Economics of Climate Change

How do digitalization and decarbonization efforts interact?

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Executive summary

- **Digitalization is expected to help decarbonization in the medium and long term** in low digitized countries, while it is already fostering CO2 emission reductions in highly digitized economies. Consequently, a long-term tradeoff does not exist between investments in digitalization and emissions.
- The empirical results suggest an **inverted U-shaped relationship between digitalization and CO2 emissions,** consistent with a level story; in early stages of digitalization emissions increase and with further development emissions decrease. That is, **specific thresholds of digitalization need to be reached in order to start reducing emissions.**
- According to our cross-country estimations between 1990 and 2019, the marginal average effect of digitalization (proxied by the percentage of internet users over that period) on CO2 emissions seems to be small compared with the effect of other variables (e.g. GDP per capita).
- But once the thresholds are reached, the **direct or pure effect** of digitalization has the potential to reduce emissions as much as 10% (if catching up to the frontier), while the **total effect**, which includes energy efficiency gains and easier access to renewables, could be close to a **maximum of 45%.**
- The thresholds estimated in this work were **58.73% of internet users for the direct effect but only 44.21% for the total effect.** Internet users have been used as the main proxy of digitalization due to two reasons: the data availability of the variable and its high cross-country variance and correlation with the digitalization Index (DiGiX) over the years under analysis.
- By 2020, almost 60% of the sample countries were above the direct-effect threshold, while the percentage increases to 70% when considering the threshold for the total effect. Persian Gulf's Arab states are the countries with the highest percentages of internet users, together with European and North American nations. On the other hand, African countries take up the last positions in the ranking.
- Looking forward, as the digital frontier continues to move outwards - with platforms, cloud computing, etc - we expect further gains from digitization well past its simple usage by a country's population.

1. Digitalization and decarbonization: opportunities and challenges

The actual socioeconomic context has reinforced and accelerated a number of long-term global trends, in particular sustainability and digitalization, two of the most disruptive. Therefore, how governments and firms face these challenges is key to their success.

Both trends pose significant challenges and, simultaneously, offer huge opportunities (see Figure 1). Sustainability has transformation costs heavily front-loaded and could be disruptive in the short-term, but at the same time, it could spur technological changes and productivity gains, as well as a higher energy efficiency and a lower carbon intensity. Sustainability could also help conserving natural capital and reversing ecosystems' degradation.

On the other hand, digitalization is the engine of productivity growth[1] and thus, long-run prosperity. Nevertheless, at the same time, it poses significant challenges to firms and people that cannot keep up, requires high investment costs, creates labor market risks derived from polarization (caused by cognitive routinary task automation) and could even defy sustainability if not properly managed.

Figure 1. **MAIN OPPORTUNITIES AND CHALLENGES OF SUSTAINABILITY AND DIGITALIZATION**

SUSTAINABILITY

OPPORTUNITIES

Higher energy efficiency and lower carbon intensity

More competitive, productive and sustainable economy

Conservation of natural capital and reversion of ecosystems' degradation

CHALLENGES

High transformation costs

Near-term economic adjustment (it may be disruptive in the short term)

DIGITALIZATION

OPPORTUNITIES

Engine of productivity growth

Long-run prosperity

Helps decarbonization

CHALLENGES

Risks on labour market: polarization

High investment costs

Source: BBVA Research

1: Brynjolfsson & McAfee, A. (2011).

2. Using digitalization to achieve decarbonization

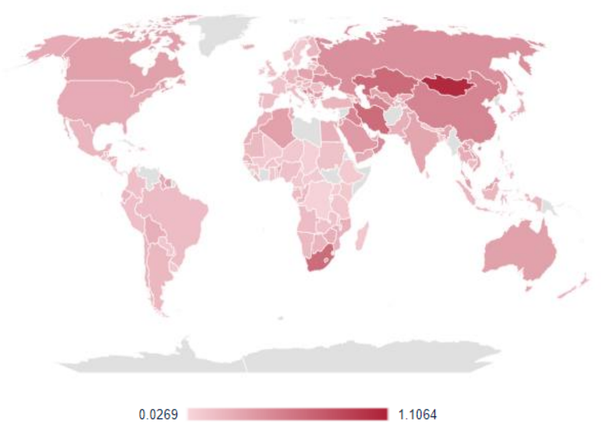
Digitalization has the potential to either help or hinder the fight against climate change. Thus, reconciling these two trends to ensure they complement each other is one of the great challenges of our time, given that both are crucial for economic and social prospects. Digitalization has become an indispensable tool for achieving the objectives of a green economy, but yet, technology itself is also responsible for a significant amount of pollution (Martín & Ortega, 2021).

What is the net-effect of digitalization on decarbonization? **Several studies[2] indicate that digitalization reduces carbon emissions in the medium and long-term.** Put another way, digitalization is increasingly seen as a key driver for decarbonization, and lately, economists and politicians are arguing that increases in digitalization have a net-positive effect on the environment (e.g. Li et. al. (2021); World economic forum (2019); Kopp and Lange (2019); Teufel (2022)). Nevertheless, these studies could be overestimating the effects through increases in resource efficiency while underestimating rebound effects and the negative environmental impact of complex digital infrastructures.

The literature on the environmental impact of Information and Communication Technologies (ICT) usually distinguishes between different layers of digitalization. Most taxonomies include first higher order effects (Horner et al., 2016; Pohl et al., 2019), which entail the production, use phase and disposal of technologies, but the total ICT impact also involves additional mechanisms (substitution, optimization and rebound effects). Rebound effects occur when an increase in production efficiency leads to lower consumer prices. This, in turn, involves more economic activity and a higher demand.

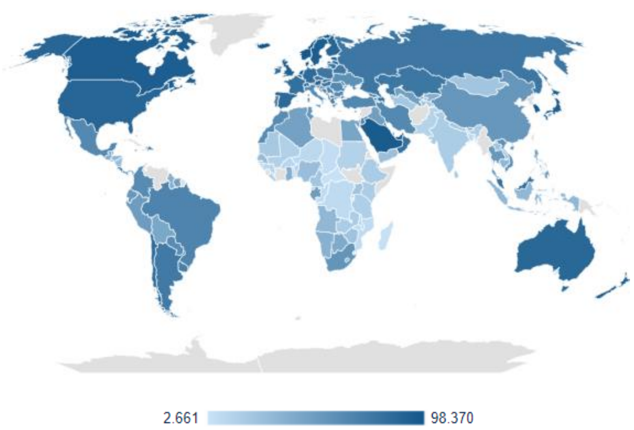
In this context, only with an aggregated analysis and considering all the mechanisms, the net-impact of digitalization on climate change can be assessed. Figure 2 and 3 below show the 2017 CO2 intensity (kg / PPP US$) and internet users (as a percentage of population) for more than 160 countries in the world. As it can be seen, assessing the relationship between these two variables is very complicated, and hence, a simple level comparison may lead us to confusion, being primordial to control for the effects that variables as GDP per capita have.

Figure 2. **CO2 INTENSITY** (KG/GDP PPP US$, 2017)



Source: BBVA Research

Figure 3. **INTERNET USERS** (%, 2017)



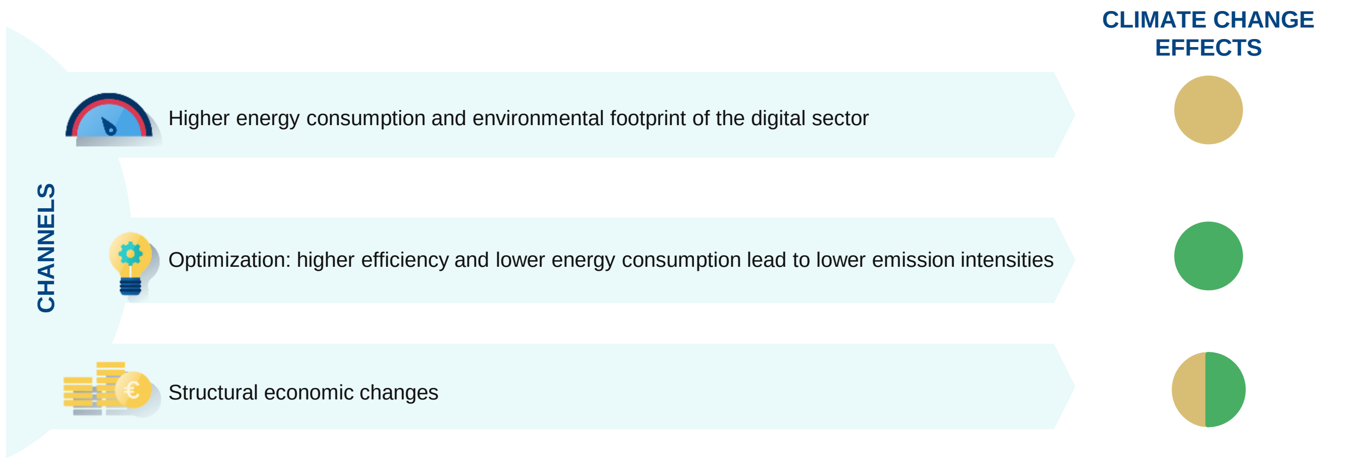
Source: BBVA Research

2: See Li et. al. (2021), Digitales (2020) or Kopp and Lange (2019) for example.

2.1. Impact of digitalization on carbon emissions: channels

Digitalization may impact decarbonization through three different channels: higher energy consumption and carbon footprint of the digital sector, optimization, and structural economic changes (see Figure 4).

Figure 4. **CHANNELS THROUGH DIGITALIZATION MAY IMPACT CARBON EMISSIONS**



Source: BBVA Research

Channel 1. Higher energy consumption and carbon footprint of the digital sector

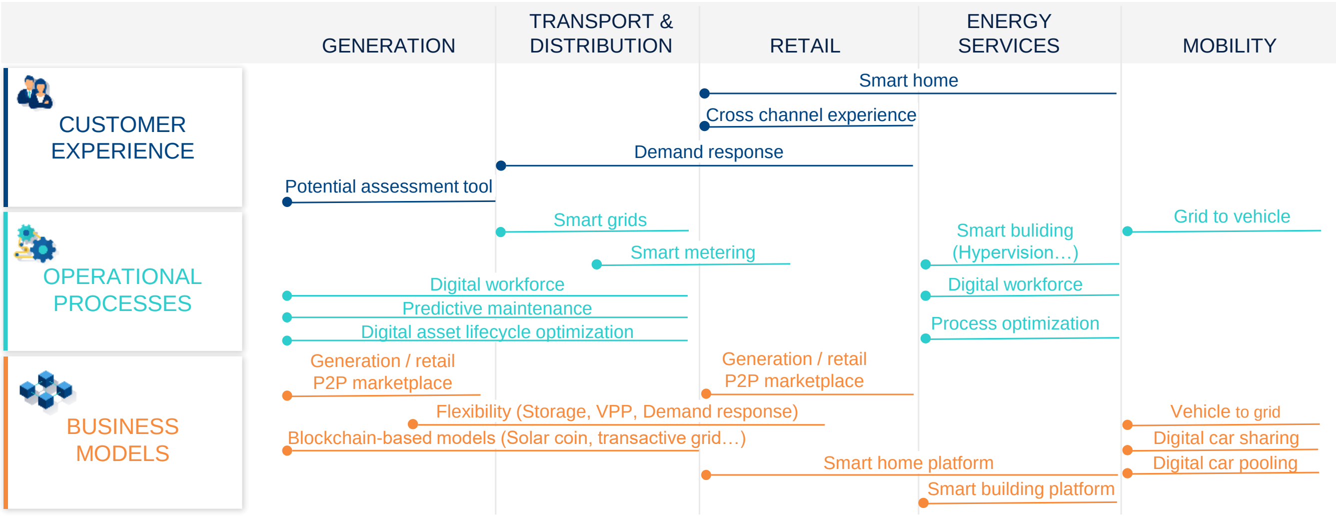
Digitalization has become a decisive instrument for the ecological transformation process and also for achieving the Sustainable Development Goals (SDGs) within the 2030 Agenda, set up in 2015 by the United Nations General Assembly. Nevertheless, the digital sector is responsible for a significant amount of energy consumption and pollution. In the period 2018-2020, the primary energy and the electricity consumed by the sector respectively amounted to 3% and 7% of total consumption in the world, and generated 5% of total CO2 emissions. Moreover, the electricity consumed by the sector is rapidly increasing, 9% a year (Martín & Ortega, 2021), although its effects on climate depend on the source of energy (whether it comes from fossil fuels or from clean sources). This is a key aspect in which both business and national and international institutions are making progress.

Channel 2. Optimization

Another relevant channel is optimization, which helps improve production processes and products, makes activities more efficient and reduces mobility and CO2 emissions (agriculture, energy, buildings…). For example, energy efficiency in buildings could increase with the automation and optimization of energy consumption, or the production and storage of equipment could be more efficient without reducing the level of comfort and quality parameters of the working environment.[3] Put another way, digital technologies, such as sensors, networked devices, and data analytics, are already changing how energy is produced, used and consumed across the economy. As digitalization expands, it is creating new opportunities to optimize energy production and use, and decrease CO2 emissions. Figure 5 (please see below) illustrates the range of opportunities that digital levers provide to the energy system.

3: Robust optimization for energy transition planning in manufacturing firms

Figure 5. **OPTIMIZATION: LOWER AND GREENER ENERGY CONSUMPTION**



Source: BBVA Research

Channel 3. Structural economic changes

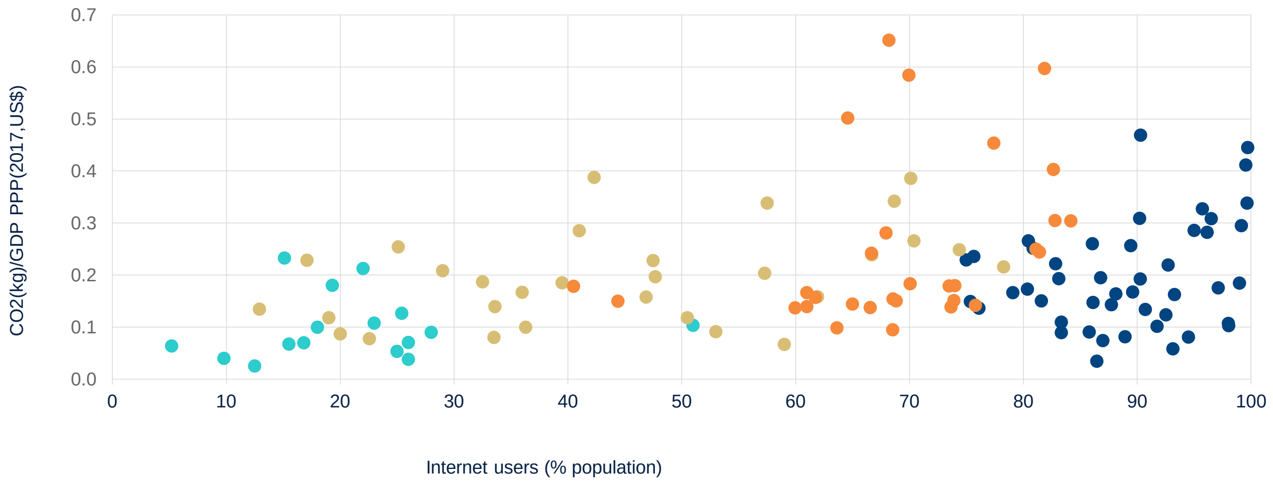
Structural economic changes such as consumer preference changes and dematerialization may also impact carbon emissions, positively or negatively.

Dematerialization through the replacement of physical products with virtual goods is seen as one of the possibilities to abate the environmental impacts through ICT applications, e.g. video streaming vs. DVD watching, ebooks vs. paper books (Liu et. al., 2019). On the other hand, structural economic changes include the intended and unintended consequences of the wide application of digitalization such as the medium or long-term adaptation of behavior (e.g. consumption patterns) or economic structures. These changes may be positive or negative for the environment. As an example, (Liu et. al., 2019) mention that the optimization of logistics has decreased the cost of logistic services, so retailers can afford to offer free delivery and return to consumers, which has dramatically changed consumer online shopping behavior, increasing energy usage (higher demand) and hence, emissions. On the contrary, digitalization has facilitated teleworking, which reduces transport, and hence, CO2 emissions.

Figure 6 below illustrates internet users' percentages and CO2 emissions per GDP PPP for more than 160 countries classified by their income level according to the World Bank's categorization[4]. From Figure 6, it can be stated that the effect of digitalization in carbon emissions has a close relationship with the income level of the country. Moreover, as suggested by different quantitative studies (see how and Li, 2014; Neagu, 2019; Li et al, 2021) an inverted U-shaped relationship between both variables seems to exist, at least graphically and cross-sectionally. Persian Gulf's Arab states are the countries with the highest percentages of internet users, together with European and North American nations. On the other hand, African countries take up the last positions in the internet users ranking.

4: Four groups are defined: low income, $1,045 or less; lower middle income, $1,046 to $4,095; upper middle income, $4,096 to $12,695; and high income, $12,696 or more.

Figure 6. **INTERNET USERS AND CO2 EMISSIONS PER UNIT OF GDP PPP** (2017 US$). 2019



Source: BBVA Research

3. Global panel model

In order to analyze the relationship that may exist between decarbonization and digitalization, a fixed-effect global panel has been estimated.

Our panel data estimation can be supported by models such as Li, X. et. al., (2021) (see Annex II). Li, X. et. al. (2021) present a theoretical model where digitalization is introduced into the Solow growth model as an additional component of technological progress, building a dynamic equilibrium model between carbon emissions and digitalization. Due to the technological progress derived from digitalization, companies renew their equipment and increase their CO2 intensive output in the early stage of economic development, thus increasing CO2 emissions, while in high digitalization stages the cost of pollution treatment is lower due to digitalization, thus reducing emissions.

3.1. Empirical models

3.1.1. Data

Homogeneous and widely available series of data to proxy digitalization and decarbonization have been considered in order to construct the analysis. Produced CO2 per capita has been selected as the main decarbonization proxy, assuming that countries with less emissions per capita are more decarbonized, and the proportion of internet users over the total population has been used to proxy digitalization.

Production-side annual data of CO_2 emissions per capita for 167 countries, measured in tonnes for the period 1990-2019, was retrieved from the Global Carbon Budget. This accounting method (production-side), which is sometimes referred to as 'territorial' emissions, is used when countries report their emissions and set targets domestically and internationally. Note that these series measure territorial CO_2 emissions but not the ones emerging from international trade. The decision of choosing this variable as the main proxy of decarbonization instead of consumption-based CO_2 emissions per capita is related with the fact that digitalization affects emissions (mainly) from the production perspective, together with the fact that production-side emissions are more accurate and widely available as they are required by the United Nations.

	Variable, model name	Type	Description, source,unit	Sample
CO2 emissions	**Production-side CO2 emissions, pco2a**	Dependent variable	**Production-based CO2 emissions per capita; Global Carbon Budget and Penn World Table; tonnes per million individuals (annual)**	**1990-2019**
	Consumption-side CO2, cco2a		Consumption-based CO2 emissions per capita; Global Carbon Budget and Penn World Table; tonnes per million individuals (annual)	1990-2018

The variable internet users as percentage of the total population includes both estimates and survey data corresponding to the proportion of individuals using the Internet. These data are based on results from national household surveys. Among other digitalization proxies (unit servers, fixed-broadband subscriptions,...), internet users have been used as the main proxy of digitalization due to two reasons: the data availability of the variable and its high cross-country variance and correlation with the digitalization Index (DiGiX) over the years under analysis.

	Variable, model name	Type	Description, source,unit	Sample
Digitalization proxy	**Internet users, iusea**	Main independent variable	**Internet users (%), ITU. This indicator can include both; estimates and survey data corresponding to the proportion of individuals using the Internet; based on results from national households surveys**	**1990-2019**
	Unit servers, serva		Secure Internet serves per capita. Source: Netcraft and World Bank (2020). Definition: The number of distinct, publicly-trusted TLS/SSL certificates found in the Netcraft Secure Server Survey per million individuals.	2010-2019
	Fixed-broadband subscriptions, broaa		Fixed subscriptions to high-speed access to the public Internet (a TCP/IP connection); at downstream speeds equal to; or greater than; 256 kbit/s. World bank. Per million individuals.	2000-2019

Finally, as control variables five relevant variables that influence CO_2 emissions have been included, as long as they were statistically significant in the analyzed models. These variables, detailed in the table below, are the following: GDP per capita, real output-side gross domestic product at chained PPPs (2017 US$); Energy consumption, terawatt-hours per million (2017 US$); Share of renewables, percentage of total final energy consumption; Urbanization, people living in urban areas as percentage of total population; and Industry, value added in mining, manufacturing, construction, electricity, water and gas, as percentage of GDP. Data, which has been retrieved from several sources (the Penn World Table, World Bank, Global Carbon Budget, ITU and British Petroleum databases...) goes from 1990 to 2019 and covers 167 countries.

	Variable, model name	Type	Description, source,unit	Sample
Control variables	Real GDP at chained PPPs: Output side (rgdpoa), expenditure side (rgdpea).	Control variables, independent variables.	Penn World table. Output-side real GDP per individual to compare relative productive capacity across countries and over time. Expenditure-side real GDP per individual to compare relative living standards across countries and over time. In million 2017US$ per capita.	1970-2019
	Energy consumption, enera		Energy consumption in terawatt-hours per million 2017 US$. British Petroleum.	1965-2019
	Share of renewables, reni		Renewable energy consumption is the share of renewable energy in total final energy consumption. World Bank.	1985-2019
	Urbanization, urba		Urban population (% total population) refers to people living in urban areas as defined by national statistical offices. Our World in data.	1960-2019
	Industry, indu		Industry (% GDP) corresponds to ISIC divisions 10-45. It comprises value added in mining, manufacturing, construction, electricity, water, and gas. World Bank.	1960-2019

3.1.2. Model specifications

The main goal of this study is to analyze the relationship that exists between CO2 emissions and digitalization. For that, and according to the theoretical model, the following assumption has been made: the relationship between CO2 and digitalization is not linear. This nonlinearity may be related with tipping points or even a quadratic relationship, as it is concluded in Li, X. et. al., (2021). So, in order to check if this is the case, a quadratic component of internet users, the proxy used for digitalization, has been introduced in the model. The quadratic component captures the non-linearities between digitalization and CO2 emissions.

The models have been estimated in levels, so concerns about spurious or not true causal relationships between variables may arouse. In a spurious correlation, what appears to be a cause-and-effect relationship between two variables is often a coincidental relationship or a third confounding factor that is affecting both variables. However, a long term cointegration relationship can be assumed[5] between digitalization and CO2 emissions, according to the Kao and Pedroni tests, which do not reject the cointegration hypothesis at a 1% significance level. The significance and the good behavior of the variables included in the models, even when estimated with robust standard errors, also provide additional evidence on the strength and robustness of the results.

All in all, the reference models can be defined as fixed-effect global panel models, with data from 1990 to 2019 and for 167 countries. Produced CO2 emissions is the dependent variable, while the explanatory variables consist of the linear term of digitalization, the quadratic term of digitalization and a set of control variables that the literature has suggested as variables that influence CO2 emissions; GDP per capita, urbanization level, energy consumption, industry share and renewables share. Note that other variables, such as the share of the service sector in the total economy, have also been tested, but they were not included in the model as they were not significant in statistical terms. Moreover, year and country fixed effects have also been included according to the Hausman test. Note that fixed effects help to decrease the concern regarding omitted factors that may be correlated with key predictors at the group level and mitigate the time trend (time invariant cross country effects or, fixed cross country time variant effects). Finally, robust standard error estimators have been used to solve possible problems of heteroskedasticity and autocorrelation in the panel data[6].

5 Note that if two variables share a non-stationary term in such a way that a linear combination of the two variables is stationary, then both variables are said to be cointegrated. When the two variables are cointegrated the estimated long-term relationship is not spurious.
6 The reason for robust standard errors in panel data is because the idiosyncratic errors can have heteroskedasticity or autocorrelation and clustering handles all of these issues.

Figure 7. **FIXED-EFFECT GLOBAL PANEL DATA**

$$\ln CO2 = \beta 0 + \beta 1(\ln digital) + \beta 2 (\ln digital)^2 + \beta 3 X + FE + \varepsilon$$

CLIMATE CHANGE (CO2)

Production based CO2 emissions per capita (tonnes per capita)

DIGITALIZATION (digital)

Internet users (% population)

CONTROL VARIABLES (X) AND FE

GDP per capita

Urbanization level (% population)

Industrialization (% GDP)

Renewable energy share (% total energy)

Country and year fixed-effects (FE)

SAMPLE

167 countries

Annual data 1990-2019

Source: BBVA Research

In this context, two main models have been proposed in the study. The first model (Mod 1) controls for possible indirect effects that digitalization may have in CO2 emissions through control variables (i.e. energy intensity or the use of renewables), reflecting, the digitalization coefficients, the direct net-effect or the pure shock of digitalization on CO2 emissions. Therefore, the effect of digitalization captured by this model is not directly related to the optimization and energy consumption channels presented in the previous section, but could be related with structural economic changes such as the transition from physical to virtual products or changes in consumer preferences driven by higher digitalization (e.g. more information available or more connected societies) towards more sustainable products or lifestyles. Equation [1] below presents the direct model specification:

Mod 1

$$[1]\ \ ln\,(pco2a) = \beta_0 + \beta_1\, iusea + \beta_2\, iusea2 + \beta_3\, ln\,(rgdpoa) + \beta_4\, ln(enera) + \beta_5\, reni + \beta_6 urba + \beta_7 indu + FE + \varepsilon$$

$$[1]\ ln\,(pco2a) = 12.43 + 0.0015 iusea - 0.000026 iusea2 + 0.64 ln\,(rgdpoa) + 0.54 ln(enera) - 0.012 reni + 0.005 urba + 0.003 indu + FE + \varepsilon$$

Table 1 includes the estimated coefficients of Mod 1. All the coefficients are significant at a 10% significance level and have the expected sign, suggesting a statistically significant relationship between digitalization and CO2 emissions (the quadratic term of digitalization is significant at a 1% significance level).

Table 1. **PANEL DATA. MODEL SELECTION**

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
iusea	-0.00552***	0.00616***	0.00334**	0.00171	0.0012	0.00151	**0.0015***
iusea2		-0.00012***	-0.00009***	-0.00004***	-0.00003***	-0.00003***	**-0.00003*****
rgdpoa			0.27689***	0.20418***	0.64889***	0.64772***	**0.63849*****
reni				-0.02209***	-0.01329***	-0.01274***	**-0.01233*****
enera					0.53513***	0.54911***	**0.54068*****
indu						0.00271*	**0.00286***
urba							**0.0050***
constant	14.48785***	14.51084***	12.06032***	13.39229***	12.69597***	12.69036***	**12.43055*****
Adjusted R-squared	0.1789	0.2569	0.3112	0.4829	0.6473	0.6548	**0.6569**
Within R-squared	0.1849	0.2625	0.3165	0.4870	0.6503	0.6581	**0.6603**

*p<0.1,**p<0.05, ***p<0.01.
Source: BBVA Research

The second model specification (Mod 2) tries to capture the total effect of digitalization on emissions. For that, two different approaches have been developed. First, in order to break down the total effect arising from energy intensity, from a higher use of renewable energy, and the direct impact of digitalization, the effects of digitalization on renewable energy and on energy intensity have been approximated (see Equations [2] and [3]). Then, assuming unidirectionality, that is, that digitalization impacts energy intensity and renewables, but not vice-versa, the effect of digitalization on these indirect channels, and consequently on emissions, can be approximated and added to the direct impact calculated in the first model specification [1] (Mod 1).

It is worth noting that the total effect obtained this way (see the results section below) is almost identical to the one obtained if energy intensity and renewables are taken from Equation [1], and hence, the indirect effects of digitalization are taken into account (related with the energy consumption and optimization channels).

$$[2]\quad ln\,(enera) = \beta_0 + \beta_1\, iusea + \beta_3\, ln\,(rgdpoa) + \beta_6 urba + \beta_7 indu + FE + \varepsilon$$

$$[3]\quad reni = \beta_0 + \beta_1\, iusea + \beta_3\, ln\,(rgdpoa) + \beta_6 urba + \beta_7 indu + FE + \varepsilon$$

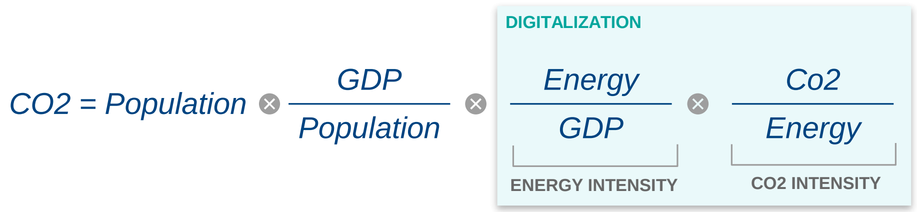
Mod 2

$$[4]\ ln\ (pco2a) = \beta_0 + \beta_1\ iusea + \beta_2\ iusea2 + \beta_3\ ln\ (rgdpoa) + \beta_6 urba + \beta_7 indu + FE + \varepsilon$$

$$[4]\ ln\ (pco2a) = 11.37 + 0.0037 iusea - 0.000083 iusea2 + 0.22 ln\ (rgdpoa) + 0.018 urba + 0.006 indu + FE + \varepsilon$$

The variables energy intensity and renewable share are closely related with Kaya's decomposition of emissions, with renewable share being inversely related to CO2 intensity. The Kaya identity is a simple mathematical framework, introduced in 1995 to assess the main factors governing global CO2 emissions (Kaya, 1995); changes in CO2 emissions can be traced to population growth, economic activity per capita, energy intensity and carbon or CO2 intensity as percentage of the total energy consumption. Thus, with a growing global population and increasing economic production, the Kaya identity reveals that overall emissions will increase unless the energy intensity and/or carbon intensity are reduced. Therefore, the indirect effect of digitalization on these two terms is crucial to capture the whole effect on CO2 emissions.

Figure 8. **KAYA'S DECOMPOSITION OF CO2 EMISSIONS**



Source: BBVA Research

3.2. Results

Direct impact of digitalization on CO2 emissions

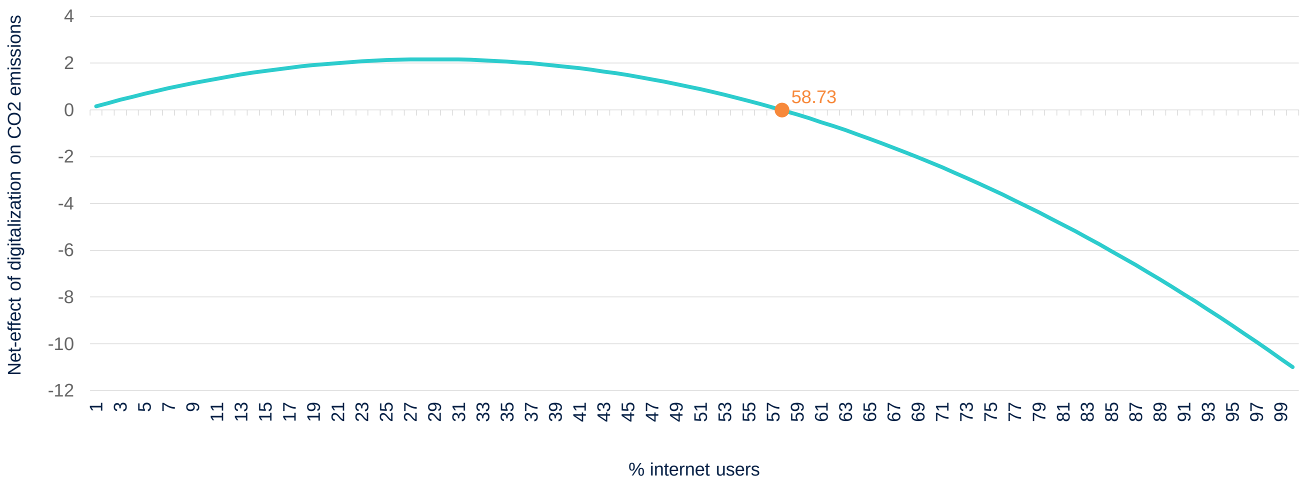
First of all, a discussion is presented with the focus on the digitalization coefficients (iusea and iusea2) (Table 1) to determine whether these are significant or not and to assess if an inverted U-shaped relationship between CO2 emissions and digitalization exist. In Model 2 above, without control variables, iusea and iusea2 are statistically significant at the 1% significance level. Regarding their signs, the linear component is positive (0.00616) and the quadratic component is negative (-0.00012), indicating that CO2 emissions increase at early stages of digitalization and decrease after a threshold is reached. So, an inverted U-shaped relationship seems to exist between digitalization and CO2 emissions.

By adding control variables (GDP per capita, share of renewables in total energy, energy intensity, industry share and urbanization level) into the model (Models 3 to 7 on Table 1), the digitalization coefficients remain statistically significant in both cases, decreasing their value when energy intensity and renewable share are included in the model. This suggests that the indirect effects of digitalization in these two variables seem to exist.

Among all the model specifications, Model 7 would be the most appropriate according to the adjusted R-squared measurement. In this estimated model, the threshold or turning point is 58.73% (see Figure 9), noting that digitalization reduces CO_2 emissions once the internet users ratio is equal or higher than this level. It is worth stressing that this model shows the average direct effect of digitalization on CO_2 emissions (in percentage) as long as the effect of other variables is controlled. So, it could be interpreted as the pure effect of a shock of digitalization in emissions. Note that the figures below show the net effect of digitalization for different digitalization levels, that is, the net effect of the lineal and the quadratic component.

In this context, although the average marginal effect of digitalization is low compared to the effect of other control variables, as GDP per capita, it goes as high as 10% at the maximum. That is, an accumulated 10% reduction in emissions could be reached if ceteris paribus, a country that has just arrived at the threshold, fully digitalized itself. The decision to take the 59% as our threshold is based on the fact that from 59% onwards the net effect of digitalization starts being negative, and hence, in terms of emissions, a country is indifferent between being 0% or 59% digitalzed. In 2020, around 60% of the sample countries were above the threshold.

Figure 9. **DIRECT NET EFFECT OF DIGITALIZATION ON CO2 EMISSIONS (%)**



Source: BBVA Research

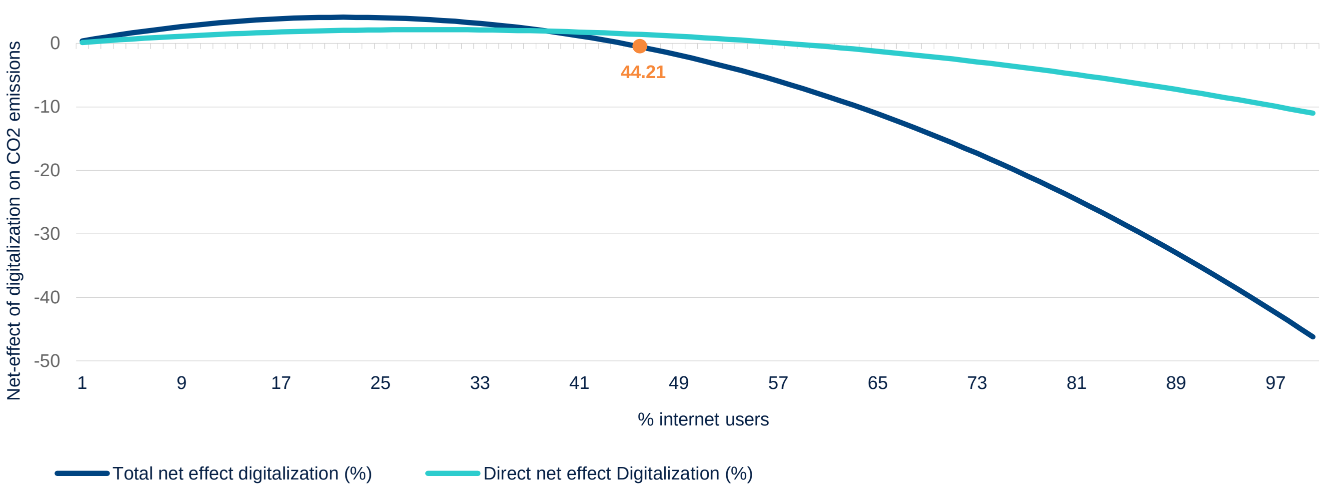
In summary, the direct effect model suggests that the relationship between digitalization and CO_2 emissions tells a level history, or in other words, specific levels of digitalization have to be reached in order to obtain environmental benefits. In order to corroborate this hypothesis (and since once the threshold is passed the quadratic component loses strength and the relationship is almost linear) a linear specification has also been tested with similar results, where digitalization is defined by a dummy equal to zero if the country is below the threshold at time t; and equal to the difference between the internet users ratio and the threshold (iusers - threshold) if the country is above the threshold (see the robustness test section in Annex I for further details regarding this and other additional checks performed).

Total impact -direct and indirect- of digitalization on CO2 emissions

However, digitalization also seems to have indirect effects on CO2 emissions through the optimization channel, which may influence both energy intensity and CO2 intensity in the Kaya's identity. For example, a higher use of apps thanks to digitalization may be beneficial at the time of reducing and controlling energy consumption, while higher digitalization levels may facilitate the expansion of renewables. That is, both data and theory suggest that digitalization also decreases energy intensity and increases renewable use (inversely related to CO2 intensity), consequently reducing CO2 emissions per capita indirectly. Thus, if energy intensity and renewable share are modeled as dependent variables, the analysis shows that the expected effects are statistically significant in both cases.

In this context and assuming unidirectionality, the direct and indirect effects can be added, or what it has resulted similar in quantitative terms, remove energy intensity and renewables' share from the specification. So, including indirect effects, digitalization could reduce CO2 emissions as much as 45% since the threshold is reached until the population is fully digitalized (100% of internet users). From this total average effect, and thanks to the equations presented above, it can be said that 12% comes from the direct effect and the rest from the indirect effects (17% from renewables' share and another 17% from energy intensity impact).[7] Furthermore, if indirect effects are included the minimum threshold decreases from 59% to 44% (see Figure 10), being 70% of the sample countries above this new threshold in 2020. Therefore, the results suggest that digitalization is expected to help decarbonization, at least, in the medium and long term, as it helps decarbonization once the threshold is reached. Note again that Figure 10 below shows the net effect of digitalization for different digitalization levels, that is, the net effect of the lineal and the quadratic component.

Figure 10. **TOTAL NET EFFECT OF DIGITALIZATION ON CO2 EMISSIONS (%)**



Source: BBVA Research

7 iusea is statistically significant at a 1% significance level in both Equations [2] and [3]. Equation [2]: iusea = -0.003 and Equation [3] iusea = 0.128. Therefore, as long as the effect of renewable share and energy intensity on emissions is known from Equation [1], the indirect effect of digitalization on emissions can be calculated.

4. Conclusions

The existing research suggests that digitalization is expected to help decarbonization in the medium and long term in low digitized countries, while it is already fostering emission reductions in highly digitized economies. In other words, digitalization has the potential to reduce carbon emissions once a threshold or minimum level of digitalization is reached. The empirical results point to an inverted U-shaped relationship between digitalization and CO_2 emissions, consistent with a level story; in early stages of digitalization emissions increase and with further development emissions decrease.

According to the analysis, the marginal direct or pure effect of digitalization on CO_2 emissions has been small compared with those of other variables, such as GDP per capita, but once the threshold or the minimum level of digitalization is reached, a maximum reduction of 10% could be reached in economies that are fully digitalized. On the other hand, the total average effect, including indirect effects, have been close to 45% at the maximum. These thresholds are at 58.73% (percentage of internet users) for the direct effect and at 44.21% for the total effect. From this total effect, 12% comes from the direct component, 17% from the indirect impact on renewables and the other 17% from the indirect impact on energy intensity (Annex III below presents the limitations of the study).

Looking into the future and as the digital frontier continues to move outwards - with platforms, cloud computing, etc - we expect further gains from digitization well past its simple usage by the population of any given country.

ANNEX I. Robustness tests

In order to ensure the reliability of the results of the estimated panel models, a set of robustness tests, which can be classified in four different groups, were carried out. The first set of robustness checks are related with the digitalization proxy used, the second set with possible changes in the model specification, the third set with alternative decarbonization proxies and the last set with the variability of the results when countries are grouped into different time periods or by income-level groups.

Alternative digitalization proxies

The variables secure internet servers and broadband subscribers have been used as alternative proxies of digitalization. Secure internet servers refers to the number of distinct, publicly-trusted TLS/SSL certificates found in the Netcraft Secure Server Survey and is retributed from Netcraft and the World Bank webpages. On the other hand, fixed-broadband subscriptions refers to the number of fixed subscriptions to high-speed access to the public Internet (a TCP/IP connection); at downstream speeds equal to; or greater than; 256 kbit/s. This includes cable modem; DSL; fiber-to-the-home/building; other fixed (wired)-broadband subscriptions; satellite broadband and terrestrial fixed wireless broadband. Fixed broadband subscribers are obtained from the World Bank webpage.

Table 2. **The direct effect point in the same direction with other digitalization proxies**

coefficient p value	digi	digi2	rgdpoa	indu	urba	reni	enera	constant
Reference model (iusea) (obs=3603)	0.0015 (0.099)*	-0.000026 (0.006)***	0.6385 (0.000)***	0.0029 (0.064)*	0.005 (0.10)*	-0.0123 (0.000)***	0.5407 (0.000)***	12.105 (0.000)***
***log* Servers** (obs=1288)	0.0302 (0.001)***	-0.00203 (0.008)***	0.7706 (0.000)***	0.00143 (0.464)	-0.00784 (0.165)	-0.0159 (0.000)***	0.6792 (0.000)***	12.755 (0.000)***
***log* Broadband** (obs=2410)	0.0285 (0.002)***	-0.000439 (0.484)	0.7257 (0.000)***	0.00422 (0.005)***	0.00175 (0.587)	-0.012 (0.000)***	0.671 (0.000)***	12.286 (0.000)***
Reference model (iusea) (obs=1224)	0.0033 (0.055)*	-0.000033 (0.020)**	0.773 (0.000)***	0.0009 (0.602)	-0.00627 (0.257)	-0.0169 (0.000)***	0.6541 (0.000)***	12.720 (0.000)***
***log* Servers** (obs=1224)	0.0278 (0.003)***	-0.0017 (0.029)**	0.775 (0.000)***	0.0015 (0.420)	-0.0062 (0.272)	-0.0163 (0.000)***	0.6544 (0.000)***	12.671 (0.000)***
***log* Broadband** (obs=1224)	0.0336 (0.284)	-0.00098 (0.633)	0.794 (0.000)***	0.0008 (0.638)	-0.0029 (0.616)	-0.0175 (0.000)***	0.656 (0.000)***	12.175 (0.000)***

*p<0.1,**p<0.05, ***p<0.01.
Source: BBVA Research

Table 2 shows how results vary when the digitalization proxy is modified, with the only difference being that the number of observations is limited to the common sample of the three variables in the second table. A difference between these two alternatives and internet users is that the new proxies are defined in natural logarithms while the internet users variable has been introduceded in levels (percentage). Therefore, the net effect on emissions of the alternative digitalization coefficients can be interpreted as an elasticity of CO2 emissions to digitalization.

Both internet servers and broadband subscriptions show a positive linear coefficient and a negative quadratic coefficient, providing additional evidence on the non-linear, quadratic relationship between emissions and digitalization. Being more specific, the linear and quadratic components are statistically significant at a 1% significance level in the case of serves, whereas the relationship is not significant with broadband subscriptions. The difference may be explained by the quality and abundance of the data, but the common sample also points in the same direction. Therefore, further analysis may be needed in order to assess if the relationship holds with other proxies and understand the difference behind the results. The significance and magnitude of the core control variables GDP per capita, energy intensity and renewable share are stable to digitalization proxy changes, a fact that sustains the results of our main specification. Finally, note that the effect of internet users is limited, as internet users can go higher than hundred-percent. This is not the case for servers and subscriptions, and hence, they may be more adequate variables to assess the relationship in the future if data availability and comparability problems are solved.

Alternative model specification

The reference models seem to suggest that specific levels of digitalization have to be accumulated in order to enjoy the benefits. To corroborate this level intuition, and seeing that once the threshold is passed the quadratic component loses strength and the relationship is almost linear, a linear specification has also been tested, where the digitalization variable enters with a dummy, iusersthreshold, that is zero if the country is below the threshold at time t, and if the country is above, the dummy shows how much above the country is (Mod 3)[8]. Note that the net direct effect of digitalization is again close to a maximum of 10%, when the country is fully digitalized and the significance and magnitude of the control variables GDP per capita, energy intensity, industry share, urbanization and renewable share are similar to the ones obtained in Equation [1], providing additional evidence to the level story.

Mod 3

5] $ln\ (pco2a)\ = \beta_0\ + \beta_1\ iusersthreshold + \beta_3\ ln\ (rgdpoa) + \beta_4\ ln(enera) + \beta_5\ reni + \beta_6 urba + \beta_7 indu\ +\ FE\ +\ \varepsilon$

[5] $ln\ (pco2a)\ = 12.39 - 0.0027 iusersthreshold + 0.64 ln\ (rgdpoa) + 0.54 ln(enera) - 0.012 reni + 0.005 urba + 0.003 indu\ +\ FE\ +\ \varepsilon$

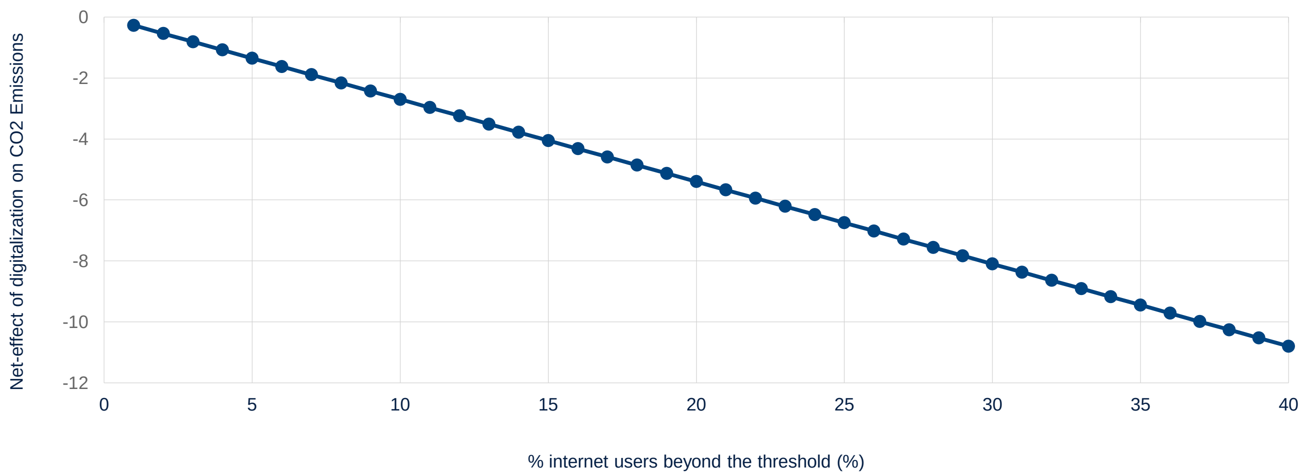
8: 0 if iusea < 58.73 and (iusea - 58.73) if iusea ≧ 58.73.

Table 3. **THE DIRECT EFFECT POINT IN THE SAME DIRECTION WITH THE ALTERNATIVE MODEL SPECIFICATION**

coefficient p value	iusersthreshold	rgdpoa	indu	urba	reni	enera	constant
Coefficient (obs=3603)	-0.00279 (0.006)***	0.6423 (0.000)***	0.0029 (0.064)*	0.005 (0.10)*	-0.0125 (0.000)***	0.541 (0.000)***	12.394 (0.000)***
95% Confidence interval	-0.00454	0.5265	-.00009	-0.001	-0.016	0.434	11.694
	-0.00103	0.7582	0.006	.0112	-0.009	0.648	13.094

Source: BBVA Research

Figure 11. **THE DIRECT EFFECT POINT IN THE SAME DIRECTION WITH THE ALTERNATIVE MODEL SPECIFICATION**



Source: BBVA Research

Alternative decarbonization proxy

Reliable carbon emissions statistics are essential for formulating responses to climate change and to inform global negotiations. Typically, emissions statistics are compiled according to production-based or territorial emission accounting methods: measuring emissions occurring within sovereign borders. However, these estimates do not reflect production chains which extend across borders. In this context, the substitution of domestic for foreign suppliers of intermediate inputs may result in a reduction of a nation's emissions, but the effect on global emissions will depend on whether the foreign suppliers use less ("cleaner") or more ("dirtier") carbon-intensive energy and other inputs (OECD, 2016). These trade-corrected emissions are known as consumed or demand-based emissions, they represent consumption-based emissions of carbon dioxide (CO_2) measured in tonnes and are retrieved from the Global Carbon Budget.

In order to assess if the relationship still holds when consumed-emissions are introduced as the dependent variable, an alternative model specification is presented, where the direct effect of digitalization on consumed emissions is analyzed.

$$[6]\quad ln\,(cco2a) = \beta_0 + \beta_1\, iusea + \beta_2\, iusea2 + \beta_3\, ln\,(rgdpoa) + \beta_4\, ln(enera) + \beta_5\, reni + \beta_6 urba + \beta_7 indu + FE + \varepsilon$$

$$[6]\ ln\,(cco2a) = 12.24 + 0.0001 iusea - 0.000018 iusea2 + 0.67 ln\,(rgdpoa) + 0.50 ln(enera) - 0.011 reni + 0.003 urba + 0.00004 indu + FE + \varepsilon$$

Table 4 below shows the results for the consumption-based emissions. Note that although the sign of the digitalization coefficients is maintained, the significance of the digitalization variables disappears. This may indicate that digitalization may be directly related to territorial or produced emissions, as long as digitalization has the ability to alter preferences and production processes within the country border but has no influence on the emissions of other countries, where their own digitalization values will be in play. Furthermore, consumed emissions are approximated, with the consequences that this may have in data accuracy, and hence, on the model estimation. Moreover, as long as the GDP is now an expenditure-side GDP, in order to be consistent with the emissions perspective[9], changes in the result may be partly explained by this modification. Finally note that more digitized countries are usually highly developed countries, net-importers of emissions, and hence, if digitalization has the ability to foster international trade, which seems reasonable with the emergence of the internet and digital trade, off-setting effects may be in play when consumed-emissions are taken into account, altering the relationship found when produced or territorial emissions were considered.

Table 4. **THE DIRECT EFFECT OF DIGITALIZATION ON CONSUMED CO2 EMISSIONS**

coefficient *p value*	**iusea**	**iusea2**	**rgdp(e/o)a**	**indu**	**urba**	**reni**	**enera**	**constant**
Reference model (produced) (obs=3603)	0.0015 (0.099)*	-0.000026 (0.006)***	0.6385 (0.000)***	0.0029 (0.064)*	0.005 (0.10)*	-0.0123 (0.000)***	0.5407 (0.000)***	12.105 (0.000)***
Produced CO2 (limited dataset) (obs=2669)	0.0015 (0.123)	-0.000026 (0.014)**	0.662 (0.000)***	0.0042 (0.072)*	0.0041 (0.211)	-0.0127 (0.000)***	0.5318 (0.000)***	12.22 (0.000)***
Consumed CO2 (obs=2669)	0.00012 (0.939)	-0.000018 (0.320)	0.675 (0.000)***	0.000042 (0.988)	0.0027 (0.527)	-0.011 (0.000)***	0.50422 (0.000)***	12.239 (0.000)***

*p<0.1,**p<0.05, ***p<0.01.
Source: BBVA Research

9: See Output-side GHG Emission Intensity: A consistent international indicator (here).

Alternative regressions with countries grouped in different time periods and income-level groups

Finally, two additional analyses have been performed in order to assess if the relationship found in the global model stands when countries are grouped in income groups or time is divided in time-periods. Calculations are made with Mod 1 or the direct effect model.

First, countries were divided into Upper income and Lower income countries. The income classification used (World Bank) classifies all World Bank member countries and all other economies with populations of more than 30,000. For operational and analytical purposes, economies are divided among income groups according to 2020 gross national income (GNI) per capita, calculated using the World Bank Atlas method. The groups are: lower income, $4,095 or less and upper income, $4,096 or more.

Table 5. **THE DIRECT EFFECT OF DIGITALIZATION ON CO2 EMISSIONS BY INCOME GROUPS**

coefficient p value	iusea	iusea2	rgdpoa	indu	urba	reni	enera	constant
Upper income (obs=2303, 103 countries)	0.0024 (0.017)**	-0.0000248 (0.022)**	0.667 (0.000)***	0.0033 (0.151)	0.005 (0.150)	-0.011 (0.000)***	0.634 (0.000)***	12.836 (0.000)***
Lower income (obs=1300, 64 countries)	-0.00461 (0.214)	0.0000295 (0.559)	0.646 (0.000)***	0.0027 (0.170)	0.00371 (0.502)	-0.012 (0.000)***	0.4679 (0.000)***	11.591 (0.000)***
Reference model (all) (obs=3603)	0.0015 (0.099)*	-0.000026 (0.006)***	0.6385 (0.000)***	0.0029 (0.064)*	0.005 (0.10)*	-0.0123 (0.000)***	0.5407 (0.000)***	12.105 (0.000)***

*p<0.1,**p<0.05, ***p<0.01.
Source: BBVA Research

Table 5 above shows the results of the analysis performed. Note that digitalization proxies are significant for the Upper income group, but are statistically not significant for the Lower income group. This reinforces the idea that certain levels of digitalization need to be reached in order to benefit from emission reductions driven by digitalization, as Upper income countries have higher levels of internet users than Lower income countries, which in many cases have very small increases in internet users in the period considered. Therefore, Lower income countries, with a low percentage of internet users in the majority of the cases and with residual increases in digitalization, have not significant coefficients. The rest of the coefficients show similar coefficients in both groups, with the difference that industry share and urbanization are not-significant in Lower income countries (these two variables are more sensible in high income countries) and that energy intensity, although significant, shows a lower coefficient in countries with a lower GNI.

Second, several regressions were performed over four time periods, in order to check if the differences between periods are considerable or not (see Table 6). Note that the sample is reduced by ten years in every regression.

Table 6. **THE DIRECT EFFECT OF DIGITALIZATION ON CO2 EMISSIONS DIVIDED IN TIME PERIODS**

coefficient p value *p<0.1,**p<0.05, ***p<0.01	iusea	iusea2	rgdpoa	indu	urba	reni	enera	constant
Produced CO2 (reference model) Data: (1990-2019)	0.0015 (0.099)*	-0.000026 (0.006)***	0.6385 (0.000)***	0.0029 (0.064)*	0.005 (0.10)*	-0.0123 (0.000)***	0.5407 (0.000)***	12.105 (0.000)***
Produced CO2 Data: (2000-2019)	0.00137 (0.189)	-0.000026 (0.009)***	0.698 (0.000)***	0.0028 (0.067)*	0.0015 (0.602)	-0.012 (0.000)***	0.6507 (0.000)***	12.769 (0.000)***
Produced CO2 Data: (2010-2019)	0.00312 (0.062)*	-0.000036 (0.011)**	0.788 (0.000)***	-0.00003 (0.987)	-0.006 (0.226)	-0.0152 (0.000)***	0.699 (0.000)***	12.894 (0.000)***

Source: BBVA Research

Digitalization proxies are especially relevant after 2010, which seems to suggest that the effect of digitalization has increased with time, as more countries reached the minimum thresholds. Note that the third wave of digitalization, or digitalization as we know today, gained an incredible momentum in 2007-2008, coinciding with the emergence of the iPhone. As mentioned in Forbes (2021), in some ways, the digital age can be seen as beginning with the release of Apple's iPhone in 2007. Fifteen years after that, in 2022, the iPhone is still going strong and Apple has created not just an industrial-era product, but a digital platform and a digital era, where customers and firms all over the world have engaged in digital technologies. The analysis backed up this idea and highlights that digitalization has had a more prominent role in determining emissions after 2010.

Annex II. CO2 emissions and the digital economy

Although many studies analyzed the relationship between digitalization and carbon emissions, the majority present a descriptive analysis of this relationship. That is, they describe the positive and negative effects of digitalization in the reduction of CO2 emissions. However, newly released quantitative studies are starting to measure the impact of digitalization and air pollution by testing the environmental Kuznets curve (EKC) hypothesis with different sets of data at country and global scale. The work of Wu et. al. (2021) discusses an inverted U-shape relationship among the digital economy and CO2 emissions by studying the provincial data of China from 2011 to 2017. The empirical work of Li, X., et. al (2021) found evidence supporting the existence of an inverted U-shape relationship between digital economy and CO2 emissions by testing a panel data of 190 countries from 2005 to 2016, with the conclusion that in the early stage of digitalization, CO2 emissions increase, but when digitalization reaches higher levels, CO2 emissions begin to decrease. In the case of this study, the international trade of digitally deliverable services per capita was used as a proxy of digitalization, together with five variables as controls: GDP per capita, foreing direct investment per capita, industrialization level, urbanization level and power supply level. The theoretical model used by Li, X., et. al associates digitalization with an improvement on labor productivity and the optimization in the allocation of production factors.

Theoretical model (Li, X. et. al., 2021)

Li, X. et. al. (2021) presented a theoretical model where digitalization is introduced into the Solow growth model as an additional component of technological progress, building a dynamic equilibrium model between carbon emissions and digitalization. Due to the technological progress derived from digitalization, companies renew their equipment and increase their output in the early stage of economic development, thus increasing CO2 emissions, while in high development stages the output is more stable and the cost of pollution treatment is lower due to digitalization, thus reducing emissions.

The main assumptions of the theoretical model as well as the dynamic behavior and the equilibrium state of the economy are described in Box 1.

Box 1.

Theoretical model

Hypothesis of Production Function

Assume that the **production function** of a firm is:

$$Y = F(K, DL)$$

where ***Y* is the total output, *K* the total amount of capital, *L* the total amount of labor and *D* the firm's digitalization level** (i.e., technological progress). Digitalization can optimize the allocation of production factors and improve labor productivity.

Assume that the production function is **constant returns to scale and diminishing marginal productivity:**

$$\hat{y} \equiv \frac{Y}{DL} = Y = F\left(\frac{K}{DL}, 1\right) \equiv f\left(\hat{k}\right)$$

where *k(hat) = K/DL* is the capital stock of the effective labor per capita and *y(hat) ≡ Y/DL* is expressed as the output of the effective labor per capita.

Thus, the **equation above shows the functional relationship between the effective capital per capita and the effective output per capita.**

Assume that the labor population grows at the rate of n and the digitalization degree (labor productivity) increases at the speed of g_D:

$$\dot{L} = nL$$

$$\dot{D} = g_D D$$

Dynamic Behavior and Equilibrium State of the Economy

When the commodity market is in equilibrium, **investment equals saving** (Taylor):

$$\frac{\dot{K}}{K} = s\left(\frac{Y}{K} - \delta - \frac{E}{K}\right) = s\left[\frac{f\left(\hat{k}\right) - \hat{e}}{\hat{k}}\right] - s\delta$$

where s is a fixed savings rate and capital accumulates via savings and precedes at rate δ. E is the cost of CO2 treatment, Z is the CO2 emissions of the firm, which is related to Y, and θ is the treatment cost of CO2 emissions per unit

$$E = \theta z(Y)$$

$$\hat{e} \equiv \frac{E}{DL} = \frac{\theta z(Y)}{DL} = \theta z(\hat{y}) = \theta z\left(\hat{k}\right)$$

By substituting the equations above:

$$\frac{\dot{K}}{K} = s\left(\frac{Y}{K} - \delta - \frac{E}{K}\right) = s\left[\frac{f\left(\hat{k}\right) - \hat{e}}{\hat{k}}\right] - s\delta$$

Therefore, the **dynamic equation of the effective capital per capita is written as:**

$$\dot{\hat{k}}/\hat{k} = \dot{K}/K - \dot{D}/D - \dot{L}/L = s\left[1 - \theta z\left(\hat{k}\right)\right]\frac{f\left(\hat{k}\right)}{\hat{k}} - s\delta - g_D - n$$

$$\dot{\hat{k}} = sf\left(\hat{k}\right) - s\theta z\left(\hat{k}\right) - (s\delta + g_D + n)\hat{k}$$

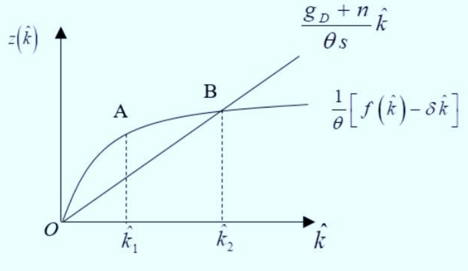
$$z\left(\hat{k}\right) = \frac{1}{\theta}\left[f\left(\hat{k}\right) - \delta\hat{k}\right] - \frac{g_D + n}{\theta s}\hat{k}$$

Dynamic Behavior and Equilibrium State of the Economy

When the economy is in **equilibrium, the growth rate of the effective capital per capita is 0,** $\dot{\hat{k}} = 0$.

In addition, the **growth rate of digitalization, g_D, and the population growth rate n remain unchanged** in the steady state.

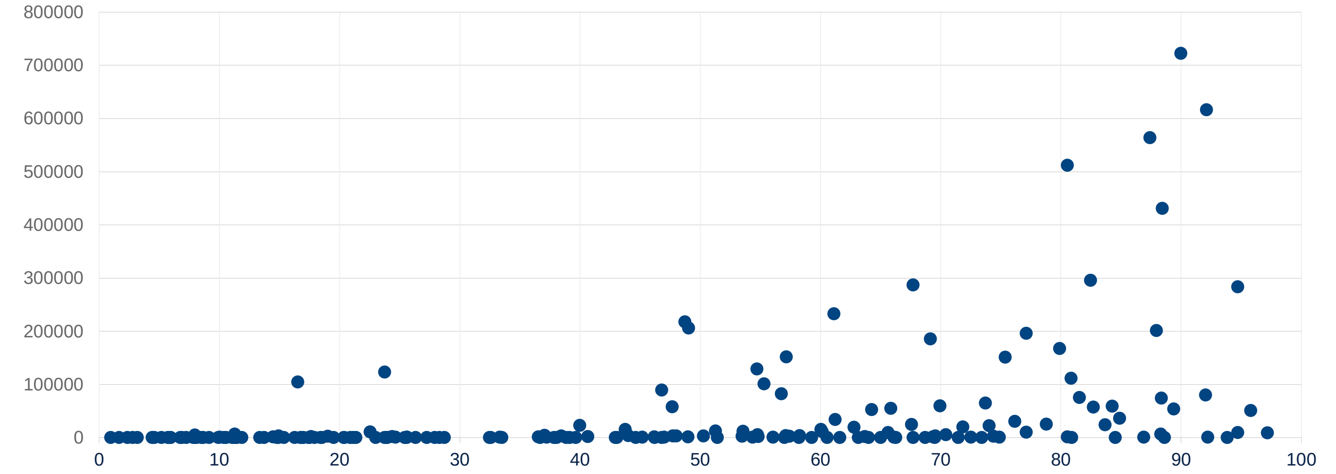
In short, **the first item implies that the output increases due to continuous capital accumulation, thus increasing CO2** emissions. **The second item** on the right side implies that the **CO2 emissions in the production process are decreasing with the continuous improvement of digitalization.**



Annex III. Limitations of the study

The results of the study should be interpreted with caution as the study has some limitations, such as limited data availability or measuring digitalization based on a sole variable. That is, further analysis is needed to confirm the relationship found in this study and other methodological approaches may be helpful, as an error-correction model. Internet-users are an appropriate variable to proxy digitalization for the period considered, but other proxies such as big-data analysis or artificial intelligence may be more suitable when data availability increases and more advanced digitalization proxies can be constructed. That is, more advanced digitalization proxies may be more appropriate to further assess the relationship between digitalization and emissions, as they do not have an upper bound and they capture high-level digitalization technologies more judiciously. Nevertheless, note that the variable internet users, due to its generality, capture digitalization advances in the country quite fitly, as countries with high percentages of internet users, in general, also present leading indicators on other digitalization proxies (see Figure 12 below).

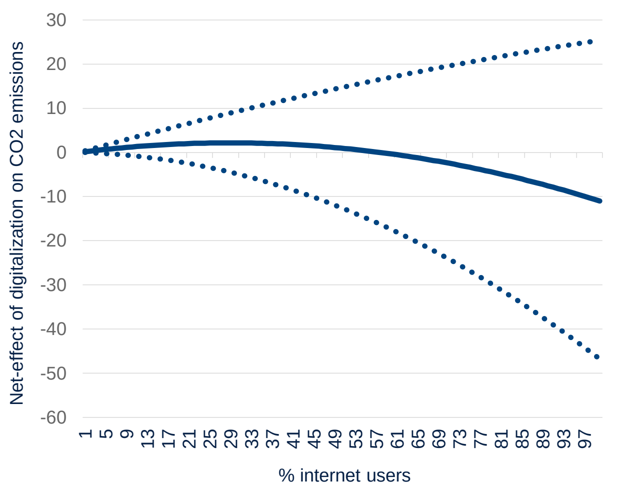
Figure 12. **INTERNET USERS (X-AXIS, AVERAGE 2010-2019) AND INTERNET SERVERS (Y-AXIS, AVERAGE 2010-2019)**



Source: BBVA Research

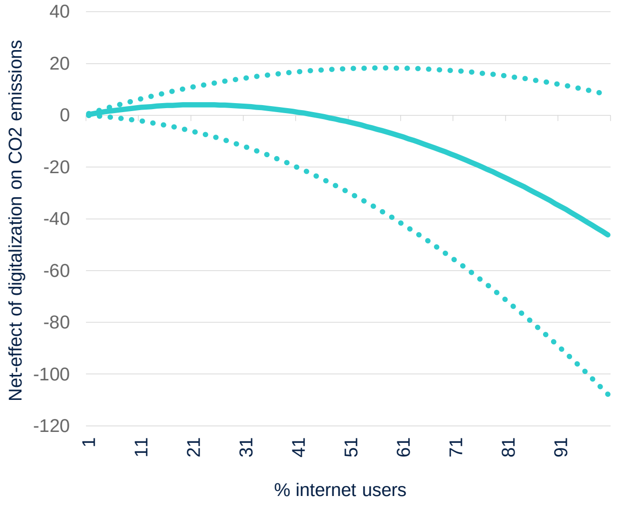
Furthermore, note that although the digitalization proxies analyzed in the work present the expected sign and are statistically significant, the net effect of the linear and the quadratic coefficient is considerably wide when the 95% confidence intervals of both coefficients are considered (see Figure 13 and 14 below).

Figure 13. **DIRECT NET EFFECT DIGITALIZATION (%).** COEFFICIENT AND 95% CONFIDENCE INTERVALS



Source: BBVA Research

Figure 14. **TOTAL NET EFFECT DIGITALIZATION (%).** COEFFICIENT AND 95% CONFIDENCE INTERVALS



Source: BBVA Research

In any case, the global model results are fairly robust, according to the tests carried out, which give similar results to those of the main panel model.

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