ICT and energy consumption in Sub-Saharan Africa: Effects and transmission channels

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ABSTRACT

This paper contributes to the literature on the relationship between information and communication technologies (ICTs) and energy consumption. Despite increasing attention on the subject, existing studies have not yet investigated the channels through which ICTs affect energy demand. We use a stochastic impact model extended to the population, wealth, and technology regression model to estimate both the effect and transmission of ICTs on energy demand in 24 sub-Saharan African countries from 1995 to 2018. Empirical results show that ICT use, measured by mobile and fixed-line telephone penetration, significantly reduces energy consumption.

In addition, the mediation analysis reveals that ICTs not only have a direct negative effect on energy consumption but also an indirect negative effect through its impact on GDP per capita and industrial sector development, and a mixed indirect effect through financial development. However, the total effect is negative and indicates that ICTs are reducing energy consumption in sub-Saharan Africa (SSA). To accentuate the negative effects of ICTs on energy consumption, governments should design policies to improve access to credit for the private sector, reduce income inequalities among populations, promote the use of industrial development, and provide financial incentives for the development of green technologies.

Keywords: ICT, energy consumption, sub-Saharan Africa (SSA), transmission channels

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1. INTRODUCTION

As with the economic growth-ICT relationship, there is a growing debate on the effects of ICTs on energy consumption. Three key facts justify this renewed interest. Firstly, global growth in energy consumption is coming from developing economies, while the trend for many high- income countries is downward. This energy consumption differential between developing and developed countries is attributed by some authors to the technology differential used in the production process between these groups of countries. Certainly, ICTs allow developed countries to produce more with less energy. This idea is also shared by the Global Commission on Information and Infrastructure (GIIC, 2008), which emphasizes the role of ICTs in reducing energy consumption with no sacrifice in economic production. Indeed, companies offering such technologies are now essential drivers of economic growth, and their added value lies in the manipulation of ideas rather than in energy and materials. Secondly, these technologies are reformulating the national productivity equation, leading to significant increases in the efficiency with which materials and energy are used (Kelly, 1999). According to this view, ICT development would be the catalyst for the dematerialization of products, services and even consumption (Hilty, 2008). Thirdly, there is no unanimity on the contribution of ICTs to reducing energy consumption. Indeed, there are two conflicting arguments in the literature. The first argument postulates that the development of ICTs can lead to a significant reduction in energy consumption (Toffel and Horvath, 2004). The second argument states that the development of ICTs leads to an increase in energy consumption.

This dilemma is also visible in empirical studies of the relationship between ICTs and energy consumption. Several conclusions can be drawn from existing studies. Indeed, some authors (Hilty, 2008; Barratt, 2006) show that ICT development contributes to the reduction of overall energy consumption through dematerialization in large industrial sectors by substituting and optimizing the consumption of materials or energy. Other authors are sceptical about the idea that ICT development automatically leads to a substantial reduction in energy consumption, mainly because of concerns about the negative side effects of ICT development (Rejeski, 2002; Cho and al., 2007; Yi and Thomas, 2006; Fuchs, 2008; Chiabai and al., 2010; Hilty and Ruddy, 2010).

The estimation technique used, the periodicity, and the sample of countries in the study can partly explain this difference in position in the literature. In addition, existing work has ignored the role and importance of the channels through which ICT can affect energy consumption. This could however be useful in identifying key factors that policies could operate on to lead to better management of energy resources. To fill this gap, we analyze the effects of ICT adoption on energy consumption in Sub-Saharan Africa (SSA) with a focus on transmission channels. Specifically, our aim is to provide answers to the following questions: Is ICT adoption energy intensive? What are the transmission channels for the effects of ICTs on energy consumption? What then are the implications for sustainable development?

This study is important for at least three reasons. First, all countries in sub-Saharan Africa (SSA) are in search of their economic development, which points to an explosion in energy consumption. Second, most SSA countries are increasingly relying on ICTs to ensure the market competitiveness of their economies through technical innovation and global entrepreneurship. This probably justifies the growth in ICT adoption in SSA. Indeed, since the years 2000, developing countries, particularly in SSA, have experienced a rapid diffusion of ICTs. Indeed, the average proportion of individuals with internet access in SSA has increased from 0.84% of the population in 2000 to more than 17% in 2015 (ITU, 2020). The sector with the highest growth is mobile telephony. Far from being a luxury good, the mobile phone is now one of the most consumed goods on the continent. Between 2000 and 2015, the number of subscriptions to mobile phones increased from 11 million to more than 750 million (ITU, 2020). The rapid growth of the use of mobile phones can also explain that of the internet. African countries are the regions facing the biggest gap, where 23 per cent of the population have no access to a mobile-broadband network. In 2020, SSA achieved 21 per cent growth in 4G roll out, while growth was negligible in all the other regions. In Africa, only 28 per cent of households in urban areas had access to the Internet at home, but that was still 4.5 times as high as the percentage in rural areas, which stood at 6.3 per cent (ITU, 2020).

Third, SSA countries have responded to the global calls for action on climate change with commendable policy frameworks supported by other agreements and pacts as well as measures to reduce their energy consumption (Appiah and Jonhson, 2017). Thus, understanding the determinants of energy consumption provides an empirical basis for an effective fight against global warming.

After this introductory part, we structure the rest of the paper as follows. Section 2 presents the literature review. Section 3 describes the data and the econometric approach. Section 4 presents and discusses the main empirical results obtained. We give the conclusion and policy implications in section 5.

2. LITERATURE REVIEW

Opinion on the relationship between energy consumption and ICTs is far from unanimous among researchers. Two groups of authors are at odds with each other on this issue.

For the first group of authors, the development of ICTs is accompanied by a reduction in energy consumption. For them, there are several reasons to explain the beneficial effects of ICT development in reducing energy consumption. Toffel and Horvath (2004) point out how the use of wireless information technology can create potential energy savings by eliminating the need to read newspapers and reducing business travel. Hilty (2008) argues that ICTs enable the optimisation of material or energy consumption through the dematerialisation they offer in large industrial sectors. In addition, Barratt (2006) argues that education and training in environmental management and technology can be achieved through distance learning via the Internet. Yu et al (2020) reach the same result with Japan. They estimate the long-term relationship between ICT, energy consumption and economic growth in Japan. The results show that there is a stable long-term relationship not only for the production function but also for the energy demand function. The results also show that the long-run elasticity of energy consumption regarding ICT investment is 0.155. On this basis, they conclude that while ICT investment could, other things being equal, contribute to a moderate reduction in energy consumption, it would not lead to an increase in GDP. The authors in the second group are sceptical that ICT development automatically leads to a substantial reduction in energy consumption, mainly because of concerns about the negative side effects of ICT development (Rejeski, 2002; Cho and al., 2007; Yi and Thomas, 2006; Fuchs, 2008; Chiabai and al., 2010; Hilty and Ruddy, 2010). As Hilty (2008) argues, ICT development could affect energy consumption in the economy through two channels: direct and indirect impacts. The direct impact relates to the production, use, and disposal of ICT equipment. The magnitude of these direct impacts remains controversial. For example, Huber and Mills (1999) estimate that energy requirements for computers, office equipment and the Internet account for between 8 and 13 percent of total electricity consumption in the United States, while Forge (2007) highlights the unsustainable nature of ICT development, for example, in electricity consumption in data centres. Conversely, Roth and al. (2002) suggest that office and communication equipment in the United States consumes less than 3% of the electricity supplied nationally. As a result, and as Laitner (2002) points out, the complexity of the relationship between ICT development and economic activity leads to considerable uncertainty about the direct impact of ICT development on energy consumption.

Estimating the indirect impact of ICTs on energy consumption is even more complicated. First, it is possible that ICT development may stimulate energy demand through the globalisation of markets and the distribution of forms of production induced by the growth of telecommunications networks (referred to as the "induction effect" by Hilty (2008)). Second, it is also possible that ICT development may reduce energy demand through economic growth, (Ishida, 2014; Cheng and al., 2020; Vu and al., 2020) financial development, and industrialisation (Cheng and al., 2020). After all, the impact of ICTs on overall energy consumption depends on whether these negative effects (direct and indirect) outweigh the associated substitution and optimisation effects.

Compared to studies on the link between ICT growths, empirical study at the macro level of the relationship between ICT development and energy consumption is less common, apparently despite its importance for the environment. Takase and Murota (2004) and Yu and al. (2020) have conducted one of the few studies on this topic. They analyse the effects of ICT investment on energy consumption in the United States and Japan, and they conclude that while Japan can save energy by increasing ICT investment, increased ICT investment in the United States would increase energy consumption. Elsewhere, Cho and al. (2007) study the effects of ICT investment on electricity consumption in South Korean industries and conclude that ICT investment in some manufacturing sectors reduces electricity consumption, while ICT investment in the service sector and most manufacturing sectors increases electricity consumption. Similarly, Sadorsky (2012) examines the impact of ICTs on electricity consumption in 19 emerging countries and finds a positive relationship between ICTs (as measured by tele-density) and electricity consumption.

However, similar work has not yet been carried out in Sub-Saharan Africa, despite the growth in ICT penetration in this region. Moreover, previous work has not focused on transmission channels to highlight the direct and indirect effects of this impact.

3. MODEL VARIABLES AND DATA.

3.1 Empirical model

Because of the very close link between energy consumption and environmental degradation, we propose to adapt one model used to capture the impacts of anthropogenic activities on the environment. Moreover, the variables determining environmental degradation are similar to the determinants of energy consumption. Shahbaz and al (2017) and Yu and al (2020) also made this adaptation. In the present study, we thus use a STIRPAT (Stochastic Impact by Regression on

Population, Affluence and Technology) model proposed by Dietz and Rosa (1994). The basic STIRPAT model for our study is:

$$I_{it} = aP_{it}^{b} A_{it}^{c} T_{it}^{d} \varepsilon_{it} \quad (1)$$

Where energy consumption (I) is a function of population size (P), affluence (A) and technology (T); a is a constant term while b, c and d are parameters associated with P, A and T respectively and Ɛ is the error term. The indices i and t represent country and time, respectively.

To account for other variables, the basic STIRPAT model is extended as follows:

$$I_{it} = aP_{it}^{b} A_{it}^{c} T_{it}^{d} Z_{it}^{e} \varepsilon \qquad (2)$$

Where Z represents other exogenous variables that can influence energy consumption and e the parameter associated with Z. Z is a vector of the transmission channels. The linear model is obtained by introducing the log into equation 2. This results in the following equation:

$$\ln I_{it} = a + b\ln P_{it} + c\ln A_{it} + d\ln T_{it} + e\ln Z_{it} + \varepsilon_{it} \quad (3)$$

Where ln (...) is the Nerian logarithm.

To analyse the effects of ICTs on energy consumption in SSA, we have reworded equation 3 as follows:

$$\ln En_{it} = \alpha_0 + \alpha_1 \ln(ICT)_{it} + \alpha_2 \ln(GDP)_{it} + \alpha_3 \ln(Z)_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

Where En stands for energy consumption, and ICT stands for information and communication technology. Z is the matrix of control variables, and of the transmission channels, and includes financial development (fidev), urbanization (urb), foreign direct investment (FDI) and the industrial sector (Ind).

In order to verify whether some of our control variables have a mediating effect on energy consumption, we use causal mediation analysis (Baron and Kenny, 1986; Zhao et al., 2010). This approach is useful to understand whether and to what extent the effect of ICTs on energy demand is mediated by mediators. However, it seems important to note that the analysis of mediation assumes that the adoption of ICTs predates the transmission channels.

Relaxing this assumption may over- or underestimate the indirect effect. Thus, the results will serve as simple guidelines for policy makers. This analysis follows the method of Papyrakis and Gerlagh (2004), who study the transmission channels of the resource curse hypothesis. Yogo and Mallaye (2015) also use mediation analysis to study the transmission channels of health aid. To our knowledge, no previous attempts have focused on channels ranging from ICTs to energy consumption.

The analysis of mediation is established by estimating the following models:

$$\ln Z^{j}_{it} = \beta_0 + \beta_1 \ln ICT_{it} + \psi_{it} \qquad (5)$$

Where Z^j is the j^{th} channel. β_1 is the effect of ICT on the transmission channel, β_0 is the constant and Ψ_{it} is the error term. In the first step of the algorithm, equation (5) is estimated to determine the impact of ICT on each transmission channel. If β_1 is statistically significant, i.e., if ICT penetration explains part of the variation in the transmission channel, then we calculate the indirect effects of ICT on energy consumption. By replacing equation (5) in equation (4), we obtain:

$$\ln En_{it} = \alpha_0 + \alpha_3\beta_0 + (\alpha_1 + \alpha_3\beta_1)\ln ICT_{it} + \alpha_2 \ln(GDP)_{it} + \alpha_3 \psi_{it}$$
$$+ \mu_i + \eta + \varepsilon_{it} \qquad (6)$$

α_1 is the direct effect of ICTs on energy consumption; $\alpha_3\beta_1$ is the indirect effect of ICTs on energy consumption; and $(\alpha_1 + \alpha_3\beta_1)$ is the total effect of ICTs on energy consumption. We estimate these effects using the structural equation modelling approach, which allows these effects to be tested in a single analysis instead of testing separate regressions. According to Zhao et al. (2010), mediation is empirically valid only if the indirect effect (i.e. $\alpha_3\beta_1$) is statistically significant.

3.2 Specification of variables

i) Dependent variable.

The dependent variable for our empirical model is energy consumption per GDP purchasing power parity. Like Shahbaz and al. (2017) we use this variable as a proxy for national energy demand. It refers to primary energy use before transformation into other end-use fuels, which is equal to domestic production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

ii) Variable of interest

For this study, we selected information and communication technologies (ICT) as a variable of interest. We use two proxy variables to capture it, i.e., the fixed and mobile phone subscription rate. The number of fixed telephone subscriptions (Fixed) refers to the sum of the number of active analogue fixed telephone lines, Voice over IP (VoIP) subscriptions, and fixed wireless local loop. Cellular mobile telephone subscriptions (Mobile) are subscriptions to a public mobile telephone service that provides access to the PSTN using cellular technology. This indicator includes the number of postpaid subscriptions and the number of active prepaid accounts (i.e., used within the last three months).

iii) Control variables

Based on the two models IPAT (Holdren and Ehrlich, 1974) and STIRPAT (Dietz and Rosa, 1994, 1997), we introduced five control variables into equation 4. The first is income per capita. This variable is used to capture national development. Income per capita could have a significant positive impact on energy consumption through scale effects (Sadorsky, 2013). Second, we control for the role of foreign direct investment (FDI) on internal energy consumption. The choice of this variable is justified by the fact that foreign investment generally focuses on energy and carbon-intensive industries (Al-Mulali and Tang, 2013). We use the share of FDI in GDP as an indicator of FDI. Third, we control for the impact of financial development through domestic credit to the private sector as a percentage of GDP (Yu and al., 2020). Fourth, energy consumption increases with the development of the industrial sector (Elliott et al., 2017). We use the share of industry's value added in GDP to measure it. Finally, we use urbanisation, which includes two dimensions, namely urban land expansion and urban demography. However, because of the lack of data on urban land expansion, only urban demographics will be used in this study. This variable can be approximated by the total population in urban areas as pointed out by Ye and Wu (2014).

3.3 Data

Our sample is a panel of 24 countries in Sub-Saharan Africa over the period 1995-2018. Angola, Benin, Botswana, Cameroon, Democratic Republic of the Congo, Republic of the Congo, Cote d'Ivoire, Ethiopia, Gabon, Ghana, Kenya, Libya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Togo, Zambia, and Zimbabwe are the countries in our sample. The others were excluded because of lack of data. Data are from the World Bank database (WDI, 2020). The descriptive statistics and the correlation matrix between the variables are presented in Tables 1 and 2, respectively. Looking at all the correlation coefficients, we can see that they all have values below 0.7, so we can say that there is no multicollinearity problem. The difference in the number of observations is because of missing data.

Table 1: Descriptive statistics

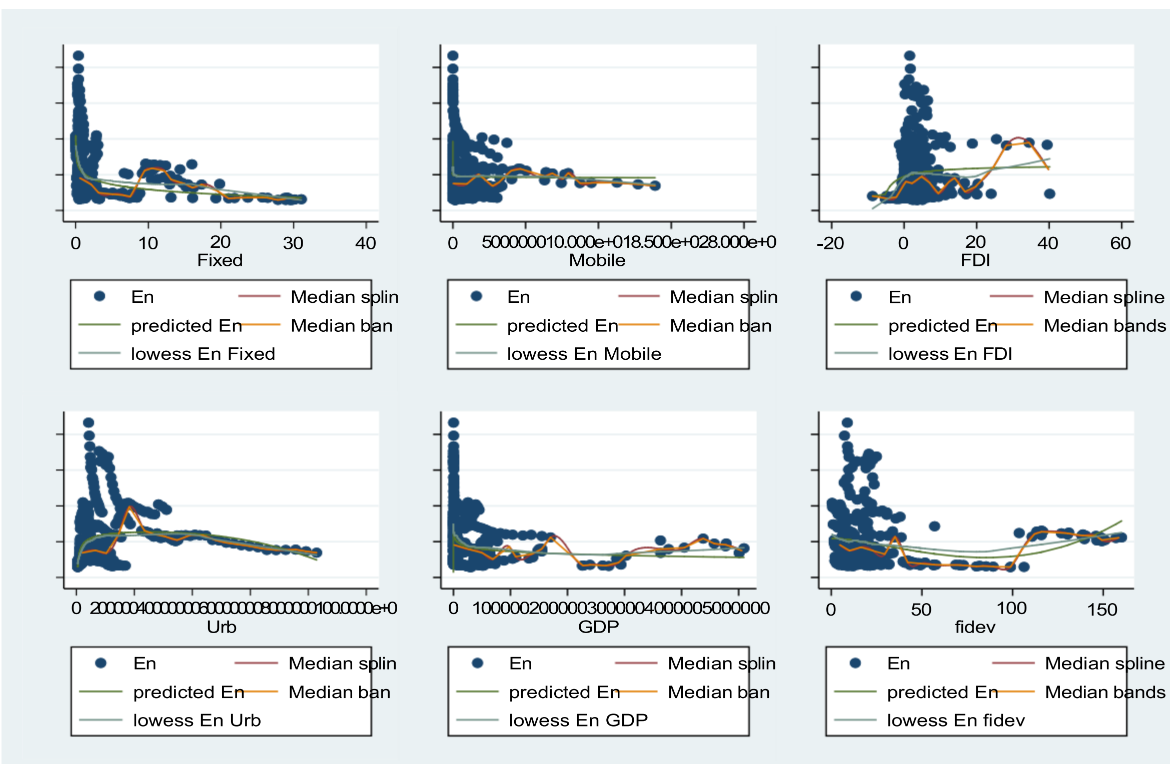
Variable	Obs	Mean	Std. Dev.	Min	Max
En	469	202.6303	140.2003	57.76555	865.1604
Fixed	572	3.473111	6.141875	0	34.27282
Mobile	572	1.02e+07	2.11e+07	0	1.73e+08
GDP	576	388069.3	785155.7	1.076736	5094031
Ind	553	28.39607	15.01647	2.073173	87.79689
Urb	576	1.00e+07	1.36e+07	485315	9.86e+07
FDI	576	3.4683	5.732769	-8.70307	50.63641
Fidev	558	23.84682	29.38838	.4913875	160.1248

Both Figure 1 and Table 2 suggest an inverse relationship between energy consumption and the ICT indicators used in this study.

Table 2: Correlation matrix between variables

	En	Mobile	Fixed	GDP	Ind	Urb	FDI	Fidev
En	1.0000							
Mobile	-0.2838	1.0000						
Fixed	-0.0515	-0.0350	1.0000					
GDP	-0.1572	-0.0943	-0.0239	1.0000				
Ind	-0.3450	0.0727	-0.0657	0.4133	1.0000			
Urb	0.1071	-0.1334	0.7508	-0.1293	-0.0577	1.0000		
FDI	0.0741	-0.0893	-0.0264	-0.0181	0.1709	-0.0709	1.0000	
fidev	-0.0793	0.6230	0.2849	-0.1512	-0.1219	0.1732	-0.0776	1.0000

Figure 1: Evolution of energy consumption as a function of the independent variables selected



4 RESULTS

4.1. Preliminary analysis

i. Cross-sectional dependency test results

A large part of the literature on panel data has shown that models using panel data are likely to be subject to cross sectional dependence in error terms. This cross-sectional dependence may be due to the presence of common shocks and common unobserved factors and to a spatial dependence (De Hoyos and Sarafidis, 2006). Failure to take account of cross-sectional dependence in a panel study has many consequences.

Table 3: Result of the cross-sectional dependence test

Variables	Cross-sections included	Total panel observations	Test	Stattistics	p-value
LnEn	24	469	Pesaran's test	7.194782***	0.0000
LnFixed	24	566	Pesaran's test	13.59640***	0.0000
lnMobile	24	552	Pesaran's test	76.43347***	0.0000
Lnfidev	24	558	Pesaran's test	39.61069***	0.0000
LnGDP	24	576	Pesaran's test	72.40117***	0.0000
LnInd	24	553	Pesaran's test	44.28456***	0.0000

Table 3 presents the results of the cross-sectional dependence test. The coefficient shows that the null hypothesis of the non-existence of cross-sectional dependence is rejected at 1% confirming the existence of a spatial effect between the countries in our panel. The results of the dependency test further imply that second generation stationarity tests are the most appropriate.

ii. Results of unit root tests

The results in Table 3 showed us the existence of cross-sectional dependence. Thus, the first-generation unit root tests (Levin, Lin and Chin, Im, Pesaran and Shin, the panel unit root tests of Augmented Dickey Fuller and Phillips-Perron) are no longer appropriate. We therefore use the second-generation panel unit root tests developed by Pesaran (2007). These are the Pesaran cross-sectionally augmented Dickey-Fuller (CADF) and the Pesaran cross-sectionally augmented Im, Pesaran and Shin (CIPS) tests. Both tests are compatible with the existence of cross-sectional dependence. The results are reported in Table 4. From this table, it can be seen that all variables are integrated of order 1 with the Pesaran CADF test. It then becomes necessary to carry out a cointegration test to analyse the existence of a long-term relationship between the variables.

Table 4: Results of the unit root tests

Variables	Level Intercept and trend	1st difference Intercept and trend	Order of integration
Pesaran CADF test			
lnEn	0.62	-5.047***	I(1)
lnFixed	1.379	-4.843***	I(1)
lnMobile	-8.886***		I(0)
lnGDP	0.666	-5.006 ***	I(1)
lnfidev	-1.140	-8.024***	I(1)
lnInd	2.137	-4.600 ***	I(1)

*Notes: the choice of the number of the lags based on AIC criteria. *** indicate the significance level at 1%.*

iii. Westerlund Co-integration Test Results

The cointegration test performed is Westerlund's cointegration test, which takes into account the existence of cross-sectional dependence, unlike Pedroni and Kao's cointegration tests. The coefficient obtained leads us to reject the null hypothesis of non-cointegration between the variables. Thus, the estimation of our model will be carried out by the cointegration relation estimation methods.

Table 5: Results of the Westerlund cointegration test

Test	Intercept and trend	p-value
Variance ratio	-2.2960**	0.0108

Notes: ** indicate the significance level at 5%.

The existence of a cointegrating relationship between the variables makes it necessary to use an appropriate estimation technique to calculate the model parameters. This is one of the following methods: Fully Modified Ordinary Least Squares (FMOLS), Dynamic Panel Ordinary Least Squares (PDOLS), Mean Group (MG), Pool Mean Group (PMG), CCEP and CCEMG. In our study, we first use FMOLS and PDOLS. We then check the robustness of the estimators using the GMMs (Gaussian Mixture Models).

4.2 Baseline Estimates

The results of the estimates by the FMOLS and DOLS cointegration methods are reported in Table 6. These two analytical techniques developed by Pedroni (2001, 2004) are shown to be more powerful than the OLS method because they correct endogeneity and serial correlation problems. Table 6 shows the long-term estimation results obtained by FMOLS and DOLS. We observe that the estimated coefficients are statistically significant.

The results in Table 6 show that the two ICT indicators used in this study, namely fixed telephone and mobile cellular subscription rates, are inhibitors of energy consumption in SSA. This is the meaning of the negative and significant sign of their parameters. This shows that ICT development is contributing to the reduction of energy consumption in SSA. Specifically, a unit increase in the number of fixed and mobile cellular subscriptions leads to a decrease in energy consumption of 5.735% and 2.52%. This result is in line with those of Rejeski, 2002; Cho et al. 2007; Yi and Thomas, 2006; Fuchs, 2008; Chiabai and al. 2010; Hilty and Ruddy, 2010; Ishida, 2014; Lange and al. (2020).

As expected, energy consumption is positively and significantly associated with income per capita and industry. On the other hand, financial development contributes to the reduction of energy consumption.

Like Yu and al. (2020), we also find a positive and significant impact of income per capita. Thus, as the level of economic development improves, the impact on energy demand of population transfer from rural to urban areas increases. The estimated energy elasticity ranges from 0.065709 to 0.146857. Industrial developments are energy intensive. This is the meaning of the positive and significant sign of the parameters associated with this variable. Therefore, the industrial fabric of SSA countries is still heavily made up of primary and secondary sector enterprises. This result is like that of Elliott and al. (2017).

Table 6: Estimation of ICT effects on energy consumption

	Dependent variable lnEn			
Variables	Method: Panel Fully Modified Least Squares (FMOLS)		Method: Panel Dynamic Least Squares (DOLS)	
lnFixed	-0.057350*** (0.0060)		-0.009366 (0.7178)	
lnfidev	-0.091065*** (0.0029)	-0.086352*** (0.0001)	-0.073316*** (0.0007)	-0.149166*** (0.0000)
lnGDP	0.065709*** (0.0000)	0.076829*** (0.0000)	0.094088*** (0.0000)	0.146857*** (0.0000)
lnInd	0.132336*** (0.0000)	0.133193*** (0.0000)	0.131770*** (0.0026)	-0.003770 (0.9096)
lnMobile		-0.025200* (0.0788)		-0.012724* (0.0713)
Cross-sections included	24	24	20	21
Total panel observations	415	399	356	357
Adjusted R-squared	0.932310	0.921752	0.952861	0.953535

Notes: p-value in parentheses, *, *** indicate the significance level at 10% and 1%.

Financial development, on the other hand, helps to reduce energy consumption. This result can be explained by the fact that private sector investors are increasingly using financing to modernise their investment. Moreover, the use of ICTs by these investors is a definite reality, which undoubtedly justifies the growth of e-commerce in SSA.

4.3 Robustness Check

To verify the sensitivity of our results reported in Table 6, we test the robustness. We do so by introducing other control variables (urbanisation and foreign direct investment) and by using another estimation method, namely GMMs. The results of the diagnostic tests show that all models are well specified. The Hansen test does not reject the validity of the instruments, and the absence of second-order serial correlation is also not rejected.

The results reported in Table 7 are qualitatively similar to those reported in Table 6. More specifically, all coefficients associated with ICT measures are negative and statistically significant at conventional rates with energy consumption. This suggests that ICTs are beneficial in controlling energy consumption in SSA. Thus, the empirical results are robust to the inclusion of more control variables and by using other estimation methods.

Urban expansion can lead to growth in energy consumption. The estimation results (columns 4 and 9) do show that urbanisation leads to an increase in energy consumption. This shows thatthe more densely a city is populated, the greater the demand for energy. This result is like those of Farhani and Ozturk, 2015; Azam and al., 2015; Lin and Du, 2015; Yan, 2015; Rafiq and al., 2016; Wang and al., 2016; Shahbaz and al., 2017; Yu and al., 2020. Similarly, FDIs are energy intensive. This justifies the positive and significant sign of its parameter. This result confirms that foreign investment generally focuses on energy and carbon- intensive industries (Al-Mulali and Tang, 2013). This invalidates the hypothesis of technology transfer to SSA countries via FDI.

Table 7: Estimation of ICT effects on energy consumption: GMM estimation

	lnEn								
VARIABLES	1	2	3	4	5	6	7	8	9
L.lnEn	0.897***	1.054***	1.009***	0.959***	0.902***	0.926***	1.004***	0.966***	0.942***
	(0.0359)	(0.0159)	(0.0135)	(0.0266)	(0.0138)	(0.00906)	(0.00635)	(0.00502)	(0.0181)
LnFixed	-0.0251***	-0.00645**	-0.00626**	-0.0363**					
	(0.00704)	(0.00311)	(0.00255)	(0.0170)					
LnGDP		0.0118***	0.00537***	0.00142		0.00479***	0.00717***	0.00543***	0.0115***
		(0.00215)	(0.00189)	(0.00782)		(0.00142)	(0.00105)	(0.00150)	(0.00367)
LnInd			0.0553***	-0.0358			0.0433***	0.0159**	0.00378
			(0.00483)	(0.0241)			(0.00470)	(0.00632)	(0.0188)
LnUrb				0.0384***				0.00720	0.00957*
				(0.0112)				(0.00961)	(0.00525)
Lnfidev				-0.00361				0.00361	
				(0.0124)				(0.00314)	
LnFDI				0.0174**					0.0109*
				(0.00788)					(0.00573)

lnMobile					-0.00245***	-0.00302***	-0.00377***	-0.00414***	-0.00475**
					(0.000802)	(0.000354)	(0.000363)	(0.00127)	(0.00200)
Constant	0.522**	-0.412***	0.0560	0.893**	0.519***	0.355***	-0.198***	-0.0159	0.0775
	(0.187)	(0.104)	(0.0834)	(0.373)	(0.0754)	(0.0571)	(0.0411)	(0.139)	(0.110)
Observations	443	443	431	392	436	436	424	411	398
Number of id	24	24	24	24	24	24	24	24	24
AR (1)	0.0633	0.0744	0.00103	0.00177	0.0745	0.0746	0.000940	0.00118	0.00125
AR (2)	0.664	0.638	0.294	0.247	0.649	0.645	0.297	0.338	0.330
Instruments	12	20	22	23	14	20	18	20	20
Hansen (OIR)	0.719	0.433	0.703	1.000	0.529	0.432	0.710	0.533	0.537
Fisher	893.3	128221	9128	7085	3109	17270	7259	18576	2707

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

4.4 Testing the importance and significance of the transmission channels

The above estimates are interesting as they provide useful information on how ICT development affects energy consumption in SSA. However, the estimates do not show the importance and significance of the channels from ICT to energy demand. In order to test the channels highlighted in the literature review, we use a causal mediation analysis. We show the effect of ICTs on each transmission channel in Table 8.

Table 8: Results of the structural model

Variables	lnfidev	LnGDP	LnInd	Lnfidev	lnGDP	lnInd
lnFixed	0.503***	0.0379	0.0472***			
	(0.0271)	(0.0608)	(0.0158)			
lnMobile				0.102***	0.221***	0.0048408
				(0.0154)	(0.04805)	(0.00896)
Constant	2.521***	10.89***	3.240***	1.249***	8.003***	3.1937***
	(0.0309)	(0.127)	(0.0261)	(0.213)	(0.69791)	(0.12574)
Observations	441	441	441	426	426	426

Note: Bootstrap standard errors in parentheses; *** is statistical significance at 1% level.

The results show that fixed and mobile penetration has a positive and significant effect on all three channels. Other things being equal, an increase in the adoption of ICTs significantly stimulates financial development, income per capita, and industrial development. In fact, a 1% increase in the number of fixed-line telephone users will significantly increase credit to the private sector, income per capita, and industrial value added by 0.503%, 0.0379% and 0.0472%, respectively. Similarly, a 1% increase in mobile phone penetration will significantly increase credit to the private sector, per capita income, and industrial value added by 0.102%, 0.221%, and 0.00484% respectively. The positive effect of ICT (fixed and mobile telephony) on financial development is consistent with the study by Edo and al. (2019) who concluded that increased ICT adoption significantly improves financial development in Kenya and Nigeria. On the other hand, Choi (2010) and Yushkova (2014) conclude that ICT penetration intensifies trade flows in several countries, hence its positive effects on the industrial sector and income per capita. This result is also significant with Cheng and al. (2020) and Vu and al. (2020).

Since ICT penetration partly explains the variation in transmission channels, we calculate the direct and indirect effects of ICT on the energy consumption. The estimated coefficients in equation (7) are presented in Table 6 and the ICT coefficient includes both the direct andindirect effect. Besides the total effect of ICT, we calculated its indirect effects using the product-of-the-Sobel coefficients approach. Standard errors are corrected using the bootstrap procedure. We present the results in Table 9.

Table 9: Indirect effects of ICT on carbon emissions

Transmission channel	ICT= Fixed phone			ICT= Mobile phone		
	Lnfidev	lnGDP	lnInd	lnfidev	lnGDP	lnInd
Indirect effect ($\beta_1\varphi$)	0.0874***	-0.0017***	-0.013***	-0.0181***	-0.0082***	-.002164
	(0.0239)	(0.002762)	(0.00490)	(0.0033484)	(0.0028036)	(0.0041781)
% of the mediated effect	44 %	1 %	4 %	200 %	43 %	9 %

Note: Bootstrap standard errors in parentheses; *** is statistical significance at 1% level

The first observation in Table 9 is that all three channels mediated the effects of ICTs on energy demand. Over the study period, the fixed telephone indirectly increased energy consumption through financial development, while the indirect effect of the mobile telephone on financial development is negative and statistically significant. Similarly, the selected ICT indicators indirectly reduced energy consumption through income per capita and the industrial sector. We also try to calculate the contribution of each channel to the total effect of ICT on energy demand using the formula $(\frac{\beta_1\gamma}{\varphi+\beta_1\gamma})$. We find that about 44% of the total negative effect of fixed telephones on energy consumption is due to financial development. Conversely, the indirect effect of income per capita and industry is positive and represents 1% and 4% of the total effect, respectively. In addition, we find that 200% of the indirect positive effect of mobile phone subscription on energy demand comes from financial development, 43% from GDP per capita, and 9% from industry.

The fact that they offer fewer possibilities in managing transactions than mobile cellular and the Internet could explain the indirect negative effect of fixed-line telephones on energy consumption. Also, they are more energy consuming. In addition, the penetration of cell phones contributes to improving the financial system by reducing information asymmetry and transaction costs, thus improving the flow of information on investment opportunities, leading to greater financial integration. This will help to limit the movement of individuals and thus reduce energy consumption. Finally, ICTs could reduce energy consumption through their effect on income per capita and the industrial sector. It is difficult to directly compare our results with existing research because previous studies have not highlighted the role and importance of transmission channels.

5 CONCLUSION AND POLICY IMPLICATIONS

Sub-Saharan African countries have experienced rapid growth in ICTs, in terms of the number of fixed and mobile phone users in recent years. However, this increase in ICT penetration poses challenges in terms of job creation/destruction, growth, and energy use. Another important issue is the contribution of ICTs to achieving energy-efficient development.

This study estimates the impact of ICT adoption on energy consumption in SSA. Specifically, we study the direct and indirect aspects of the effects of fixed and mobile telephone penetration on energy demand in a sample of 24 SSA countries over the period 1995-2018. The results of the static panel show that increasing ICT penetration, both in terms of fixed and mobile phone subscribers, has a negative significant effect on energy demand.

As a complement to the previous analysis, we use causal mediation analysis to highlight the role and importance of channels ranging from ICTs to energy consumption. Overall, the results show that financial development, income per capita, and industrial development are the channels through which ICT penetration affects energy consumption in SSA. More specifically, ICTs have an indirect impact on energy consumption in SSA. ICTs have a negative impact on energy consumption through their impact on income per capita and industrial development, and a mitigating effect through financial development.

Overall, this study showed that there is an energy benefit (reduced energy demand) associated with increasing ICT penetration in SSA. From a policy perspective, we could adopt the following measures to achieve energy-efficient development. Indeed, technologies to reduce energy consumption are eagerly awaited. Thus, because of the scarcity and environmental cost associated with energy consumption, policies aimed at improving energy efficiency in other sectors through the use of ICTs could contribute to this. Firstly, governments should create facilities for access to credit to the private sector, as this gives them the necessary means to gain ICTs and modernise their investments. This could increase the indirect effect of ICTs on reducing energy demand. Secondly, governments should promote industrialisation while strengthening legislation on energy-intensive industrial equipment. This includes developing green solutions and reducing constraints on the cost of financing environmentally friendly technologies and projects. These incentives should take the form of green subsidies for the development and/or adoption of technologies. In addition, we could raise the standardregarding ICT equipment transfer. Thirdly, policymakers could reduce income inequality through a better distribution of national wealth. This would enable people to have the necessary income to gain and use ICTs, which could reduce their energy consumption. Finally, campaigns to increase public awareness of the energy benefits associated with the growing penetration of ICTs in sub-Saharan Africa could be encouraged.

One of the limitations of this study is that the conclusions and policy recommendations apply at the regional level and do not consider the specificities of each country. In fact, there are some differences in the pattern of ICT growth in SSA countries. Therefore, it is important to extend this study to the national level to get additional information on the impact of these policies. Future studies could also extend this work by identifying additional transmission channels.

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