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Mobile Phone Innovation and Environmental Sustainability in Sub-Saharan Africa

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Abstract

This study investigates how the mobile phone can complement knowledge diffusion in order to influence CO_2 emissions in 44 Sub-Saharan African countries for the period 2000-2012. The empirical evidence is based on Generalised Method of Moments. Three knowledge diffusion variables representing three of the four pillars of the World Bank's Knowledge Economy Index are employed: educational quality, information and communication technology (ICT) and scientific output. Six CO_2 emission variables are used, namely: CO_2 per capita, CO_2 from electricity and heat, CO_2 from liquid fuel, CO_2 from manufacturing and construction, CO_2 from transport and CO_2 intensity. In the assessments, a decreasing tendency in these variables translates into positive conditions for environmental sustainability. Based on net effect from complementarities, the following findings are established. *First*, the mobile phone complements education to have a net negative effect on CO_2 emissions per capita and CO_2 emissions from the consumption of liquid fuel. *Second*, where some positive net effects of knowledge diffusion are apparent, corresponding marginal effects are negative. Corresponding mobile phone penetration thresholds at which the positive net effects on CO_2 emissions can be dampened and reversed are largely within policy range. Practical and theoretical implications are discussed.

JEL Classification: C52; O38; O40; O55; P37
Keywords: CO2 emissions; ICT; Economic development; Africa

1. Introduction

This chapter is motivated by three main trends in policy and scholarly circles, notably: the substantial potential for mobile penetration in Sub-Saharan Africa (SSA); the challenges of environmental sustainability and gaps in the literature[1]. We engage the points in chronological order.

First, compared to more advanced economies in North America, Europe and Asia that have been experiencing saturation levels in mobile phone penetration, Africa still has a high potential for the penetration of information and communication technology (ICT) (see Penard et al., 2012; Asongu, 2013; Asongu, 2017). Such a potential for the mobile phone can be leveraged by policy makers in order to address sobering policy syndromes like global warming and environmental pollution.

Second, environmental sustainability is a key theme in the post-2015 sustainable development agenda (Asongu et al., 2016a). This concern is relevant for SSA development challenges for at least four reasons, notably: comparatively high economic growth, persistent energy crisis, unsound management of energy and consequences of global warming. (i) Africa has enjoyed more than two decades of growth resurgence (see Fosu, 2015) and recently hosted seven of the ten fastest growing world economies (Asongu & Rangan, 2016). (ii) Energy crisis has been documented to represent one of the most significant challenges in the post-2015 era (Akinyemi et al., 2015). Shurig (2015) emphasized that according to the International Energy Agency (IEA), only 5% of SSA has energy access. To put this point into perspective, the total energy consumption in the sub-region is equivalent to that of the New York state of the USA and the consumption of electricity per capita in SSA is one-sixth of the global average. (iii) The management of energy crisis has been inefficient in most African countries (Anyangwe, 2014). For instance, in some countries (like Nigeria), high demand for government-subsidized fossil fuels has been at the expense of renewable energy because the absence of electricity is compensated with substantial reliance on generators that depend on petroleum fuel (see Apkan, 2012). (iv) Global warming is a consequence of the consumption of fossil fuels in an unsustainable manner (Huxster et al., 2015). Furthermore, it is estimated that the population in Africa could be the most affected by the consequences of global warming (Kifle, 2008). The emission of carbon dioxide (CO_2) is important in global warming

[1] Throughout this study the terms, 'mobile phone penetration', 'mobile telephony', 'mobile' and 'mobile phones' are used interchangeably.

because it represents about 75 percent of greenhouse gas emissions in the world (Akpan, 2012).

Third, this inquiry assesses how the mobile phone can be innovated for environmental sustainability, focusing on CO_2 emissions. Such positioning steers clear of recent CO_2 literature which has largely concentrated on linkages between energy consumption, CO_2 emissions and economic growth. Two fundamental strands constitute this dominant literature. The *first* strand addressed the nexus between environmental pollution and economic growth with particularly emphasis on assessing the Environmental Kuznets Curve (EKC) hypothesis (see Akbostanci et al., 2009; Diao et al., 2009; He & Richard, 2010)[2]. The *second* strand embodies two research themes: on the one hand, linkages between pollution, energy consumption and economic growth and on the other, the relationship between economic growth and the consumption of energy. While the latter theme is substantially documented (Mehrara, 2007; Esso, 2010)[3], the former theme which is a comparatively new area of research has been characterised with conflicting findings for both developing and developed nations (Jumbe, 2004; Ang, 2007; Apergis & Payne, 2009; Odhiambo, 2009a, 2009b; Ozturk & Acaravci, 2010; Menyah & Wolde-Rufael, 2010; Begum et al., 2015 ; Bölük & Mehmet, 2015).

The engaged studies have a fundamental shortcoming: the absence of policy variables with which to mitigate CO_2 emissions. We argue that, just stating how economic growth, energy consumption and environmental pollution are connected has little practical significance for policy markers if they are not provided with instruments by which policy syndromes (e.g. CO_2 emissions) can be mitigated. This study addresses the highlighted gap by employing the mobile phone as the innovative policy variable because of its penetration potential in SSA.

The present inquiry contributes to the extant literature by assessing how the mobile phone can complement the following three pillars of knowledge diffusions variables. They are (i) educational quality, (ii) ICT (e.g. internet penetration) and (iii) innovation (proxied by the number Scientific and Technical Journal Articles). In order to make these assessments, the mobile phone is interacted with each of the three knowledge diffusion variables in order to

[2] It is important to note that the EKC hypothesis postulates that in the long term there is an inverted U-shaped relationship between per capita income and environmental degradation.
[3] Also see Olusegun (2008) and Akinlo (2009).

examine both the conditional and unconditional net effects on environmental outcome variables. The intuition of mobile phone innovation is the fact that development externalities are likely to be enhanced when the mobile phone is complemented with the suggested proxies of knowledge diffusion. Such development externalities may ultimately contribute to environmental sustainability. For instance, a mobile phone that is connected to the internet may: (i) prevent unnecessary travelling and mitigate corresponding CO_2 emissions from citizens with or without private vehicles and (ii) enhance household management efficiency through the use of energy-saving mobile applications. In the same vein, the use of mobile phone applications for sustainable development initiatives require a minimum level of education and the overall impact on society is also contingent on the average level of scientific output.

The positioning of this inquiry unites the aforementioned three strands of literature. It investigates how the mobile phone penetration potential (first strand) can be leveraged to address environmental challenges (second strand) in order to complement existing studies (third strand). The rest of the study is structured as follows. Section 2 discusses the data and methodology while section 3 presents the empirical results. Concluding remarks and future research directions are covered in Section 4.

2. Data and methodology

2.1 Data

The study assesses a panel of 44 countries in SSA with data from the World Development Indicators (WDI) of the World Bank for the period 2000-2012[4]. The choice of the periodicity is contingent on data availability constraints. Six dependent indicators of CO_2 emissions are used, namely: (i) CO_2 per capita, (ii) CO_2 from electricity and heat, (iii) CO_2 from liquid fuel, (iv) CO_2 from manufacturing and construction, (v) CO_2 from transport and (vi) CO_2 intensity. In this investigation, a decrease in these CO_2 emission variables implies positive conditions for environmental sustainability.

Three out of the four existing Knowledge Economy Index (KEI) variables from the World Bank are employed as knowledge diffusion variables. They are: (i) education, (ii)

[4] The 44 countries are: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo Democratic. Republic., Congo Republic, Cote d'Ivoire, Djibouti, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda and Zambia.

innovation and (iii) information and communication technology (ICT). This choice is consistent with recent ICT literature (Asongu & Nwachukwu, 2016a). Educational quality is measured as the 'pupil-teacher ratio' in primary education. Both data availability constraints and the comparative relevance of primary education motivate the selection of this variable. Concerns surrounding degrees of freedom are apparent in other measurements of educational quality (e.g. 'pupil-teacher ratio in secondary education'). Moreover, primary education has been established in the literature to be more connected with positive development externalities when nations are at an initial stage of the process industrialisation (see Petrakis & Stamatakis, 2002; Asiedu, 2014).

Given the limited variation in the other variables of innovation (e.g. patent and trademark applications), we are in conformity with recent literature in employing the number of Scientific and Technical Journal Articles (STJA) published annually as a proxy for innovation (Tchamyou, 2016). The internet penetration rate (per 100 people) is also used as a complement to the main policy variable: mobile phone penetration rate (per 100 people).

In order to avoid variable omission bias, five main control variables are used. They comprise: (i) Gross Domestic Product (GDP) growth rate, (ii) population growth rate, (iii) foreign direct investment, (iv) trade openness and (v) regulation quality. The selected variables represent market (GDP growth and population growth), globalisation (trade openness and foreign investment) and institutional (regulation quality) indicators that are likely to influence industrial and market dynamism which affect CO_2 emissions. Intuitively, we expect the first-four variables to positively influence CO_2 while regulation quality should have a negative effect. However, this perception should be taken with caution because the influence of the control variables may be contingent on the role of country-specific factors which are taken into account in the Generalised Method of Moments (GMM) specifications. The full definitions of variables, corresponding summary statistics and the correlation matrix are disclosed in Appendix 1, Appendix 2 and Appendix 3 respectively.

2.2 Methodology

We adopt a *two-step* GMM estimation technique for five principal reasons: (i) the adopted number of countries (44) is considerably higher than the periodicity in the individual countries (13); (ii) the CO_2 emission variables are persistent as shown in Appendix 4 given that their correlation coefficients with their respective first lags are higher than the rule thumb threshold of 0.800; (iii) owing to the fact that the GMM estimation approach is compatible with a panel data structure, cross-country differences are considered in the regressions; (iv) inherent biases in the *difference* estimator are corrected with the *system* estimator; and (v) the estimation technique further accounts for endogeneity by controlling for simultaneity in the explanatory variables using an instrumentation process. In addition, usage of time-invariant indicators also enables the study to control for endogeneity.

We employ the Roodman (2009ab) extension of Arellano and Bover (1995) because, compared to traditional GMM techniques, it mitigates the proliferation of instruments (or restricts over-identification) and is more efficient in the presence of cross-sectional dependence (Love & Zicchino, 2006; Baltagi, 2008; Boateng et al., 2016).

The following equations in level (1) and first difference (2) summarise the standard *system* GMM estimation procedure.

$$CO_{i,t} = \sigma_0 + \sigma_1 CO_{i,t-\tau} + \sigma_2 M_{i,t} + \sigma_3 K_{i,t} + \sigma_4 MK_{i,t} + \sum_{h=1}^{5} \delta_h W_{h,i,t-\tau} + \eta_i + \xi_t + \varepsilon_{i,t}$$

(1)

$$CO_{i,t} - CO_{i,t-\tau} = \sigma_1 (CO_{i,t-\tau} - CO_{i,t-2\tau}) + \sigma_2 (M_{i,t} - M_{i,t-\tau}) + \sigma_3 (K_{i,t} - K_{i,t-\tau}) + \sigma_4 (MK_{i,t} - MK_{i,t-\tau}) + \sum_{h=1}^{5} \delta_h (W_{h,i,t-\tau} - W_{h,i,t-2\tau}) + (\xi_t - \xi_{t-\tau}) + \varepsilon_{i,t-\tau}$$

(2)

where, $CO_{i,t}$ is a CO_2 emissions indicator of country i at period t, σ_0 is a constant, M represents mobile phone penetration, K is a knowledge diffusion variable (educational quality, internet penetration and scientific output), MK is the interaction between a knowledge diffusion variable and the mobile phone penetration policy variable, W is the vector of control variables (GDP growth, population growth, foreign direct investment, trade and regulation quality), τ represents the coefficient of auto-regression which is one for the specification, ξ_t is the time-specific constant, η_i is the country-specific effect and $\varepsilon_{i,t}$ the error term.

We briefly engage properties of identification and exclusion restrictions because they are essential for a sound GMM specification. All explanatory indicators are acknowledged as suspected endogenous or predetermined and only time-invariant variables are considered to exhibit strict exogeneity. This process is in accordance with recent literature (see Asongu & Nwachukwu, 2016b, Boateng et al., 2016). Furthermore, time-invariant variables or years are unlikely to become endogenous after a first difference (see Roodman, 2009b)[5]. In this light, the time invariant indicators affect CO_2 emissions exclusively via the suspected endogenous

[5] Hence, the procedure for treating *ivstyle* (years) is 'iv (years, eq(diff))' whereas the *gmmstyle* is employed for predetermined variables.

indicators. In addition, the statistical relevance of the underlying exclusion restriction is assessed with the Difference in Hansen Test (DHT) for the exogeneity of instruments. Within this framework, the alternative hypothesis of the DHT should be rejected in order for the time invariant variables to affect CO_2 emissions exclusively via the predetermined variables. Hence, in the findings that are presented subsequently, the hypothesis of exclusion restriction is validated if the null hypothesis of the DHT connected to instrumental variables (IV) (year, eq(diff)) is not rejected. Such a process is in accordance with the standard IV procedure where-by, a rejection of the alternative hypothesis of the Sargan Overidentifying Restrictions (OIR) test is an implication that strictly exogenous variables influence CO_2 emissions exclusively through the suspected endogenous variable mechanisms (see Beck et al., 2003; Asongu & Nwachukwu, 2016c).

3. Empirical results

Table 1 and Table 2 respectively present the first and second sets of specifications on linkages between mobile phone innovation and CO_2 emissions. Table 1 focuses on: CO_2 per capita, CO_2 from electricity and heat and CO_2 from liquid fuel. Table 2 is concerned with: CO_2 from manufacturing and construction, CO_2 from transport and CO_2 intensity. For each CO_2 emission indicator, there are three specifications pertaining to the knowledge diffusion variables, namely: educational quality, internet penetration and scientific output.

Four information criteria are employed to assess the validity of the GMM models with forward orthogonal deviations[6] and the net effect is computed to examine the overall impact of the complementarity between the mobile phone policy variable and knowledge diffusion in CO_2 emissions. For example, in Table 1, in the second column, the net effect from the interaction between mobile phones and education is -0.0272 ([0.00003× 24.428] + [-0.001]). In the computation, the mean value of mobile phone penetration is 24.428, the unconditional impact of mobile phone penetration is -0.001 while the conditional impact from the interaction between education and mobile phones is 0.00003.

[6] "*First, the null hypothesis of the second-order Arellano and Bond autocorrelation test (AR (2)) in difference for the absence of autocorrelation in the residuals should not be rejected. Second the Sargan and Hansen over-identification restrictions (OIR) tests should not be significant because their null hypotheses are the positions that instruments are valid or not correlated with the error terms. In essence, while the Sargan OIR test is not robust but not weakened by instruments, the Hansen OIR is robust but weakened by instruments. In order to restrict identification or limit the proliferation of instruments, we have ensured that instruments are lower than the number of cross-sections in most specifications. Third, the Difference in Hansen Test (DHT) for exogeneity of instruments is also employed to assess the validity of results from the Hansen OIR test. Fourth, a Fischer test for the joint validity of estimated coefficients is also provided*" (Asongu & De Moor, 2017, p.200).

Table 1: Mobile phone innovation and CO_2 emissions (1)

	Dependent variables: CO_2 emissions								
	CO_2 emissions (metric tons per capita)			CO_2 emissions from electricity and heat production, total (% of total fuel combustion			CO_2 emissions from liquid fuel consumption (% of total)		
	Education	Innovation	Internet	Education	Innovation	Internet	Education	Innovation	Internet
Constant	**0.299*** **	**0.060***	0.054	8.651	6.179	**29.125** **	0.138	0.271	**7.437*** **
	(0.000)	**(0.072)**	(0.383)	(0.745)	(0.674)	**(0.015)**	(0.932)	(0.923)	**(0.000)**
CO_2 per capita (-1)	**0.938*** **	**0.818*** **	**0.937*** **	---	---	---	---	---	---
	(0.000)	**(0.000)**	**(0.000)**						
CO_2 from electricity and heat (-1)	---	---	---	**0.912*** **	**1.024*** **	**0.751*** **	---	---	---
				(0.000)	**(0.000)**	**(0.000)**			
CO2 from liquid fuel (-1)	---	---	---	---	---	---	**0.949*** **	**1.030*** **	**0.906*** **
							(0.000)	**(0.000)**	**(0.000)**
Mobile phones (Mob)	-0.0003	**0.003*** **	**0.002*** **	-0.044	-0.042	-0.019	0.019	**0.022***	-0.014
	(0.332)	**(0.000)**	**(0.000)**	(0.532)	(0.567)	(0.644)	(0.106)	**(0.077)**	(0.258)
Education	**-0.001*** **	---	---	-0.138	---	---	0.008	---	---
	(0.007)			(0.715)			(0.615)		
Innovation (STJA)	---	**0.0007*** **	---	---	-0.002	---	---	-0.002	---
		(0.000)			(0.509)			(0.102)	
Internet	---	---	**0.015*** **	---	---	**0.420***	---	---	**-0.218*** **
			(0.000)			**(0.089)**			**(0.000)**
Education.Mob	**0.00003*** **	---	---	**0.003***	---	---	-0.0003	---	---
	(0.001)			**(0.082)**			(0.100)		
STJA.Mob	---	**-0.000002 *** **	---	---	0.00001	---	---	**0.00001***	---
		(0.000)			(0.644)			**(0.078)**	
Internet.Mob	---	---	**-0.0001*** **	---	---	**-0.004***	---	---	**0.002*** **
			(0.000)			**(0.097)**			**(0.000)**
GDP growth	-0.001	**0.001*** **	**0.001** **	-0.037	0.138	0.443	**-0.055*** **	-0.004	**-0.076*** **
	(0.128)	**(0.003)**	**(0.036)**	(0.869)	(0.633)	(0.157)	**(0.006)**	(0.880)	**(0.000)**
Population Growth	**-0.069*** **	**-0.055*** **	**-0.052*** **	-3.845	-0.421	**-10.866** **	**1.121*** **	**1.203*** **	**0.708*** **
	(0.000)	**(0.000)**	**(0.000)**	(0.170)	(0.899)	**(0.024)**	**(0.005)**	**(0.003)**	**(0.001)**
Foreign Direct Investment	**0.00004**	**-0.002*** **	**0.0008***	**-0.432***	0.014	0.040	0.015	**0.107*** **	**0.072*** **
	(0.931)	**(0.003)**	**(0.098)**	**(0.081)**	(0.919)	(0.737)	(0.236)	**(0.001)**	**(0.000)**
Trade	**-0.0006*** **	**0.001*** **	**-0.001*** **	0.025	-0.044	-0.014	0.008	**-0.057*** **	-0.004
	(0.002)	**(0.000)**	**(0.008)**	(0.790)	(0.642)	(0.781)	(0.276)	**(0.000)**	(0.775)
Regulation Quality	-0.032	0.012	**-0.085*** **	-6.807	2.282	-2.577	-0.316	**4.597*** **	**2.048*** **
	(0.101)	(0.701)	**(0.001)**	(0.188)	(0.691)	(0.546)	(0.577)	**(0.000)**	**(0.008)**
Net Effects mobile phones	-0.0272	0.0006	0.012	na	na	0.322	na	na	-0.169
AR(1)	(0.099)	(0.159)	(0.127)	(0.208)	(0.022)	(0.142)	(0.006)	(0.098)	(0.059)
AR(2)	**(0.205)**	**(0.472)**	**(0.535)**	**(0.167)**	**(0.954)**	**(0.577)**	(0.044)	(0.077)	(0.029)
Sargan OIR	(0.000)	(0.000)	(0.000)	**(0.998)**	**(0.998)**	**(0.899)**	**(0.861)**	**(0.204)**	(0.033)
Hansen OIR	**(0.905)**	**(0.551)**	**(0.586)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.465)**	**(0.335)**	**(0.910)**
DHT for instruments									
(a)Instruments in levels									
H excluding group	**(0.859)**	**(0.626)**	**(0.725)**	**(1.000)**	**(0.985)**	**(0.975)**	**(0.533)**	**(0.245)**	**(0.572)**
Dif(null, H=exogenous)	**(0.779)**	**(0.436)**	**(0.417)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.394)**	**(0.446)**	**(0.924)**
(b) IV (years, eq(diff))									
H excluding group	**(0.684)**	**(0.676)**	**(0.856)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.186)**	**(0.470)**	**(0.837)**
Dif(null, H=exogenous)	**(0.942)**	**(0.278)**	**(0.179)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.901)**	**(0.210)**	**(0.777)**
Fisher	**384323*** **	**683066*** **	**288845*** **	**337.06*** **	**4119.33*** **	**549.97*** **	**3037.91*** **	**37606*** **	**6913.25*** **
Instruments	44	42	44	44	42	44	44	42	44
Countries	44	44	44	22	22	22	44	44	44
Observations	388	340	416	167	175	215	338	340	416

*,**,***: significance levels of 10%, 5% and 1% respectively. CO_2: Carbon monoxide. DHT: Difference in Hansen Test for Exogeneity of Instruments' Subsets. Dif: Difference. OIR: Over-identifying Restrictions Test. The significance of bold values is twofold. 1) The significance of estimated coefficients, Hausman test and the Fisher statistics. 2) The failure to reject the null hypotheses of: a) no autocorrelation in the AR(1) and AR(2) tests and; b) the validity of the instruments in the Sargan and Hansen OIR tests. na: not applicable because at least one estimated coefficient needed for the computation of net effects is not significant. The mean value of mobile phone penetration is 24.428.

Table 2: Mobile phone innovation and CO_2 emissions (2)

Dependent variables: CO_2 emissions

	CO_2 emissions from manufacturing industries and construction (% of total fuel combustion)			CO_2 emissions from transport (% of total fuel combustion)			CO_2 intensity (kg per kg of oil equivalent energy use)		
	Education	Innovation	Internet	Education	Innovation	Internet	Education	Innovation	Internet
Constant	-5.709	-0.102	-10.908	-1.890	-11.201	2.162	-0.325	-0.927	-0.650
	(0.552)	(0.993)	(0.502)	(0.846)	(0.209)	(0.858)	(0.833)	(0.422)	(0.507)
CO_2 from manufacturing and construction (-1)	**0.865*** **	**0.911*** **	**0.983*** **	---	---	---	---	---	---
	(0.000)	**(0.000)**	**(0.000)**						
CO_2 from transport (-1)	---	---	---	**1.063*** **	**0.880*** **	**0.881*** **	---	---	---
				(0.000)	**(0.000)**	**(0.000)**			
CO_2 intensity (-1)	---	---	---	---	---	---	**0.988*** **	**0.986*** **	**0.982*** **
							(0.000)	**(0.000)**	**(0.000)**
Mobile phones (Mob)	0.023	0.002	-0.030	-0.073	0.025	0.010	-0.0008	-0.005	0.001
	(0.772)	(0.969)	(0.589)	(0.424)	(0.731)	(0.745)	(0.932)	(0.450)	(0.721)
Education	0.078	---	---	**0.194***	---	---	-0.004	---	---
	(0.706)			**(0.053)**			(0.854)		
Innovation (STJA)	---	0.002	---	---	0.001	---	---	**0.0005***	---
		(0.390)			(0.482)			**(0.077)**	
Internet	---	---	0.007	---	---	-0.163	---	---	0.013
			(0.977)			(0.561)			(0.641)
Education.Mob	-0.0003	---	---	0.0003	---	---	0.00008	---	---
	(0.827)			(0.886)			(0.742)		
STJA.Mob	---	-0.00002	---	---	-0.000007	---	---	-0.000001	---
		(0.272)			(0.775)			(0.316)	
Internet.Mob	---	---	0.0009	---	---	0.001	---	---	-0.00007
			(0.758)			(0.627)			(0.773)
GDP growth	-0.020	0.224	-0.021	0.034	-0.158	-0.154	-0.004	**-0.021*** **	0.001
	(0.899)	(0.184)	(0.911)	(0.822)	(0.343)	(0.748)	(0.787)	**(0.006)**	(0.942)
Population Growth	**3.897***	-3.564	**5.483** **	-1.104	4.048	-0.202	0.025	0.001	0.013
	(0.061)	(0.534)	**(0.045)**	(0.766)	(0.195)	(0.973)	(0.955)	(0.997)	(0.961)
Foreign Direct Investment	-0.006	0.075	0.019	0.028	0.038	0.090	0.003	-0.009	-0.0007
	(0.966)	(0.594)	(0.868)	(0.891)	(0.682)	(0.755)	(0.872)	(0.645)	(0.973)
Trade	0.010	**0.084***	0.033	0.015	**0.081***	0.034	0.002	**0.017** **	0.003
	(0.846)	**(0.090)**	(0.597)	(0.779)	**(0.091)**	(0.456)	(0.810)	**(0.034)**	(0.837)
Regulation Quality	7.518	-3.148	5.233	6.956	-2.628	-3.221	-0.096	-0.511	-0.196
	(0.272)	(0.574)	(0.235)	(0.346)	(0.648)	(0.653)	(0.734)	(0.294)	(0.741)
Net Effects mobile phones	na	na	na	na	na	na	na	na	na
AR(1)	(0.047)	(0.037)	**(0.122)**	**(0.163)**	**(0.140)**	**(0.356)**	**(0.753)**	(0.026)	**(0.803)**
AR(2)	**(0.397)**	**(0.587)**	**(0.705)**	**(0.596)**	**(0.906)**	**(0.817)**	**(0.779)**	**(0.841)**	**(0.593)**
Sargan OIR	**(0.635)**	(0.009)	**(0.177)**	**(0.989)**	**(0.999)**	**(0.986)**	**(1.000)**	(0.000)	(0.000)
Hansen OIR	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.993)**	**(1.000)**
DHT for instruments									
(a)Instruments in levels									
H excluding group	**(0.887)**	**(0.890)**	**(0.991)**	**(0.971)**	**(0.886)**	**(0.953)**	**(1.000)**	**(0.997)**	**(0.999)**
Dif(null, H=exogenous)	**(1.000)**	**(1.000)**	**(0.999)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.943)**	**(1.000)**
(b) IV (years, eq(diff))									
H excluding group	**(0.998)**	**(0.997)**	**(0.990)**	**(1.000)**	**(0.999)**	**(0.991)**	**(1.000)**	**(0.996)**	**(1.000)**
Dif(null, H=exogenous)	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(1.000)**	**(0.660)**	**(1.000)**
Fisher	**1294.61*** **	**3346.94*** **	**34.87*** **	**263.92*** **	**1875.11*** **	**2478.15*** **	**937.52*** **	**225.40*** **	**85.45*** **
Instruments	44	44	44	44	44	44	44	42	44

Countries	22	22	22	22	22	22	31	31	31
Observations	167	175	215	167	175	215	187	201	241

*,**,***: significance levels of 10%, 5% and 1% respectively. CO_2: Carbon monoxide. DHT: Difference in Hansen Test for Exogeneity of Instruments' Subsets. Dif: Difference. OIR: Over-identifying Restrictions Test. The significance of bold values is twofold. 1) The significance of estimated coefficients, Hausman test and the Fisher statistics. 2) The failure to reject the null hypotheses of: a) no autocorrelation in the AR(1) and AR(2) tests and; b) the validity of the instruments in the Sargan and Hansen OIR tests. na: not applicable because at least one estimated coefficient needed for the computation of net effects is not significant. The mean value of mobile phone penetration is 24.428.

In the light of the criteria for the validity of GMM regressions, the following findings are established in Table 1. *First*, the mobile phone complements education to have a net negative effect on CO_2 emissions per capita and CO_2 emissions from the consumption of liquid fuel. *Second*, where some positive net effects are apparent, corresponding marginal effects are negative. Regressions reflecting this finding include, the complementarity between mobile phones and: (i) scientific output in per capita CO_2 emissions, (ii) internet penetration in per capita CO_2 emissions and (iii) internet penetration in CO_2 emissions from electricity and heat production . Significant net effects are not apparent in Table 1 because at least one of the estimated coefficients needed for their computation is not significant in the respective specifications.

4. Concluding implications and future research directions

This study has investigated how the mobile phone can complement knowledge diffusion variables in order to influence CO_2 emissions in 44 Sub-Saharan African countries for the period 2000-2012. The empirical evidence is based on Generalised Method of Moments. Three knowledge creation and diffusion variables representing three of the four pillars of the World Bank's Knowledge Economy Index have been employed: educational quality, information and communication technology (ICT) and scientific output. Six CO_2 emission variables have also been used: namely: CO_2 per capita, CO_2 from electricity and heat, CO_2 from liquid fuel, CO_2 from manufacturing and construction, CO_2 from transport and CO_2 intensity. In the empirical analysis, a decrease in these variables implies positive conditions for environmental sustainability.

Based on net effect from complementarities, the following findings have been established. *First*, the mobile phone complements education so as to have a net negative effect on CO_2 emissions per capita and CO_2 emissions from the consumption of liquid fuel. *Second*, where some positive net effects are apparent, corresponding marginal effects are negative. It is important to note that, in the light of the negative unconditional effects pertaining to the net positive effect, mobile phone thresholds at which the mobile phone can dampen the positive net effects are largely within the mobile phone penetration range (i.e. 0.000 to 147.202). In essence, two of the three possible thresholds make economic sense and have policy relevance, notably: 33.333 (0.001/0.00003) mobile penetration per 100 people for scientific output in per capita CO_2 emissions and 105 (0.420/0.004) mobile penetration per 100 people for internet penetration in CO_2 emissions from electricity and heat production. Conversely, the 150 (0.015/0.0001) mobile penetration per 100 people threshold related to internet penetration in per capita CO_2 emissions is not within range. It follows that for thresholds that are within the range provided by the summary statistics, critical levels of mobile phone penetration could revert the positive net effects on CO_2 emissions to negative. This will require policy to put in place measures that increase ICT access in the sub-region. Before we suggest some policies in this direction, it is important to clarify the notion of threshold. In essence, the notion of threshold is similar to: critical masses for appealing effects (Batuo, 2015; Roller & Waverman, 2001); the minimum requirement for reaping expected effects (Cummins, 2000); the requirements for Kuznets and U shapes (Ashraf & Galor, 2013) and essential information sharing critical masses at which market power can be reduced for financial access (Asongu et al., 2017).

In the light of the above, the main practical implication is that ICT can be consolidated in order to reverse potentially adverse effects that its low penetration has on CO_2 emissions when complemented with knowledge diffusion variables. Hence, for sampled countries mobile phone needs to be enhanced beyond identified policy thresholds. Moreover, it is important for policy makers to tackle issues that are linked with the lack of adequate mobile phone infrastructure as well as those pertaining to affordability, which represents a critical access barrier. In this vein, schemes encouraging universal coverage and low pricing are steps in the right direction. In a nutshell, the mobile phone acts as an appropriate interface between knowledge diffusion mechanisms and activities that could decrease CO_2 emissions. For instance a quick dial on a mobile phone can save transport and energy cost which are associated with CO_2 emissions. Decreasing such costs and corresponding CO_2 emissions will therefore be substantially enhanced if mobile phone policies are designed to boost, *inter alia*: adoption, access, interactions, reach and effectiveness.

The principal theoretical contribution is that the mobile phone by means of information sharing can reduce information asymmetry linked to CO_2 emissions. Accordingly, given that a mobile phone is an information sharing instrument, such ability to share information when combined with knowledge diffusion channels can substantially curb costs that promote CO_2 emissions. Thus, the role of decreasing informational rents associated with environmental degradation is broadly consistent with the theoretical framework of financial intermediation efficiency through information sharing offices (public credit registries and private credit bureaus) (see Asongu et al., 2016b). Hence, in the light of this underlying analogy, the theoretical underpinning for enhancing financial intermediation by means of information sharing offices is consistent with complementing the mobile phone with knowledge diffusion variables in order to decrease information asymmetry that promote CO_2 emissions.

Future research can improve the extant literature by assessing whether the established linkages withstand further empirical scrutiny from country-specific standpoints. Such country-specific findings are essential for more targeted policy implications.

Appendices

Appendix 1: Variable Definitions

Variables	Signs	Variable Definitions (Measurement)	Sources
CO_2 per capita	CO2mtpc	CO_2 emissions (metric tons per capita)	World Bank (WDI)
CO_2 from electricity and heat	CO2elehepro	CO_2 emissions from electricity and heat production, total (% of total fuel combustion)	World Bank (WDI)
CO_2 from liquid fuel	CO2lfcon	CO_2 emissions from liquid fuel consumption (% of total)	World Bank (WDI)
CO_2 from manufacturing and construction	CO2mainucon	CO_2 emissions from manufacturing industries and construction (% of total fuel combustion)	World Bank (WDI)
CO_2 from transport	CO2trans	CO_2 emissions from transport (% of total fuel combustion)	World Bank (WDI)
CO_2 intensity	CO2inten	CO_2 intensity (kg per kg of oil equivalent energy use)	World Bank (WDI)
Educational Quality	Educ	Pupil teacher ratio in Primary Education	World Bank (WDI)
Innovation	STJA	Scientific and Technical Journal Articles	World Bank (WDI)
Internet	Internet	Internet penetration (per 100 people)	World Bank (WDI)
Mobile phones	Mobile	Mobile phone subscriptions (per 100 people)	World Bank (WDI)
GDP growth	GDPg	Gross Domestic Product (GDP) growth (annual %)	World Bank (WDI)
Population growth	Popg	Population growth rate (annual %)	World Bank (WDI)
Foreign investment	FDI	Foreign Direct Investment inflows (% of GDP)	World Bank (WDI)
Trade Openness	Trade	Imports plus Exports of goods and services (% of GDP)	World Bank (WDI)
Regulation Quality	RQ	"Regulation quality (estimate): measured as the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development"	World Bank (WDI)

WDI: World Bank Development Indicators.

Appendix 2: Summary statistics (2000-2012)

	Mean	SD	Minimum	Maximum	Observations
CO_2 per capita	0.901	1.820	0.016	10.093	567
CO_2 from electricity and heat	23.730	18.870	0.000	71.829	286
CO_2 from liquid fuel	78.880	23.092	0.000	100	567
CO_2 from manufacturing and construction	15.439	9.931	0.000	53.962	286
CO_2 from transport	48.248	20.208	10.987	92.941	286
CO_2 intensity	2.044	6.449	0.058	77.586	321
Mobile phone penetration	24.428	28.535	0.000	147.202	525
Educational Quality	43.784	14.731	12.466	100.236	425
Innovation (STJA)	97.342	375.405	0.000	2915.5	441
Internet Penetration	4.222	6.618	0.005	43.605	521
GDP growth	4.851	5.000	-32.832	33.735	567
Population growth	2.334	0.866	-1.081	6.576	529
Foreign Direct Investment inflows	5.279	8.639	-6.043	91.007	566
Trade Openness	76.881	35.326	20.964	209.874	555
Regulation Quality	-0.607	0.544	-2.238	0.983	530

S.D: Standard Deviation.

Appendix 3: Correlation matrix (uniform sample size: 155)

CO$_2$ emissions dynamics						Knowledge diffusion			Control Variables						
CO2mtpc	CO2elehepro	CO2lfcon	CO2mainucon	CO2trans	CO2inten	Educ	STJA	Internet	GDPg	Popg	FDI	Trade	RQ	Mobile	
1.000	0.690	-0.721	0.030	-0.626	0.805	-0.369	0.906	0.411	-0.057	-0.611	-0.148	-0.0004	0.593	0.558	CO2mtpc
	1.000	-0.695	-0.006	-0.845	0.703	-0.502	0.581	0.527	-0.052	-0.524	-0.277	-0.099	0.505	0.432	CO2elehepro
		1.000	-0.118	0.618	-0.551	0.246	-0.673	-0.232	0.020	0.364	0.238	0.113	-0.366	-0.349	CO2lfcon
			1.000	-0.372	0.011	0.085	-0.024	0.067	0.017	-0.086	-0.037	-0.052	0.273	-0.015	CO2mainucon
				1.000	-0.667	0.425	-0.501	-0.461	0.106	0.539	0.359	0.178	-0.615	-0.357	CO2trans
					1.000	-0.509	0.544	0.527	-0.055	-0.698	-0.161	0.186	0.676	0.565	CO2inten
						1.000	-0.199	-0.444	0.104	0.515	0.123	-0.147	-0.515	-0.403	Educ
							1.000	0.236	-0.017	-0.365	-0.154	-0.187	0.386	0.430	STJA
								1.000	0.021	-0.580	-0.022	0.256	0.536	0.718	Internet
									1.000	0.074	0.107	-0.136	-0.140	-0.128	GDPg
										1.000	0.064	-0.406	-0.624	-0.580	Popg
											1.000	0.386	-0.244	0.096	FDI
												1.000	0.128	0.270	Trade
													1.000	0.505	RQ
														1.000	Mobile

CO2mtpc: CO_2 emissions (metric tons per capita). CO2elehepro: CO_2 emissions from electricity and heat production, total (% of total fuel combustion). CO2lfcon: CO_2 emissions from liquid fuel consumption (% of total). CO2mainucon: CO_2 emissions from manufacturing industries and construction (% of total fuel combustion). CO2trans: CO_2 emissions from transport (% of total fuel combustion). CO2inten: CO_2 intensity (kg per kg of oil equivalent energy use). Educ: Quality of primary education. STJA: Scientific & Technical Journal Articles. Internet: Internet penetration. GDPg: GDP growth. Popg: Population growth. FDI: Foreign Direct Investment inflows. RQ: Regulation Quality. Mobile: Mobile Phone penetration.

Appendix 4: Persistence of CO_2 emissions

	CO2mtpc	CO2elehepro	CO2lfcon	CO2mainucon	CO2trans	CO2inten
CO2mtpc (-1)	0.9945					
CO2elehepro (-1)		0.9760				
CO2lfcon (-1)			0.9773			
CO2mainucon (-1)				0.9558		
CO2trans (-1)					0.9825	
CO2inten (-1)						0.9644

CO2mtpc: CO_2 emissions (metric tons per capita). CO2mtpc (-1): first lag of CO2mtpc . CO2elehepro: CO_2 emissions from electricity and heat production, total (% of total fuel combustion). CO2lfcon: CO_2 emissions from liquid fuel consumption (% of total). CO2mainucon: CO_2 emissions from manufacturing industries and construction (% of total fuel combustion). CO2trans: CO_2 emissions from transport (% of total fuel combustion). CO2inten: CO_2 intensity (kg per kg of oil equivalent energy use).

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