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ICT for Sustainable Development: Global Comparative Evidence of Globalisation Thresholds

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Abstract

The objectives of this paper are to investigate the effect of ICT on sustainable development and the mechanisms through which the effect is modulated. The methodology involves the: (i) Fixed Effects estimator to control for individual heterogeneity, (ii) Driscoll and Kraay estimator to control for cross-section dependence between panels, (iii) the Mean Group estimator to take into account the averages between panel groups, (iv) the system GMM to correct for unobserved heterogeneity and simultaneity bias and (v) the instrumental variable Fixed Effects Tobit to take in to account the limited range in our dependent variable. The results show that ICT has a positive and significant effect on sustainable development. Whereas overall net effects are positive, the findings are contingent on the choice of the ICT measurement, the geographical location of the economy and the income group category. The study recommends policy makers to take into account ICT and the advantages it offers in the elaboration of measures for the sustainable development agenda.

Keywords: ICT; Sustainable development; panel data; trade openness; foreign direct investments

JEL Codes: C52, O38, O40, O55, P37

1. Introduction

Achieving sustainable development goals (SDGs) is the buzzword of development discourse around the globe today. However, many economies are still faced with challenges or still seeing the corresponding targets with perspectives of desolation especially when their development policies are not actually respecting the desired/targeted deadlines. Several factors can be cited to be at the origin of the adjournments in meeting incremental targets leading to the achievement of SDGs. These can be listed among others to include unavailability of a communication tool that enables diffusion of knowledge, so as to reduce ignorance associated with the processes and efforts required in meeting these goals (Asongu et al., 2018). Information and communication technology (ICT) tools and their development have offered diverse and extended routes for information diffusion through the Internet, telephones and even other media.

Increase in ICT diffusion has varying economic effects moving through economic growth, financial development, educational outcomes or even environmental sustainability. At the same time, while these effects vary per sector, the impact on sustainability has gained research grounds in recent years. Accordingly, with the advent of globalisation, the heightened diffusion of ICT across many countries that are far away from each other around the globe, represents opportunities for the achievement of many inclusive and sustainable development outcomes. Nonetheless, such sustainable development outcomes must be tailored such that three main aspects of sustainable development are taken on board in a balanced approach, namely, the economic, social and environmental dimensions. Besides, it is relevant for policy makers to be concerned about the environmental dimension and tailor the relevant policies such that environmentally-friendly technologies are prioritised in order to minimise the impacts of economic activities on the environment (Jayaprakash and Pillai, 2021).

Looking at the environmental dimension, ICT can have both favourable and adverse effects on the environment. On the one hand, ICT can reduce transaction and travelling costs that are associated with CO2 emissions in households and coporations. In fact, ICT reduces information asymmetry associated with environmental sustainability by decreasing information rents that are associated with CO2 emissions (Asongu et al., 2018; Avom et al., 2020). Also, ICT is expected to reduce CO2 emissions through the development of smarter cities, transportation systems, electrical grids, industrial processes, and energy saving gains

whose usage emit less CO2 than other alternative systems (Higón et al., 2017). On the other hand, ICT adoption leads to increase in energy consumption by individuals and firms, as a result, increase in CO2 emission. Moreover, ICT improves the financial system and information flow leading to greater financial integration and a boost in economic activities. Improvement in activities within the economy upsurges CO2 emissions (Avom et al., 2020). ICT can therefore have negative or positive effects on environmental sustainability depending on specificities. This has prompted many scholars to argue for an inverted U-curve nexus between the two concepts (Higón et al., 2017; Zhang and Meng, 2019; Khan et al., 2020; Chien et al., 2021).

Away from the environmental dimension, ICT has varying effects on social development. ICT through mobile telephony has transformed lives through innovative applications and services. It is therefore not surprising that recent literature has paid a notable attention to the impact of ICT on economic and human well-being (Aker and Mbiti, 2010; Asongu, 2020). In this respect, ICT could boost inclusive human development through its positive impact on globalization and CO2 emission (Asongu and Odhiambo, 2020a). Equally education can complement ICT through mobile technology to enhance inclusive human development (Asongu and Nwachukwu, 2018). This positive effect of ICT on inclusive human development however varies across the dimensions of human development specified and ICT dynamics, natural resources abundance, and even openness to the sea (Asongu and Le Roux, 2017; Nchofoung et al., 2021 a). Another strand of the literature looks at social development in terms of health status of the population. In this light, several scholars have elucidated the effect of ICT on the former. ICT has helped in the decentralization of health systems by reducing the geographical constraints and bringing the health care providers and the beneficiaries closer (Dutta et al., 2019). Majeed and Khan (2019) have suggested that health policies should focus on promoting digital inclusion. To however improve on the quality of life through ICT, ICT usage should be tailored towards promoting human rights, privacy and security of persons online (Adam and Alhassan, 2021).

Equally, ICT for sustainable development could be achieved through the economic dimension. In this respect, policies that encourage economic growth and poverty alleviation are highlighted as sustainable policies. ICT development can lead to higher economic growth through increase in productivity and reduction in transaction cost (Nasab and Aghaei, 2009; Cheng et al., 2021). It can equally enhance financial development (Alshubiri et al., 2019; Asongu et al., 2019; Chien et al., 2020), with favourable externalities on economic growth

(Ibrahim and Alagidede, 2018). Globalization could equally be boosted as a result of ICT adoption which in turn increases economic growth due to improvements in economies of scale (Latif et al., 2018; Kurniawati, 2020; Asongu and Odhiambo, 2020b). On the other hand, ICT could rather be harmful on economic growth especially in the absence of economic transformation (Albiman and Sulong, 2017).

The argument often raised in literature is that ICT only boosts productivity and provides other economic gains in developed countries. And that in developing countries, especially low income countries, the adequate human capital necessary for handling technology is underdeveloped. ICT can thus be harmful to sustainable development as a whole either through its social, environmental or economic dimensions. These dimensions are however interlinked, making economic policies at times very difficult. For instance, ICT development increases CO2 emission (Avom et al., 2020) and economic growth (Nasab and Aghaei, 2009; Cheng et al., 2021). Increase in CO2 emission is harmful to health outcomes (Jacobson et al., 2019; Naeem et al., 2021) and reduces inclusive human development (Nchofoung et al., 2021 b), boosts persistence in inequality (Asongu and Odhiambo, 2021; Njangang et al., 2021) and decrease human welfare as a whole (Omri and Belaïd, 2021). These links between ICT development and the different indicators of sustainable development, as well as the economic relationships established in literature between these various indicators raise concern on the need to examine the effect of ICT on sustainable development. The objective of this paper is therefore to empirically investigate the effect of ICT on sustainable development and the mechanisms through which this effect is possible.

This paper contributes to the extant literature (critically discussed in Section 2) in the following ways. Firstly, while existing literature has focused on the nexus between ICT and individual components of sustainable development, the present study departs from the extant literature by investigating the effect of ICT on sustainable development through the use of the composite sustainable development index. Secondly, the study puts forth the transmission mechanisms through which ICT affects sustainability. Most specifically, globalisation through trade and foreign direct investments were verified as possible transmission mechanisms. In essence, given the rapid growth trend of globalisation accompanied by importation of foreign technology, ICT would enhance industrial productivity and economic activities. A rise in economic activities causes domestic firms to look for foreign markets for their products. This will in turn affect the environmental, social and economic dimensions of sustainable development. Thirdly, the effect is verified across different income groups, and

regional groupings. In essence, the development of ICT is not uniform across the globe. High income countries have the potential to invest more in ICT and other sectors that will facilitate sustainable development compared to low income countries. Moreover, the geographical location of countries could act as an advantage or disadvantage in meeting the SDGs. For instance, continents like Africa and Asia lag behind economically compared to European countries. The rest of the paper is organised with a review of literature in section 2 that immediately follows this introductory section, the econometric strategy adopted in further exposed in section 3, the estimation methodology and its justifications then follow in section 4, the results and corresponding discussion are covered in section 5 and finally, section 6 concludes the article.

2. A review of the literature

The literature on the relationship between ICT and sustainable development principally focuses on the effect of ICT on the individual SDGs highlighted by the United Nations in 2015. In this respect, the literature that follows will be based on three principal strands, namely the environment, the social and the economic views of the goals. The environmental strand principally involves the effect of ICT on the emission of greenhouse gases; the social strand touches on the effect of ICT on education, health, inequality, and even human development; while the economic strand involves the effect of ICT on economic development through growth and poverty reduction.

In the first strand of the literature, several authors argue for a positive relationship between ICT and CO2 emission (Avom et al., 2020; Chen, 2021; Liu et al., 2021; Su et al., 2021). ICT will increase economic activities through trade and foreign direct investments. It will enhance industrialization and economies of scale. A boom in economic activities will increase CO2 emission through the use of energy (e.g. fossil fuels) for electrification and functioning of mechanical systems. In this line thus, Avom et al. (2020) posit that ICT mostly increases CO2 emission through trade and financial development and energy consumption. CO2 emission through energy consumption however depends on the type of energy. While renewable energy rather mitigates CO2 emission, non-renewable energy upsurges CO2 emission (Dogan and Seker, 2016). Besides, trade openness promotes economic integration and global value chains which have been identified as the main source of CO2 emission in recent years (Essandoh et al., 2020).

Other groups of authors argue that ICT has a negative relationship with CO2 emission (Ahmed and Le, 2021; Wang and Xu, 2021; N'dri et al., 2021;Chien et al., 2021). As a result, increase in ICT or ICT investments mitigate the effect of CO2 emission. In essence, economic growth and financial development contribute in CO2 emissions across all quantiles while ICT significantly mitigates the effect of CO2 emission only at lower quantiles (Chien et al., 2021). Improvement in ICT through the multiplicity of the adoption of electronic commodities (i.e. goods and services) such as online meetings, online education, e (electronic)-books, e-banking, and e-commerce, has reduced the use of many traditional commodities. Online meetings for instance have replaced traditional meetings up to a great extent. Moreover, e-commerce has reduced the need for travelling, traditional books have been replaced by e-books, and letters have equally been substituted for e-mails. This overwhelming switch of traditional commodities reduces the use of resources and by extension, corresponding activities related to the use of underlying resources that engender environmental degradation. Moreover, the ICT revolution has led to the adoption of modern transport systems and the putting in place of modern software that help in traffic management, leading to less energy consumption and less emissions (Jorisch et al. 2018; Haseeb et al. 2019; Ahmed and Le, 2021). In this respect thus, ICT has brought forth the enhancement of electronic trade in replacement of other systems of trade, reducing human contacts and transports as well as energy consumption which are the main areas of CO2 emission.

Away from the linear effects highlighted above, several groups of studies have highlighted non-linear relationships between ICT and CO2 emission (Usman et al., 2021; Azam et al., 2021; Su et al., 2021). ICT could contribute to the increasing levels of CO2 emissions within the remit of producing ICT devices and machinery, energy consumption, and electronic waste recycling. At the same time, it is anticipated that ICT can mitigate CO2 emissions at the global level if such ICT is tailored towards the development of smarter transportation systems, cities, electrical grids and industrial processes. These two impacts are apparent in opposite directions, thus creating an inverted-U nexus between CO2 emissions and ICT (An Hign et al., 2017). When ICT is adopted by firms, it could contribute to productivity and increase in emissions through a scale effect. As the ICT capital is in place, the production process is optimised and energy efficiency is realised leading to reductions in emissions through the technological effect. Some authors however have argued that ICT has no effect on the environment. In this respect, Asongu et al. (2018) posit that ICT through

mobile phones has no significant effect on CO2 emission on its own but the overall effect within the remit of an interactive regression yields net positive and negative effects contingent on the CO2 dynamics.

In the second strand of literature, some authors have argued on the effect of ICT on social development. In this respect, several studies have approached social sustainability in terms of inclusive human development (Asongu and Nwachukwu, 2016; Asongu and Le Roux, 2017;Asongu et al., 2017; Asongu et al., 2019; Asongu and Odhiambo, 2019a). Policies based on boosting ICT development will increase inclusive human development and the decree of this variation depends on the income level, political stability, legal origin, oil wealth, and whether the country is landlocked (Asongu and Le Roux, 2017). Moreover, ICT can be employed to mitigate the damaging effect of CO2 on inclusive human development. This mitigating impact of ICT on CO2 emissions is greater in English Common law countries, Middle income countries and Oil-wealthy countries than in French Civil law countries, Low income countries and Oil-poor countries, respectively (Asongu et al., 2019). Besides, social development could be seen in the angle of improved health outcomes (Mimbi and Bankole, 2015; Majeed and Khan, 2019; Dutta et al., 2019;Kouton et al., 2020). Economic freedom is however necessary for ICT diffusion to the health sector and their interaction produces a negative net effect on "under five" mortality especially for the African continent (Kouton et al., 2020). It could also produce positive outcomes on some health dimensions. In this light, Lee and Lio (2016) argue that the diffusion of the internet, mobile phones and fixed phones is associated with higher life expectancy and a reduction in infant mortality. Whereas, the internet is associated with high prevalence of the human immunodeficiency virus (HIV).

The next aspect of social development is the ability of ICT to improve on the quality of education, and reduce inequality. In this context, Asongu and Odhiambo (2019b) argue that ICT has varying effects on the educational quality in countries that are above the median values of poor educational quality: mobile phone and internet penetration rates improve the quality of education and improving internet penetration has a net negative effect. Tchamyou et al. (2019) on their part argue that ICT interacts with primary education to reduce income inequality while the interaction with secondary education produces negative net effects on the Gini index and that this effect is insignificant through tertiary education. However, there are inequality thresholds that should not be exceeded for ICT to have an enhancing impact on inclusive education (Asongu et al., 2019). Adams and Akobeng (2021) posit that ICT reduces

inequality and this relationship is reinforced by a good governance system put in place. However, the impact of ICT on income inequality is contingent on the specific type of ICT as well as the measure of income inequality employed. Moreover, the magnitude of the effect of ICT on inequality compares with more traditional forms of economic infrastructure and the nexus between inequality and ICT is contingent on other economic and political factors (Richmond and Triplett, 2018). From this perspective, studies have shown that ICT rather increases wealth inequality by increasing the billionaires' wealth and the top wealth shares in the society and that this negative effect can be mitigated through democracy (Njangang et al., 2021).

The last strand of literature examines the effect of ICT on economic growth and poverty reduction. In fact, recent growth theories have acknowledged the importance of technological progress for economic growth (Romer, 1990, 1994). The effect of ICT on growth can be enhancing (Nasab and Aghaei, 2009; Cheng et al., 2021). This could be through its enhancing effect on financial development (Alshubiri et al., 2019; Asongu et al., 2019; Chien et al., 2020), and globalisation (Latif et al., 2018; Kurniawati, 2020; Asongu and Odhiambo, 2020b). On the other hand, ICT could rather be harmful on economic growth especially in the absence of economic transformation (Albiman and Sulong, 2017).

The highlighted literature examines the effect of ICT on individual SDGs. However, no study has actually examined the effect of ICT on sustainable development through the use of a composite index for sustainable development. There is need to integrate this shortcoming in an empirical analysis and to examine the transmission channels through which this is possible.

3. Econometric Strategy

3.1.Data

Data are collected for 140 countries around the globe between the 2000-2019 period. The data sources include: the World Development Indicators (WDI) of the World Bank, the World Governance Indicators (WGI) of the World Bank, and Hickel (2020).

Dependent variable

Our dependent variable is the sustainable development index (SDGI) of Hickel (2020), which represents the efficiency of nations in achieving human development. The index is computed

as a quotient of two factors namely: the human development and the ecological impact indexes. The human development index (HDI) is calculated as the geometric mean between life expectancy index, the education index, and a modified income index. The ecological impact index (EII) on its part is calculated as the extent to which material footprint and CO2 emission that is consumption-based, exceed per capita shares of planetary boundaries. These calculations are provided in Equation (1), Equation (2) and Equation (3) respectively, for the SDGI, the HDI and the EII.

$$SDGI_{it} = \frac{Development\ index_{it}}{ecological\ impact\ index_{it}} \qquad (1)$$

$$Human\ 怒evelopment\ index_{it} = (life\ expency\ index * education\ index * income\ index)^{1/3} \qquad (2)$$

$$ecological\ impact\ index_{it} = 1 + \frac{e^{AO} - e^{1}}{e^{4} - e^{1}} \qquad (3)$$

Where AO is the average overshoot, which is the ratio of the material footprint and each of their emission values to their respective per capita planetary boundaries[1]. The SDGI has been applied in literature for empirical studies by Din et al. (2021)[2].

Independent variable of interest

Our independent variable of interest is ICT. Three main measures are used to proxy for ICT: (i) It is measured at first place through number of mobile telephone subscribers per 100 people (mobile). (ii) Secondly, the internet penetration rate is proxied by the number of internet users per 100 people (internet). (iii) Lastly, it is also measured in terms of the number of fixed telephone subscribers per 100 people (Fixed_phone). Avom et al. (2020) have adopted similar measures of ICT. They argue for a positive effect of ICT on CO2 emission. Moreover, ICT could enhance inclusive human development (Asongu and Le Roux, 2017), stimulate economic growth (Nasab and Aghaei, 2009; Cheng et al., 2021), and reduce inequality (Adams and Akobeng, 2021; Njangang et al., 2021). ICT is thus expected to have a positive effect on inclusive development in this study. The first hypothesis can be formulated thus:

[1] See Hickel (2020) for details on the computation procedure of these indexes

[2]The data for all the dependent variables are extracted from:https://www.sustainabledevelopmentindex.org/time-series

Hypothesis 1: **ICT enhances sustainable development across the world.**

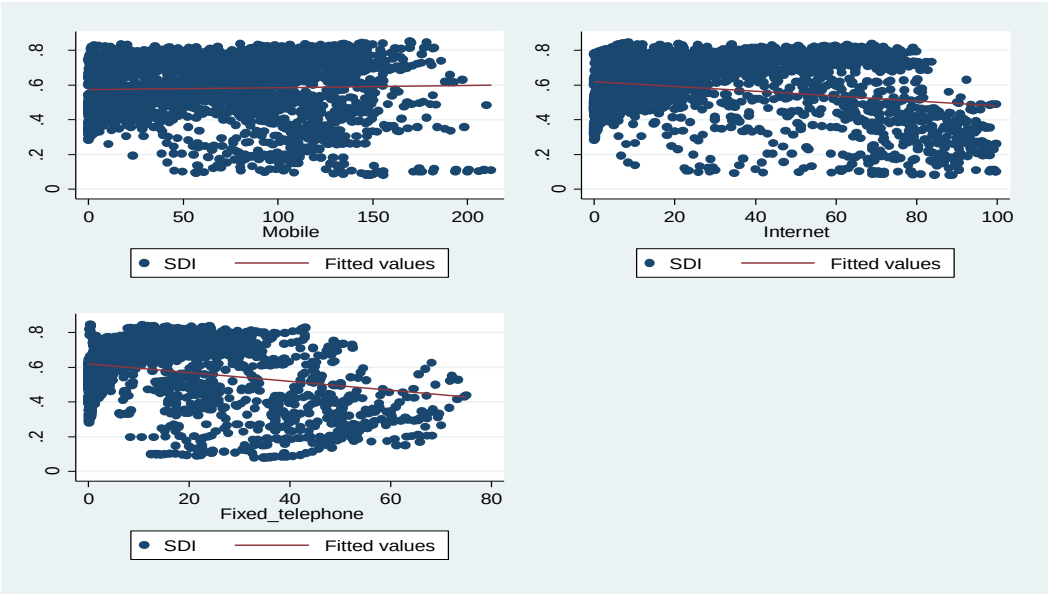
Control variables

(i)The first control variable taken into account is financial development. This is proxied by domestic credit to the private sector (Domestic_credit). ICT could affect environmental quality through financial development (Avom et al., 2020; Chien et al., 2021). In this light, Chien et al. (2021) argue that ICT mitigates CO2 emission through financial development especially in the lower quantile. Financial development is therefore expected to have a positive effect on sustainable development. (ii) Furthermore, globalisation in the social, economic and political spheres has an enhancing effect on inclusive human development (Asongu and Nwachukwu, 2017; Asongu and Odhiambo, 2020 a). Besides, trade openness is very essential for economic prosperity (Frankel and Romer, 1999). Globalization through trade openness (trade) and foreign direct investments (FDI) is expected to have enhancing effects on sustainable development in this study. (iii) Also, good governance is needed to enhance inclusive development (Asongu and Odhiambo, 2020c). In fact, governance has a strong positive effect on sustainable development. Governance proxy through government effectiveness (gov_effectiv) is expected to have a positive sign in this study. (iv)The last but not the least variable included in the model is economic growth. In fact, no economic development can actually take place without growth. Economic growth leads to an increase in economic activities and CO2 emission (Chien et al., 2021), which consequently has an impact on social development (Asongu and Odhiambo, 2020 a, 2020c). Though growth is a measure of development itself, it is however an explicative component of social development and equally greatly explains environmental sustainability. This variable could have a positive or a negative effect.

The next hypothesis is then stated thus:

Hypothesis 2: The effect of **ICT on sustainable development is modulated through trade openness and foreign direct investment.** Figure 1 shows a preview of the link between ICT and sustainable development in this study.

Figure 1. Fitted plot of ICT effect on sustainable development



Source: Authors' computation.

The two-way fitted plots in Figure 1 show that ICT has a preview negative and insignificant effect on sustainable development, though the effect seems to be weakly significant with internet and fixed phones. This relationship can however be influenced by several other control variables in a modelling framework. There is therefore the need to verify this relationship through an empirical model. Table 1 highlights the summary statistics of the variables considered in this regard.

Table 1. Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max
Sustainable development index	2755	.582	.172	.079	.853
life expectancy	2800	68.597	9.289	39.4	84.6
expected school	2795	12.08	3.053	2.9	23.3
mean school	2773	7.489	3.121	1.1	13.4
co2 capita	2787	4.465	5.85	.01	32.41
footprint capita	2792	10.749	11.519	.06	78.19
Mobile	2758	70.078	49.265	0	212.639
Internet	2596	28.003	28.496	0	99.702
fixed telephone	2745	14.855	15.801	0	74.988
domestic credit	2438	46.53	42.263	.491	304.575
Foreign direct investment	2775	4.296	6.584	-40.33	103.337
Trade	2628	82.078	45.193	.167	437.327
Government effectiveness	2799	-.135	.893	-2.279	2.437
GDP per capita	2766	8.290007	1.434198	5.272348	11.43089

Source: Authors' computation

The statistics in Table 1 show that the variables are more or less distributed around the mean, for the SDI, which is the main dependent variable, the maximum value is 0.853 while the minimum value is 0.079 with an average value 0.582 which is just slightly above average. As for the ICT variable, the statistics shows that more than 70 in every 100 people around the world use mobile phones, while only slightly above 28% of the population had access to the internet between the 2000-2019 period. The rate of fixed phone subscribers still remains very low, maybe attributed to the advent of mobile phones which is more practicable. The per capita growth has been presented in logarithm.

3.2.Modelling and regression methodologies

3.2.1. Model specification

Since the adoption of the post-2015 sustainable development agenda, policy institutions have been seeking for the right path and the appropriate policies to put in place to realise this dream that still seems like an illusion in the eyes of many countries, especially the developing countries. However, for this dream to be a reality, every sphere that could impact social, environmental and economic developments should be exploited. In this regard, ICT is one of the sectors that have grown substantially over the past two decades. ICT development could impact the economy through its ability to enhance productivity, leading to economies of scale. This could enhance economic activities by increasing trade. Moreover, an increase in economic activities creates more wealth for firms which they could seek to invest in foreign markets through foreign direct investments. Besides, countries with high economic activities will equally attract foreign direct investment inflows, as investors are sure of potential markets, leading to the creation of more wealth per capita. Increase wealth lead to further domestic investments, as a result, more jobs are created which increases the social status of citizens. Increase investments in industries motivate investments in formal education so as to meet the requirements of skilled labour needed for industrial positions. On the other hand, an increase in industrial activities would lead to the emission of CO2, thereby degrading the environment. Therefore, ICT could be a good drive for sustainable development through its ability to drive globalisation. A theoretical model could thus be derived linking ICT and sustainable development as in Equation (4):

$$SDI = f(ICT, Globalisation) \qquad (4)$$

The empirical model can thus be specified with SDI as dependent variable thus.

$$SDI_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 trade_{it} + \beta_3 FDI_{it} + \beta_4 X_{it} + \varepsilon_{it} \quad (5)$$

Where X is the vector of other control variables, i is the cross-sectional dimension at period, t, β is the coefficient associated to each variable, ε is the stochastic error term.

Accounting for transmission mechanisms through globalisation (trade and FDI), Equation (5) can be transformed to Equation (6) in accordance to Nchofoung et al. (2021) as:

$$SDI_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 trade_{it} + \beta_3 FDI_{it} + \beta_4 X_{it} + \pi_1 (ICT_{it} \text{ x } trade_{it}) + \pi_2 (ICT_{it} \text{x } FDI_{it}) + \varepsilon_{it} \quad (6)$$

Where π is the coefficient of the modulating variables. Differentiating Equation (6) with respect to ICT yields Equation (7) below:

$$\frac{\partial SDI_{it}}{\partial ICT_{it}} = \beta_1 + \pi_1 trade_{it} + \pi_2 FDI_{it} \quad (7)$$

Where $\boldsymbol{\partial}$ is the partial derivative operator. As such, a unit change in the SDI as a result of a change in ICT depending on the signs and coefficients of β_1 and π. Depending on the signs and coefficient of the direct and indirect effects, a net effect could eventually be computed only if both the direct and indirect coefficients are significant and opposing in signs.

$$SDI_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 trade_{it} + \beta_3 FDI_{it} + \beta_4 X_{it} + \pi_1 (ICT_{it} \text{ x } trade_{it}) + \pi_2 (ICT_{it} \text{x } FDI_{it}) + (\beta_1 + (\Omega \times \pi)) + \varepsilon_{it} \quad (8)$$

Equation (8) can only be feasible if β_1 and π are opposing in signs and both significant,. Ω is the average of the policy modulating variable. If these conditions are met, then there exist a policy threshold in Equation (9) for the modulating variables retained such that;

$$\frac{\partial SDI_{it}}{\partial ICT_{it}} = 0 \quad (9)$$

In this case the thresholds retained are such as provided in Equation (10)

$$\begin{cases} trade_{threshold = \beta_1/\pi_1} \\ FDI_{threshold = \beta_1/\pi_2} \end{cases} \quad (10)$$

The given threshold is only computed if the values fall within the range of values of the modulating variables presented in the summary statistics in Table 1.

3.2.2. Estimation Technique

3.2.2.1.IV-Tobit

Given the limited range of the SDI (between 0 and 1), the Tobit model is appropriate since methods such Ordinary Least Squares (OLS) will produce biased results. In this respect, the double censored Tobit regression is worthwhile given that it takes into account the limited range in the outcome variable (see Kumbhakar and Lovell, 2000; Koetter et al., 2008; Ariss, 2010; Coccorese and Pellecchia, 2010; Asongu and Le Roux, 2017; Nchofoung et al., 2021). The lowest possible outcome (0) for our dependent variable is absent in our dataset. Our data for the SDI varies between 0.075 and 0.853 as apparent in Table 1. Estimating the model with a doubled censored Tobit is thus similar to estimating through a linear regression because the likelihood functions coincide. We thus adopt the instrumental variable Tobit (IV-Tobit) instead of the simple Tobit because of its ability to control for simultaneity. The procedure starts through a simple Tobit model in Equation (11):

$$SDI^{*}_{it} = \alpha_0 + \beta X_{it} + \mu_{it} \qquad (11)$$

Where SDI^{*} is the hidden response variable to the vectors of explanatory variables, X. α_0 is the constant term, while μ is identically and independently distributed. The observations of the latent response variable are based on the value of the random error term ε as apparent in Equation (12).

$$SDI_{it} = \begin{cases} SDI^{*}_{it} \; if \; SDI^{*}_{it} > \varepsilon \\ 0 \; if \; SDI^{*}_{it} \leq \varepsilon \end{cases} \qquad (12)$$

In order for the regression to be valid, it is relevant that the Wald test of exogeneity should be significant. It represents a Chi2 test under the null hypothesis of exogeneity. Rejecting the null hypothesis is an indication that the variable is endogenous and hence, the IV-Tobit is a valid/robust estimator.

3.2.2.2. System GMM

Following Rodman (2009), the first condition for GMM to be used in any regression is that the cross-sectional dimension should be greater than the time dimension, which is the case with our global data and some sub-samples. The inclusion of the lagged dependent variable which is usually typical of the GMM framework correlates with the fixed effects in the error term and this results in a dynamic panel bias when estimated with methods like OLS (Nickell,

1981). The GMM estimation method resolves this bias and equally control for cross-country dependence across panels (Nchofoung et al., 2021). The method however has a plethora of merits given that it controls for the observed heterogeneity and simultaneity biases.

The following Equation (13) and Equation (14) respectively, summarize the GMM procedure in level and in difference.

$$SDI_{it} = \beta_0 + \beta_1 SDI_{i(t-\tau)} + \beta_2 ICT_{it} + \sum_{h=1}^{k} \delta_h W_{h,i(t-\tau)} + \upsilon_t + \gamma_i + \varepsilon_{it} \qquad (13)$$

$$SDI_{it} - SDI_{i(t-\tau)} = \beta_1 \left(SDI_{i(t-\tau)} - SDI_{i(t-2\tau)}\right) + \beta_2 \left(ICT_{i<} - ICT_{i(t-\tau)}\right) + \sum_{h=1}^{k} \delta_h \left(W_{h,i(t-\tau)} - W_{h,i(t-2\tau)}\right) \left(\upsilon_t - \upsilon_{t-\tau}\right) + \varepsilon_{i(t-\tau)} \qquad (14)$$

The variables are defined as above. The problem that the GMM estimation could have is that of identification, simultaneity and restrictions. In this regards, all our explanatory variables are suspected to be a source of endogeneity and treated as endogenous in accordance with contemporary literature (Asongu and Nwachukwu, 2016; Nchofoung et al., 2021).

4. Results and Discussion

In this sub-section, the baseline results are presented before the instrumental variable results from 2SLS and IV-Tobit regressions.

4.1.Baseline Results

This sub-section presents the results of the: (i) Fixed Effects model, (ii) Driscoll and Kraay (1998) standard error procedure and (iii) Mean Group (MG) estimation.

Table 2. Baseline results

	(1)	(2)	(3)
	Dependent variable: sustainable development index		
Variables	FE	Driscoll/Kraay	MG
Mobile	0.000420***	0.000420***	0.000303**
	(2.81e-05)	(4.00e-05)	(0.000136)
Domestic credit	-0.000192**	-0.000192	0.000149
	(8.03e-05)	(0.000141)	(0.000194)
Foreign direct investment	0.000113	0.000113	-0.000210
	(0.000161)	(0.000146)	(0.000552)
Trade	8.05e-06	8.05e-06	-0.000201
	(6.03e-05)	(5.67e-05)	(0.000148)
Government effectiveness	-0.0143***	-0.0143**	-0.00889
	(0.00474)	(0.00603)	(0.00617)
GDP per capita	-1.11e-05***	-1.11e-05***	8.41e-05***
	(5.63e-07)	(1.42e-06)	(2.05e-05)
Constant	0.680***	0.680***	0.667***
	(0.00796)	(0.00870)	(0.0439)
Observations	2,233	2,233	2,192
R-squared	0.201		
Number of individuals	133		125
Fisher	88.01***	596.3***	
chi2			26.53***

NB: Standard errors in parentheses;*** p<0.01, ** p<0.05, * p<0.1; MG is Mean Group estimator; FE is Fixed Effects estimator

Source: Authors' computation

Table 2 shows a positive and significant effect of ICT on sustainable development across all the baseline estimations. These results however cannot be interpreted at this level because the estimations do not control for certain econometric biases such as double causality and unobserved heterogeneity. The system GMM and the IV-Tobit are used in this case.

4.2.Direct effect Results

The results of the direct effect of ICT on sustainable development are presented in this section. Table 3 presents the global sample results across different dynamic estimation methods, Table 4 discloses the results across different geographical groupings and Table 5 shows the findings across different income groups. Further analysis is based on the IV-Tobit as opposed to the system GMM because some sub-samples contain less number of countries compared to the period of study.

Table 3. Direct effect results for the global sample

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Dependent variable: sustainable development index (SDI)					
	IV-Tobit			System GMM		
Mobile	0.00103***			0.0000328**		
	(7.28e-05)			(1.56e-05)		
Internet		0.00187***			0.0000698***	
		(0.000177)			(2.00e-05)	
fixed telephone			0.00272***			-0.000145
			(0.000337)			(7.71e-05)
domestic credit	7.61e-05	4.12e-05	0.000232**	2.39e-05	2.29e-05	-4.13e-06
	(0.000112)	(0.000119)	(0.000116)	(3.09e-05)	(3.03e-05)	(2.09e-05)
FDI	-0.00110*	-0.000925*	-0.00188**	2.66e-05*	2.64e-05*	-1.04e-05*
	(0.000832)	(0.000879)	(0.000867)	(6.25e-05)	(7.29e-05)	(3.73e-05)
Trade	0.000250***	0.000123*	7.08e-05*	-2.87e-07*	1.56e-06*	6.16e-06**
	(8.65e-05)	(9.13e-05)	(9.03e-05)	(1.81e-05)	(2.46e-05)	(1.34e-05)
Government effectiveness	0.0369***	0.0236***	0.0128*	0.00151*	0.00119*	0.000927*
	(0.00643)	(0.00710)	(0.00759)	(0.00191)	(0.00201)	(0.00142)
GDP per capita	-8.57e-06***	-9.17e-06***	-8.85e-06***	-5.48e-07***	-6.76e-07***	-3.41e-07**
	(2.80e-07)	(3.00e-07)	(2.99e-07)	(1.69e-07)	(1.44e-07)	(1.36e-07)
SDI(-1)				0.943***	0.930***	0.967***
				(0.0185)	(0.0136)	(0.0151)
Constant	0.620***	0.639***	0.633***	0.0368***	0.0462***	0.0274***
	(0.0101)	(0.0105)	(0.0109)	(0.0115)	(0.00914)	(0.00969)
Observations	1,963	1,816	1,948	1,957	1,811	1,942
Prop>Chi2 exogeneity	0.589	0.412	0.155			
chi2	1603***	1373***	1345***			
Number of countries				133	133	133
Prop>AR1				0.00112	0.00149	0.00117
Fisher				2757***	2570***	6117***
Prop> Hansen				0.871	0.457	0.255
Prop>Sargan				0.171	0.0667	1.05e-08
Instruments				19	19	25
Prop>AR2				0.602	0.658	0.668

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; FDI is foreign direct investments; SDI is sustainable development index

Source: Authors' computation

Table 3 shows that ICT has a significant positive effect on sustainable development across different proxies of ICT and different estimation methodologies. ICT could enhance inclusive human development (Asongu and Le Roux, 2017), stimulate economic growth (Cheng et al., 2021), improve environmental quality (Chien et al., 2021), and reduce inequality (Njangang et al., 2021). Sustainable development is enhanced by ICT when the latter succeeds in enhancing the economic, environmental and social dimensions of sustainability. ICT offers the right forum for proper education on the sustainable development goals through the internet and telephony. It eases trading and investment opportunities, increases economic activities and economies of scale. This as a result, increases the level of income within the economy which can be used for financing the SDGs as set out by the United Nations (UN). Based on these results, a conclusion cannot be reached without assessing if it is robust across different groupings. Table 4 shows the results across different geographical regions while Table 5 shows the results across different income groups.

Table 4. Direct effect of ICT on SDI across different Geographical regions

	(1)	(2)	(3)	(4)	(5)
	Dependent variable: sustainable development index (SDI)				
Variables	Africa	Europe	America	Asia	Oceania
Mobile	0.000966***	-0.000529	0.000233**	0.000558***	0.00107***
	(9.67e-05)	(0.000354)	(0.000114)	(0.000104)	(0.000381)
Domestic credit	0.00142***	-0.000773***	-0.000180	-0.000330**	0.000692
	(0.000196)	(0.000236)	(0.000213)	(0.000149)	(0.000703)
FDI	-0.00176**	-0.00107	0.00415**	0.00376**	0.00256
	(0.000746)	(0.00230)	(0.00195)	(0.00162)	(0.00305)
Trade	-8.12e-05	0.00117***	-0.000698***	-0.000713***	0.00386***
	(0.000146)	(0.000316)	(0.000208)	(0.000125)	(0.00103)
Government effectiveness	-0.0260***	-0.0403***	0.0704***	0.0482***	0.122***
	(0.00903)	(0.0152)	(0.00927)	(0.0110)	(0.0329)
GDP per capita	2.39e-06*	-4.02e-06***	-1.47e-05***	-1.01e-05***	-1.23e-05***
	(1.36e-06)	(5.48e-07)	(7.94e-07)	(3.85e-07)	(9.79e-07)
Constant	0.437***	0.723***	0.860***	0.721***	0.249***
	(0.0138)	(0.0376)	(0.0179)	(0.0158)	(0.0900)
Observations	669	265	433	541	55
Prop>Chi2 exogeneity	0.120	0.128	0.483	0.877	0.869
chi2	291.7***	1116***	830.9***	1259***	2004***
Tobitll	0.295	0.151	0.170	0.0790	0.150
Tobitul	0.803	0.839	0.853	0.843	0.785

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; FDI is foreign direct investments: ICT is information and communication technology.

Source: Authors' computation.

Table 5. Direct effect of ICT on SDI across different income groups

	(1)	(2)	(3)	(4)
	Dependent variable: sustainable development index			
Variables	LIC	LMIC	UMIC	HIC
Mobile	0.000913***	0.000813***	-0.000226**	-0.000192
	(0.000117)	(7.46e-05)	(9.83e-05)	(0.000189)
Domestic credit	0.00158***	0.000982***	-8.22e-05	-0.000903***
	(0.000499)	(0.000161)	(0.000138)	(0.000195)
Foreign direct investment	-0.000102	-0.00106	0.00771***	-0.00151
	(0.000438)	(0.00124)	(0.00129)	(0.00359)
Trade	0.000406***	0.000191*	-0.000312**	-0.000652***
	(0.000125)	(0.000112)	(0.000141)	(0.000229)
Government effectiveness	0.0253***	0.0247***	-0.0497***	0.0665***
	(0.00878)	(0.00736)	(0.00947)	(0.0163)
GDP per capita	-5.03e-06***	5.53e-06***	3.02e-06**	-7.19e-06***
	(1.47e-06)	(1.99e-06)	(1.52e-06)	(5.09e-07)
Constant	0.398***	0.532***	0.711***	0.774***
	(0.0119)	(0.0110)	(0.0198)	(0.0244)
Observations	266	671	546	468
Prop>Chi2 exogeneity	0.886	0.262	0.0238	0.533
chi2	150.4	499.0	103.0	673.0
Tobitll	0.295	0.438	0.329	0.0790
Tobitul	0.586	0.843	0.853	0.816

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; LIC is low-income countries, LMIC is lower-middle-income countries, UMIC is upper-middle-income countries and HIC is high income countries

Source: Authors' computation

Tables 4 and 5 show that the results are robust across different geographical regions and income groups, except for Europe and upper-middle-income countries where the effect of ICT on sustainable development is insignificant and negative, respectively. The results across these two sub-samples equally differ across other explanatory variables especially with the effect of trade and foreign direct investments. To better provide explanations on this relationship between ICT and sustainable development, there is need to exploit the transmission mechanisms through which this is possible. In what follows, trade and foreign direct investment are investigated as possible modulating mechanisms.

4.3.Transmission Mechanisms

In this sub-section, it is the question of investigating the mechanisms through which ICT affects sustainable development. Table 6 investigates these mechanisms on a global sample while Tables 7-12 present the results per regional groupings and income groups.

In Table 6, mobile phone adoption interacts with trade openness and foreign direct investment to produce positive direct effects and negative indirect effects though non-significant for FDI. The direct effect outweighs the indirect effect producing a positive net effect with trade openness up to a trade threshold of 148.3870968 (%GDP) when this positive effect is nullified. Similar patterns are followed by their interactions with internet and fixed phones; all producing positive net effects. The trade openness thresholds required to nullified this net effect is 131.7460 (%GDP) and 134.79167 (%GDP) respectively through the internet and fixed phones while the respective FDI thresholds required to nullify this positive net effects are 25.203252 (%GDP) and 19.405405 (%GDP).

Table 6. Indirect effect of ICT on sustainable development (global sample)

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: sustainable development index					
Mobile	0.00230***	0.00112***				
	(0.000128)	(0.000100)				
Domestic credit	2.10e-05	6.19e-05	-0.000148	7.48e-05	-4.46e-05	0.000185
	(0.000108)	(0.000112)	(0.000117)	(0.000121)	(0.000116)	(0.000117)
FDI	-0.00123	0.000481	-0.00245***	0.000211	-0.00237***	-0.000524
	(0.000801)	(0.00134)	(0.000870)	(0.000894)	(0.000825)	(0.000855)
Trade	0.00129***	-0.000215**	0.00153***	2.06e-06	0.00128***	0.000221**
	(0.000156)	(9.33e-05)	(0.000165)	(0.000127)	(0.000141)	(0.000107)
Government effectiveness	0.0366***	0.0376***	0.0303***	0.0290***	0.0187**	0.0160**
	(0.00620)	(0.00646)	(0.00693)	(0.00755)	(0.00739)	(0.00766)
GDP per capita	-8.44e-06***	-8.59e-06***	-8.90e-06***	-9.15e-06***	-8.66e-06***	-9.01e-06***
	(2.70e-07)	(2.80e-07)	(2.94e-07)	(3.10e-07)	(2.90e-07)	(3.03e-07)
Mobile ×trade	-0.0000155***					
	(1.32e-06)					
Mobile ×FDI		-0.0000215				
		(1.69e-05)				
Internet			0.00415***	0.00186***		
			(0.000267)	(0.000213)		
Internet ×trade			-0.0000315***			
			(2.58e-06)			
Internet ×FDI				-0.0000738*		
				(4.28e-05)		
Fixed telephone					0.00647***	0.00359***
					(0.000469)	(0.000425)
Fixed ×trade					-0.0000480**	
					(4.29e-06)	
Fixed ×FDI						-0.000185***
						(5.26e-05)
Net effect	0.00102779	--	0.00156454	0.001542955	0.002530256	0.00279524
Threshold	148.3870968	-----	131.7460	25.203252	134.79167	19.405405
Constant	0.504***	0.612***	0.537***	0.633***	0.558***	0.620***
	(0.0139)	(0.0118)	(0.0135)	(0.0119)	(0.0125)	(0.0117)
Observations	1,963	1,963	1,816	1,816	1,948	1,948
Prop>Chi2 exogeneity	0.899	0.701	0.280	0.106	0.104	0.333
chi2	1872***	1604***	1573***	1308***	1558***	1345***
Tobitll	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790
Tobitul	0.853	0.853	0.846	0.846	0.846	0.846

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; FDI is foreign direct investment; ICT is information and communication technology
Source: Authors' computation

Table 7. Indirect effect of ICT adoption (mobile phone) on sustainable development (geographical groupings)

Variables	(1) Africa	(2) Europe	(3) America	(4) Asia	(5) Oceania	(6) Africa	(7) Europe	(8) America	(9) Asia	(10) Oceania
	Through trade openness (trade)					Through foreign direct investments (FDI)				
Mobile	0.00237***	-0.00207	0.000902***	0.00156***	-0.000763	0.00133***	-0.00191***	0.000456**	0.000904***	0.000112
	(0.000192)	(0.00128)	(0.000244)	(0.000161)	(0.00198)	(0.000155)	(0.000710)	(0.000181)	(0.000128)	(0.000957)
Domestic credit	0.00114***	-0.000759***	-0.000205	-0.000281**	0.00119	0.00124***	-0.000677***	-0.000199	-0.000408***	0.00124
	(0.000190)	(0.000236)	(0.000211)	(0.000141)	(0.000954)	(0.000208)	(0.000248)	(0.000213)	(0.000147)	(0.000861)
FDI	-0.00162**	-0.00172	0.00508***	0.00447***	0.00170	0.00291*	-0.0326**	0.00990**	0.0158***	-0.00911
	(0.000712)	(0.00206)	(0.00197)	(0.00153)	(0.00333)	(0.00163)	(0.0141)	(0.00440)	(0.00306)	(0.00908)
Trade	0.000837***	-0.000786	4.75e-05	0.000645***	0.00332***	1.80e-05	0.00126***	-0.000764***	-0.000632***	0.00424***
	(0.000181)	(0.00178)	(0.000316)	(0.000205)	(0.00117)	(0.000151)	(0.000325)	(0.000213)	(0.000125)	(0.00112)
Govern't effectiveness	-0.0187**	-0.0380**	0.0693***	0.0419***	0.138***	-0.0221**	-0.0345**	0.0673***	0.0520***	0.120***
	(0.00865)	(0.0150)	(0.00919)	(0.0104)	(0.0345)	(0.00922)	(0.0160)	(0.00954)	(0.0108)	(0.0355)
GDP per capita	2.97e-06**	-4.11e-06***	-1.46e-05***	-9.83e-06***	-1.20e-05***	2.64e-06*	-4.34e-06***	-1.45e-05***	-1.01e-05***	-1.22e-05***
	(1.30e-06)	(5.30e-07)	(7.87e-07)	(3.68e-07)	(1.07e-06)	(1.38e-06)	(5.88e-07)	(8.05e-07)	(3.77e-07)	(1.02e-06)
Mobile ×trade	-0.0000163***	0.00001.80	-0.0000863***	-0.0000123***	0.0000167					
	(1.98e-06)	(1.53e-05)	(2.82e-06)	(1.59e-06)	(1.70e-05)					
Mobile ×FDI						-0.0000887**	0.000274**	-0.0000462	-0.000115***	0.000114
						(2.89e-05)	(0.000117)	(3.00e-05)	(2.62e-05)	(0.000123)
Net effect	0.0010321	----	-0.00618133	0.00055044	-----	0.000948945	-0.0007329	-------	0.00040996	----------
Threshold	145.39877	---	0.14592	126.829268	-----	14.99436	6.970802	--------	7.8608695	---------
Constant	0.372***	0.890***	0.798***	0.610***	0.285***	0.417***	0.871***	0.838***	0.684***	0.260***
	(0.0155)	(0.142)	(0.0266)	(0.0208)	(0.0960)	(0.0151)	(0.0752)	(0.0227)	(0.0177)	(0.0918)
Observations	669	265	433	541	55	669	265	433	541	55
tobitul	0.803	0.839	0.853	0.843	0.785	0.803	0.839	0.853	0.843	0.785
tobitll	0.295	0.151	0.170	0.0790	0.150	0.295	0.151	0.170	0.0790	0.150
chi2	388.9***	1111***	858.5***	1466***	1943***	294.2***	1044***	836.8***	1334***	1881***
Prop>Chi2 exogeneity	0.159	0.954	0.794	0.326	0.139	0.135	0.137	0.556	0.231	0.106

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; FDI is foreign direct investments; ICT is information and communication technology

Source: Authors' computation

Table 8. Indirect effect of ICT penetration (internet penetration) on sustainable development (geographical groupings)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Dependent variable: Sustainable development index									
Variables	Africa	Europe	America	Asia	Oceania	Africa	Europe	America	Asia	Oceania
	Through trade openness					Through foreign direct investments inflows				
internet	0.00795***	-0.000999	0.00278***	0.00180***	-0.00782**	0.00322***	-0.00118**	0.00280***	0.000246	-0.00128
	(0.000630)	(0.00126)	(0.000552)	(0.000330)	(0.00373)	(0.000580)	(0.000476)	(0.000405)	(0.000260)	(0.00141)
Domestic credit	0.00118***	-0.000639***	-0.000498**	-0.000295*	0.00185**	0.00145***	-0.000506**	-0.000362*	-0.000234	0.00255***
	(0.000207)	(0.000234)	(0.000221)	(0.000157)	(0.000935)	(0.000253)	(0.000251)	(0.000219)	(0.000165)	(0.000934)
FDI	-0.00284***	-0.00365	0.00367*	0.00376**	0.00256	0.000139	0.00902**	0.0108***	0.00835***	-0.00735
	(0.000756)	(0.00240)	(0.00220)	(0.00156)	(0.00399)	(0.000962)	(0.00420)	(0.00278)	(0.00207)	(0.00468)
Trade	0.00164***	0.00234**	-5.07e-05	0.000635***	0.000559	0.000752***	0.00124***	-0.000517**	-0.000463***	0.00188**
	(0.000212)	(0.00105)	(0.000348)	(0.000196)	(0.00104)	(0.000232)	(0.000285)	(0.000205)	(0.000138)	(0.000927)
Gov't effectiveness	-0.0240**	-0.00460	0.0594***	0.0537***	0.122***	-0.0251**	-0.0277*	0.0696***	0.0577***	0.105***
	(0.00946)	(0.0172)	(0.0106)	(0.0109)	(0.0340)	(0.0114)	(0.0165)	(0.0111)	(0.0116)	(0.0320)
GDP per capita	6.01e-06***	-3.97e-06***	-1.56e-05***	-9.52e-06***	-1.03e-05***	3.10e-07	-3.63e-06***	-1.65e-05***	-9.67e-06***	-1.66e-05***
	(1.70e-06)	(5.38e-07)	(8.28e-07)	(3.98e-07)	(2.37e-06)	(1.92e-06)	(5.03e-07)	(8.93e-07)	(4.18e-07)	(1.39e-06)
Internet ×trade	-0.0000777***	-0.0000129	-0.0000134**	-0.0000229**	0.0000948***					
	(6.34e-06)	(1.43e-05)	(6.72e-06)	(2.80e-06)	(3.45e-05)					
Internet ×FDI						-0.000501***	-0.000144**	-0.000260***	-0.000148***	0.000528***
						(0.000105)	(7.15e-05)	(7.93e-05)	(3.71e-05)	(0.000193)
Net effect	0.00157253	------	0.001680155	-0.00007959	-0.00003900	0.0010677	s.e	0.00168304	---------	---------
Threshold	102.3166023	------	207.462687	78.60262	82.48945147	6.4271457	----	10.76923076	-----	------
Constant	0.352***	0.669***	0.793***	0.658***	0.549***	0.413***	0.682***	0.806***	0.729***	0.445***
	(0.0169)	(0.0839)	(0.0224)	(0.0188)	(0.0926)	(0.0186)	(0.0377)	(0.0182)	(0.0167)	(0.0906)
Observations	603	255	402	506	50	604	255	404	507	50
Prop>Chi2 exogeneity	0.188	0.133	0.809	0.843	0.630	0.678	0.146	0.497	0.136	0.978
chi2	370.5***	1030***	902.6***	1341***	1298***	176.2***	1150***	904.8***	1165***	1587***
tobitll	0.295	0.151	0.170	0.0790	0.150	0.295	0.151	0.170	0.0790	0.150
tobitul	0.801	0.839	0.846	0.836	0.785	0.801	0.839	0.846	0.836	0.785

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; FDI is foreign direct investment, s.e is synergy effect; ICT is information and communication technology

Source: Authors' computation

Table 9. Indirect effect of ICT adoption (Fixed phones) on sustainable development (geographical groupings)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Dependent variable: sustainable development index									
Variables	Africa	Europe	America	Asia	Oceania	Africa	Europe	America	Asia	Oceania
	Through trade openness (trade)					Through foreign direct investments (FDI)				
fixed telephone	0.0149***	-0.00143	0.00559***	0.00372***	-0.00991***	0.00657***	0.000532	0.00487***	0.000614	0.00324**
	(0.00169)	(0.00183)	(0.00119)	(0.000590)	(0.00263)	(0.00123)	(0.000717)	(0.000943)	(0.000539)	(0.00132)
domestic credit	0.00142***	-0.000833***	-0.000138	-0.000577***	0.000902*	0.00161***	-0.000543**	6.33e-05	-0.000408**	0.00267***
	(0.000204)	(0.000228)	(0.000223)	(0.000147)	(0.000526)	(0.000217)	(0.000263)	(0.000218)	(0.000162)	(0.000368)
FDI	-0.00132*	-0.00112	0.00616***	0.00439***	-0.00937**	-0.000712	0.00730	0.0136***	0.00947***	-0.00756
	(0.000692)	(0.00215)	(0.00221)	(0.00152)	(0.00370)	(0.000742)	(0.00711)	(0.00264)	(0.00192)	(0.00568)
trade	0.000902***	0.000552	-7.44e-06	0.000740***	-0.00260**	0.000296	0.000956***	-0.000717***	-0.000280*	0.00134*
	(0.000201)	(0.000698)	(0.000274)	(0.000173)	(0.00112)	(0.000192)	(0.000290)	(0.000201)	(0.000150)	(0.000686)
Govern't effectiveness	-0.0399***	-0.0319*	0.0589***	0.0643***	-0.0195	-0.0415***	-0.0489**	0.0569***	0.0675***	0.00191
	(0.00955)	(0.0181)	(0.0122)	(0.0110)	(0.0316)	(0.0100)	(0.0196)	(0.0120)	(0.0122)	(0.0264)
GDP per capita	3.18e-06**	-4.19e-06***	-1.71e-05***	-9.62e-06***	-1.26e-05***	9.68e-07	-3.97e-06***	-1.77e-05***	-9.52e-06***	-1.53e-05***
	(1.56e-06)	(6.10e-07)	(9.75e-07)	(3.65e-07)	(1.22e-06)	(1.67e-06)	(5.56e-07)	(9.80e-07)	(3.98e-07)	(1.00e-06)
Fixed telephone ×trade	-0.000119***	0.0000140	-0.0000455***	-0.0000489***	0.000224***					
	(1.42e-05)	(1.99e-05)	(9.87e-06)	(4.28e-06)	(4.30e-05)					
Fixed telephone ×FDI						-0.000604***	-0.000226	-0.000480***	-0.000462***	0.000135
						(0.000135)	(0.000149)	(8.29e-05)	(8.36e-05)	(0.000285)
Net effect	0.0051327	----	0.001855	-0.0002936142	0.008475	0.003975	-----	0.0028079	-------	-------
Threshold	125.21008	-----	122.8571	76.0736	44.24107	10.87748	-------	10.1458	-----	------
Constant	0.397***	0.730***	0.796***	0.664***	0.917***	0.435***	0.650***	0.808***	0.725***	0.452***
	(0.0156)	(0.0646)	(0.0235)	(0.0169)	(0.121)	(0.0154)	(0.0368)	(0.0206)	(0.0171)	(0.0657)
Observations	664	265	431	532	56	664	265	431	532	56
Prop>Chi2 exogeneity	0.809	0.135	0.336	0.487	0.132	0.153	0.149	0.924	0.206	0.104
chi2	265.4***	1112***	865.7***	1548***	2043***	199.2***	1218***	904.0***	1220***	2599***
tobitll	0.295	0.151	0.170	0.0790	0.150	0.295	0.151	0.170	0.0790	0.150
tobitul	0.803	0.839	0.846	0.843	0.787	0.803	0.839	0.846	0.843	0.787

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; ICT is information and communication technology; FDI is foreign direct investments

Source: Authors' computation

Table 10. Indirect effect of ICT adoption (Mobile) on sustainable development (Income groups)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable: sustainable development index							
Variables	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC
	Through trade openness (trade)				Through foreign direct investments (FDI)			
mobile	0.00118***	0.00149***	0.000118	0.000437	0.000771***	0.00121***	-0.000371**	0.000201
	(0.000307)	(0.000154)	(0.000262)	(0.000366)	(0.000164)	(0.000118)	(0.000153)	(0.000284)
domestic credit	0.00169***	0.00127***	-8.48e-05	-0.000881***	0.00146***	0.00103***	-6.29e-05	-0.000887***
	(0.000512)	(0.000169)	(0.000138)	(0.000194)	(0.000516)	(0.000160)	(0.000139)	(0.000195)
FDI	2.83e-05	-0.000533	0.00786***	-0.000720	-0.00210	0.0101***	0.00420	0.0108
	(0.000458)	(0.00121)	(0.00129)	(0.00336)	(0.00170)	(0.00278)	(0.00296)	(0.00811)
trade	0.000481***	0.000709***	6.50e-05	0.000110	0.000465***	0.000103	-0.000291**	-0.000583***
	(0.000145)	(0.000150)	(0.000304)	(0.000445)	(0.000145)	(0.000111)	(0.000141)	(0.000224)
Gov't effectiveness	0.0230**	0.0194***	-0.0487***	0.0661***	0.0277***	0.0236***	-0.0495***	0.0651***
	(0.00911)	(0.00732)	(0.00947)	(0.0159)	(0.00920)	(0.00728)	(0.00946)	(0.0164)
GDP per capita	-4.82e-06***	3.12e-06	2.91e-06*	-7.15e-06***	-5.23e-06***	3.88e-06*	2.98e-06**	-7.15e-06***
	(1.49e-06)	(2.00e-06)	(1.52e-06)	(4.91e-07)	(1.51e-06)	(2.00e-06)	(1.51e-06)	(5.12e-07)
Mobile ×trade	-0.00000412	-0.00000898***	-0.00000403	-0.00000647**				
	(4.45e-06)	(1.83e-06)	(2.85e-06)	(3.27e-06)				
Mobile ×FDI					0.0000383	-0.000122***	0.0000296	-0.000103*
					(3.00e-05)	(2.91e-05)	(2.41e-05)	(5.54e-05)
Net effect	0.0008418	0.0007529	-------	------	-------	0.00068589	----	------
threshold	286.4077	165.924276	--------	--------	--------	9.9180	------	------
Constant	0.389***	0.487***	0.680***	0.696***	0.406***	0.507***	0.725***	0.721***
	(0.0151)	(0.0143)	(0.0297)	(0.0458)	(0.0131)	(0.0125)	(0.0226)	(0.0378)
Observations	266	671	546	468	266	671	546	468
Prop>Chi2 exogeneity	0.866	0.166	0.323	0.618	0.902	0.170	0.415	0.545
chi2	153.5***	548.5***	105.5***	691.0***	146.0***	532.3***	103.6***	682.3***
tobitll	0.295	0.438	0.329	0.0790	0.295	0.438	0.329	0.0790
tobitul	0.586	0.843	0.853	0.816	0.586	0.843	0.853	0.816

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; LIC is low-income countries, LMIC is lower-middle-income countries, UMIC is upper-middle-income countries and HIC is high income countries; FDI is foreign direct investments; ICT is information and communication technology

Source: Authors' computation

Table 11. Indirect effect of ICT penetration (Internet penetration) on sustainable development (Income groups)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable: sustainable development index							
Variables	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC
	Through trade openness (trade)				Through foreign direct investments (FDI)			
internet	0.00899***	0.00307***	0.000685	-0.00162**	0.00525***	0.00313***	0.000555	-0.000587
	(0.00114)	(0.000528)	(0.000568)	(0.000665)	(0.000848)	(0.000409)	(0.000351)	(0.000401)
Domestic credit	0.00114**	0.00143***	-0.000149	-0.000885***	0.00159***	0.00129***	-0.000161	-0.000822***
	(0.000541)	(0.000205)	(0.000143)	(0.000204)	(0.000587)	(0.000190)	(0.000143)	(0.000219)
FDI	-0.000341	0.000854	0.00803***	-0.00254	0.000432	0.00960***	0.00943***	0.00588
	(0.000562)	(0.00135)	(0.00150)	(0.00343)	(0.000748)	(0.00177)	(0.00240)	(0.00461)
Trade	0.000841***	0.000436***	-0.000197	-0.00112**	0.000768***	9.24e-05	-0.000348**	-0.000656***
	(0.000252)	(0.000155)	(0.000301)	(0.000508)	(0.000257)	(0.000123)	(0.000143)	(0.000231)
Gov't effectiveness	0.00946	0.0181**	-0.0487***	0.0880***	0.0234**	0.0247***	-0.0485***	0.0845***
	(0.0105)	(0.00831)	(0.0102)	(0.0176)	(0.0104)	(0.00814)	(0.0100)	(0.0175)
GDP per capita	-1.64e-05***	3.16e-07	2.11e-06	-6.96e-06***	-1.95e-05***	2.64e-06	2.05e-06	-6.86e-06***
	(2.37e-06)	(2.50e-06)	(1.65e-06)	(4.84e-07)	(2.21e-06)	(2.38e-06)	(1.65e-06)	(4.88e-07)
Internet ×trade	-0.00003545***	-0.0000199***	-0.00000392	0.00000675				
	(8.54e-06)	(5.42e-06)	(6.56e-06)	(6.32e-06)				
Internet ×FDI					-0.000214*	-0.000509***	-0.0000534	-0.000122
					(0.000125)	(9.14e-05)	(7.41e-05)	(7.89e-05)
Net effect	0.006080	0.0014366	---------	----------	0.004331	0.0009433	-------	-------
Threshold	253.5966	154.27136	---------	----------	7.57009	4.54420	-------	----------
Constant	0.369***	0.529***	0.677***	0.834***	0.391***	0.531***	0.685***	0.754***
	(0.0150)	(0.0146)	(0.0266)	(0.0437)	(0.0135)	(0.0131)	(0.0208)	(0.0296)
Observations	241	609	511	443	241	610	514	443
Prop>Chi2 exogeneity	0.421	0.146	0.175	0.685	0.526	0.103	0.835	0.446
chi2	172.9***	359.9***	90.90***	651.3***	135.8***	389.9***	89.23***	630.9***
tobitll	0.295	0.438	0.329	0.0790	0.295	0.438	0.329	0.0790
tobitul	0.576	0.836	0.846	0.816	0.576	0.836	0.846	0.816

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; LIC is low-income countries, LMIC is lower-middle-income countries, UMIC is upper-middle-income countries and HIC is high income countries

Source: Authors' computation

Table 12. Indirect effect of ICT adoption (Fixed Phone) on sustainable development (Income groups)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable: sustainable development index							
Variables	LIC	LMIC	UMIC	HIC	LIC	LMIC	UMIC	HIC
	Through trade openness				Through foreign direct investments			
Fixed telephone	0.00739	0.00190	0.00323*	-0.00484***	-0.00137	0.00463***	0.00477***	-0.00218***
	(0.00509)	(0.00130)	(0.00176)	(0.00112)	(0.00408)	(0.000745)	(0.000797)	(0.000751)
Domestic credit	0.00298***	0.00138***	-0.000113	-0.000791***	0.00298***	0.00140***	-0.000101	-0.000885***
	(0.000509)	(0.000169)	(0.000133)	(0.000193)	(0.000516)	(0.000166)	(0.000136)	(0.000209)
FDI	-6.38e-05	0.000528	0.00688***	-0.00104	2.13e-05	0.00514***	0.0157***	-0.00768
	(0.000504)	(0.00132)	(0.00144)	(0.00307)	(0.000527)	(0.00174)	(0.00239)	(0.00870)
Trade	0.000694***	0.000108	-3.09e-05	-0.00215***	0.000591**	0.000157	-0.000345**	-0.000666***
	(0.000233)	(0.000141)	(0.000346)	(0.000509)	(0.000230)	(0.000119)	(0.000139)	(0.000241)
Gov't effectiveness	0.0292***	0.0178**	-0.0577***	0.0925***	0.0293***	0.0232***	-0.0545***	0.103***
	(0.0102)	(0.00783)	(0.00981)	(0.0183)	(0.0103)	(0.00789)	(0.00989)	(0.0204)
GDP per capita	-1.26e-06	2.62e-06*	5.86e-08	-7.60e-06***	-6.92e-06**	3.13e-06	-7.64e-07	-7.76e-06***
	(3.89e-06)	(2.73e-06)	(1.57e-06)	(4.80e-07)	(2.94e-06)	(2.68e-06)	(1.58e-06)	(5.70e-07)
Fixed ×trade	-0.000111*	0.0000126	-0.0000131	0.0000372***				
	(6.02e-05)	(1.68e-05)	(1.94e-05)	(1.15e-05)				
Fixed ×FDI					-0.0000454	-0.000746***	-0.000554***	0.000141
					(0.000482)	(0.000175)	(0.000128)	(0.000157)
Net effect	--------	----------	---------	-0.001866	---------	0.001425	0.0023900	-----
Threshold	---------	------	---------	130.107526	-------	6.2064	8.61010	------
Constant	0.396***	0.560***	0.657***	0.920***	0.407***	0.548***	0.646***	0.816***
	(0.0150)	(0.0124)	(0.0306)	(0.0439)	(0.0142)	(0.0116)	(0.0208)	(0.0318)
Observations	260	669	545	462	260	669	545	462
Prop>Chi2 exogeneity	0.533	0.184	0.139	0.802	0.624	0.683	0.266	0.854
chi2	75.35***	354.4***	111.7***	726.3***	70.57***	378.2***	126.0***	669.7***
Tobitll	0.295	0.438	0.329	0.0790	0.295	0.438	0.329	0.0790
Tobitul	0.586	0.843	0.846	0.816	0.586	0.843	0.846	0.816

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; LIC is low-income countries, LMIC is lower-middle-income countries, UMIC is upper-middle-income countries and HIC is high income countries; FDI is foreign direct investments; ICT is information and communication technology.

Source: Authors' computation

Looking at the geographical groupings in Table 7, mobile phones penetration interacts with trade openness producing positive net effects in Africa and Asia and a negative net effect in America. These effects are respectively nullified at trade openness thresholds of 145.39877(%GDP), 126.829265 (%GDP), and 0.14592 (%GDP). Also, mobile phone interacts with FDI producing positive net effects for Africa and Asia and negative net effects for Europe. These effects are respectively nullified at FDI thresholds of 14.99436 (%GDP), 7.8608695 (%GDP) and 6.970802 (%GDP). These are practicable thresholds as they are within the range of these moderating variables apparent in Table 1. In Table 8, internet penetration interacts with trade openness producing positive net effects for Africa and America and negative net effects for Asia and Oceania. The trade openness thresholds required to nullify these effects are 102.3166023 (%GDP), 207.462687 (%GDP), 78.60262 (%GDP) and 82.48945147 (%GDP) respectively for Africa, America, Asia and the Oceania. Equally, internet interacts with FDI producing positive net effects in Africa and America up to FDI thresholds of 6.4271457 (%GDP) and 10.76923076 (%GDP) respectively, while a synergy negative effect is obtained for Europe. Moreover, in Table 9, fixed telephone subscription interacts with trade openness producing positive net effects for Africa, America and Oceania and a negative net effect for Asia. These effects are nullified at trade openness thresholds of 125.21008 (%GDP), 122.8571 (%GDP), 76.0736 (%GDP) and 44.24107 (%GDP) respectively for Africa, America, Asia and Oceania. Its interaction with FDI produces positive net effects in Africa and America up to FDI thresholds of 10.87748 (%GDP) and 10.1458 (%GDP), when these positive effects are nullified. These regions thus have to consider these thresholds in elaborating policies of sustainable development.

Examining these mechanisms across different income groups, in Table 10, mobile subscription interacts with trade openness and foreign direct investments producing positive net effects in low-income countries (LIC) via trade and lower-middle-income countries (LMIC) through both trade and FDI. The trade openness thresholds required to nullify these positive effects are 286.4077 (%GDP) and 165.924276 (%GDP) respectively for LIC and LMIC while the positive net effect is nullified at a FDI threshold of 9.9180 (%GDP) for LMIC. In Table 11, positive net effects are obtained in LIC and LMIC in both the interactive effects of trade openness and FDI with internet penetration. The trade openness thresholds required to nullify this effect is 253.5966 (%GDP) and 154.27136 for LIC and LMIC while the respective FDI thresholds are 7.57009 (%GDP) and 4.54420 (%GDP). Further, negative net effects are apparent in high income countries (HIC) in the interaction between fixed

telephone subscription and trade openness up to a trade openness threshold of 130.107526(%GDP) when this negative effect is nullified. Also, positive net effects are apparent in LMIC and upper-middle-income countries (UMIC) in the interaction of fixed telephone subscriptions with FDI up to FDI thresholds of 6.2064 (%GDP) and 8.61010 (%GDP) respectively for LMIC and UMIC.

Summarily, there exists a significant positive effect of ICT on sustainable development. And this effect is modulated through trade openness and foreign direct investment. The interaction of ICT with these variables produces positive net effects in most of the cases. The effect is shown to be persistently non-significant in Europe. Though recent studies like Jayaprakash and Pillai (2021) have argued that ICT is not a hope to rely on in achieving the sustainable development goals, this study has supported this claim only in some few regions and income groups. Even in these groups, there are policy thresholds that policy makers can rely on in achieving these goals. ICT enhances innovation and entrepreneurship, improves on trade and economic activities leading to economies of scale. Increase industrialisation as a result of ICT will provide employment opportunities which help in reducing the income gaps in the economy and by extension, enhancement of inclusive development. Moreover, ICT will augment economic growth through persistent increase in productivity, leading to an improvement in economic sustainability. Though an increase in economic activities and industrialisation will at the initial stages of development/industrialisation degrade the environment, overall, the benefits from the economic and social dimensions of sustainable development outpaced this possible pitfall from the environmental dimension. In essence, above the trade openness and FDI thresholds, economic activities are characterised by uncontrollable levels of greenhouse emissions. Besides, at high levels of FDI inflows, the economies act as pollution havens for some other economies which are in comparative advantage as far as FDI is concerned.

5. Conclusion, Policy implications and Caveats

The objective of this paper has been to empirically investigate the effect of ICT on sustainable development. The methodology involves: (i) the Fixed Effects estimator to control for individual heterogeneity, (ii) the Driscoll and Kraay estimator to control for cross-section dependence between panels, (iii) the Mean Group estimator to take into account the averages between panel groups, (iv) the system GMM to correct for unobserved heterogeneity and simultaneity biases and (v) the instrumental variable Fixed Effects Tobit to

take into account the limited range in our dependent variable. The results show that ICT has a positive and significant effect on sustainable development, a result that is modulated through trade openness and foreign direct investments. Mobile phone adoption interacts with trade openness and FDI to produce positive direct effects and negative indirect effects though non-significant for FDI. Mobile phones interact with trade and FDI to reveal a positive net effect with trade openness up to a trade threshold of 148.3870968 (%GDP) when this positive effect is nullified. Similar patterns are followed by their interactions with internet and fixed phones, all producing positive net effects. The trade openness thresholds required to nullify this net effect is 131.7460 (%GDP) and 134.79167 (%GDP), respectively through internet and fixed phones while the respective FDI thresholds required to nullify this positive net effects are 25.203252 (%GDP) and 19.405405 (%GDP). This result though in majority had positive net effects through these mechanisms, varies contingent on the choice of the ICT measurement used, the geographical location of the economy and the income group.

The policy implications of this study require policy makers to consider ICT development in their quest to meet the SDGs. In this respect, ICT development in all its forms is encouraged. Caution has to be taken however in this drive. The policy thresholds for trade openness and FDI should be considered. In this respect, avoidable thresholds for policy variables to have a devastating effect on the positive relationship between ICT and sustainable development should be kept in mind. When such cannot be avoided owing to the ineluctable process of globalisation, complementary policies should be taken on board at the critical thresholds in order to avoid the unfavourable incidences from the interactions on sustainable development once such thresholds have been attained. Therefore, the trade openness thresholds of 148.3870968 (%GDP), 131.7460 (%GDP), 134.79167 (%GDP) should be avoided for mobile phones, internet and fixed phones to respectively continue enhancing sustainable development. On the other hand, the FDI thresholds of 25.203252 (%GDP) and 19.405405 (%GDP) should be avoided respectively, in order for the internet and fixed phones to continue enhancing sustainable development. Besides, specific policies should be considered with respect to the geographical location and income groups for more reliable and oriented thresholds.

The research is not however without limits. Future research works in this direction should consider other mediating channels like institutional governance. Besides country-specific studies could be carried out for more elaborated policy orientations.

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Appendix 1: correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) sdi	1.000													
(2) life expectancy	0.143	1.000												
(3) expected school year	0.092	0.801	1.000											
(4) mean school year	0.069	0.744	0.844	1.000										
(5) co2_capita	-0.565	0.565	0.573	0.587	1.000									
(6) footprint per capita	-0.522	0.562	0.628	0.590	0.859	1.000								
(7) mobile	0.048	0.550	0.589	0.563	0.411	0.420	1.000							
(8) internet	-0.231	0.653	0.697	0.710	0.614	0.619	0.690	1.000						
(9) fixed telephone	-0.258	0.635	0.678	0.705	0.662	0.672	0.324	0.664	1.000					
(10) domestic credit	-0.283	0.576	0.607	0.595	0.582	0.612	0.410	0.683	0.684	1.000				
(11) fdi	-0.008	0.035	0.029	0.032	0.048	0.096	0.087	0.012	0.050	0.021	1.000			
(12) trade	-0.082	0.208	0.180	0.215	0.323	0.398	0.263	0.214	0.156	0.177	0.371	1.000		
(13) gov_effectiv	-0.342	0.602	0.641	0.651	0.676	0.732	0.372	0.716	0.795	0.757	0.045	0.268	1.000	
(14) GDP per capita	-0.577	0.539	0.580	0.582	0.816	0.742	0.339	0.687	0.717	0.668	-0.004	0.161	0.772	1.000

NB: SDI is sustainable development index; FDI foreign direct investment; gov_effectiv is government effectiveness