The Impact of Frontier Technology Adoption on Gender Inequality: Evidence from Africa

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Abstract

The surge in frontier technology adoption (FTR) in education, health, and labour markets cannot be overemphasised. Notwithstanding, rigorous empirical findings concerning their socioeconomic impacts in the Global South are hard to find. Accordingly, this study explores the impact of FTR on gender inequality in low-income, and middle- and high-income African countries. Second, this study investigates the moderating role of electricity access in the FTR-gender inequality nexus. Third, the study examines the threshold effect of electricity access in the FTR-gender inequality relationship. Compelling evidence, based on country-level data for 29 African countries from 2010-2020, reveals that FTR promotes gender equality in both low-income, and middle- and high-income African countries. However, this impact is striking in the middle- and high-income African countries. Further, the contingency analysis establishes that electricity access amplifies the effect of FTR on gender equality but only in middle- and high-income African countries. Additionally, the threshold analysis demonstrates that broadening electricity access coverage conditions FTR to further enhance gender equality. However, this positive impact eludes low-income African countries. We conclude that investments in broadening electricity access and the capacity of African countries in adopting, mastering, and adapting frontier technologies are critical for inclusive human development.

Keywords: : Africa; Agenda 2063, Frontier technology adoption; Gender Inequality; Inclusive human development

JEL Codes: J16, O3, O55, Q01, O43

1. Introduction

Gender inequality remains a major socioeconomic concern in Africa. Indeed, gender gaps in health, education, and income are highest in Africa when compared to developing regions such as South America, Asia, and Latin America and the Caribbean (United Nations Development Programme [UNDP], 2022). Accordingly, Africa's Agenda 2063 prioritises human resource development, fairer access to decent socioeconomic opportunities, and improved wellbeing (African Union Commission, 2015). Success in this direction is critical per anecdotal evidence that gender inequality inhibits social cohesion and sustainable development (United Nations Women, 2018; UNDP, 2022).

An emerging pathway with the potential to significantly contribute to gender equality in Africa but has received little attention in the shared growth scholarship is frontier technology adoption (hereafter: FTR). Frontier technologies refer to cutting-edge technological innovations, for example, the Internet of Things (IoT), robots, drones, machine learning, 3D printers, 5G technologies, and artificial intelligence (AI) that are transforming sectors such as finance, health, agriculture, education, and security (United Nations Conference on Trade and Development [UNCTAD], 2023).

Frontier technology adoption (FTR) can mitigate gender inequality in several ways. Foremost, FTR can reduce income inequality by fostering entrepreneurship, production efficiency, and decent employment opportunities (UNCTAD, 2023, 2021). For instance, generative AI (e.g., Copilot and ChatGPT), 3D printers and robots can be leveraged to start and/or expand businesses, mitigate unemployment, and empower both men and women (Bessen, 2020; Acemoglu & Restrepo, 2019). Further, FTR can reduce inequalities in healthcare by providing timely access to medical supplies while facilitating telehealth, accurate diagnosis and surgery. To exemplify, drones can be deployed to deliver vaccines, blood, first aid kits, and stethoscopes to remote and inaccessible areas (Umlauf & Burchardt, 2022). Similarly, FTR can bridge the gender gap in human capital and empowerment by facilitating equal access to quality education, skill training, information, and productive tools. Illustratively, 5G technologies, machine learning tools and the IoT can enable the youth to acquire/enhance their technical competencies (e.g., in coding, prediction, and forecasting) to stay competitive in a rapidly changing job market and better manage socioeconomic shocks (World Economic Forum [WEF], 2020, p.6).

One factor that enables countries to benefit significantly from frontier technologies is access to cheaper, reliable, and modern electricity. Stable and cheaper electricity can enable the financially constrained, who are primarily women, to deploy and profit from frontier technologies. Also, clean and stable electricity enables healthcare providers to strengthen information flow, store vaccines, power oxygen plants, and effectively handle emergencies (World Health Organization [WHO], 2018). Additionally, reliable electricity enables new or established entrepreneurs to collaborate with other firms, withstand competition, and access e-commerce platforms to improve profitability. Nonetheless, in Africa, where at least half a million people are energy-poor (IEA, 2022), the pace of frontier technology adoption can be slow, potentially widening the technological and gender gap. This is particularly possible in low-income African countries where the infrastructure for embracing frontier technologies is least developed (UNCTAD, 2023).

The above intuitive linkages between FTR, electracy access, and gender inequality call for rigorous empirical scrutiny that establishes or disproves such relationships to guide policymaking. However, a careful review of the social progress literature shows that evidence-based recommendations in this direction in the context of Africa are hard to find. The few we identified only assess the impact of various innovation dynamics such as ICTs, financial innovation, patenting, digital innovation, and research and development on economic growth, employment, income inequality, inclusive growth, and human development in Africa but fail to explore the heterogenous impact of frontier technology adoption on gender inequality (see e.g., Ibrahima et al., 2023; Asongu et al., 2021; Ngoa & Song, 2021; Avenyo et al., 2019; Anakpo & Oyenubi, 2022; Bara et al., 2016; Gyedu et al., 2021; Roger et al., 2022; Azuh et al., 2020; Ejemeyovwi et al., 2019).

Accordingly, this study set out to address objectives. First, we examine how FTR impacts gender inequality in Africa. Second, we investigate whether electricity access forms a relevant synergy with FTR to reduce gender inequality in Africa. Third, we explore whether the (un)conditional effects of FTR on gender inequality (if any) differ across low-income and middle- and high-income African countries.

The attendant findings are based on macro data for 29 African countries from 2010-2020. We find that FTR mitigates gender inequality in both low-income, and middle- and high-income African countries, however, the impact is notable in the latter. Second, the interactive analysis reveals that access to electricity enhances the impact of FTR on gender equality, but only in middle- and high-income African countries. Third, the threshold analysis suggests that expanding electricity access coverage conditions FTR to significantly enhance gender equality. However, this positive effect eludes low-income African countries.

This novel study makes three major contributions to the extant scholarship. First, we show the extent to which FTR reduces inequalities in education, health, and income in low-income and middle- and high-income African countries. This finding is particularly timely as it comes at a time when African governments are strategizing to promote inclusive human development. Also, this study brings to the fore the crucial synergistic relationship between electricity access and FTR in addressing gender inequality. More importantly, we show how FTR becomes ineffective in mitigating gender inequality in countries where energy poverty is high. Third, we pay attention to Africa, where frontier technology readiness is low and gender inequality remains a major roadblock to socioeconomic sustainability. In particular, we deepen the understanding concerning the nuanced relationship between FTR, electricity access, and gender inequality in low-income, and middle- and high-income African countries.

The remainder of the study is structured as follows: Section 2 puts the study into theoretical and empirical perspective; Section 3 describes the data and methods, while Section 4 reports the findings. Section 5 concludes with some policy remarks.

2. Literature review

2.1. Theoretical and empirical linkages between technological innovation and gender inequality

The study draws on the neo-Schumpeterian theory to explain the link between innovation and gender inequality (inclusive human development). Neo-Schumpeterian economics builds upon Schumpeter's (1911) idea that entrepreneurial activity is at the heart of long-term economic growth and development. The evolutionary Neo-Schumpeterian theory treats innovation systems, knowledge creation, complex interactions, and systemic change as inextricably linked to technological change and growth (Nelson & Winter, 1982; Windrum & García-Goñi, 2008). The theory considers these complex dynamics and learning processes as a significant driver of incremental and radical innovation (in product, market, process, and input) and sustained economic development (Lundvall et al. 1988). The theory is inherently linked to gender inequality/inclusive human development from three perspectives.

First, technological innovation can provide a fair opportunity for men and women to participate in labour markets. In particular, the emergence of cutting-edge innovations such as IBM Watson Analytics can enable economic agents to understand/predict market trends and create new businesses. Additionally, technological advancements in e-commerce (e.g., Shopify, eBay, and Amazon) and digital finance (e.g., mobile money innovations like the Kenyan M-Pesa) can dismantle barriers to entry for new entrepreneurs. In low-income countries, this can empower women by addressing vulnerable employment and unemployment.

Second, advancements in technological innovation can also minimise gender disparities in quality healthcare by accelerating remote consultation, diagnosis, timely information flow, and medical supplies. As an example, drones help reduce maternal mortality by facilitating access to medical supplies in emergencies. Similarly, 3D printers empower gynaecologists to accurately assess female reproductive health conditions and provide invaluable guidance for women to make informed reproductive choices.

Third, technological innovations promote fairness in human capital development across the gender divide. To illustrate, frontier technologies such as robots, DreamBox, 5G networks, the IoT, and Knewton equip educational institutions to tailor curricula to suit both males and females through structured/personalised online courses and/or training. This way, technological innovation can reduce gender gaps in human capital by supporting more women in navigating sociocultural roles to pursue education and careers in science, technology, engineering, and mathematics (STEM) fields traditionally dominated by men.

However, consistent with skill-biased technical change, technological innovation can trigger unemployment or deepen income inequality (Acemoglu, 2021, 2002; Acemoglu & Restrepo, 2019; Acemoglu & Autor, 2011; Aghion et al., 2002). In Africa, where women have limited social mobility, technologically-induced floundering of businesses and job losses can swell the gender inequality gap. Moreover, spatial and infrastructure gaps in marginalised societies can exacerbate gender inequality by empowering men (who mostly have command over resources) to access frontier technologies more than women.

As clearly articulated in the introductory section, studies have not explored the impact of frontier technology adoption on gender inequality. The few we find only assess the effects of some aspects of innovation on human development. For instance, in a panel of 15 West African countries spanning 2004-2014, Azuh et al. (2020) apply the generalized least square estimator to a dataset spanning 2004-2014 for 15 West African countries. The research shows that innovation proxied by research and development fosters human development. In a related study, Ejemeyovwi et al. (2019) investigate the effect of innovation on human development in 15 Economic Community of West African States. Results, based on data from 2004-2014, as well as the fixed and random effect estimators, reveal that innovation proxied by scientific and knowledge journals positively enhances human development.

2.3. Theoretical and empirical linkages between energy access and gender inequality

The relationship between energy access and gender inequality is deeply rooted in energy justice theory, as chiefly advocated by Sovacool and Dworkin (2015), Heffron and McCauley (2017), and Baker et al. (2019). Energy justice refers equity in the allocation of burdens and benefits among all persons regardless of social, cultural, political, educational, and racial background in energy systems. The framework stresses that fairness in energy systems manifests in three domains, namely distributional, procedural, and restorative justice. Distributional energy justice means the economic and social costs and benefits derived from energy systems should be fairly distributed among all genders. Procedural justice also denotes the voice all persons from the gender divide have in energy-related decisions. Third, recognition justice emphasises the importance of understanding the various types of vulnerabilities and specific needs related to energy services among different social groups, particularly marginalised societies.

The above suggests that energy access inequity can heighten gender inequality. For instance, Baker et al. (2019) stress that inequalities in electricity access affect women and men disproportionately in educational attainment and labour market participation, consequently widening the gender gap. Besides, electricity access inequality across the rural-urban divide causes women to rely on biomass, which is harmful to their reproductive health and general well-being, for cooking and heating (WHO, 2022). Also, widespread energy poverty forces women to spend more time managing household energy needs, restricting their ability to pursue education, income-generating activities, and leisure. This can further perpetuate gender inequality (Sovacool et al., 2016).

On the empirical front, Nguyen and Su (2021) assess the effect of energy poverty on gender inequality in 51 developing countries with macro data from 2002-2017. The study relies on the system GMM model to show that electricity access increases employment opportunities for women in industry and service but not in agriculture. The authors further highlight that these findings lead to improvement in the number of female wage and salaried workers compared to their male counterparts. The authors further confirm that reducing energy poverty mitigates gender inequality in health.

Ouedraogo (2013) also examines the nexus between electricity consumption and human development, employing 15 developing countries and data from 1988-2008. Compelling evidence from the study shows that electricity consumption increases human development in the selected countries. A similar contribution is that of Nguyen et al. (2023), who analysed the effect of renewable energy on human development in 77 high- and middle-income countries from 2000-2019. Results from the panel-corrected standard error estimator show that renewable energy adoption is positively related to human development. In addition, the authors find that renewable energy has a negative effect on high-income countries while that of middle-income countries is insignificant.

Similarly, Niu et al. (2013) explore the relationship between electricity consumption and human development in 50 countries for the period 1990-2009. The authors provide strong evidence that electricity consumption promotes human development. The study further establishes that the higher the income of a country, the larger the impact of electricity consumption on human development. A comprehensive study by Adom et al. (2021) also assesses the role of direct and conditional effects of energy poverty on development outcomes such as income, poverty, education, employment, life expectancy, and risk of drinking unsafe water. The study utilises time series data from 1975-2017 for Ghana and a non-linear ARDL estimator for the analysis. The study reveals that energy poverty decreases life expectancy, employment, income, and educational attainment while increasing the risk of drinking unsafe water. The contingency analysis shows that renewable energy consumption partially compensates for the adverse impacts of energy poverty on life expectancy, employment, income, and educational attainment.

3. Methods and Data

3.1 Data

The study analyses country-level data for 29 selected African countries from 2010-2020. Table A.1 lists these countries. The dataset is retrieved from the World Bank's World Development Indicators (World Bank, 2024), the UNCTAD's Data Centre (UNCTAD, 2023b), the African Infrastructure Knowledge Program Statistics (African Development Bank [AfDB], 2022), and the United Nations Development Programme Data Centre (UNDP, 2024).

3.1.1 Outcome variables

The primary dependent variable in this study is the gender inequality index (GII). The GII measures gender-based disparities among males and females in attainments across three human development outcomes, namely, labour market participation, empowerment, and reproductive health. To allow for robustness checks, the study employs inclusive human development (IHDI), proxied by the inequality-adjusted human development index as an alternative outcome variable. Borrowing from the UNDP (2022, p.285), we consider the IHDI index to be a good measure of gender inequality because it accounts for inequalities in a country's achievement across three pillars of human development, viz. income, education, and health. Both indices range from 0 to 1. However, whereas a higher IHDI indicates social progress, higher values of GII suggest otherwise. Data for the IHDI and GII are taken from UNDP (2024).

3.1.2 Main predictor variable

The main predictor variable of interest is frontier technology adoption (FTR). According to the UNCTAD (2023a), FTR is defined as a country's capacity to use, adopt, and adapt frontier technologies. FTR thus reflects country-level capacities in physical, human resource, and technological efforts to leverage industry 4.0 technologies in its real sector. FTR is an index ranging from 0 to 1, with higher values signifying better preparedness for frontier technology adoption and adaption. The FTR series are collected from the UNCTAD statistics (UNCTAD, 2023b).

3.1.3 Moderating variable

The moderating variable in this study is electricity access, which is appreciated as the percentage of a country's population with access to electricity. As clearly argued in Sections 1 and 2, electricity access is essential considering the indispensable role of renewable energy in the production process (e.g., in powering frontier technologies), as well as access to quality healthcare and education. The study retrieves the electricity access data from the WDI (World Bank, 2024).

3.1.4 Control variables

Following the innovation- and gender-centric literature, we control for political stability, economic globalisation, transport infrastructure, and climate change vulnerability in the conditioning information set. Political stability is measured as the prevalence of political stability and the absence of violence and terrorism. We expect political stability because it lessens socioeconomic uncertainty, protects livelihoods, safeguards human resources, and enables policymakers to implement gender-tailored interventions. We retrieve the political stability data from the WDI (World Bank, 2024). Also, climate change vulnerability refers to a country's exposure, sensitivity, and ability to adjust to the adverse impacts of climate change. The study expects climate change vulnerability to increase gender inequality as it increases the susceptibility of properties and economic agents, particularly women, to the ravaging impacts of climate change. The study obtains the corresponding data from the Notre Dame Global Adaptation Initiative [ND-GAIN] (2023). Transport infrastructure measures the quality of a country's road, air, maritime, and railway transport infrastructure. We expect quality transport infrastructure to mitigate gender inequality since it reduces the cost of doing business and enhances fairer access to quality education, health, and socioeconomic opportunities. The attendant data are drawn from AfDB (2022). Economic globalisation signifies the degree of cross-border trade, capital flows, and the stock of foreign assets and liabilities between countries. It is relevant in gender inequality analysis because it enables both men and women to access open innovation, international markets, and decent employment. Notwithstanding, globalisation can also lead to job displacement and income inequality by intensifying capital flight and collapsing indigenous businesses. We source the data from Gygli et al. (2019). Table 1 presents the definition and expected signs of the variables.

Table 1: Variable description and data sources

Variables	Symbols	Description	Sign	Sources
Dependent variables				
Gender inequality	*Gii*	Measures gender inequalities in three important aspects of human development—health, empowerment, and economic status		UNDP (2024)
Inclusive human development	*Ihdi*	The Inequality-adjusted Human Development Index (IHDI) combines a country's average achievements in health, education and income with how those achievements are distributed among country's population by "discounting" each dimension's average value according to its level of inequality		UNDP (2024)
Main predictor				
Frontier technology readiness	*Ftr*	Frontier technology readiness index measuring a country's preparedness to use, adopt and adopt frontier technologies in its economy.	–	UNCTAD (2023b)
Moderating variable				
Electricity access	*Electr*	Access to electricity (percentage of the population)	–	World Bank (2024)
Control variables				
Political stability	*Polstab*	Perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism (Estimate).	–	World Bank (2024)
Economic globalisation	*Ecoglob*	Index measuring the degree of exchange of goods and services over long distances, capital flows and stock of foreign assets and liabilities for a given country (de facto)	–/+	Gygli et al. (2019)
Transport infrastructure	*Transp*	Composite index measuring the quality of road, air, maritime, and railway transport infrastructure.	–	AfDB (2024)
Climate change vulnerability	*Ecostr*	Measures a country's exposure, sensitivity and ability to adapt to the negative impact of climate change	+	ND-GAIN (2023)

2.2 Empirical model specification

Drawing on the theoretical underpinnings concerning technological innovation and gender equality/inclusive human development highlighted in Section 2.1, this study follows Andrès et al. (2017) by specifying Equation (1) to respond to the objectives.

$$Gii_{it} = \alpha_0 + \beta_1 Polstab_{it} + \beta_2 Ecoglob_{it} + \beta_3 Transp_{it} + \beta_4 Climvul_{it} + \beta_5 Eleca_{it} + \beta_6 Ftr_{it} + \beta_7 (Ftr_{it} \times Eleca_{it}) + \nu_i + \varepsilon_{it} \quad (1)$$

where Gii_{it} is the gender inequality index in country i at time t. Also, $Polstab$ is political stability; $Ecoglob$ is economic globalisation; $Transp$ is transport infrastructure, $Climvul$ is climate change vulnerability and ε_{it} is the error term. Similarly, $Eleca$ represents electricity access, Ftr is frontier technology readiness, and $Ftr \times Electa$ is their interaction term. The parameters of interest in Equation 1 are β_6 and β_7. As aptly articulated in Section 1, we expect both parameters to be negative and statistically different from zero. Whereas $\beta_6 < 0$ will suggest that FTR mitigates gender inequality, $\beta_7 < 0$ will also indicate that electricity access forms a synergy with FTR to reduce gender inequality. Following Brambor et al. (2006), we compute the total effect of FTR on gender inequality from β_6 and β_7 as:

$$\frac{\partial(Ihdi_{it})}{\partial(Ftr_{it})} = \beta_6 + \beta_7\left(\overline{Electr_{it}}\right) \quad (2)$$

where $\overline{Electri_{it}}$ is the average of electricity access while all other symbols remain as earlier defined. Equation 2 means that the total effect of FTR on gender inequity will be evaluated at the mean of electricity access.

3.2 Preliminary tests

To ensure consistent and unbiased inference, the study subjects the datasets to some rigorous preliminary tests. Specifically, we test for the presence of (i) unit root, (ii) strong correlation, and (iii) cross-sectional dependence in the data. For the cross-sectional dependence assessment, we employ the Pesaran (2004) test. The test is based on the hypothesis that the data exhibits no cross-sectional dependence. This means that if there is no evidence for the alternative hypothesis at 1%, 5%, or 10% significance levels, then there is no cross-sectional dependence in the dataset. Additionally, to ascertain the correlation among the variables, we apply the pairwise correlation test.

The preliminary test results are as follows: firstly, the correlation test results in Table A.2 indicate that the adoption of frontier technology is positively linked to IHDI but negatively associated with gender inequality. Similarly, electricity access shows a negative correlation with gender inequality and a positive correlation with IHDI. The correlation signs of the control variables also support the theoretical expectations. Specifically, we find that political stability, economic globalization, and transport infrastructure are negatively associated with gender inequality and positively associated with IHDI. Additionally, climate change vulnerability is positively correlated with gender inequality, as anticipated.

Also, Table A.3 shows the presence of cross-sectional dependence in the data. But for political stability, we find evidence of cross-sectional dependence among all the variables. Accordingly, this study applied the second-generation unit root tests, namely, the cross-sectionally augmented panel unit root (CIPS) and the Pesaran (2007) cross-sectionally augmented Dickey-Fuller (PESCADF) tests, for the stationarity analysis. The attendant results in Table A.4 confirm stationarity among the variables. We find that climate change readiness and electricity access are at levels while all other variables become stationary only after the first difference.

3.3. Estimation strategy

In accordance with the preliminary tests above, this study employs the Driscoll-Kraay (1998) fixed effect estimator for the estimation. The choice of this estimator is informed by the following. Foremost, the Driscoll-Kraay estimator is robust to various forms of cross-sectional and temporal dependence. Cross-sectional dependence has been identified in this study through Pesaran's (2004) test. Second, the Driscoll-Kraay estimator is both heteroskedastic and autocorrelation consistent. Third, the Driscoll-Kraay (1998) estimator is more suitable for studies with a larger number of cross-sections compared to other estimation techniques, such as Beck and Katz's (1995) panel-corrected standard errors, especially when the number of cross-sections exceeds the study period, as seen in this study with 29 countries and 11 years. Fourth, the Driscoll and Kraay estimator addresses constant differences across countries and mitigates the risk of heterogeneity bias. This is particularly important considering the country-level collaboration and interdependence characterising frontier technology adoption (see UNCTAD, 2023).

4. Results and discussion

This section is split into three sections. Section 4.1 reports the preliminary findings, while Sections 4.2 and 4.3 present the empirical results and the contribution to the extant scholarship, respectively.

4.1 Preliminary results

Figure 1 shows that although inequality in health has been declining across the gender divide in the past decade, progress in education and income has stagnated or worsened in the same period. This translates into an average GII score of 0.535 for the entire sample, as apparent in Table 2. Across the low-income, middle- and high-income dichotomy, we report mean values of 0.574 and 0.499, respectively. Similarly, IHDI averages 0.462 and 0.329 in low-income, and middle- and high-income African countries. Thus, whether measured by the GII or IHDI, middle- and high-income African countries are better in educational attainment, health, and labour market participation across the gender divide.

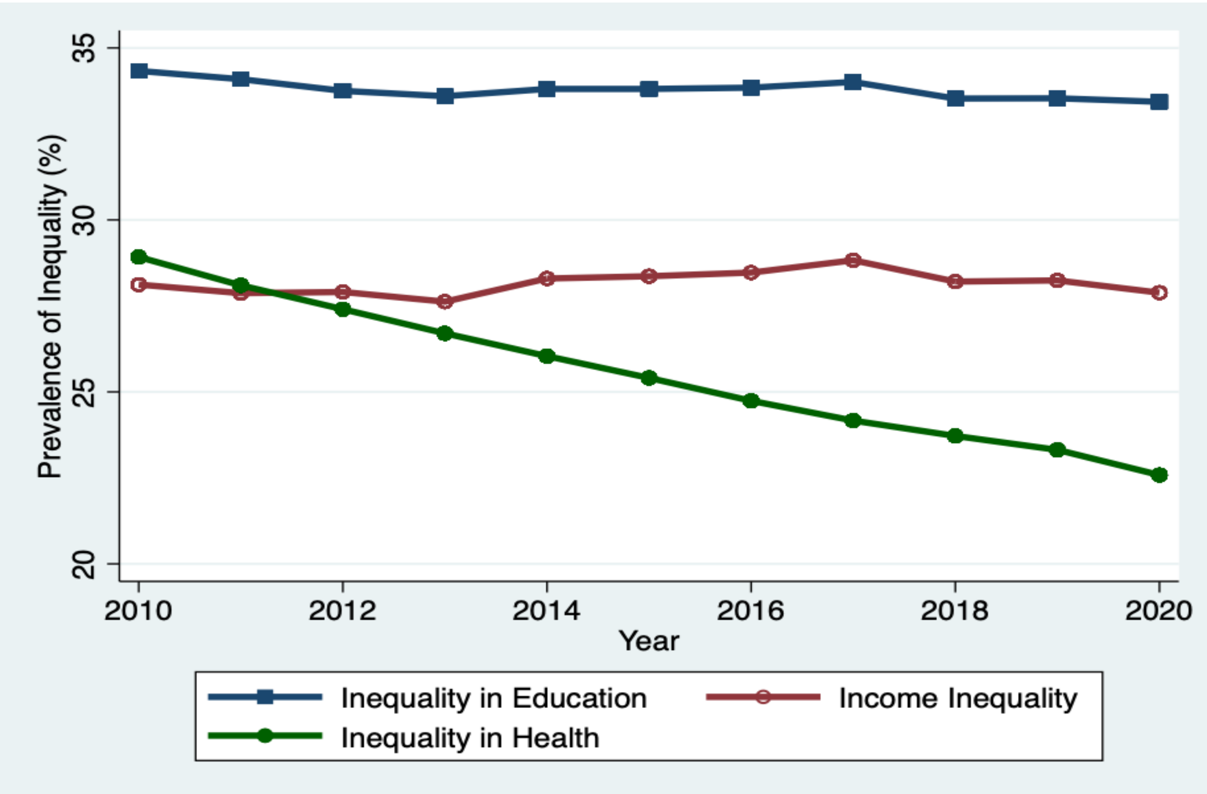

Figure 1: Prevalence of Inequalities in Health, Education, and Income, 2010-2020

Table 2: Summary Statistics

	Full Sample					Middle- and High-Income Countries					Low-Income Countries				
Variables	Obs	**Mean**	Std. Dev.	Min	Max	Obs	**Mean**	Std. Dev.	Min	Max	Obs	**Mean**	Std. Dev.	Min	Max
Gender inequality	319	**0.535**	0.089	0.253	0.677	165	**0.499**	0.094	0.253	0.66	154	**0.574**	0.063	0.388	0.677
Inclusive human development	319	**0.398**	0.098	0.259	0.681	165	**0.462**	0.092	0.292	0.681	154	**0.329**	0.038	0.259	0.417
Frontier technology adoption	290	**0.196**	0.136	0.000	0.567	150	**0.283**	0.133	0.051	0.567	140	**0.102**	0.053	0.000	0.237
Electricity access	319	**52.765**	29.59	5.300	100.0	165	**73.436**	23.461	19.200	100.0	154	**30.617**	16.628	5.300	70.40
Political stability	319	**-0.438**	0.745	-2.201	1.111	165	**-0.304**	0.793	-1.639	1.111	154	**-0.582**	0.663	-2.201	0.394
Economic globalisation	319	**50.113**	13.224	25.237	89.99	165	**52.609**	13.453	28.377	89.998	154	**47.43**	12.471	25.237	81.44
Transport infrastructure	308	**11.131**	11.313	1.661	56.511	165	**15.768**	13.525	2.200	56.511	143	**5.779**	3.402	1.661	13.817
Climate change vulnerability	319	**0.508**	0.066	0.379	0.611	165	**0.459**	0.053	0.379	0.554	154	**0.560**	0.026	0.516	0.611`

Note: Obs is Observations, Std. Dev is Standard Deviation, Min is Minimum, and Max is Maximum, Furthermore, Table 2 indicates that relative to low-income African countries (0.102), middle- and high-income African countries (0.283) have higher capacity in deploying and adapting frontier technologies in their real sector. Also, Table 2 demonstrates that middle- and high-income African countries are less vulnerable to the adverse impacts of climate change (0.459) compared to their low-income counterparts (0.560).

A deeper scrutiny of the data through graphical analysis shows that the Top 5 African countries with robust capacities for leveraging frontier technologies are South Africa, Tunisia, Morocco, Mauritius, and Egypt. Similarly, the Gambia, Burundi, Burkina Faso, Ethiopia, and Tanzania report fragile capacity in deploying frontier technologies.

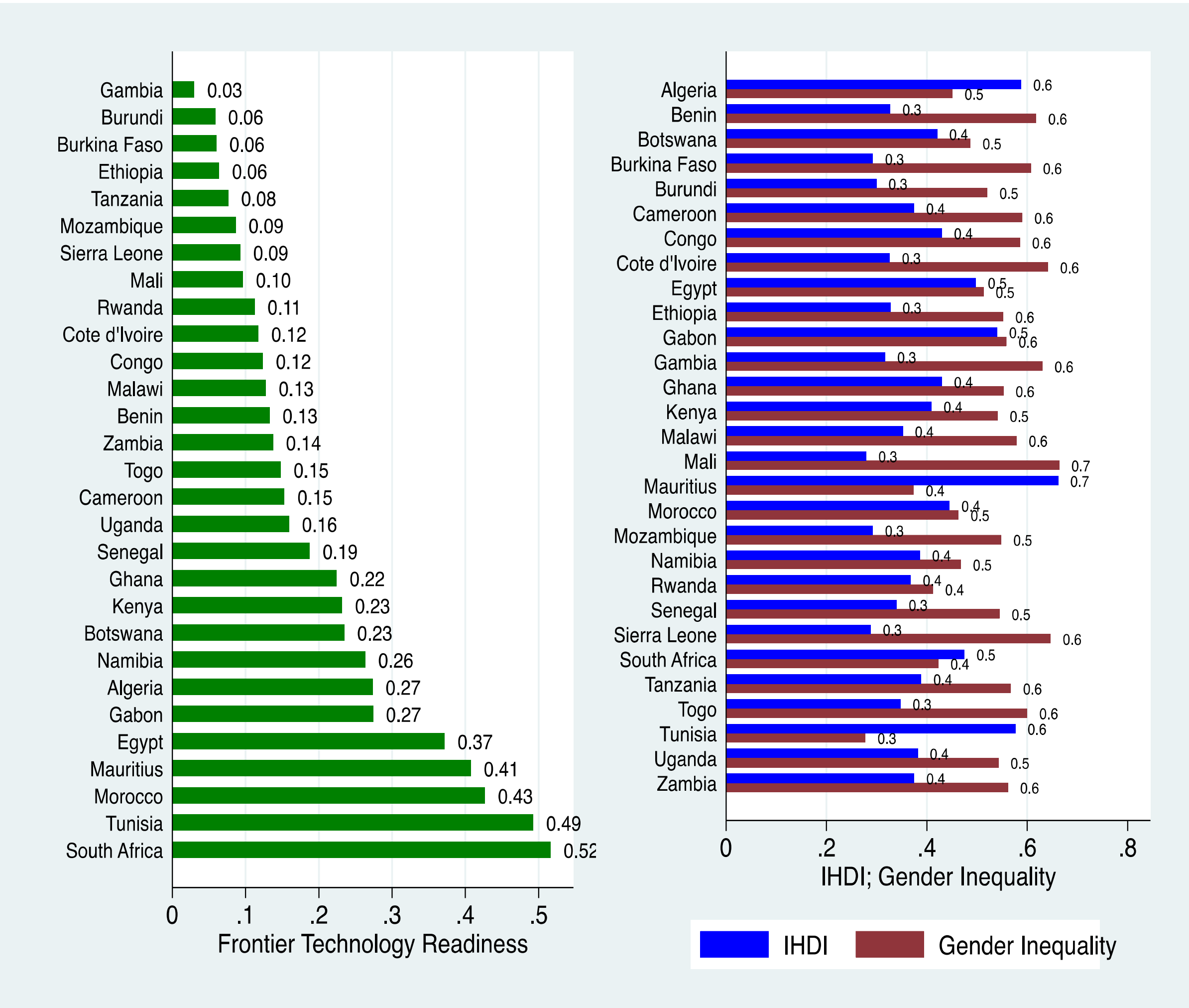

Figure 1: In-country Frontier Technology Adoption, Gender Inequality and Inclusive human Development, 2010-2020.

More importantly, we note from Panels A and B of Figure 2 that FTR has a strong negative (positive) relationship with gender inequality (inclusive human development), signifying the potential socially progressive impacts of frontier technologies.

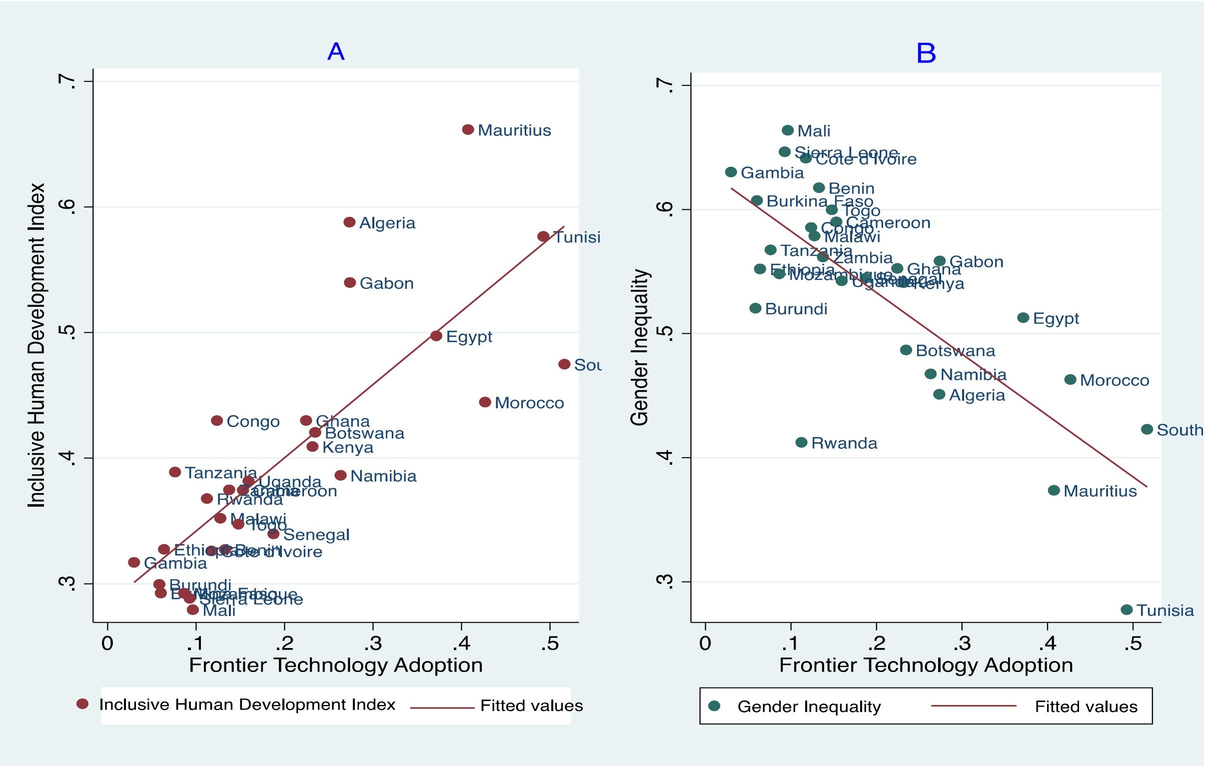

Figure 2: Relationship between frontier technology Adoption, Gender Inequality, and Inclusive Human Development, 2010-2020

4.2 Effects of FTR and electricity access on gender inequality

Columns 1-3 of Table 3 present results for the conditional and unconditional effects of FTR on gender inequality (GII). The evidence in Column 2 suggests that a 1% increase in FTR reduces GII by 0.1046 points, ceteris paribus. This result is statistically significant at the 1% significance level. We extend the analysis to Objective 2 by assessing the contingency effect of electricity access in the FTR and GII nexus. First, we find a negative and statistically significant negative coefficient for the interaction term between FTR and electricity access (i.e., -0.0032). This suggests that electricity access complements FTR to reduce GII in Africa. That said, we proceed to compute the attendant total/marginal effect from this interactive term based on Equation 2. We report a total effect of -0.0914, which is obtained by engaging the direct effect of FTR on GII (0.0778), the coefficient of the FTR-electricity access interaction term (-0.0032), and the average electricity access value of 52.7% (see Table 3).

Table 3: Effects of Frontier Technology Readiness on IHDI and Gender Inequality

	Gender inequality			IHDI		
Variables	(1)	(2)	(3)	(4)	(5)	(6)
Political stability	-0.0001	-0.0005	-0.0004	-0.0052***	-0.0053***	-0.0054***
	(0.0015)	(0.0020)	(0.0020)	(0.0012)	(0.0012)	(0.0012)
Economic globalisation	0.0003	0.0001	0.0001	-0.0001	0.0000	0.0001
	(0.0002)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Transport infrastructure	-0.0013*	-0.0007	-0.0006	-0.0005	-0.0008	-0.0010
	(0.0006)	(0.0007)	(0.0009)	(0.0005)	(0.0006)	(0.0007)
Climate change vulnerability	0.4157***	0.4296***	0.4452***	-0.6577**	-0.6207**	-0.6334***
	(0.1261)	(0.1209)	(0.1260)	(0.2205)	(0.1915)	(0.1931)
Electricity access (Eleca)	-0.0015***	-0.0014***	-0.0009***	0.0012***	0.0011***	0.0007***
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0002)
Technological readiness		-0.1046*	0.0778**		0.0678**	-0.0816
		(0.0502)	(0.0291)		(0.0268)	(0.0451)
Technological readiness × Eleca			-0.0032**			0.0026**
			(0.0010)			(0.0009)
Total effect	–	–	**-0.0914****	–	–	**0.0570****
	–	–	**(0.0393)**	–	–	**(0.0196)**
Constant	0.4035***	0.4138***	0.3892***	0.6804***	0.6452***	0.6654***
	(0.0643)	(0.0606)	(0.0720)	(0.1130)	(0.0960)	(0.1002)
Country fixed-effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	308	280	280	308	280	280
Countries	28	28	28	28	28	28
Wald Statistic	109.1***	110.7***	162.2***	184***	136***	1483***

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

These findings remain consistent when the IHDI is used as an alternative outcome variable. Foremost, we find evidence at the 5% significance level that FTR increases the IHDI by 0.0678 points (Column 5). Also, consistent with the results in Column 3, we show that electricity access forms a synergy with FTR to enhance IHDI, evidenced by the positive interaction term (0.0026). The corresponding total effect from this interaction on the IHDI is 0.570 points. The uniqueness and relevance of this study lie in the robust evidence that, directly or indirectly, FTR promotes social progress – IHDI and gender equality – in Africa. These findings answer Objectives 1 and 2, confirming that frontier technologies present a new window of opportunity that African countries can embrace to promote IHDI and gender equality.

4.4 Results for low-income, and middle- and high-income African countries

Thus far, the study has established that (un)conditionally, FTR enhances social progress in Africa. Although this can guide policy formulations in Africa, it remains unclear whether these effects differ across low-income, and middle- and high-income African countries. This disaggregation is policy-relevant because Table 2 clearly shows that low-income African countries have low FTR capacity and electricity access levels when compared to their middle- and high-income counterparts.

Table 4 presents compelling evidence that middle- and high-income African countries decrease (increase) their gender inequality (IHDI) score by 0.136 points (0.158%) for every 1% increase in FTR (Columns 2 & 4). Concerning the contingency analysis, the results in Columns 3 and 6 reveal that FTR forms a significant synergy with electricity access to reduce (increase) gender inequality (IHDI) by 0.1208 points (-0.1405 points).

However, in low-income African countries, although progress in FTR mitigates gender inequality, it has no statistically significant effect on the IHDI (see Table 5). Precisely, we report a 0.0645-point decline in the GII for every 1 percentage point improvement in FTR. Moreover, unlike in the case of middle- and high-income African countries, we find that FTR and electricity access do not synergistically enhance gender equality and the IHDI. This is supported by the positive (negative) coefficient of the FTR-electricity access interaction terms on the GII and IHDI. The attendant conditional effects of FTR on both the GII and IHDI are also statistically insignificant.

Table 4: Effects of Technological Readiness on IHDI and Gender Inequality in Middle- and High-Income African Countries

	Gender inequality			IHDI		
Variables	(1)	(2)	(3)	(1)	(2)	(3)
Political stability	0.0065	0.0027	0.0040	-0.0042	-0.0011	-0.0022
	(0.0077)	(0.0054)	(0.0062)	(0.0027)	(0.0019)	(0.0021)
Economic globalisation		0.0000	-0.0001	0.0001	0.0005**	0.0005***
	(0.0005)	(0.0004)	(0.0003)	(0.0002)	(0.0001)	(0.0001)
Transport infrastructure	-0.0011	-0.0004	-0.0007	-0.0005	-0.0011	-0.0009
	(0.0007)	(0.0010)	(0.0009)	(0.0006)	(0.0008)	(0.0008)
Climate change vulnerability	0.4892*	0.3176	0.4404*	-0.5772	-0.4168	-0.5208
	(0.2236)	(0.2677)	(0.2085)	(0.4169)	(0.3566)	(0.2910)
Electricity access (Eleca)	-0.0018***	-0.0017***	-0.0010***	0.0014***	0.0013***	0.0007**
	(0.0002)	(0.0002)	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Technological readiness		-0.1587*	0.1706*		0.1362**	-0.1427
		(0.0726)	(0.0844)		(0.0567)	(0.0838)
Technological readiness × Eleca			-0.0042**			0.0036**
			(0.0016)			(0.0013)
Total effect	–	–	**-0.1405****	–	–	**0.1208****
	–	–	**(0.0531)**	–	–	**(0.0452)**
Constant	0.4058***	0.5334***	0.4373***	0.6234**	0.5128**	0.5942***
	(0.1268)	(0.1376)	(0.1104)	(0.2134)	(0.1831)	(0.1471)
Country fixed-effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	165	150	150	165	150	150
Countries	15	15	15	15	15	15
Wald Statistic	302***	1285***	355.2***	181.9***	58.29***	508.1***

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

Table 5: Effects of Technological Readiness on IHDI and Gender Inequality in Low-Income African Countries

	Gender inequality			IHDI		
Variables	(1)	(2)	(3)	(1)	(2)	(3)
Political stability	-0.0011	-0.0014	-0.0019	-0.0067***	-0.0071***	-0.0070***
	(0.0032)	(0.0037)	(0.0038)	(0.0012)	(0.0010)	(0.0010)
Economic globalisation	0.0001*	0.0002**	0.0002**	-0.0003	-0.0002	-0.0002
	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
Transport infrastructure	0.0024**	0.0030*	0.0036*	-0.0021*	-0.0022	-0.0024*
	(0.0010)	(0.0015)	(0.0017)	(0.0010)	(0.0012)	(0.0013)
Climate change vulnerability	0.3052**	0.3710*	0.3334*	-0.6328***	-0.6344***	-0.6245***
	(0.1369)	(0.1672)	(0.1485)	(0.1705)	(0.1779)	(0.1685)
Electricity access (Eleca)	-0.0012***	-0.0011***	-0.0014***	0.0010***	0.0010***	0.0011***
	(0.0002)	(0.0002)	(0.0003)	(0.0001)	(0.0001)	(0.0002)
Technological readiness		0.0042	-0.0645**		-0.0178	0.0003
		(0.0203)	(0.0232)		(0.0232)	(0.0267)
Technological readiness × Eleca			0.0028**			-0.0007
			(0.0009)			(0.0008)
Total effect	–	–	**0.0197**	–	–	**-0.0219**
	–	–	**(0.0240)**	–	–	**(0.0228)**
Constant	0.4109***	0.3656***	0.3880***	0.6770***	0.6777***	0.6718***
	(0.0715)	(0.0902)	(0.0782)	(0.0868)	(0.0912)	(0.0855)
Country fixed-effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	143	130	130	143	130	130
Countries	13	13	13	13	13	13
Wald Statistic	98.14***	68.66***	128.8***	123.1***	213.3***	3152***

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

4.5 Threshold analysis

The evidence so far suggests that FTR promotes gender equality and inclusive human development. However, this finding differs across low-income, and middle- and high-income African countries. We find that FTR significantly increases both gender equality and inclusive human development in middle- and high-income African countries. However, the conditional effect of FTR on gender equality and inclusive human development is not statistically significant in low-income countries. It is imperative to note that these FTR total effects are based on the average electricity access of 30.6% and 73.4% in low-income, and middle- and high-income African countries, respectively.

Accordingly, in this section, we deepen the analysis by assessing whether progress in electricity access coverage (i) amplifies the gender equality- and IHDI-enhancing effects of FTR in middle- and high-income countries or (ii) conditions FTR to promote gender equality and inclusive human development in low-income African countries. To this end, we re-estimate Equation 2 by considering electricity access thresholds of 80.0%, 90.0%, 99.9% and 100.0%. Table 6 reports the corresponding findings.

Table 6: Conditional effects of FTR across electricity access thresholds

	1	2	3	4	5	6
Electricity access thresholds	Gender inequality	IHDI	Gender inequality	IHDI	Gender inequality	IHDI
30.6	**0.0197****	**-0.0219**	–	–	–	–
	(0.0240)	**(0.0228)**	–	–	–	–
52.7	–	–	**-0.0914****	**0.0570****	–	–
	–	–	**(0.0393)**	**(0.0196)**	–	–
73.4	–	–	–	–	**-0.1405****	**0.1208****
	–	–	–	–	**(0.0531)**	**(0.0452)**
80.0	0.1557**	-0.0577	-0.1791**	0.1288***	-0.1685**	0.1445***
	(0.0622)	(0.0513)	(0.0644)	(0.0367)	(0.0617)	(0.0495)
90.0	0.1833**	-0.0650	-0.2112**	0.1551***	-0.2109**	0.1804***
	(0.0709)	(0.0585)	(0.0740)	(0.0449)	(0.0758)	(0.0579)
99.0	0.2105**	-0.0721	-0.2430**	0.1812***	-0.2529**	0.2159***
	(0.0796)	(0.0657)	(0.0837)	(0.0532)	(0.0904)	(0.0676)
100.0	0.2108**	-0.0722	-0.2433**	0.1814***	-0.2533**	0.2163***
	(0.0797)	(0.0658)	(0.0838)	(0.0533)	(0.0906)	(0.0677)

Note: Columns 1-2: Low-income countries; Columns 3-4: Full sample; Columns 5-6: Middle- and High-Income Countries; Standard errors in parenthesis; *** p<0.01, ** p<0.05, * p<0.1

We find that improving electricity access from the current average of 52.7% to 80.0% reduces (increases) gender inequality (IHDI) from -0.0914 (0.0570) points to -0.1791 (0.1288) points for the entire sample (Column 1 and 2). When 100% of the population has access to electricity, the FTR yields a significant reduction in gender inequality (-0.2433) and an enhancement in IHDI (0.1814).

However, the income decomposition analysis reveals that these gender equality- and IHDI-enhancing impacts of FTR accrue only to middle- and high-income African countries. For instance, an increase in electricity access from 80.0% to 100% leads to a decline (an increase) in gender inequality (IHDI) from -0.1685 (0.1445) to -0.2533 (0.2163) points. However, results in Columns 5 and 6 show that FTR instead deepens gender inequality as access to electricity improves. For instance, an improvement in electricity access coverage from 80.0% to 100.0% moderates FTR to increase gender inequality from 0.1557 to 0.2108 points.

4.6 Discussion and contribution to the literature

The study makes three significant contributions to advance the social progress scholarship. First, evidence from this novel study suggests that FTR is socially progressive but has a greater impact in middle- and high-income Africa. This is plausibly due to the relatively well-developed physical and digital infrastructure of the latter. The positive effect can manifest in several ways. For instance, in the education sector, drones can be employed to save lives through timely delivery of medical supplies, anti-snake venom serum, surgical kits, vaccines and blood. Anecdotal evidence is the recent development in Ghana and Rwanda, where the Zipline drone delivery system is being used to reach remote and inaccessible communities (Umlauf & Burchardt, 2022). Similarly, 3D printing technologies can be employed by physicians to make the anatomy of patients clearer during emergency sessions. Also, in terms of human capital development, the rise in generative AI, the IoT and robotics facilitates quality and inclusive education. For instance, the IoT dismantles geographical and financial barriers in education, enabling males and females to access quality education worldwide. Also, Copilot and ChatGPT are enhancing students' coding and computing proficiency by providing information from several sources (WEF, 2020). This can improve the labour market prospects of both young men and women. Furthermore, robots and drones can be used on farmlands to accurately spray pesticides and fertilisers to improve yields and enhance profit prospects (Puri et al., 2017).

Second, the evidence indicates that electricity access amplifies the gender inequality-reducing effect of FTR. Again, this contingency effect of electricity access benefits middle- and high-income African countries but not low-income African countries. This is plausibly due to the relatively low energy poverty and insecurity in middle- and high-income African countries. In such societies, women and men effectively employ the IoT to access finance, education, quality healthcare, and employment opportunities. Similarly, a reliable energy supply provides fairer opportunities for both men and women to leverage the IoT, generative AI, and robots to establish businesses and/or improve production efficiency, access wider markets, and create jobs (Bessen, 2020). For example, the IoT creates new entrepreneurs, especially women who would ordinarily face financial barriers entering traditional markets, to leverage global commerce platforms (e.g., eBay, Alibaba, Etsy, and Amazon) to sell their products online, enhance profit and achieve financial independence. In addition, reliable electricity is crucial for advancing telehealth, public-governance interaction, and remote work, all of which are vital for promoting inclusive human development (WHO, 2018).

Third, the threshold analysis reveals that improvements in electricity access intensify the gender equality-enhancing effect of FTR in middle- and high-income African countries. The evidence suggests that broadening rural-urban electrification enables middle- and high-income African countries to broaden the dynamics alluded to above. However, in low-income countries, improving energy access causes FTR to entrench gender inequality. This evidence is revealing, signifying that failure to build capacity for frontier technology adoption can work to the advantage of a few elites in society. For instance, in the presence of poor physical and digital infrastructure (e.g., poor internet connectivity, roads, railways, electronic vehicle charging ports), the cost of deploying, mastering, and adapting frontier technologies becomes high. This way, men, established firms, and multinational companies who mostly have the financial mettle would be in a pole position to deploy frontier technologies in their business to increase productivity and profits.

5. Concluding remarks and policy recommendations

This research contributes to the discourse concerning the socioeconomic impacts of frontier technology adoption (FTR) in the Global South. This novel research provides fresh evidence concerning the heterogeneous effects of frontier technology readiness on gender inequality in low-income, and middle- and high-income African countries. Three objectives underpin this empirical scrutiny. First, this study assesses the impact of frontier technology on gender inequity in Africa. Second, this study examines the contingency effect of electricity access in the relationship between frontier technology adoption and gender inequality. Third, the study examines whether the interaction between electricity access and frontier technology readiness differs across middle- and high-income income and low-income countries.

Compelling evidence from this empirical enquiry reveals that FTR promotes gender equality in both low-income and middle- and high-income African countries. However, this impact is striking in middle- and high-income African countries. Further, the contingency analysis establishes that electricity access amplifies the effect of FTR on gender equality but only in middle- and high-income African countries. Additionally, the threshold analysis demonstrates that broadening electricity access coverage conditions FTR to yield remarkable impacts on gender equality. This positive impact, however, eludes low-income African countries. The findings remain consistent when the inequality-adjusted human development index is used as an alternative outcome variable.

For middle- and high-income African countries, we recommend that policymakers enhance and expand frontier technology access and infrastructure while ensuring comprehensive electricity coverage. Policies should, therefore, focus on further building robust digital infrastructure, promoting STEM education for the youth, and ensuring equal access to technological tools and resources.

For low-income countries, focus on addressing issues such as lack of education, social norms, and economic barriers that hinder men and women from benefitting equally from frontier technologies. We recommend that comprehensive science, technology, and innovation policies, along with investments to enhance the capacity of economic agents in adopting, mastering, and adapting frontier technologies, should be prioritised. To this end, we recommend that development organisations, such as the World Bank, the United Nations Development Programme, the African Development Bank, the Bill and Melinda

Gates Foundation and the European support African countries both financially and technologically in building their human, digital, and physical infrastructure required for embracing, mastering and adapting frontier technologies.

A major limitation of this study is the data. Of the 55 African countries, 29 were sampled because several countries, for example, South Sudan, Somalia, and Eritrea, lack sufficient data for gender inequality and inequality-adjusted human development index. We suggest that future contributors revisit the FTR-gender inequality linkages should data become available. Additionally, we do not explore the FTR-gender inequality linkages across the various economic blocs of Africa. We entreat other researchers to take up the challenge.

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Table A.1: List of sampled countries

Countries	Income classification
1. Algeria	High-income country
2. Benin	Low-income country
3. Botswana	Middle-income country
4. Burkina Faso	Low-income country
5. Burundi	Low-income country
6. Cameroon	Middle-income country
7. Congo	Middle-income country
8. Cote d'Ivoire	Middle-income country
9. Egypt	High-income country
10. Ethiopia	Low-income country
11. Gabon	High-income country
12. Gambia	Low-income country
13. Ghana	Middle-income country
14. Kenya	Middle-income country
15. Malawi	Low-income country
16. Mali	Low-income country
17. Mauritius	Middle-income country
18. Morocco	Middle-income country
19. Mozambique	Low-income country
20. Namibia	Middle-income country
21. Rwanda	Low-income country
22. Senegal	Low-income country
23. Sierra Leone	Low-income country
24. South Africa	High-income country
25. Tanzania	Low-income country
26. Togo	Low-income country
27. Tunisia	High-income country
28. Uganda	Low-income country
29. Zambia	Middle-income country

Table A.2: Pairwise correlation matrix

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Inclusive human development	1							
(2) Gender inequality	-0.712***	1						
(3) Frontier technology adoption	0.770***	-0.718***	1					
(4) Electricity access	0.825***	-0.556***	0.829***	1				
(5) Political stability	0.222***	-0.224***	0.206***	0.0986	1			
(6) Economic globalisation	0.284***	-0.228***	0.259***	0.266***	0.326***	1		
(7) Transport infrastructure	0.549***	-0.442***	0.536***	0.526***	0.160**	0.0799	1	
(8) Climate change vulnerability	-0.810***	0.624***	-0.829***	-0.885***	-0.186**	-0.275***	-0.461***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.3: Stationarity test results

Variable	PESCADF Level statistic	PESCADF First difference statistic	CIPS Level statistic	CIPS First difference statistic
Gender inequality	-1.726	-2.540	-2.302	-3.021*
Inclusive human development	-2.023	-3.054***	-1.978	-2.562
Frontier technology adoption	-2.138	1.700	-2.427	-3.523***
Electricity access	-3.595***	-2.867**	-3.058***	-3.041**
Climate change readiness	-2.235	-3.205***	-2.568	-3.105**
Political stability	-2.932***	-2.867**	-2.515	-2.809*
Economic globalisation	-2.750***	-2.726**	-3.003***	-3.378***
Transport infrastructure	-1.102	-1.523	-1.632	-2.810**

**** p<0.01, ** p<0.05, * p<0.1*

Table A.4: Cross-sectional dependence test results

Variable	**CD-test**	**Corr**	**Corr(abs)**
Gender inequality	45.53***	0.838	0.838
Inclusive human development	53.39***	0.152	0.401
Frontier technology adoption	24.58***	0.386	0.464
Electricity access	42.50***	0.667	0.675
Climate change readiness	19.71***	0.306	0.519
Political stability	1.49	0.023	0.446
Economic globalisation	16.48***	0.256	0.390
Transport infrastructure	4.88***	0.076	0.430

*NB: Under the null hypothesis of cross-sectional independence; *** p<0.01, ** p<0.05, * p<0.1*