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Information technology, gender economic inclusion and environment sustainability in sub-Sahara Africa

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Abstract

Purpose – This study examines the relevance of information and communication technologies in the effect of gender economic inclusion on environmental sustainability.

Design/methodology/approach – The focus is on a panel of 42 sub-Saharan African countries over the period 2005–2020. The empirical evidence is based on generalized method of moments. The environmental sustainability indicator used is CO2 emissions per capita. Three indicators of women's economic inclusion are considered: female labour force participation, female employment and female unemployment. The chosen ICT indicators are mobile phone penetration, Internet penetration and fixed broadband subscriptions.

Findings – The results show that: (1) fixed broadband subscriptions represent the most relevant ICT moderator of gender economic inclusion for an effect on CO2 emissions; (2) negative net effects are apparent for the most part with fixed broadband subscriptions (3) both positive ICT thresholds (i.e., critical levels for complementary policies) and negative ICT thresholds (i.e., minimum ICT levels for negative net effects) are provided; (4) ICT synergy effects are apparent for female unemployment, but not for female employment. In general, the joint effect of ICTs or their synergies and economic inclusion should be a concern for policymakers in order to better ensure sustainable development. Moreover, the relevant ICT policy thresholds and mobile phone threshold for complementary policy are essential in promoting a green economy.

JEL Classification — C52, O38, O40, O55, P37

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Originality/value – The study complements the extant literature by assessing linkages between information technology, gender economic inclusion and environmental sustainability.

Keywords ICT, Gender inclusion, Environment sustainability, Sub-Saharan Africa

Paper type Research paper

1. Introduction

Environmental degradation has become a global concern in recent decades (Rasool and Rizvi, 2023). The global surface temperature has risen by 1.1°C, over the periods 1850–1900 and 2011–2020 (IPCC, 2023). Greenhouse gas emissions are increasing, contributing to warming of 1.0°C, over the same period, exposing millions of people in underdeveloped countries to acute food insecurity and reduced security of water supply. In terms of governance, progress in safeguarding the environment is poor as environmental indicators are the slowest to progress among the 17 Sustainable Development Goals (Arora and Mishra, 2019). In 2023, no country had yet achieved full parity between men and women (WEF, 2023). However, at the global level, the gender gap in economic participation and opportunity has narrowed by 60.1% (WEF, 2023). The contribution of information and communication technologies (ICTs) to global carbon dioxide (CO2) emissions in 2020 is expected to rise sharply and is estimated at 1.8–2.8% (Freitag *et al.*, 2021). Internet usage levels are low for developing countries (22%) compared to high-income countries (91%) (ITU, 2022). Globally, only 57% of women use the internet compared to 62% of men. Motivated by these facts, this paper analyses the role of ICT in the relationship between gender economic inclusion and CO2 emissions.

There is increasing research interest in the glass ceiling against women (Singh *et al.*, 2023) and as well as the relationship between gender and the management of environmental resources, its preservation or the process of adaptation to climate change (Wani *et al.*, 2023). Men and women experience environmental degradation and the effects of climate change differently (Andrijevic *et al.*, 2020). Given the power structures within patriarchal societies, women are very sensitive to the impacts of climate change and environmental vulnerabilities (Arora-Jonsson, 2011). Therefore, gender equality will catalyse better environmental outcomes (Wang *et al.*, 2021). Understanding gender dynamics in environmental discourses will support the effective implementation of the SDGs (Buckingham, 2020).

To fully involve women in the fight against environmental degradation, it is necessary to promote ICTs. ICTs enhance women's economic participation (Efobi *et al.*, 2018). ICTs promote human development (Asongu and Le Roux, 2017). ICTs are also associated with sustainable development (Nchofoung and Asongu, 2022). The effects of ICTs can be felt in terms of economic growth (Awad and Albaity, 2022). ICT dynamics are also associated with the environment. The effects of ICTs on CO2 emissions are mixed. These effects may be positive due to the increase in energy consumption resulting from the consumption or mass production of ICT-related products (Karakara and Osabuohien, 2019). However, due to increased adoption, improving the efficiency of the energy sector, ICT can have negative effects on CO2 and other greenhouse gas emissions (Susam and Hudaverdi Ucer, 2019; Abid *et al.*, 2022).

This paper therefore investigates whether ICT enhances the effects of gender economic inclusion on per capita emissions. The study hypothesizes that female economic participation and unemployment associated with ICT generate lower per capita CO2 emissions. The possible explanation for these negative relationships is twofold: (1) greater female economic inclusion is associated with lower CO2 emissions; and (2) ICT enhances economic inclusion, as found by Asongu and Le Roux (2017). Therefore, this paper provides relevant information on whether different types of ICT with female economic participation are associated with low levels of greenhouse gas (GHG) emissions.

This study contributes to the literature in several ways. First, to our knowledge, it is the first study to examine the role of ICTs in the impact of gender economic inclusion on CO2 emissions.

Previous studies have been limited to examining the relationship between gender inclusion and CO_2 emissions (Sahoo *et al.*, 2023) as well as between ICT and CO_2 emissions (Asongu *et al.*, 2018). Sahoo *et al.* (2023) measure gender through the parity index and find a negative relationship for 6 emerging economies in a sample over the period 1990–2019. This result contradicts that of Asongu *et al.* (2018), which shows that the direct effect of ICT on CO_2 emissions is not significant. This exercise becomes important because of the different effects of ICT on economic inclusion and CO_2 emissions, and we address both questions using the same data. Second, while the study approaches gender from the view of economic inclusion, many studies have studied the relationship between gender inclusion and emissions from the perspective of political participation (Asongu *et al.*, 2022; Mirziyoyeva and Salahodjaev, 2022). The present study stands out from this body of work by considering the economic inclusion of gender. In this context, the extant studies to the best of knowledge have not taken into account the multiple facets of women's economic inclusion (Bilgili *et al.*, 2023). In their study in India over the period 1990–2019, Shastri *et al.* (2023) analysed the effects of women's employability and unemployment on the environment. Bilgili *et al.* (2023) consider only women's economic participation in their study. Third, to better assess the relevance of policies, the study provides forecast thresholds for technological spillovers. In this context, the present study departs from the recent literature on technology spillovers, which has focused on: energy efficiency (Zafar *et al.*, 2021); industrialization (Hu *et al.*, 2020); economic growth (Ahmed, 2021); energy efficiency (Zafar *et al.*, 2021); and the environment (Wen *et al.*, 2020). Fourth, the analysis is limited to SSA countries because the region is comparatively more affected by the consequences of CO_2 emissions (Traoré *et al.*, 2023). To the best of knowledge, there is no study of this kind that has focused on African countries.

The study employs a GMM model over the period 2005–2020 for a panel of 42 sub-Saharan African countries. The results show that: (1) fixed broadband subscriptions represent the most relevant ICT moderator of gender economic inclusion for an effect on CO_2 emissions; (2) negative net effects are apparent for the most part with fixed broadband subscriptions (3) both positive ICT thresholds (i.e., critical levels for complementary policies) and negative ICT thresholds (i.e., minimum ICT levels for negative net effects) are provided; (4) ICT synergy effects are apparent for female unemployment, but not for female employment. The remainder of the paper is structured as follows. The data and methodology are disclosed in Section 2. Section 3 presents the empirical results and discussion. Section 4 concludes with policy recommendations.

2. Data and methodology

2.1 Data

This research uses a sample of 42 sub-Saharan African countries over the period 2005–2020. The frequency and number of countries included are due to data availability constraints at the time of study. To obtain the necessary data, this study relies primarily on two sources: (1) the International Labour Organization's data on women's economic inclusion, which includes women's participation in the labour force and women's unemployment rate and (2) the World Bank's World Development Indicators, which provide information on access to ICTs, including fixed broadband subscription, mobile phone penetration and internet penetration. Three gender economic inclusion variables are also used, consistent with the extant gender inclusion literature, namely: female labour force participation rate, female unemployment rate and female unemployment rate (Asongu and Odhiambo, 2020; Ofori *et al.*, 2023). In addition, two control variables are used in the model, namely: (1) the growth rate of gross domestic product (GDP) per capita and (2) foreign direct investment (FDI). Justification for the choice of these variables is provided in the last-two paragraphs of this section.

As for the endogenous variable measured with carbon emissions, it remains consistent with the literature. Studies have shown that CO2 emissions are the biggest environmental protection problem. While studies have used footprint indicators to measure environmental degradation, in the present study, carbon emissions are preferred to footprint indicators (Shahbaz *et al.*, 2023; Ansari *et al.*, 2023).

The variables related to women's economic inclusion adopted in this study are inspired by contemporary literature that highlights the crucial role of gender in environmental preservation (McGee *et al.*, 2020; Bilgili *et al.*, 2023). Similarly, the ICT variables used are in line with recent literature that stresses the importance of incorporating these indicators into environmental empirical analyses (Shobande and Asongu, 2023; Li *et al.*, 2023; Charfeddine and Umlai, 2023). The selection of control variables is in line with the current literature on CO2 emissions (Mahmood, 2023; Pata *et al.*, 2023). It is important to note that increasing the number of control variables can enhance the number of instruments in the GMM model and the corresponding instrument proliferation problem biases the estimated coefficients (Asongu and Nwachukwu, 2017).

The theoretical literature offers two basic explanations for the effect of FDI on carbon dioxide (CO2) emissions in developing countries. Firstly, it is argued that, in these contexts, FDI flows can lead to environmental deterioration due to the relaxation of environmental regulations. This hypothesis is in line with the "pollution haven" concept formulated by Copeland and Taylor (1994). According to this idea, globalization encourages companies in developed countries to relocate their polluting activities to developing economies, where environmental standards are often less stringent. On the other hand, FDI can also contribute to technological improvements in host countries, which can have a positive impact on environmental quality. Several studies, such as those by Mahmood (2023) and Lin *et al.* (2022), have highlighted the positive impact of FDI on the environment.

With regard to the GDP variable, it should be noted that the literature has debated the impact of economic growth on CO2 emissions. The starting point for this debate is the work of Eckstein and Kuznets (hence the acronym ECK), who formulated the so-called "Environmental Kuznets Curve" (EKC) hypothesis. According to this hypothesis, environmental impact, as measured by per capita CO2 emissions, is consistent with an inverted U-shaped nexus with per capita income. In other words, emissions would rise at the start of the development process, reach a peak and then fall as per capita income continues to rise. However, the literature on this subject is somewhat ambiguous. On the one hand, some studies, citing the World Bank in particular, maintain that economic growth is beneficial to the environment because an increase in per capita income is supposed to contribute to an improvement in environmental quality (Zhang *et al.*, 2023). On the other hand, it is also suggested that economic growth can be detrimental to the environment, particularly due to the higher levels of production and consumption associated with increased economic growth (Naseem *et al.*, 2023; Ayhan *et al.*, 2023). The definition and sources of variables, summary statistics, correlation matrix and list of countries are provided in Appendixes 1–4, respectively.

2.2 Methodology

2.2.1 GMM specification. This study is based on the generalized method of moments (GMM) estimation technique. The use of dynamic panel estimators from the Arellano-Bond (Arellano and Bond, 1991) and Arellano Bover/Blundell-Bond (Arellano and Bover, 1995; Blundell and Bond, 1998) families is becoming increasingly widespread in the empirical literature, as Roodman (2009) points out. The GMM specification requires compliance with a number of criteria, which the corresponding specification most consider. Firstly, it requires that the study has a large number of individuals (i.e. countries in this study) and a few periods (i.e. years in this study); the underlying criterion is met in this study because it covers 42 countries over a 15-year period, from 2005 to 2020. Secondly, the dependent variable or left-hand side variable must be dynamic (i.e. it must depend on its own past values). The literature shows that CO2 emissions are persistent and the correlation between the dependent variables and its first lag exceeds the empirical threshold of 0.800 (Tchamyou *et al.*, 2019). Third, the GMM regression method considers a data structure where the independent variables are not strictly exogenous (i.e., they are correlated with past observations and possibly with the error term). GMM estimation corrects for endogeneity bias, not least because, time-varying variables are used to address the simultaneity problem (Boateng *et al.*, 2018). Fourth, GMM estimation is designed for fixed individual effects. The extension proposed by Roodman (2009) of Arellano and Bover (1995) is adopted to solve the problem of instrument proliferation or to limit overidentification. Finally, by controlling for time-invariant variables, the study takes into account cross-sectional dependence in sampling to solve the problem of instrument proliferation or to limit over-identification (Baltagi *et al.*, 2007).

The estimation procedure for the standard system GMM gives the following equations in level (1) and first difference (2):

$$CO_{it} = \varnothing_0 + \varnothing_1 CO_{it-\tau} + \varnothing_2 ICT_{it} + \varnothing_3 GEI_{it} + \varnothing_4 Inter_{it} + \sum_{k=1}^{2} \delta_k W_{hit-\tau} + \varphi_i + \omega_t + \varepsilon_{it} \tag{1}$$

$$\begin{aligned} CO_{it} - CO_{it-\tau} = {} & \varnothing_1 (CO_{it-\tau} - CO_{it-2\tau}) + \varnothing_2 (ICT_{it} - ICT_{it-\tau}) + \varnothing_3 (GEI_{it} - GEI_{it-\tau}) \\ & + \varnothing_4 (Inter_{it} - Inter_{it-\tau}) + \sum_{k=1}^{2} \delta_k (W_{hit-\tau} - W_{hit-2\tau}) + (\omega_t - \omega_{t-\tau}) + (\varepsilon_{it} - \varepsilon_{it-\tau}) \end{aligned}$$

CO: represents CO_2 emissions; θ_0: the constant; ICT: is the matrix of telecommunication variables (namely, internet penetration, fixed broadband subscriptions and mobile phone penetration); GEI: represents the matrix of gender economic inclusion variables (i.e., female labour force participation and female unemployment); W: represents the vector of control variables (namely, Growth Domestic Product per capita growth and Foreign Direct Investment); τ: is the unit coefficient of autoregression given that a lagged year is sufficient to capture former information; ω_t shows the time-specific constant of the study; φ_i reflects the effects that are country-specific and ε_{it} shows the error term.

2.2.2 Identification and exclusion restrictions. The identification and restriction properties are of fundamental importance in the GMM specification. In this context, the control and independent variables of interest are generally recognized as not strictly exogenous, while the "years" are assumed to be strictly exogenous, in line with the argument put forward by Tchamyou *et al.* (2019). This identification strategy is in line with the argument of Roodman (2009), who demonstrates that "years" can be considered as ideally strictly exogenous variables. Indeed, after an initial differentiation, "years" are unlikely to become endogenous.

With regard to the exogeneity of the instruments, given the above identification, the exclusion restriction hypothesis is evaluated using the Difference in Hansen Test (DHT). The alternative hypothesis of this test suggests that the strictly exogenous variables identified do not exhibit strict exogeneity, as they do not exclusively influence the outcome indicators (i.e., the CO2 emissions variable) via the predetermined variables (i.e., the control variables and the independent variables of interest). Thus, for the identification and exclusion restriction strategies to be valid, it is essential that the null hypothesis of the DHT is not rejected. The instrumental variables technique is consistent with these hypotheses, while respecting the corresponding criteria for assessing their validity. For the identified instruments to affect the dependent variable only through the exogenous components of the explanatory variables, estimation by instrumental variables requires the rejection of the alternative hypothesis of the Sargan/Hansen test (Beck *et al.*, 2003; Asongu and Nwachukwu, 2017). In the context outlined above, the DHT plays a crucial role in assessing the effectiveness of exogenous instruments. In order to guarantee the strict exogeneity of these instruments, it is imperative not to reject the null hypothesis.

In line with the work of Roodman (2009), the DHT is an essential indicator for assessing the exogeneity of instruments. As demonstrated by Roodman (2009), the variable considered to be strictly exogenous in this study is the time element, namely "years." To ensure the validity of the estimates, this research is based primarily on four information criteria from the literature. Firstly, with regard to Arellano and Bond's second-order autocorrelation test [AR (2)], it is important to note that the null hypothesis, which states that the residuals are not autocorrelated, should not be rejected. Secondly, concerning the Sargan and Hansen tests, the results indicate that the over-identifying restrictions (OIR) tests should not significant. In other words, the null hypotheses associated with these tests validate the relevance of the instruments used or demonstrate their lack of correlation with the error terms. However, it should be noted that the Sargan OIR test is not to be robust, although it is not weakened by instruments. As for Hansen OIR test, it is robust, although weakened by instruments. In order to restrict the identification or limit the proliferation of instruments, it is important to point out that the number of instruments used is less than the number of cross-sections for all specifications. In addition, the DHT, which confirms the exogeneity of the instruments, is also included to validate the results of the Hansen OIR test. Finally, a Fisher test is applied to validate the estimated coefficients, thus completing the process of assessing the validity of the results.

3. Empirical results

3.1 Presentation of results

Appendix 2 presents the descriptive statistics for the variables. The dependent variable, CO2 emissions (metric tons per capita), has a mean value of almost 0.845, while its standard deviation is about 1.474. This indicates a fairly small variation in the amount of CO2 emissions among Sub-Saharan African countries. However, the independent variables show significant variations. The correlation table shows that the variables are not collinear (Appendix 3). Cross-sectional dependence (CD) tests were also performed to avoid biased results, namely, those from Pesaran (2021) and Fan *et al.* (2015). The results of these tests (Appendix 5) are statistically significant at the 1% level, confirming the existence of CD among the countries in the sample. Panel A of Appendix 6 shows the results of the panel's unit root tests. The results of the estimated unit root tests show that almost all the variables are stationary in first difference or I (1). The results of the Westerlund and Edgerton cointegration test (2007) show the existence of long-term relationships between the variables (Panel B of Appendix 6).

The results of the GMM model are presented in Tables 1–3 below. Two main specifications are apparent for each ICT dynamic: one without control variables and another with control variables. For each specification, we performed sub-specifications by considering female labour force participation (Table 1), female unemployment (Table 2) and female employment (Table 3). Within these sub-specifications, we ran regressions taking into account the variables "fixed broadband subscriptions", "mobile phone penetration" and "internet penetration". Using different criteria, we also validated the GMM model, with the Arellano and Bond autocorrelation test [AR (2)] being more relevant as an information criterion than the first-order test [AR (1)]. The results also show that although the Sargan test is not robust, it is not weakened by the instruments. The Hansen test is robust but is weakened by the instruments.

Table 1. ICT, Female labour force participation and CO2 emissions

Dependent variable: CO2 emissions (metric tons per capita)

	Without a conditioning information set			With a conditioning information set		
	Fixed	Mobile	Internet	Fixed	Mobile	Internet
Constant	−0.143 (0.070)	−0.078 (0.034)	0.13004	*0.486*** (0.101)*	−0.043 (0.044)	
Fixed	*0.092*** (0.022)*	–	-	*0.079*** (0.018)*	-	-
Mobile	–	0.0001 (0.0004)	–	–	*−0.001** (0.0006)*	-
Internet	–	–	0.0003 (0.001)	–	–	*−0.005*** (0.001)*
Participation	*0.002** (0.001)*	0.0006 (0.0004)	*0.002*** (0.002*	*−0.008*** (0.001)*	0.0001 (0.0005)	*0.001** (0.0005)*
Fixed × Participation	*−0.002*** (0.0004)*	–	-	*−0.002*** (0.0003)*	–	–
Mobile × Participation	–	4.85e-06 (9.67e-06)	-	–	*0.00001** (7.64e-06)*	–
Internet × Participation	–	–	*−0.0001*** (0.00005)*	–	–	0.00001 (0.00004)
GDP	–	–	–	*0.004*** (0.0009)*	*0.006*** (0.0013)*	*0.006*** (0.001)*
FDI	–	–	–	−0.0002 (0.0001)	−0.0004*** (0.000)	−0.001*** (0.0002)
Net effects of gender inclusion	0.0006	na	0.0007	−0.0094	na	na
ICT Thresholds	1.000	na	20	na	na	na
AR (1)	(0.043)	(0.046)	(0.042)	(0.042)	(0.039)	(0.040)
Threshold	*na*	*na*	*na*	*na*	*na*	*na*
AR (2)	*(0.189)*	*(0.238)*	*(0.181)*	*(0.152)*	*(0.194)*	*(0.155)*
Sargan (OIR)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Hansen (OIR)	*(0.504)*	*(0.226)*	*(0.352)*	*(0.497)*	*(0.510)*	*(0.224)*
DHT for instruments						
(a) Instruments in levels						
H excluding group	*(0.327)*	*(0.475)*	*(0.239)*	*(0.433)*	*(0.383)*	*(0.763)*
Dif (null, H = exogenous)	*(0.557)*	*(0.164)*	*(0.444)*	*(0.485)*	*(0.537)*	*(0.098)*
(b) IV (years, eq(diff))						
H excluding group	-	-	-	*(0.693)*	*(0.697)*	*(0.098)*
Dif (null, H = exogenous)	-	-	-	*(0.379)*	*(0.391)*	*(0.340)*
Fisher	*104791.9****	*20913.74****	*10189.97****	*133962.2****	*67911.33****	*61140.31****
Instrument	28	28	28	36	36	36
Countries	42	42	42	39	39	39
Observations	525	583	580	446	488	487

Note(s): *, **, ***significance levels of 10, 5 and 1%, respectively. CO2 emissions: CO2 emissions (metric tons per capita); Internet: Internet users (per 100 people); Mobile: Mobile cellular subscriptions (per 100 people) Penetration; Fixed: Fixed broadband subscriptions (per 100 people); Participation: labour force participation rate (15 + female %) (model ILO estimate); GDP: Gross Domestic Product per capita growth; FDI: Foreign direct investment, net inflows (% of GDP). DHT is the difference in Hansen test for instruments' subsets exogeneity. OIR overidentifying restrictions test. Dif difference. Italic values have two main significances. (1) The Fisher statistics and estimated coefficients that are significant. (2) Inability to reject the null hypotheses of (a) absence of autocorrelation in the AR (1) and AR (2) tests and (b) instrument validity as it pertains to the Sargan and Hansen OIR tests. na: not applicable because for the computation of net effects and/or thresholds, at least one estimated coefficient is not significant. The mean of fixed broadband is 0.714. The mean value of the internet is 13.222. Values in parentheses are standard errors for the estimated coefficients and p-values for the information criteria (i.e. AR, Sargan, Hansen, DHT and IV tests). Lagged outcome variables are included in the regressions

Source(s): Authors own creation

Table 2.
ICT, Female unemployment and CO2 emissions

Dependent variable: CO2 emissions (metric tons per capita)

	Without a conditioning information set			With a conditioning information set		
	Fixed	Mobile	Internet	Fixed	Mobile	Internet
Constant	*0.0276* (0.0158)*	−0.015 (0.019)	*0.0007*** (0.011)*	*0.035** (0.016)*	−0.035 (0.015)	*−0.040*** (0.0119)*
Fixed	*0.0146*** (0.004)*	-	-	*0.015*** (0.003)*	–	–
Mobile	–	*0.0007** (0.0003)*	–	-	*0.0004*** (0.0001)*	–
Internet	–	–	0.0008 (0.0006)	-	-	*0.0004*** (0.0003)*
Unemployment	*−0.006*** (0.002)*	−0.0001 (0.001)	0.0009 (0.001)	*−0.009*** (0.002)*	0.0006 (0.001)	0.001 (0.001)
Mobile × Unemployment	-	*−0.00005*** (0.00001)*	-	–	*−0.00004*** (8.01e-06)*	–
Internet × Unemployment	-	-	*−0.0001*** (0.00003)*	–	–	−0.0001 (0.00001)
Fixed × Unemployment	*−0.002*** (0.0004)*	–	–	*−0.002*** (0.0002)*	–	–
GDPgr	–	–	–	0.004 (0.001)	*0.004*** (0.0009)*	*0.004*** (0.0009)*
FDI	–	–	–	−0.0006 (0.0001)	−0.0001*** (0.00006)	−3.18e-06 (0.0001)
Net effects of gender inclusion	−0.0074	na	na	−0.0104	na	na
ICT Thresholds	na	na	na	na	na	na
AR (1)	(0.048)	(0.046)	(0.045	(0.056)	(0.041)	(0.035)
AR (2)	*(0.189)*	*(0.217)*	*(0.174)*	*(0.137)*	*(0.171)*	*0.138)*
Sargan (OIR)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	((0.000)
Hansen (OIR)	*(0.601)*	*(0.413)*	*(0.228)*	*(0.831)*	*(0.646))*	*(0.586)*
DHT for instruments						
(a) Instruments in levels						
H excluding group	*(0.669)*	*(0.051)*	*(0.252)*	*(0.366)*	*(0.445)*	*(0.197)*
Dif (null, H = exogenous)	*(0.339)*	*(0.925)*	*(0.265)*	*(0.920)*	*(0.659)*	*(0.813)*
(b) IV (years, eq(diff))						
H excluding group	-	-	-	*(0.233)*	*(0.157)*	*(0.293)*
Dif (null, H = exogenous)	-	-	-	*(0.932)*	*(0.833)*	*(0.657)*
Fisher	*250952.5****	*25172.44****	*267181.64****	*1.58e+07****	*71995.58****	*1.61e+06****
Instrument	28	28	28	36	36	36
Countries	42	42	42	39	39	39
Observations	525	583	580	446	488	487

Note(s): *, **, *** significance levels of 10, 5 and 1%, respectively. CO2 emissions: CO2 emissions (metric tons per capita); Internet: Internet users (per 100 people); Mobile: Mobile cellular subscriptions (per 100 people) Penetration; Fixed: Fixed broadband subscriptions (per 100 people); Unemployment: Unemployment rate (15+ female %) (model ILO estimate); GDPgr: Gross Domestic Product per capita growth; FDI: Foreign direct investment, net inflows (% of GDP). DHT is the difference in Hansen test for instruments' subsets exogeneity. OIR overidentifying restrictions test. Dif difference. Italic values have two main significances. (1) The Fisher statistics and estimated coefficients that are significant. (2) Inability to reject the null hypotheses of (a) absence of autocorrelation in the AR (1) and AR (2) tests and (b) instrument validity as it pertains to the Sargan and Hansen OIR tests. na: not applicable because for the computation of net effects and/or thresholds, at least one estimated coefficient is not significant. The mean of fixed broadband is 0.714. Values in parentheses are standard errors for the estimated coefficients and *p*-values for the information criteria (i.e. AR, Sargan, Hansen, DHT and IV tests). Lagged outcome variables are included in the regressions
Source(s): Authors own creation

Table 3. ICT, Female Employment and CO2 emissions

Dependent variable: CO2 emissions (metric tons per capita)	Without a conditioning information set			With a conditioning information set		
	Fixed	Mobile	Internet	Fixed	Mobile	Internet
Constant	−0.0417*** (0.0129)	−0.0230 (0.021)	−0.0002 (0.013)	*−0.067*** (0.011)*	0.005 (0.020)	−0.062*** (0.0153)
Fixed	*−0.0186*** (0.001)*	–	-	*−0.020*** (0.002)*	-	-
Mobile	–	0.00002 (0.0002)	–	–	*−0.001*** (0.0003)*	-
Internet	–	–	−0.002*** (0.0004)	–	–	*−0.004*** (0.0005)*
Employment	*0.002** (0.001)*	−0.003 (0.003)	0.001 (0.001)	*0.003*** (0.001)*	*−0.012*** (0.003)*	*0.004** (0.002)*
Fixed × Employment	*0.0007*** (0.0002)*	–	-	*0.0001*** (0.0003)*	–	–
Mobile × Employment	–	0.0001 (0.00003)	-	–	*0.0002*** (0.00003)*	–
Internet × Employment	–	–	0.00005 (0.00005)	–	–	−0.00007 (0.00006)
GDPgr	–	–	–	*0.005*** (0.0009)*	*0.006*** (0.001)*	*0.0059*** (0.0009)*
FDI	–	–	–	−0.0002 (0.0001)	−0.0007 (0.0004)	−0.0004** (0.0002)
Net effects of gender inclusion	0.0024	na	na	0.003	−0.011	na
ICT Thresholds	na	na	na	na	60	na
AR (1)	(0.051)	(0.045)	(0.042)	(0.045)	(0.023)	(0.040)
AR (2)	*(0.214)*	*(0.280)*	*(0.195)*	*(0.141)*	*(0.243)*	*(0.155)*
Sargan (OIR)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Hansen (OIR)	(0.073)	*(0.089)*	*(0.650)*	*(0.358)*	*(0.091)*	*(0.224)*
DHT for instruments						
(a) Instruments in levels						
H excluding group	*(0.552)*	*(0.184)*	*(0.471)*	*(0.562)*	*(0.395)*	*(0.602)*
Dif (null, H = exogenous)	(0.037)	*(0.116)*	*(0.629)*	*(0.269)*	*(0.068)*	*(0.360)*
(b) IV (years, eq(diff))						
H excluding group	-	-	-	*na*	*na*	*na*
Dif (null, H = exogenous)	-	-	-	*na*	*na*	*na*
Fisher	*94815.1****	*21389.84****	*40250.27****	*134575.43****	*10526.37****	*27985.78****
Instrument	28	28	28	32	32	32
Countries	42	42	42	39	39	39
Observations	525	583	580	446	488	487

Source(s): *, **, *** significance levels of 10, 5 and 1%, respectively. CO2 emissions: CO2 emissions (metric tons per capita); Internet: Internet users (per 100 people); Mobile: Mobile cellular subscriptions (per 100 people) Penetration; Fixed: Fixed broadband subscriptions (per 100 people); Employment: Employment rate (15+ female %) (model ILO estimate); GDPgr: Gross Domestic Product per capita growth; FDI: Foreign direct investment, net inflows (% of GDP). DHT is the difference in Hansen test for instruments' subsets exogeneity. OIR overidentifying restrictions test. Dif difference. Italic values have two main significances. (1) The Fisher statistics and estimated coefficients that are significant. (2) Inability to reject the null hypotheses of (a) absence of autocorrelation in the AR (1) and AR (2) tests and (b) instrument validity as it pertains to the Sargan and Hansen OIR tests. na: not applicable because for the computation of net effects and/or thresholds, at least one estimated coefficient is not significant. The mean of fixed broadband is 0.714. Values in parentheses are standard errors for the estimated coefficients and p-values for the information criteria (i.e. AR, Sargan, Hansen, DHT and IV tests). Lagged outcome variables are included in the regressions

Source(s): Authors own creation

To solve this problem, the Hansen test was adopted while avoiding the proliferation of instruments. We avoided instrument proliferation by ensuring that the number of cross-sections exceeded the number of instruments. With regard to the calculation of net effects, we examine the role of ICTs in the impact of women's economic inclusion on CO2 emissions. For example, in the second column of Table 1, the net effect of the interaction between "fixed broadband subscriptions" and "participation" is 0.0005 ($[-0.002 \times 0.714] + [0.002]$). In this net effect calculation, the mean value of the variable "fixed broadband subscriptions" is 0.714, the unconditional effect is 0.002, while the conditional effect of the interaction between "participation" and "fixed broadband subscriptions" is -0.002. The main conclusions to be drawn from the calculations of the net effects are as follows: (1) the net effects are only visible for the regressions where the variable "fixed broadband subscriptions" is present; (2) these net effects are negative overall, which indicates that "fixed broadband subscriptions" have a complementary role with the economic inclusion of women in reducing CO2 emissions.

3.2 Extension with policy thresholds

It should be noted that the net effects of the role of ICTs in moderating women's economic inclusion with a view of environmental protection are systematically favourable. Indeed, all the net effects are systematically negative when we consider the variable "fixed broadband subscriptions". It should be noted that in Table 1 and Table 2, there is only one instance, in the second column, in which the net effect is positive. These negative net effects, which are favourable to environmental protection, result from the conditional interaction between ICTs and the economic inclusion of women, as well as from the direct effects, which are almost all negative. In Table 1, the positive net effect is attributable to the predominance of a positive direct effect, which outweighs the negative conditional effect.

Consequently, the negative conditional effects emphasize that promoting ICT dynamics above certain thresholds will attenuate the associated direct effects and, consequently, cancel-out the positive net effects. The threshold analysis is therefore relevant. The choice of calculating thresholds is consistent with the extant literature on interactive regressions (Asongu and Odhiambo, 2020).

In Table 3, in the penultimate column, the positive threshold is 60 ($[0.012/0.0002]$) for the "mobile phone penetration" variable for every 100 people. Consequently, at this threshold of "mobile penetration subscriptions", the corresponding net effect on CO2 emissions is equal to 0 ($[0.0002 * 60] + [-0.012]$). Above this threshold, the "mobile phone penetration" variable moderates female employment to produce a positive net effect on CO2 emissions. This threshold is of significant economic relevance, as it lies between the minimum and maximum values of the "mobile telephony penetration" variable in the summary statistics. It follows that it represents a threshold for complementary policy. In other words, when the threshold is reached, policy makes need to engage complementary policies in order to maintain the unconditional negative effect on CO2 emissions. This is contrary to the left-hand side of Table 1 where negative thresholds were apparent. These negative thresholds which are 1 (per 100 people) and 20 (per 100 people), respectively for fixed broadband subscription and the internet, are an indication that above the corresponding thresholds, the established net effects on CO2 emissions change from positive to negative.

3.3 Robustness check with ICT synergies effects

We adopt the technique of Principal Component Analysis (PCA) to group the ICT measurement indicators that we have used as explanatory variables. This approach reduces complexity and correlation issues to a minimal set of uncorrelated principal components across the set of ICT indicators. PCA is therefore used to capture synergy effects (Traoré *et al.*, 2023). The results show that the net effects are negative for female unemployment and positive for female employment

(Table 4). These results mean that overall ICTs interact with female unemployment and female employment on CO2 emissions to produce a negative and a positive sign respectively.

The results show that ICT is relevant in moderating gender economic inclusion for apparent effects on CO2 emissions. Accordingly, fixed broadband is a means of removing the constraints on women's economic inclusion. The importance of ICTs in protecting the environment is largely in line with the literature, which shows that ICTs, in their many forms (satellites, mobile phones, the internet or fixed-line), participate in promoting sustainable development either directly (through energy consumption and electronic waste) or indirectly via ICT applications in intelligent transport systems or buildings (Houghton, 2010). In addition, internet-connected mobile phones can be used for quick online searches or to facilitate communications, which can save energy and transport costs associated with globalization. This reduction in costs is positively correlated with CO2 emissions.

Dependent variable: CO2 emissions	Unemployment	Participation	Employment
Constant	0.009 (0.017)	−0.083 (0.067)	*−0.075*** (0.010)*
GDPgr	*0.002**** (0.001*	*0.003*** (0.001)*	*0.004*** (0.0008)*
ICT index	0.024** (0.011)	*0.211*** (0.052)*	*−0.041*** (0.003)*
Unemployment	*−0.008*** (0.002)*		
Participation		0.0002 (0.001)	
Employment			*0.003*** (0.0009)*
ICT index × Unemployment	*−0.003*** (0.0009)*		
ICT index × Participation		*−0.005*** (0.001)*	
ICT index × Employment			*0.001*** (0.0006)*
Net effects of gender inclusion	−0.008	na	0.041
ICT Thresholds	na	na	na
AR (1)	(0.043)	(0.037)	(0.041)
AR (2)	*(0.159)*	*(0.150)*	*(0.182)*
Sargan (OIR)	(0.000)	(0.001)	(0.000)
Hansen (OIR)	*(0.588)*	*(0.524)*	*(0.342)*
DHT for instruments			
(a) Instruments in levels			
H excluding group	*(0.373)*	*(0.212)*	*(0.484)*
Dif (null, H = exogenous)	*(0.620)*	*(0.696)*	*(0.276)*
(b) IV (years, eq(diff))			
H excluding group	-	-	-
Dif (null, H = exogenous)	-	-	-
Fisher	*254668.57****	*66280.44****	*65294.59****
Instrument	30	30	30
Countries	42	42	42
Comments	522	522	522

Note(s): *, **, ***significance levels of 10, 5 and 1%, respectively. CO2 emissions: CO2 emissions (metric tons per capita); ICT index: the ICT index obtained using the PCA method; Employment: Employment rate (15+ female %) (model ILO estimate); GDP: Gross Domestic Product per capita growth; FDI: Foreign direct investment, net inflows (% of GDP). DHT is the difference in Hansen test for instruments' subsets exogeneity. OIR overidentifying restrictions test. Dif difference. Italic values have two main significances. (1) The Fisher statistics and estimated coefficients that are significant. (2) Inability to reject the null hypotheses of (a) absence of autocorrelation in the AR (1) and AR (2) tests and (b) instrument validity as it pertains to the Sargan and Hansen OIR tests. na: not applicable because for the computation of net effects and/or thresholds, at least one estimated coefficient is not significant. The mean of fixed broadband is 0.714. Values in parentheses are standard errors for the estimated coefficients and p-values for the information criteria (i.e. AR, Sargan, Hansen, DHT and IV tests). Lagged outcome variables are included in the regressions
Source(s): Authors own creation

Table 4.
ICT synergies effects

4. Conclusion implications and future research directions

This study has focused on how information and communication technologies (ICTs) can play a role in the impact of women's economic inclusion on environmental sustainability in 42 sub-Saharan African countries for the period 2005–2020. Mobile phone penetration, internet use and fixed broadband subscriptions were used as indicators of ICT dynamics, while women's economic inclusion was measured in terms of female labour force participation, female unemployment and female employment. The regressions carried out adopted the generalized method of moments. The results clearly showed that: (1) fixed broadband subscriptions represent the most relevant ICT moderator of gender economic inclusion for an effect on CO2 emissions; (2) negative net effects are apparent for the most part with fixed broadband subscriptions (3) both positive ICT thresholds (i.e., critical levels for complementary policies) and negative ICT thresholds (i.e., minimum ICT levels for negative net effects) are provided; (4) ICT synergy effects are apparent for female unemployment, but not for female employment. In what follows, the corresponding policy implications are discussed.

First, concerning the overwhelming relevance of fixed broadband subscriptions in moderating the effect of gender economic inclusion on CO2 emissions, policy makers should note that ICT type matters in the dynamics and policy formulation of how gender economic inclusion policies should be complemented with enhanced penetration of information technology while respecting the environment. Accordingly, policy makers are more likely to use fixed broadband subscriptions as an important leverage than internet penetration and mobile phone penetration. Whether the leverage is based on fixed broadband penetration policy thresholds or fixed broadband penetration threshold for complementary policies is another question which is a subject to empirical scrutiny and validity, prior to policy prescription and implementation. What matters in this first policy implication is that compared to the other ICT dynamics, fixed broadband subscriptions matter most.

Second, we have established both ICT policy thresholds as well as a mobile phone threshold for complementary policy. These ICT thresholds are directly relevant to policy makers because these are actionable ICT penetration levels that policy makers can act upon in order to influence the interaction between ICT and gender economic inclusion in a desired macroeconomic direction. Accordingly, the ICT policy thresholds imply that penetration levels of the ICT dynamics should reach the minimum ICT critical masses in order for the desired negative effect on CO2 emissions to be established. These are negative ICT thresholds because when the thresholds are reached, the positive net effect become negative. Conversely, the positive mobile phone penetration threshold is a threshold for complementary policy. This is essentially because when the threshold is reached, in order to maintain the negative unconditional effect of gender economic inclusion on CO2 emissions, complementary policies, based on sound empirical evidence should be taken on board by policy makers in order to continuously promote environmental sustainability by means of reduction in CO2 emissions.

Third, the ICT synergy effects that are apparent for female unemployment, but not for female employment, are quite intuitive. This is essentially because unemployed females use ICT to contribute to less CO2 emissions, compared to employed females. This evidence is important for policy makers, especially in informing them about how women that are informally active conduct themselves with ICT for the environment, relative to women that are formally active.

Fourth on a whole, sub-Saharan African countries in the era of the fourth industrial revolution should prioritize ICT infrastructure development, accessibility and cost reduction. Tackling these barriers would increase ICT accessibility, empower women economically and contribute to a sustainable reduction in carbon emissions. In this context, these countries should also strengthen their ICT policies to improve access, use and effectiveness of these technologies. These recommendations are in line with the policy perspective that the United Nations should ensure that policies take women into account.

The findings in the study obviously leave space for further research, especially as it concerns assessing whether the established linkages using the relevant estimation techniques withstand empirical scrutiny. Moreover, other sustainable development goals (SDGs) considerations should also be taken into account in future studies, notably: income inequality and extreme poverty.

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Appendices

Appendix 1

Variables	Sings	Definition of variables (measurements)	Sources
CO2 emissions (metric tons per capita)		CO2 emissions (metric tons per capita)	WDI
Internet penetration		Internet users (per 100 people)	WDI
Mobile phone penetration		Mobile cellular subscriptions (per 100 people)	WDI
Fixed broadband		Fixed broadband subscriptions (per 100 people)	WDI
Female labour force participation		Labour force participation rate, 15 + female (%) (model ILO estimate)	ILO
Female unemployment		Unemployment rate, 15+ female (%) model ILO estimate)	ILO
Employment		Unemployment rate, 15+ female (%) model ILO estimate	
Gross domestic product growth		GDP per capita growth (annual %)	WDI
Foreign direct investment		Foreign direct investment, net inflows (% of GDP)	WDI

Note(s): WDI: World Development Indicators of the World Bank; ILO: International Labour Organization
Source(s): Authors own creation

Table A1. Definitions and sources of variables

Appendix 2

Variables	Mean	S.D.	Minimum	Maximum	Comments
CO2 emissions (metric tons per capita)	0.845	1.474	0.0217	8.446	672
Internet penetration	13.222	15.184	0.215	72.748	663
Mobile phone penetration	60.583	38.383	0.530	166.943	666
Fixed broadband	0.714	2.384	0	24.903	589
Female labour force participation	58.702	13.287	26	87.1	672
Female unemployment	8.345	7.655	0.2	31.3	672
Female employment	2.544	2.135	−11.3	20.3	672
Gross domestic product	4.018	4.767	−36.391	21.452	672
Foreign direct investment	0.740	4.925	−10.333	75.999	562

Note(s): S.D: Standard Deviation
Source(s): Authors own creation

Table A2.
Summary statistics

Appendix 3

Dependent variable	ICT dynamics			Female inclusion			Control variables		
CO2	Int	Mob	Fixed	FLFP	FUNMP	FEMP	GDP	FDI	
1.000	0.461	0.487	0.341	−0.295	0.650	−0.017	−0.165	0.008	CO2
	1.000	0.770	0.522	−0.338	0.390	−0.146	−0.327	−0.043	INT
		1.000	0.393	−0.422	0.431	−0.041	−0.190	−0.015	MOB
			1.000	−0.206	0.162	−0.103	−0.198	−0.0009	FIXED
				1.000	−0.480	0.0213	0.088	0.060	FLFP
					1.000	−0.067	−0.176	−0.025	FUNMP
						1.000	0.138	−0.000	FEMP
							1.000	0.059	GDP
								1.000	FDI

Note(s): CO2: CO2 emissions (metric tons per capita); Int: Internet users (per 100 people); Mob: Mobile cellular subscriptions (per 100 people) Penetration; Fixed: Fixed broadband subscriptions (per 100 people); FLPF: Labour force participation rate, 15 + female (%) (model ILO estimate); FUNMP: Female: Unemployment rate, 15+ female (%) model ILO estimate); FEMP: Female employment rate, 15+ female (%) model ILO estimate); GDP: Gross Domestic Product growth per capita; FDI: Foreign direct investment, net inflows (% of GDP)
Source(s): Authors own creation

Table A3.
Correlation matrix

Appendix 4 List of countries

Angola, Congo Republic, Lesotho, Rwanda, Benin, Cote d'Ivoire, Liberia, Senegal, Botswana, Equatorial Guinea, Madagascar, Sierra Leone, Burkina Faso, Eswatini, Malawi, South Africa, Burundi, Ethiopia, Mali, Tanzania, Cabo Verde, Gabon, Mauritania, Togo, Cameroon, the Gambia,
Mauritius, Uganda, Central African Republic, Ghana, Mozambique, Zambia, Chad, Guinea, Namibia, Zimbabwe, Comoros, Guinea-Bissau, Niger, Congo Democratic Republic, Kenya and Nigeria.

Appendix 5

Variables	Pesaran (2021)	Fan *et al.* (2015)
CO2 emissions (metric tons per capita)	29.22***	1664.42***
	(0.000)	(0.000)
Internet penetration	108.05***	3168.70***
	(0.000)	(0.000)
Mobile phone penetration	101.34***	2972.32***
	(0.000)	(0.000)
Female participation	9.23***	2133.03***
	(0.000)	(0.000)
Female employment	13.33***	891.89***
	(0.000)	(0.000)
Female unemployment	11.57***	1620.70***
	(0.000)	(0.000)
Gross domestic product per capita growth	29.18	951.41***
	(0.000)	(0.000)
Foreign direct investment	0.000	0.000
	(1.000)	(1.000)

Note(s): ***; **; *Significance at 1, 5 and 10% respectively. Under the null hypothesis of cross-sectional independence CD ~ N (0.1) and a p-value close to zero indicates data that are correlated across individuals in the panel, CD means the cross-sectional dependence statistic
Source(s): Authors own creation\calculations

Table A4. Cross-section interdependence tests

Appendix 6

Panel A: Panel unit root tests results

Variables	Levin-Lin-Chu (LLC)	Im-Pesaran-Shin (IPS)	Order of integration
CO2 emissions (metric tons per capita)	−6.5297 (0.0125)	−1.2955 (0.9276)	I (1)
Internet penetration	−4.876 (1.000)	3.0736 (1.000)	I (1)
Mobile phone penetration	0.366 (1.000)	−1.6568 (0.1658)	I (1)
Fixed broadband	0.547 (1.000)	0.334 (1000)	I (1)
Female labour force participation	−4.1605 (0.0000)	−1.3566 (0.9697)	I (1)
Employment	−10.8475 (−1.0073)	−2.0573 (0.0050)	I (1)
Female unemployment, female	−7.1138 (0.100)	−0.5307 (1.000)	I (1)
Gross Domestic product per capita growth	−12.0921 (0.0111)	−2.3776 (0.000)	I (0)
Foreign direct investment	5.876 (−0.875)	–	I (1)

Panel B: Results of Pedroni and Westerlund panel cointegration tests

Pedroni panel cointegration test		Westerlund cointegration test (2007)	
Modified Phillips-Perron t	6.324*** (0.000)	Ratio-variance	
Phillips-Perron t	−5.526*** (0.000)	−2.287	(0.011)
Augmented Dickey-Fuller t	−7.275*** (0.000)		

Note(s): ***; **; *Significance at 1, 5 and 10% respectively. H0 = homogeneous non-stationarity; bi = 0 for all I. t_stat is the LLC statistic and IPS the critical value associated with the different test statistics, which precede them. The value in parenthesis is the *P*-value. When a critical probability is greater than the critical value, then the null hypothesis is not rejected and vice versa
Source(s): Authors own creation\calculations

Table A5.
Panel unit root and cointegration tests results

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