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Fixed and mobile broadband penetration and CO_2 emissions: evidence from OECD countries

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Abstract
The recent rapid increase in Internet data traffic and use of digital technologies—observed during the pandemic and forecasted as a consequence of the massive digital transition occurring in the world economies—are feeding concerns about the related possible negative environmental impacts, in terms of both energy consumption and Carbon Dioxide (CO_2) emissions. We contribute to such debate by analysing the relation between two different digitalization dimensions, namely fixed and mobile broadband connections penetration, and CO_2 emissions at the country level. Our paper provides empirical evidence, based on a panel of 35 OECD countries, that higher fixed and mobile broadband penetration levels are associated with lower levels of CO_2 emissions, according to an Environmental Kuznets Curve-type relation. Moreover, we investigate whether the environmental effects of these two digitalization dimensions differ across high- and low-income OECD countries. By adopting fixed-effects models and fixed-effects two-stage least square estimators, the results, besides substantiating the Kuznet's hypothesis in both groups of nations, confirm that higher fixed and mobile broadband penetration levels are associated to a reduction of CO_2 emissions.

Keywords CO_2 emissions · Fixed and mobile broadband · OECD countries · Panel data

JEL Classification L86 · Q51 · Q53

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1 Introduction

There is still urgent need worldwide to reduce GHG emissions and preserve the environment as well as future generations. Countries are trying to mitigate and prevent the effects of climate change, by setting policies to reduce emissions that are considered the main cause of global warming (IPCC, 2022). There are many ongoing initiatives—such as the United Nations Agenda 2030 for Sustainable Development Goals, the Paris Agreement of 2015 (COP21), the European Green New Deal and the EU "Fit for 55" strategy, as well as the Next Generation EU—which hopefully will lead countries to quickly implement policies to make their production and consumption systems more sustainable.

Given these goals, the agenda of policy makers is still looking for the best actions to promote environmental protection while fostering economic growth and reducing disparities among countries. Therefore, it is crucial to identify the most effective determinants to reduce environmental pollution while supporting economic growth for both developed and developing countries.

Digitalisation and Information and Communication Technologies (ICTs) have increasingly and rapidly taken up the international debate over the last 25 years, especially during and after the pandemic period, over which significant efforts were made to connect people, workers, public administration, and production activities. They have elicited major modifications in production and consumption models as well as in the public sector and they are now considered important drivers to foster economic growth, fight environmental degradation, and support sustainable development of countries (Chen et al., 2019). In particular, ICTs are an important key factor to foster digital ecosystems (including digital innovation hubs) that favour the socio-economic development in terms of stakeholder engagement, research and innovation, competitiveness, employment, reduction of income inequality, quality of life improvement, education, and transparency. Digital transformation and new digital technologies (such as Artificial Intelligence, Big Data, Internet of Things, new techniques of prototyping, marketplace platforms, etc.) are creating innovative production processes, changing the relationships in the supply chain and the types of goods and service for the market (Casalino et al., 2020; OECD, 2022). Digitalization and ICTs can also be important drivers to reduce energy consumption and pollution (Usman et al., 2021). In short, the wider diffusion of these new technologies has been deeply influencing macroeconomic and environmental factors over the last two decades (Nguyen et al., 2020).

In the literature focusing on ICTs as one driver of digital ecosystems, while most papers have clearly demonstrated the overall positive effects of ICTs on economic growth (and the consensus on such relation is wide, see for instance Palvia et al., 2018; Engelbrecht & Xayavong, 2007; Kretschmer, 2012; Salahuddin et al., 2016; Lahouel et al., 2021), the debate is still open about the effects of ICTs on environmental degradation, as there is evidence in the literature of both positive and negative possible impacts.

In fact, on the one hand ICTs are considered "energy-intensive" activities: as reported in Borzycki (2012), in 2007 ICTs used approximately 8% of the electricity generated worldwide, and was responsible for 2–2.5% of total Carbon Dioxied (CO_2) emissions. Furthermore, ICTs are a possible source of future environmental harms, insofar as they will turn in e-waste (Zhang & Liu, 2015). On the other hand, some studies show that ICTs have improved energy efficiency in several economic sectors such as transport, wealth, manufacturing (i.e. Gonel & Akinci, 2018; Lu, 2018), leading to a decrease in the CO_2 emission, the magnitude of which varies across countries or regions.

The role of ICTs on growth and environment protection is frequently described referring to a well-known model introduced by Grossman and Krueger (1991), identified as Environmental Kuznet Curve (EKC), named after Simon Kuznet,[1] according to which economic growth effects on environmental degradation depend on the way technologies are used. EKC implies a relation between some key indicators of environmental degradation and per capita income (Stern, 2018). The curve has a reversed U-shape. It hypothesizes that in the first stages of economic development there is an increase of pollutant emissions and environmental degradation; once a certain level of per capita income (which depends on some drivers) is reached, economic growth leads to environmental improvements (the so called "decoupling"; Lahouel et al., 2021). The empirical validity of the EKC has been often criticized, i.e. some studies maintain that its representativeness on a global level is low compared to analyses developed at local level (Stern, 2004). However, even if the debate is still ongoing, more and more studies are confirming the relation described by EKC.

Given this general framework on ICTs and environmental goals, to the best of our knowledge, there are not any studies exploring separately the direct impact of fixed and mobile broadband penetration on the CO_2 emissions, and, at the same time, considering variables catching dynamic phenomena such as the ongoing digital transformation. Given the growing adoption of these two types of broadband connections, and the way in which firms are quickly changing their businesses and the channels to interact with consumers and suppliers, it is crucial to stress and deeply explore these points of discussion.

This paper contributes to fill this gap proposing an empirical analysis of fixed and mobile broadband penetration environmental effects, with some original elements. First of all, we analyse separately the effects of fixed and mobile broadband, as they can imply different usage patterns (Quaglione et al., 2020). Then, given that the effects of fixed and mobile broadband on environmental pollution can be influenced by countries' development level—as implied by recent empirical findings revealing significant differences in terms of environmental impact of broadband in economies with different socio-economic and institutional conditions (Higón et al., 2017)—we break down the set of 35 OECD countries in two groups: high-income[2]

[1] Kuznet suggests that income inequality first rise and then fall as economic development advances.

[2] Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, and United States.

and low-income.[3] Finally, in order to catch some dynamic phenomena related to digital transformation, we consider some other variables as described by the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence and Technology).[4]

By adopting fixed-effects (FE) models, and fixed-effects two-stage least square (FE-2SLS) estimators, the results of the paper, besides substantiating the Kuznet's hypothesis, reveal a strong and significant impact of fixed and mobile broadband in reducing CO_2 emissions in both the groups of countries.

The paper is organized as follow: Sect. 2 provides an overview of the economic literature, Sect. 3 describes the methodology and data used in the analysis, Sect. 4 shows the empirical results for fixed and mobile broadband and Sect. 5 offers some comments and policy indications.

2 Literature review

The effects of ICTs on economic systems and on the environment have been broadly debated in the literature over the last decades, in relation to both developed and developing countries, with analyses made at the national and/or local level. The scientific evidence emerged so far is mixed, as both negative and positive environmental effects of ICTs adoption have been found (Nwani et al., 2022). A significant influence on the nature of the relation is exerted by factors such as the income or the initial level of CO_2 emissions (Suryawanshi & Narkhede, 2015) of the considered countries.

The economic literature suggests that ICTs generate positive (decrease) and negative (increase) impacts on CO_2 emissions based on 3 effects: use effects, substitution effects and cost effects (Ulucak & Khan, 2020).

As concerns the use effect, some papers argue that the adoption of ICTs (i.e. production, distribution, installation, disposal) increases electricity consumption, resulting in higher CO_2 emissions, given that the leading energy sources for the electricity generation are still fossil fuels rather than renewables (Leonard et al., 2020). Other papers show that ICTs implies higher energy consumption not only because of higher electricity use but also because of the production of Internet related goods (Belkhir & Elmeligi, 2018; Hertwich & Roux, 2011; Madlener et al., 2022). Other studies show that ICTs reduces electricity consumption only in some sectors (Cho et al., 2007), or that the impact of ICTs on electricity uses is higher than that on the growth of income and that it is especially true for developing economies (Sadorsky, 2013).

[3] Chile, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Mexico, New Zeland, Poland, Portugal, Republic of Korea, Slovakia, Slovenia, and Turkey.

[4] The STIRPAT model is now considered a reliable instrument to explore the link between economic growth and environmental impact because it includes some significant variables, also ICTs, describing both economic growth and environmental impacts; it is also a useful model to test EKC (Ozturk et al., 2021).

As for the substitution effect, the implementation of ICT-based solutions leads to energy efficiency gains. This is because ICTs replace older and less efficient technologies resulting in an increase in energy efficiency, so providing benefits in terms of CO_2 emissions reduction (Yahyaoui, 2022). Some examples are smart transportation, e-commerce or e-business, sharing economy or teleconferencing, telecommuting and smart working (Danish et al., 2019; Ulucak & Khan, 2020; Zhang & Liu, 2015). ICTs improve firms' productivity and reduce energy intensity with benefits for the environment (i.e. Cardona et al., 2013; Chen et al., 2019; Niebel, 2018; Sadorsky, 2012; Salahuddin et al., 2016; Zhang & Liu, 2015). Other papers stress the role of ICTs in promoting more sustainable production processes (Higón et al., 2017; Nguyen et al., 2020) and household energy management decisions (Bastida et al., 2019).

According to the third effect, the negative impact of ICTs on the environment can be related to the following mechanism: ICTs lower the prices of goods and services, the quantities demanded increase and the consequent increase in production levels pushes CO_2 emissions up (Shabani & Shahnazi, 2019). Other studies have directly investigated the linkages between ICTs and CO_2 emissions, referring to specific sectors, such as transport. However, results and findings are not conclusive (Chen et al., 2019).

Several studies directly refer to the EKC. Zhang and Meng (2019) explore the way in which Internet penetration has affected the link between income and environment (specifically, CO_2 emissions), following the methodology proposed by Bradford et al. (2005). Using data covering years 1996–2014, on 115 countries with different levels of Gross Domestic Product (GDP) and Internet penetration, they find an EKC-type relation for both developed and developing countries, and that Internet penetration lowers the income threshold at which emissions start decreasing. Nguyen et al. (2020) analyse 13 selected G-20 countries and, using a Quantile Panel Regressions together with Fully Modified OLS, they test a model that rejects the absence of EKC. Chen et al. (2019), using a quantile regression analysis, explore the relation between ICTs (proxied by Internet and mobile phone penetration) and CO_2 emission intensity in China. The results show significant reductions of CO_2 emission intensity in the Chinese provinces part of the analysis, for both Internet and mobile phone penetration, proving that, thanks to ICTs, in developing countries economic growth occurs without an increase in CO_2 emissions. Overall, the results show that both renewable energy consumption and financial development have a slight influence and can only moderately explain CO_2 emissions and economic growth. These results indicate that in MENA countries both financial development and the renewable energy sector are still weak and poorly contribute to economic and environmental improvements.

National digital transformation and the rise of digital ecosystems are important elements in evaluating the current and future impact of fixed and mobile broadband penetration growth on CO_2 emissions. This can differ between developed and developing countries and can lead to different results in the analysis. Arshad et al. (2020) analyse the effects of ICT and other variables (trade, economic growth, financial development and energy uses) on CO_2 emissions in South and Southeast Asia over the period 1990–2014. Through a cluster analysis, they distinguish between potential and advanced countries. They find that ICT and energy consumption deteriorate the environmental quality by increasing CO_2 emissions in all panels showing that it is likely that ICT goods and services are not energy-efficient in the two clusters. They observe also that financial development increases CO_2 emissions, suggesting that financial development was not probably focused on environmental-friendly projects, for both potential and advanced countries. Yet, in advanced countries financial development mitigates CO_2 emissions. They also find that trade, economic growth, financial development, and ICT together improve the environmental quality by reducing CO_2 emissions, with unidirectional causality. In addition, the analysis confirms the validity of the EKC.

Lee and Brahmasrene (2014) examine the links among ICT, economic growth, and CO_2 emissions, using cointegration techniques and regression estimation methods on data from 1991 to 2009, focusing on 9 countries belonging to the Association of Southeast Asian Nations: evidence is found that ICT diffusion increases economic growth and CO_2 emissions.

Charfeddine and Kahia (2021) analyse if ICT and renewable energy consumption contribute to better air quality in 24 countries of Middle East and North Africa (MENA) over 1980–2019 years. They find that ICTs adoption reduces the environmental quality, while renewable energy uses alone increase environmental quality. However, these effects are temporary and last from 1 to 7 years.

Chien et al. (2021), through a moments-quantile regression, analyse the impact of ICTs, economic growth, and financial development on CO_2 emissions in BRICS countries; they also test the EKC hypothesis. Their results show that economic growth and financial development reduce CO_2 emissions for all quantiles, and ICTs reduce CO_2 emissions only for lower quantiles.

Ramzan et al. (2022) focus on the effects of ICTs, financial development, trade openness, and fossil fuel energy on ecological footprints of Pakistan, measured on quarterly data from 1960 to 2019. They use a non-parametric causality in quartile method to measure the links among the variables considered in the analysis. The study finds, in particular, that ICTs and financial development have a moderated impact on the ecological carbon footprint, and that a strict regulation on companies' emissions should be enforced in order to reduce pollution from industrial sector.

Shabani and Shahnazi (2019) analyse the long run relations among ICT, energy consumption, GDP, and CO_2 emissions focusing on different economic sectors of Iran, in 2002–2013, using dynamic ordinary least squares estimator. The main findings of the analysis confirm the validity of the EKC in all sectors, and that ICTs reduce CO_2 emissions in 2 sectors, namely transportation and services, due mainly to energy consumption.

Godil et al. (2020) explore the effects of ICTs, financial development, and institutional quality on CO_2 emissions in Pakistan, using a quantile autoregressive distributed lag model, covering the years from 1995 to 2018. They observe that, in the long run, two variables (GDP and institutional quality) influence CO_2 emissions in a negative way, especially when the starting level is already high. That is to say when these variables increase, CO_2 emissions increase. In addition, financial development and ICTs positively affect environmental quality by reducing CO_2 emissions regardless of the current level of pollution. Finally, the EKC hypothesis is confirmed even in this case.

Khan et al. (2022) investigate the impact of private investment in ICTs, renewable energy, political risk, and economic growth on CO_2 emissions in Morocco, over the period 1985–2020, using dynamic ARDL simulation model. The analysis shows that ICTs private investment has relevant positive effects in reducing CO_2 emissions, together with renewable energies. On the other hand, economic growth increases CO_2 emissions, while low political risk seems to mitigate CO_2 emissions.

Bianchini et al. (2022) analyse the impact of digital and environmental technologies on GHG emissions of industrial sector, focusing on metropolitan regions of EU and UK (2007–2016). The results show that the environmental technologies reduce GHG at the local level while digital technologies have an opposite effect by increasing the emissions, with some technologies (such as big data or computing infrastructures) having stronger impact than others. In addition, they find that the environmental technologies produce more benefits on GHG emissions in regions with significant digital technology endowments, while digital technologies produce weaker negative effects in regions with significant green technology endowments.

As some of the studies mentioned above, Park et al. (2018) focus on the effects of Internet use, financial development, economic growth and trade openness on CO_2 emissions in EU countries. They use pooled mean group estimator on panel data covering years 2001–2014. The study suggests that the Internet lowers the quality of the environment as well as electricity consumption. On the other hand, economic growth and financial development have a decreasing negative impact on CO_2 emissions.

Nguyen et al. (2020) measure the effect of ICTs on CO_2 emissions in 13 G-20 countries (both developing and developed) over the period from 2000 to 2014, adopting a Quantile Panel Regressions together with Fully Modified OLS. The results show that 5 factors contribute to the reduction of CO_2 emissions: energy prices, Foreign Direct Investment, technology, innovation expenditure and trade openness; while other dimensions, as among which financial development itself, have a negative impact on the air quality. The analysis confirms the EKC hypothesis.

Some works rely on different empirical approaches. Anochiwa et al. (2022) develop an analysis based on the STRIPAT model, focusing on 22 Sub-Saharan Africa over the period 1995–2017. They found that mobile phone penetration reduces CO_2 emissions for both production and consumption activities, with greater impact in economies where CO_2 emissions are higher. Anser et al. (2021), applying panel fixed effects and panel quantile regression approaches to 26 EU Countries in 2000–2017, show that fixed and mobile phone penetrations have positive and negative effects on CO_2 emissions respectively. Differently, Chen et al. (2019) find that both fixed and mobile phone penetrations increase the level of CO_2 emissions using a regression analysis on panel 2001–2016 data on Chinese Provinces.

Despite the large number of papers discussing the effects of fixed and mobile connectivity technologies penetration on growth and emissions, there are still some open questions to investigate. To the best of our knowledge, the studies on the impact of fixed and mobile broadband on CO_2 are still very limited. In most cases, papers include broadband, mainly fixed broadband, in an ICTs macro-variable. Ulucak and Khan (2020) use subscriptions to fixed broadband, fixed telephone, mobile telephone and Internet users as drivers to test the overall effects on CO_2 in BRICs countries. Moyer and Hughes (2012) refer to mobile and fixed broadband Internet penetration rates per 100 persons to develop an International Futures (IFs) integrated assessment system to test the overall effects of ICTs in the global system. Su et al. (2021) consider fixed telephone, broadband and just mobile phone subscriptions, without referring to mobile broadband, when exploring the effects of ICTs on CO_2 emissions in BRICs countries.

This paper explicitly investigates the relation between broadband and CO_2 emissions in 35 OECD countries, distinguishing between fixed and mobile broadband and between low- and high-income level countries.

3 Methodology and data

3.1 Methodology

The IPAT (I = PAT) model was proposed for the first time by Ehrlich and Holdren (1971) to evaluate the impact of population growth on the environment. It relies on the assumption that the environmental impacts (I) are the multiplicative product of the population size (P), the affluence (A)—represented as per capita consumption or production—, and the environmental effects determined by technology (T) (Lin et al., 2009). However, the IPAT model presents an important drawback, as it assumes that the elasticity of the environmental impact with respect to the driving forces (P, A, T) is unitary for each of them, thus implying a rigid proportionality between the driving factors and the environmental impacts (Zhang & Liu, 2015). Dietz and Rosa (1994) proposed a stochastic version of the IPAT model, named STIRPAT, which preserves the multiplicative form of the IPAT model, and at the same time allows to model non-proportional impacts of the three key determinants on the environment. The specification of the STIRPAT model is:

$$I_{it} = \alpha P_{it}^{\beta} A_{it}^{\gamma} T_{it}^{\delta} \varepsilon_{it} \tag{1}$$

In the stochastic model, α is the constant term, while β, γ, and δ are the elasticities (respectively) of population (P), affluence (A) and technology (T) to environmental impacts; ε is the error term. The subscript i represents the observational units (in our case, the 35 OECD countries), while the subscript t denotes the year (in this paper the dataset covers the period 2008–2019 and hence t = 1,…,12). By taking the natural logarithm of both sides, the model can be linearized as follows:

$$\ln I_{it} = \alpha_0 + \beta \ln P_{it} + \gamma \ln A_{it} + \delta \ln T_{it} + \mu_i + \tau_t + \varepsilon_{it} \tag{2}$$

where $\ln\alpha = \alpha_0$.

The population size (P), represented by the resident population (POP), is one of the most important determinants of CO_2 emissions as a larger population is expected to be associated to higher energy demand for power generation, industry and transport that in turn increases aggregate carbon emissions (Ohlan, 2015; Poumanyvong & Kaneko, 2010). Affluence (A) and technology (T), instead, are not single factors but categories possibly including several separate elements that affect the environment. In Affluence, GDP per capita and its square (GDP^2) have been included, in order to verify the validity of the EKC hypothesis, while the dimensions considered in Technology (T) are: productive structure (PS), fossil fuels (FF), patent intensity (PAT), fixed and mobile broadband penetrations (BB). The PS is represented by the share of employees in manufacturing (MAN) and services (SER) sectors (Shi, 2003). In recent decades, several analyses on the effects of industrialization on CO_2 emissions, at either the overall manufacturing or specific sectors level, highlight a positive relation between industrialization and carbon emissions (Shahbaz & Lean, 2012; Shahbaz et al., 2014). Basically, as the wealth of countries increases, the share of manufacturing in the total economy increases too, causing important industrial pollution-related issues (Poumanyvong & Kaneko, 2010). Strongly connected to this aspect are the emissions generated by the service sector. Butnar and Llop (2011), for instance, focus on the emissions of the Spanish service (input–output) subsystem, finding that the increase of its CO_2 emissions, associated to an increased final demand of services, can be mainly traced back to the related rise of the non-tertiary intermediate goods used in the production of services.

FF includes coal, oil, petroleum, and natural gas products and it is widely shared that an increase in burning of fossil fuels causes more CO_2 emissions, thereby deteriorating the environment (Sharma, 2011).

PAT (measured by number of patents per million of inhabitants), has been included to capture the environmental impact of knowledge creation and technological progress. If, on the one hand, this dimension could stimulate economic growth, consequently raising energy consumption and pollution, on the other hand a higher patent intensity in high-tech green and clean technologies beneficial environmental effect (Bianchini et al., 2022; Wang et al., 2012).

Finally, BB is measured in terms of fixed and mobile broadband subscribers per 100 inhabitants (FBB and MBB, respectively). In line with Moyer and Hughes (2012) we choose broadband as a critical variable to identify ICTs as a whole for the following reasons. Firstly, it is largely shared the idea that broadband connectivity is able to improve productivity, thus reducing the use of energy and the cost of renewables. Secondly, it is a general-purpose technology with several applications for industries, households and governments. Thirdly, the availability of longitudinal and cross-country data allows to operationalize this variable within a panel data framework. Nowadays, broadband is widely accepted as having strategic importance to all countries because of its ability to accelerate the contribution of ICTs to economic growth in all sectors, enhance social and cultural development and facilitate innovation.

The complete model is specified as follows:

$$\begin{aligned} \mathrm{lnCO2}_{it} &= \alpha_0 + \beta_1 \mathrm{lnPOP}_{it} + \gamma_1 \mathrm{lnGDP}_{it} + \gamma_2 \mathrm{GDP}^2_{it} + \delta_1 \mathrm{lnMAN}_{it} \\ &+ \delta_2 \mathrm{lnSER}_{it} + \delta_3 \mathrm{lnFF}_{it} + \delta_4 \mathrm{lnPAT}_{it} + \delta_5 \mathrm{lnBB}_{it} + \mu_i + \tau_t + \varepsilon_{it} \end{aligned} \tag{3}$$

As for the econometric strategy, we use two different regression approaches (FE and FE-2SLS) for both fixed and mobile broadband penetrations. In addition to considering the 35 countries altogether, we further investigate the effects of fixed and mobile broadband penetration on CO_2 emissions by considering the development level of the countries, grouping them into two homogenous categories (high- and low-income). The results of the 12 models are shown in Tables 3, 4, 5, 6. First, we report the FE estimates as the null hypothesis of the Hausman test can be rejected in every panel, thus indicating that this estimator is the most reasonable in every model. Furthermore, in order to take into account the potential endogeneity due to the reverse causality between CO_2 emissions and broadband penetration, we adopt an instrumental variable approach (FE-2SLS) aimed at obtaining an exogenous variation in the endogenous regressors. The economic literature provides several solutions on exclusion restrictions that can be relied on. As highlighted in Koutroumpis (2019) and in the reports elaborated by the International Telecommunications Union (ITU, 2018, 2020), past investments in broadband can be considered suitable instruments as they have been used, in the broadband infrastructure production equation, to explain the broadband diffusion "as this should be the main source of funding infrastructure growth by broadband firms" (Koutrompis, 2019, p. 3). Furthermore, we complement this instrument with the government effectiveness indicator elaborated by Kaufmann et al. (2011). This index, in fact, capturing "the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies" (Kaufmann et al., 2011, p. 223), can affect the broadband penetration as it synthetizes the national government's capacity to favour a positive environment that contributes to creating and improving a prolific ecosystem.

The high correlations between the instruments and the fixed and mobile broadband variables seem to prove the validity of our choice. However, although such evidence concerning the correlation is rather comforting, the relevance and orthogonality of the external instruments must be statistically assessed. The fulfilment of the relevance requirement can be verified through the under-identification test (presented in Tables 4 and 6): a Lagrange multiplier (LM) test of whether the equation is identified, i.e. that the excluded instruments correlated with the endogenous regressors. Yet, when the i.i.d. assumption is dropped, as in our case where the errors are clustered by country, the LM and Wald versions of the Kleibergen and Paap (2006) rk statistics are reported instead of the Anderson LM and Cragg–Donald Wald statistics, which are no longer valid. The tests indicate that the null hypothesis can be rejected, confirming that the model is correctly identified. As concerns the orthogonality condition, we test the validity of our instruments by relying on Hansen's (1982) J-test for overidentifying restrictions when the standard errors are robust to heteroskedasticity. In this case, the validity of the instrumental variables is confirmed by the fact that the null hypothesis cannot be rejected at 10%.

3.2 Data

As hinted at above, the analyses are carried out on a panel dataset, combining World Bank and ITU data, of 35 OECD countries observed over the period 2008–2019.

Table 1 Definition of the variables used in the empirical analysis

Variable	Definition	Source
CO_2	Carbon emissions (kilo tons)	World Bank
FBB	Percentage of fixed broadband subscribers in the total population	ITU
MBB[a]	Percentage of mobile broadband subscribers in the total population	ITU
GDP	Gross domestic product divided by population	World Bank
POP	Total resident population	World Bank
PAT	Number of patents applications per million of inhabitants	World Bank
MAN	Share of employment in manufacturing as a percentage of total employment	World Bank
SER	Share of employment in services as a percentage of total employment	World Bank
FF	Fossil fuel energy consumption (% of total)	World Bank

[a]Except for the share of mobile broadband subscribers (MBB), the other variables are available for all the 35 OECD countries and for the entire time span (2008–2019). 2008 and 2009 mobile broadband penetration data for Australia, Canada, Estonia, Luxembourg, Netherlands, New Zealand, and Slovenia are missing, as well as for Chile, Czech Republic, Greece, Ireland, Japan, Poland, Portugal, Spain, Switzerland, Turkey, and United Kingdom for the sole year 2008

Table 2 Summary statistics. *Source:* our elaborations. World Bank and ITU

Variable	Obs	Mean	SD	Min	Max
CO_2	420	348,687.6	865,709.7	1860	5,740,270
FBB	420	29.139	8.633	6.797	46.821
MBB	395	68.577	40.998	0.039	202.973
GDP	420	39,102.03	22,673.29	8947.74	111,043.5
POP	420	35,993,989	58,549,344	310,856	329,064,917
PAT	420	491.334	810.769	0.016	4274.762
MAN	420	24.082	5.717	10.76	40.53
SER	420	70.486	7.886	49.38	87.85
FF	420	72.302	19.578	10.255	96.248

The dependent variable is the CO_2 emissions (kilo tons), from the World Bank database. Fixed and mobile broadband penetration data are taken from the ITU database, while the remaining control variables are from the World Bank database. A detailed description of the variables and their sources is presented in Table 1, while Table 2 shows the related summary statistics.

4 Empirical results

4.1 Fixed broadband

In this section, we report the estimation results of the impact of fixed broadband penetration on CO_2 emissions for the whole set of countries, and for high- and low-income countries separately. As anticipated, we present the results obtained through both the FE (Table 3) and the FE-2SLS estimators (Table 4), but the

Table 3 FE estimation results for fixed broadband. *Source:* our elaborations. World Bank and ITU data

Dependent variable	All CO_2 (1)	High-income CO_2 (2)	Low-income CO_2 (3)
FBB	− 0.1220***	− 0.1014**	− 0.2471***
	(0.036)	(0.0479)	(0.0406)
GDP	3.5489***	5.3567***	3.3315**
	(0.7218)	(1.5621)	(1.5611)
GDP^2	− 0.1673***	− 0.2420***	− 0.1506*
	(0.0356)	(0.0733)	(0.0805)
POP	0.6860***	0.0359	1.6707***
	(0.1136)	(0.1576)	(0.1621)
MAN	0.9028***	0.5945***	0.3344**
	(0.0952)	(0.1203)	(0.144)
SER	0.7618***	− 0.1382	0.8755***
	(0.2746)	(0.3797)	(0.2636)
FF	0.0963**	0.0820*	0.1579***
	(0.0377)	(0.0469)	(0.0523)
PAT	0.0090**	0.0056	0.0135***
	(0.004)	(0.0041)	(0.0049)
N*T	420	240	180
N	35	20	15
Time effects	Yes	Yes	Yes
Country effects	Yes	Yes	Yes
R^2	0.590	0.631	0.726
Hausman FE/RE (p > chi2)	20.43 (*0.008*)	46.43 (*0.000*)	28.40 (*0.000*)

Standard errors clustered by countries are given in parenthesis

*Statistically significant at the 10%

**Statistically significant at 5%

***Statistically significant at 1%

discussion will focus on the evidence emerging from the latter, more robust econometric approach.

By looking at our key regressor, the fixed broadband penetration in the OECD countries, independently from the sample considered, seem to have a moderation effect on the CO_2 emissions, even though with different magnitudes. In fact, the coefficients associated to our variable of interest take on negative values and are statistically significant at the 1% level (except for the high-income countries in Table 4, in which case the effect is statistically significant at 5%). Furthermore, the coefficients range from − 0.2558 (in the high-income economies) to − 0.2460 (in the low-income ones) and since the regressors are taken in logarithm, these values also represent the elasticity of fixed broadband penetration with respect to CO_2 emissions. In other words, holding all the other variables constant, in response to a 1% increase of

Table 4 FE-2SLS estimation results for fixed broadband. *Source:* our elaborations. World Bank and ITU data

Dependent variable	All CO_2 (4)	High-income CO_2 (5)	Low-income CO_2 (6)
FBB	− 0.1223***	− 0.2558**	− 0.2460***
	(0.0368)	(0.1012)	(0.037)
GDP	3.5505***	20.2724***	3.3235**
	(0.6223)	(4.0222)	(1.6182)
GDP^2	− 0.1674***	− 0.9187***	− 0.1503*
	(0.0307)	(0.1828)	(0.0838)
POP	0.6863***	0.4227**	1.6685***
	(0.1162)	(0.1903)	(0.1418)
MAN	0.9027***	0.6250***	0.3358**
	(0.0939)	(0.2301)	(0.1362)
SER	0.7629***	− 0.0405	0.8733***
	(0.2649)	(0.9886)	(0.2577)
FF	0.0963*	0.0994*	0.1581***
	(0.0503)	(0.0601)	(0.0546)
PAT	0.0090**	0.0046*	0.0135**
	(0.0035)	(0.0025)	(0.0061)
N*T	420	240	180
N	35	20	15
Time effects	Yes	Yes	Yes
Country effects	Yes	Yes	Yes
R^2	0.59	0.629	0.726
Under-identification test (*p-value*)	32.785 (*0.000*)	21.278 (*0.000*)	32.273 (*0.000*)
Hansen's J test (*p-value*)	*0.512*	*0.254*	*0.629*

Standard errors clustered by countries are given in parenthesis

*Statistically significant at the 10%

**Statistically significant at 5%

***Statistically significant at 1%

the broadband adoption, CO_2 emissions decrease by 0.2558% in high-income countries and by 0.2460% in low-income ones. In the light of the increasing awareness about the role of digitalization for economic growth (Czernich et al., 2011; Katz et al., 2010; Koutroumpis, 2009), the reinforcement of the fixed broadband diffusion could represent a strategic policy to foster economic development, but with a focus on the environment thanks to its ability to reduce the CO_2 emissions.

As for the control variables, the coefficients associated with GDP per capita and its square give evidence of a nonlinear inverted U-shaped relation with CO_2 emissions, thus confirming the EKC hypothesis. The effect is statistically relevant in the complete model and in both sub-samples of countries and this could be due to the

Table 5 FE estimation results for mobile broadband. *Source:* our elaborations. World Bank and ITU data

Dependent variable	All CO_2 (7)	High-income CO_2 (8)	Low-income CO_2 (9)
MBB	− 0.0268***	− 0.0494***	− 0.0300***
	(0.0063)	(0.0146)	(0.0066)
GDP	3.9736***	17.9865***	3.8013**
	(0.8065)	(4.3241)	(1.8083)
GDP^2	− 0.1854***	− 0.8179***	− 0.1700*
	(0.0393)	(0.198)	(0.0928)
POP	0.7694***	0.3188	1.6858***
	(0.1374)	(0.2451)	(0.178)
MAN	0.9115***	0.8693***	0.4005**
	(0.1132)	(0.2477)	(0.1535)
SER	0.7935***	0.7269	0.5450**
	(0.2736)	(0.9489)	(0.274)
FF	0.0828**	0.0378	0.1505***
	(0.038)	(0.0495)	(0.0551)
PAT	0.0056	0.0043	0.005
	(0.0042)	(0.0057)	(0.0056)
N*T	395	227	168
N	35	20	15
Time effects	Yes	Yes	Yes
Country effects	Yes	Yes	Yes
R^2	0.562	0.621	0.685
Hausman FE/RE ($p > chi2$)	26.67 (*0.002*)	30.74 (*0.000*)	28.22 (*0.001*)

Standard errors clustered by countries are given in parenthesis

*Statistically significant at the 10%

**Statistically significant at 5%

***Statistically significant at 1%

strong regulations, policies and enforcement mechanisms that characterize OECD countries (Ibrahim & Law, 2014).

An element that contributes to increase carbon emissions—and remains robust in all the specifications of the model—is the population: the variable, in fact, is positively associated with CO_2 with coefficients that range between 0.4227 (in the high-income model) and 1.6685 (in the low-income sample). This result indicates that in both groups of OECD countries an increase in population has a detrimental effect on carbon emissions. However, given that the population of high-income countries has reached a plateau, while the population of low-income economies is still increasing (Wang & Li, 2021), in the latter group the annual flows of emissions are expected to continue to increase at a rapid rate, due to the combination of a higher elasticity with higher population growth rates.

At the same time, a higher weight of the manufacturing sector increases CO_2 emissions: the elasticity varies between 0.3358 (in the low-income countries) and 0.6250 (in the high-income economies), while the impact associated with the service sector is statistically significant only in the low-income group of countries with an elasticity equal to 0.8733. Finally, the impact of fossil fuels as well as the effect of patent intensity are positive and significant in all regressions.

4.2 Mobile broadband

This section mirrors the previous one, but focuses on the impact of mobile broadband on CO_2 emissions (FE, Table 5; FE-2SLS, Table 6).

First, when comparing the impact of the fixed broadband with that of the mobile broadband, we can observe some common aspects but also one important difference. The similarities refer to the sign and the statistical significance of the estimated coefficients, which are negative and statistically significant in every model (as in the fixed broadband models), while the main difference concerns the magnitude of the impacts. In the case of the mobile broadband, in fact, the elasticity ranges between − 0.1031 (in the high-income nations) and − 0.0705 (in the low-income countries) much lower than that found for the fixed broadband. In other words, even the mobile broadband penetration seems to have a positive effect on environment by reducing carbon emissions, but to a lower extent. This could be related to the fact that mobile networks are more energy demanding (and thus emissions intensive) compared to fixed ones because the former involve radio transmission.[5]

Concerning the other variables, the results confirm a nonlinear inverted U-shaped relation between economic growth (GDP per capita) and carbon emissions, and a crucial role associated to the population in increasing CO_2 with elasticity values that range between 0.6640 and 2.1788.

The shares of both manufacturing and service sector are positively related to CO_2 emissions when all the countries are considered altogether. However, when low- and high-income countries are considered separately, there is evidence that the manufacturing share increases CO_2 emissions only in the high-income economies (with an elasticity equal to 1.1618); on the contrary, the service sector share is positively related to CO_2 emissions only in the low-income economies (with an elasticity equal to 0.5566).

Fossil fuels confirm a detrimental effect on environment due to their positive association with carbon emissions only in the low-income economies, while patent intensity loses its statistical significance.

[5] According to the German Environment Agency (https://www.umweltbundesamt.de/en/press/pressinformation/video-streaming-data-transmission-technology. Accessed 6 Oct 2022), "HD-quality video streaming produces different levels of greenhouse gas emissions depending on the transmission technology. The CO2 emissions generated by data processing in a data centre are relatively low, at 1.5 g of CO2 per hour. However, the technology used to transmit data from the data centre to the user determines the climate compatibility of cloud services like video streaming". HD video streaming over fibre connectivity generated 2 g CO2/hr, 5 g CO2/hr for 5G and 90 g CO2/hr for 3G.

Table 6 FE-2SLS estimation results for mobile broadband. *Source:* our elaborations. World Bank and ITU data

	All	High-income	Low-income
Dependent variable	CO_2 (10)	CO_2 (11)	CO_2 (12)
MBB	− 0.0387**	− 0.1031**	− 0.0705***
	(0.017)	(0.0405)	(0.0218)
GDP	4.5846***	21.5349***	7.1490***
	(0.9808)	(4.483)	(2.4682)
GDP^2	− 0.2131***	− 0.9791***	− 0.3284***
	(0.0459)	(0.2037)	(0.123)
POP	0.8745***	0.6640**	2.1788***
	(0.1753)	(0.2913)	(0.2522)
MAN	0.8667***	1.1618***	0.1315
	(0.1296)	(0.3331)	(0.1689)
SER	0.8562***	2.7864	0.5566**
	(0.249)	(1.7474)	(0.2739)
FF	0.0827	0.049	0.1429**
	(0.0511)	(0.0603)	(0.0651)
PAT	0.0055	0.0051*	0.0023
	(0.0034)	(0.0028)	(0.0048)
N*T	395	227	168
N	35	20	15
Time effects	Yes	Yes	Yes
Country effects	Yes	Yes	Yes
R^2	0.558	0.593	0.598
Under-identification test (*p-value*)	16.932 (*0.000*)	13.673 (*0.000*)	11.823 (*0.000*)
Hansen's J test (*p-value*)	*0.833*	*0.978*	*0.250*

Standard errors clustered by countries are given in parenthesis

*Statistically significant at the 10%

**Statistically significant at 5%

***Statistically significant at 1%

5 Conclusion and policy implications

This paper provides quantitative estimations of the impact of fixed and mobile broadband adoption on CO_2 emissions in 35 OECD countries, divided into 2 groups low- and high-income, in 2008–2019, by making use of a panel dataset. The results of the analysis have showed some significant insights, useful to define information and policies for countries looking for "twin" transition (digital transformation and innovation together with the green transition).

The main findings of this paper show that, in both low- and high-income countries, a wider diffusion of both fixed and mobile broadband is associated to lower CO_2 emissions. It means that the penetration of broadband connectivity services is a relevant factor for improving the environmental quality of countries and alleviating environmental degradation, especially as far as fixed broadband is concerned.

Therefore, a first policy implication of our findings is that fostering a mix of fixed and mobile broadband investments is desirable. However, given the different contribution coming from fixed and mobile broadband to reduce CO_2 emissions, there is a need to focus on new investments in green mobile solutions, aimed, first of all, at reducing energy uses to catch wider environmental gains (and at reducing the impact of end-of-life waste linked to this technology). Some solutions are already feasible, such as the transition from 4 to 5G networks, the adoption of small antennas and Massive MIMO technologies that, when accompanied by a sound regulation, allow an efficient allocation of antennas and of the radio spectrum.

In terms of "green" investments, there is still room for improvement in addition to broadband penetration. In fact, manufacturing and service sectors still significantly contribute to the detriment of air quality, while patents seem not to play a positive role to reduce CO_2 emissions, as well as fossil fuels, especially for low-income countries. These findings suggest that, on the one hand, there could still be limited investments in green digital innovations; on the other hand that low-income countries have to accelerate energy efficiency plans and strategies. In other words, energy intensive elements are still significant contributors to environmental degradation, and technology still has an unexplored and relevant role in improving environmental conditions.

Therefore, to maintain in the long term the emissions reduction effects linked to growing broadband penetration, digital transformation processes have to be accompanied by policy measures to reduce the environmental effects associated to the changes in production, consumption and living models. From this perspective, Internet of Things, sharing platforms, pay-per-use and pay-per-performance platforms, radio frequency indicators (RFID), Global Positioning Systems (GPS) are all united by massive increases in Internet data traffic and, consequently, rapidly rising electricity demand and CO_2 emissions with the risk to offset the positive effects of new technological solutions.

In other words, policies have to be designed to reduce possible rebound effects. Both developed and developing countries should focus on a double phase strategy: providing easy access to resources in order to implement digital solutions and innovation, especially in production processes; implementing policies that lead to the reduction of the fossil fuel dependency and favour energy transition to renewables. In some cases, these increases in emissions will not be fully offset by the higher efficiency resulting from the adoption of digital services, and some specific policies are needed such as strict regulation (setting targets or standards)[6] or soft law actions,

[6] For instance, Madlener et al. (2022) show that the regulation of European video-streaming services is indispensable to compensate for the increase of video-streaming services use by consumers: regulating technical standards such as the video resolution (in the short run) and designing mechanisms that induce data centre and network operators to invest in order to increase the (electrical) energy efficiency of their systems (in the long run) are among the suggested measures.

including education to make consumers and producers or public administrations willing to choose or invest in ICTs and innovative digital technologies. In fact, a higher penetration of broadband among individuals requires that potential adopters have a sufficiently high level of digital literacy and attach to a broadband connection a value high enough to justify its subscription. Thus, digitalization strategies, and the related measures, adopted at the country level are extremely important, on two different but interrelated dimensions: on the one side, to stimulate individuals' digital literacy and involvement, through educational programs but also through the design of nudging (or gamification) schemes; on the other side, the enabling of innovative services, especially by public administrations (PA)—where there still is lot of room for enhancing e-Government activities—but also by firms, that can feed the significant and pervasive network effects characterizing the broadband ecosystem. A higher broadband penetration pushes firms to develop more Internet integrated products and services, widening the availability of digital solutions and conferring a greater awareness of the process of change on all the stakeholders involved.[7]

The findings of this paper have some additional and original implications. First of all, the population is a factor that plays a role in contributing to increase carbon emissions. Yet, in this case, the related policy implications are not as consequential and unequivocal as before: reducing the population growth would matter but of course it cannot be the key to achieve emissions reductions. Policy makers, particularly those in low-income countries where population is still on the rise, could accompany this growth by implementing measures aimed at fostering eco–solutions—i.e. when building new urban and non-urban sustainable infrastructure systems—and by increasing the awareness of citizens, firms, organizations, and institutions towards ecological issues. It is also crucial to design appropriate energy policies that promote energy efficiency and that accelerate the shift in the composition of energy sources, from fossil fuels to low carbon energy and renewable energy sources, decoupling environmental impact from economic growth.[8]

Finally, the positive coefficients of GDP per capita and the negative coefficients of its square represent an empirical support for a consolidated aspect in the economic literature: the validity of EKC in our sample of countries. Accordingly, this result suggests that OECD countries have reached, on average, an adequate level of development to start to lower CO_2 emissions. These countries, in fact, present better energy infrastructures, stringent environmental rules, and more awareness about environmental pollution that testify their growing attention towards the reduction of CO_2 emissions and, broadly, on environmental quality.

For future research, the analysis could be extended to other countries, and could be enriched by taking into consideration further information and communication technologies (ICTs), strict digitalization policies and supply-side elements such as

[7] European Union has settled different funding programmes to incentivize Member States to adopt stronger digitalization policies, thanks to the Digital Agenda. One is the funding granted to implement new Digital Innovation Hubs to support SMEs and PA in the digital transition, fostering not only productivity, competitiveness, and environmental protection, but also increasing the value that individual users attach to the subscription of a broadband connection.

[8] See also studies by Poumanyvong and Kaneko (2010) and Ibrahim and Law (2014).

the investment in telecommunication infrastructures. With particular reference to mobile broadband connectivity, it would be interesting to enrich the analyses by also including the penetration of Machine to Machine (M2M) SIMs among the regressors, given that it would be a more direct way to assess whether and to what extent emissions are affected by Industry 4.0 tools and processes adoption by firms.

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