalization infrastructure is imperative to reduce CO_2 emissions and prevent climate change in those countries with lower levels of digitalization.

The results of this study also suggest that increases in digitalization should be focused on improving energy efficiency to reduce emissions as digitalization levels are increased. One potential method of doing so is to increase digital finance infrastructure along with digitalization. Zhou (2022) found that digital finance helps to guide the flow of financial resources towards more efficient areas of the market. As the market becomes more efficient, less energy will be required to produce the same amount of output, resulting in a reduction in CO_2 emissions. Similarly, Wang et al. (2022) suggest supporting the development of the digital economy to reduce carbon emission intensity. Additionally, Guo and Ma (2022) found that increased integration between industries and communication among companies resulted in improved efficiency levels. Thus, focusing efforts on increasing communication both between and within industries as countries continue to digitalize could help improve efficiency and reduce emissions.

Although the findings of this study were robust, there are some limitations. First, since mobile financial services such as mobile banking are so new, the impact of their development and adoption may not have been fully captured by the data used in the study. This could explain why financial development was not observed to impact the relationship between digitalization and CO_2 emissions. Additionally, although a wide range of countries were studied, due to the availability of the data, the data used for analysis was slightly skewed more towards countries that are more financially and digitally developed. This could have also impacted the results by failing to fully capture the left side of the inverted U-shaped relationship.

While this research captured the inverted U-shaped relationship between digitalization and CO_2 emissions predicted by the EKC, there are some aspects that could be expanded upon in future research. Firstly, the relationship between digitalization and CO_2 emissions could be studied in different sectors of the economy. Lee et al. (2022) found the inverted U-shaped relationship between digitalization and CO_2 emissions to hold true in the transportation sector. The relationship between the two variables may be different, however, in other sectors of the economy. Additionally, it may be beneficial to determine the specific threshold or peak of the EKC at which increases in digitalization start to reduce CO_2 emissions as this would be useful when making policy decisions. Thus overall, future research in this area could focus on determining this threshold or peak and studying different sectors of the economy.

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Appendix 1:

Albania	Algeria	Argentina	Armenia
Australia	Azerbaijan	Bahamas	Barbados
Belarus	Belize	Benin	Bolivia
Bosnia and Herzegovinian	Botswana	Brazil	Brunei Darussalam
Bulgaria	Burundi	Cambodia	Central African Republic
Chile	China	Columbia	Costa Rica
Croatia	Czechia	Denmark	Dominican Republic
Ecuador	Egypt	El Salvador	Eswatini
Gambia	Georgia	Ghana	Honduras
Hungary	Iceland	Jamaica	Japan
Jordan	Kazakhstan	Kenya	Kuwait
Kyrgyz Republic	Lebanon	Lesotho	Madagascar
Malaysia	Mauritius	Mexico	Moldova
Morocco	New Zealand	Nicaragua	Niger
Norway	Oman	Paraguay	Peru
Philippines	Poland	Romania	Russian Federation
Samoa	Saudi Arabia	Senegal	Singapore
South Africa	Sweden	Switzerland	Tanzania
Thailand	Togo	Trinidad and Tobago	Tunisia
Turkey	Uganda	Ukraine	United Kingdom
United States	Uruguay	Vietnam	