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Sustainable Development in Sub-Saharan Africa through Fourth Industrial Revolution (4IR) Technologies: Addressing Poverty, Education, and Infrastructure Challenges

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Abstract: The Fourth Industrial Revolution (4IR) grants Sub-Saharan Africa (SSA) a transformative opportunity to accelerate sustainable development through technological innovation. That is why this paper explores how 4IR technologies can address key Sustainable Development Goals (SDGs), specifically poverty alleviation, education, and infrastructure development. The qualitative research design utilises a Problem-Driven Political Economy Analysis (PEA) framework. It also employs a case study of South Africa's adoption of the 4IR technology in terms of poverty, education and infrastructure to investigate how these technologies can catalyse the attainment of the SDGs and structural transformation in African economies. Although 4IR holds immense potential for enabling sustainable development, challenges such as technological inequality, inadequate infrastructure, and insufficient policy frameworks pose significant hurdles. This paper argues that harnessing 4IR for sustainable development in Africa requires a nuanced understanding of the global political economy, regional disparities, and inclusive governance models prioritising equitable growth. By assessing existing initiatives and identifying gaps, this research contributes to the discourse on how Africa can strategically position itself within the evolving global digital economy to achieve long-term sustainable development and SDG goals.

Keywords

African Economic Transformation, Artificial Intelligence, Industry 4.0, South Africa, Sub-Saharan Africa, Sustainable Development, The Fourth Industrial Revolution, The Sustainable Development Goals

Introduction

> "Africa can leap into the Fourth Industrial Revolution (4IR) to drive sustainable industrialisation, employment and transformation by investing in human skills and implementing policies supporting digital technologies…But could Africa leapfrog the third, moving from the second to the fourth industrial revolution…?" (African Development Bank Group, 2023).

The Fourth Industrial Revolution (4IR), or what is called Industry 4.0, builds on digital advancements from the mid-20th century, integrating transformative technologies such as robotics, renewable energy and artificial intelligence (AI) (*McKinsey and Company*, 2022). Part of this process is pushing boundaries with four foundational disruptive technologies across industries: 1) data, connectivity and computational power (such as cloud computing and blockchain); 2) intelligence and analytics (like machine learning and AI); and 3) human-machine interaction (for example, robotics and virtual reality); and 4) advanced engineering (such as renewable energy and 3D printing). Success in 4IR requires adopting these technologies and investing in infrastructure and workforce upskilling and

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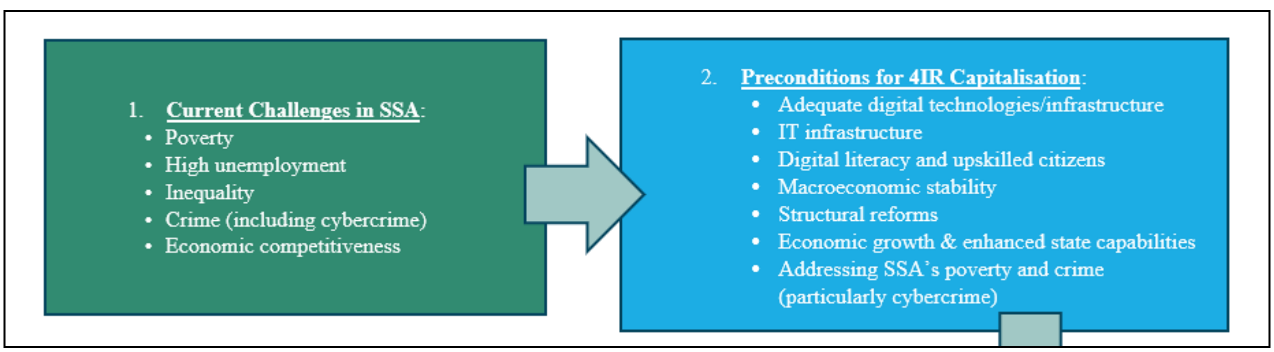
reskilling to adapt to evolving roles and sustain competitiveness (*McKinsey and Company*, 2022; Oosthuizen and Mkhize, 2024).

In recent years, the 4IR has emerged as a momentous and world-shaping force. Its significance lies in the transformative impact of its modern technologies, particularly those powered by internet connectivity, on how we live, work, and learn (Via Afrika, 2020). It builds upon the advancements of the first three industrial revolutions, pushing these innovations to unprecedented heights and never-before-seen discoveries. For example, where people from older generations had to rely solely on printed information in libraries or other physical sources when studying, these have now almost been eclipsed by the digital advancements and online sources of the 4IR. Today's students even use ChatGPT and other large language models (LLMs) to write and do research for them (Gordijn and ten Have, 2023). Thus, as technological advancements accelerate ever-increasingly, forward-thinking approaches are becoming more essential (Via Afrika, 2020).

For Africa, these advances present a range of implications, encompassing both opportunities and challenges. As Masters (2021: 362) states, the development and application of technology are essentially value-laden, carrying social, economic, environmental, and political implications. Thus, while the 4IR holds significant promise of substantial economic growth and improved welfare, it also exposes vulnerabilities that reinforce existing international knowledge hierarchies (Fox and Signé, 2022). In this context, digital technologies in global affairs underscore the 'knowledge as power,' where access to the 'right' knowledge controls its governance and distribution. This dynamic exacerbates the digital divide between those nations that are developed and those that are developing, so raising critical concerns about inclusion and equity in the 4IR (Masters, 2021: 362).

However, the view of this article is that Africa can leapfrog the previous or third industrial revolution, moving from the second revolution to the fourth, but only if it can harness the correct technologies and invest in being 4IR-ready (see Figure 1) (African Development Bank Group, 2023). The 4IR *readiness* is defined by Schulz et al. (2018, as cited in Olaitan et al., 2021: 4) as "the ability to capitalise on future production opportunities, mitigate risks and challenges, and remain resilient and agile in responding to unforeseen future shocks." This concept emphasises that states must develop sufficient capacity and institutional frameworks, as set out in Figure 1, to capitalise on the advanced manufacturing opportunities presented by the 4IR. Simultaneously, they must address the associated risks and challenges while building resilience to withstand future shocks and uncertainties.

Figure 1 The Challenges and Mitigation Strategies for 4IR Readiness in SSA



(Oosthuizen and Mkhize, 2024: 168).

Methodology

The article employs qualitative research to examine the opportunities and challenges presented by the profound global changes brought about by the 4IR in the SSA region. The main aim is to determine if states within SSA can benefit from these changes given the significant challenges they face in poverty, unemployment, crime and cybercrime (du Plooy-Cilliers et al., 2021: 200–209). Furthermore, this qualitative study is conducted by utilising data from different sources and the case study of South Africa to produce a strategic framework for SSA to help mitigate or solve these significant challenges and enhance their preparedness and ability to benefit from the 4IR.

The data was collected using current literature such as academic journals, books, policy documents, reports and statistics from international organisations (du Plooy-Cilliers et al., 2021: 117, 262–269). This collection method supports the in-depth exploration of the topic. It underpins the findings of the research, which contribute to the current debates surrounding the 4IR and its implications for SSA states. The data analysis technique is a thematic analysis of the different patterns, themes and trends associated with the 4IR and the effects of poverty, unemployment, crime and cybercrime on states in SSA to capitalise on these changes.

Furthermore, this method will necessitate the adaptation of an International Political Economy (IPE) framework. Worth (2018) stated that IPE '… draws from the traditions of political economy and the study of international relations to look at how the international economy is politically constructed and managed.' Since introducing 4IR to a country affects the economic and political landscape, the IPE framework can be used to approach the policy change appropriately (see Figure 6). Andreas (et al, 2022: 869) stated that the political economy analysis is a tool practitioners use to address policy challenges in economic development, and it will be used to conclude the findings in this article for SSA's sustainable development.

Background

According to the Millennium Development Goals (MDGs) Report of 2015, Africa achieved significant progress towards the eight Millennium Development Goals, particularly in health and education (*United Nations Department of Economic and Social Affairs*, 2022). SSA demonstrated the fastest progress among developing regions in these areas. At the same time, Northern Africa met numerous targets, including reductions in poverty and hunger, universal primary education, improving child and maternal health, and advancing sanitation. However, despite these accomplishments, substantial challenges remain. For instance, 70% of the African population lack access to adequate sanitation facilities, 41% live on less than $1.25 per day, and of the 57 million primary school-aged children out of school globally in 2015, 33 million were in SSA (*United Nations Department of Economic and Social Affairs*, 2022).

To improve on the achievements of the MDGs, there was the establishment of 17 Sustainable Development Goals (SDGs) by the United Nations (UN) in 2015. This was done to foster a more sustainable and equitable world through the combined efforts of the Department of Economic and Social Affairs and more than fifty different international and regional agencies (Schramade, 2017: 87–88; United Nations: Department of Economic and Social Affairs, 2022: 3). As shown in Figure 3, these goals are meant to be a broader and more transformative road map for "Transforming our World: the 2030 Agenda for Sustainable Development". To achieve this, each of these 17 goals comprises a series of targets—169 in total—to assist people, companies and investors in evaluating their progress in achieving the goals. The main aim of these goals is for the UN to foster development by addressing a range of social, economic and environmental issues expected to culminate in what is called the Agenda for Sustainable Development 2030 (United Nations: Department of Economic and Social Affairs, 2022: 2).

Figure 2: The UN's 17 Sustainable Development Goals

(Source: Schramade, 2017: 88).

The SDGs in Figure 2 expanded the MDGs from 8 to 17 objectives. Also, where the MDGs (see Table 1) were more narrowly focused on poverty reduction through the work of a group of experts, the SDGs have far broader goals, such as to achieve global development 'with and for sustainability' (Pietrzak, 2022: 3). The goals of the SDGs also come from a broad consultation process between 193 member states of the UN, civil society and other relevant stakeholders.

Table 1 The key differences between the MDGs and SDGs

Criterion for Comparison	MDGs	SDGS
Number of goals	8	17
Number of targets	18	169
Number of indicators	48	231
Geographic coverage	Developing countries	Entire world (rich and poor countries)
Delivery focus	Narrow: poverty reduction	Broad: global development with and for sustainability
Goal creators	Produced by a group of experts	Result of a consultation process among 193 UN member states, civil society, andother stakeholders
Implementation timeframe	2000–2015	2016–2030

(Source: Pietrzak, 2022: 3).

Examining Figure 2, SDG numbers 1, 4 and 9 are particularly significant to this research. First, SDG 1 is focused on poverty. As a multidimensional issue, poverty must be addressed, focusing on its various forms, such as education poverty and health poverty, to name a few. According to the UN (2024), to reduce poverty levels, government expenditure of countries on essential services, including health, education and social protection, increased from a level of 47% in 2015 to a higher 53% in 2021. However, despite this change, the UN (2024) forecast that by the year 2030, a staggering 575 million people will still live in what is defined as extreme poverty, most of which will be living in the least developing countries.

Second, SDG 4 addresses education. Utilising the Human Development Index (HDI), a measure of development, 84 million children and youth will not be in school. In comparison, 300 million children will lack basic literacy and numeracy skills in the near future. Furthermore, only 1 in 6 countries will achieve universal secondary school completion targets by 2030 (Willis, 2021: 7).

Third, SDG 9 is based on building resilient infrastructure and promoting and fostering inclusive, sustainable and innovative industrialisation. According to the UN (2024), the global growth in manufacturing decreased from 7.4% in 2021 to a mere 3.3% in 2022. Also, the least developing countries are most likely to miss the 2030 target of doubling the manufacturing share of the gross domestic product (GDP).

Africa's Poverty, Education, and Infrastructure Challenges

Africa is still the poorest continent globally (Ibrahim, 2022; Lone and Ahmad, 2020; Sahn and Younger, 2009). This is because a substantial proportion of global poverty is concentrated in Sub-Saharan Africa (SSA) (Addison et al., 2019; Adesina and Campbell, 2023). While Africa is home to affluent individuals, approximately 40% of its population lives below the international poverty threshold or what is measured as less than US$1.90 per day in 2018 (Schoch and Lakner, 2020; World Bank, 2023b). Consequently, SSA accounts for two-thirds of the world's extremely poor population.

Encouragingly, the poverty rate in SSA did decline from a high 56% in 1990 to a lower 40% in 2018. However, this reduction has not offset the region's increased population growth, resulting in the continual rise of impoverished individuals. As of 2022, countries such as Malawi, Mozambique, the Central African Republic (CAR), and Niger exhibited the highest extreme poverty rates in Africa, based on the US$2.15 per day poverty threshold (Galal, 2024).

Regarding education, Africa also lags behind the rest of the world. According to the UNESCO Institute of Statistics, SSA's youth literacy (measured between the ages of 15-24) only averages around 77% (*Matsh*, 2023). This is quite low, given that the global youth literacy rate is 95%. Africa also trails behind other developing nations, where Latin America/Caribbean and East Asia/Pacific both achieved a youth literacy rate of 98%.

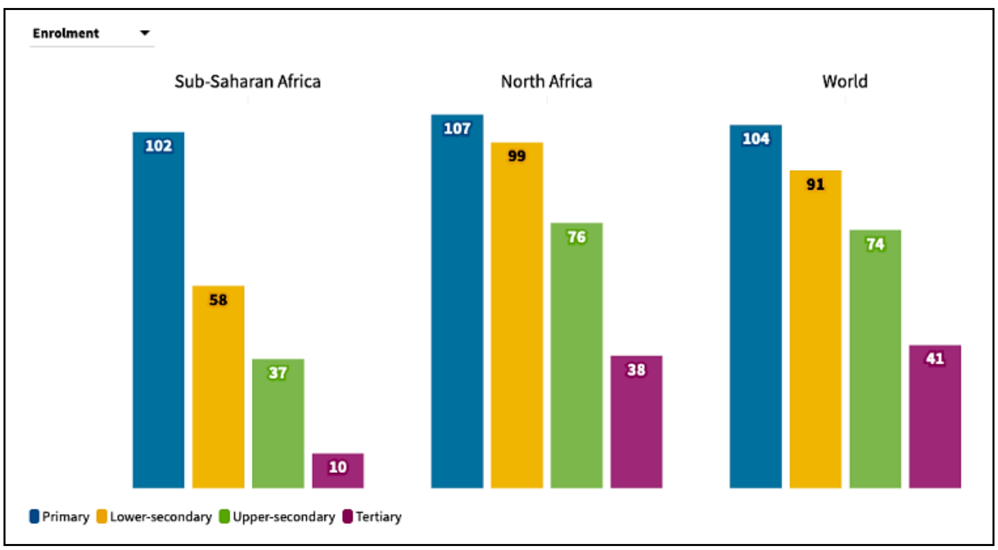
When examining secondary education, Africa only achieved a 50% gross enrolment ratio in 2019, with completion rates averaging just one-third across the region (*Matsh*, 2023). In line with this, gender disparities also persist, with enrolment for girls in secondary schools 10 percentage points lower than that of boys due to poverty, cultural norms, safety issues, and inadequate facilities. While enrolment has more than doubled since 2000, it has struggled to keep pace with rapid youth population growth similar to the trend in poverty levels.

Tertiary education participation is even more limited, with the gross enrolment ratio only reaching a staggering 9% in SSA, far below the global average of 38% (*Matsh*, 2023). In this regard, regional disparities are stark, with South Africa achieving a 20% tertiary enrolment rate compared to countries such as Sudan's 7%. Gender inequality and insufficient public university capacity remain critical obstacles. Fortunately, projections suggest a 40% increase in tertiary enrolment by 2030, driven by population growth and an expanding middle class. However, systemic barriers to quality and affordable access must be addressed urgently for this to occur (*Matsh*, 2023).

Education is crucial for Africa's development, with projections indicating that improved educational outcomes could lift millions of people out of poverty (Aikins, 2024). However, despite these postulated benefits, Africa—particularly SSA—continues to face significant challenges in advancing educational outcomes. Investigating the African Union's *Agenda 2063* of 2022, the continent failed to achieve its education targets, attaining a performance score of just 44%. Furthermore, access to basic education remains limited, and many school-aged children are not enrolled or attending classes (Aikins, 2024).

In line with this, the United Nations Educational, Scientific and Cultural Organisation (UNESCO) reports that in SSA, over 20% of children aged six to eleven and over one-third of adolescents aged twelve to fourteen are not in school. This figure rises dramatically to 60% for young people aged fifteen to seventeen. When examining Figure 3, SSA's educational enrolment and completion rates also become clear.

Figure 3 Education Enrolment vs Completion Rates in 2019



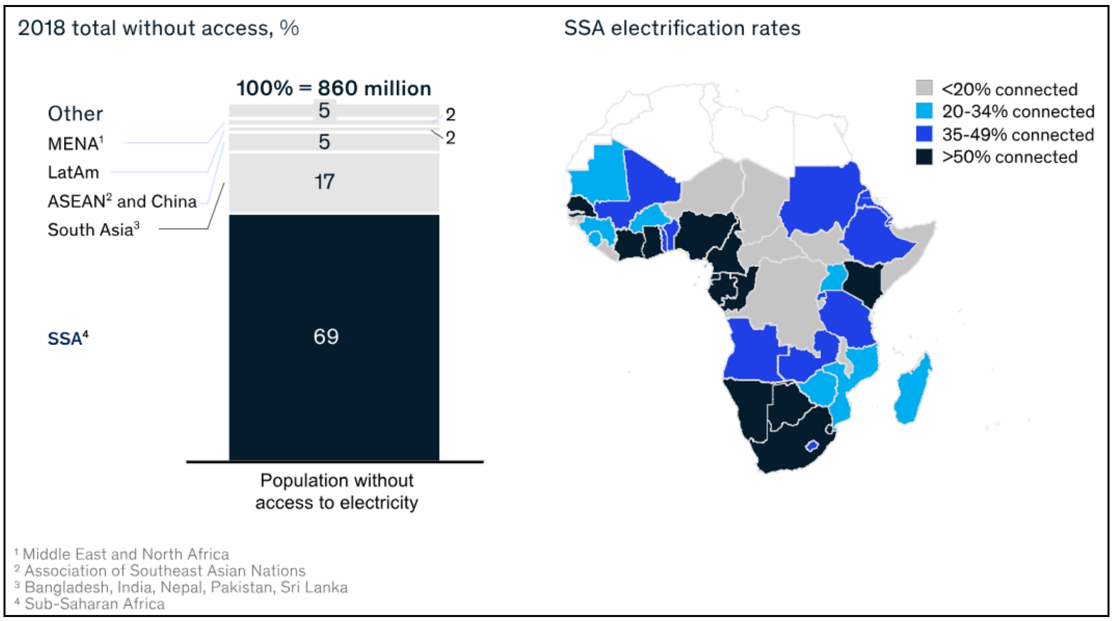
(Source: Aikins, 2024).

In 2019, SSA demonstrated high primary enrolment rates (102%), which surpassed 100% due to late or repeat enrolments but experienced significant declines in subsequent education levels, with only 58% and 37% enrolled in lower- and upper-secondary education, respectively, and a mere 10% at the tertiary level (Morsy, 2020). In contrast, the global averages highlight broader disparities, with higher participation at all levels compared to Africa, particularly in tertiary education, where the world average of 41% far exceeds SSA's. Given these trends, it is easy to see African regions' persistent challenges in transitioning students through higher education levels and aligning with global educational standards (Aikins, 2024).

When analysing infrastructure, a similar pattern emerges as with poverty and education. SSA continues to fall behind the rest of the world regarding critical infrastructure development, particularly in the areas of energy, transportation (road and rail), and water systems (Lakmeeharan et al., 2020). For instance, vast areas of the continent remain disconnected from the electricity grid, forcing households and businesses to rely on costly alternatives (see Figure 4). In 2015, the data revealed that generator-based power in SSA could cost three to six times more than grid electricity globally. Even where electricity is available, consumption levels are minimal; in Mali, for example, the annual per capita electricity usage is less than the amount a person in London needs to power a kettle (Lakmeeharan et al., 2020).

Opportunely, research indicates that infrastructure funding in Africa has risen in recent years. According to a 2018 Infrastructure Consortium for Africa (ICA) report, Africa's average annual infrastructure funding between 2013 and 2017 reached $77 billion—double the average in the early 2000s (Lakmeeharan et al., 2020). Nearly half of this investment occurred in West and East Africa, which accounted for around 27% and 19% of the total, respectively. Transport and energy projects dominated, representing almost three-quarters of the total investment.

Figure 4 The Distribution of Population without Access to Electricity by Region



(Source: Lakmeeharan et al., 2020).

Bridging the infrastructure gap is vital for Africa's economic growth, improving living standards, and expanding its business sector (Lakmeeharan et al., 2020). Encouragingly, infrastructure investment has risen over the past 15 years, and investors from abroad are showing interest and capacity to increase funding further. However, a major challenge remains: 80% of infrastructure projects are unsuccessful during the 'feasibility and business planning' stages. This 'infrastructure paradox'—a situation with a significant need and available funding alongside a robust project pipeline yet insufficient actual expenditure—highlights the critical barriers to translating potential into progress (Lakmeeharan et al., 2020).

With Africa staggering behind in the above-mentioned SDGs (1, 4 and 9), finding a relevant tool to address the social, economic and environmental challenges while yielding positive results is imperative. A plausible solution to the forecast concern of least developing countries not reaching their goals in 2030 may be resolved by the rise of the 4IR. Fundamentally grounded in digital transformation, the 4IR holds the potential to alter the livelihood and interactions between humans by merging new-age technologies with natural systems. That is, by integrating new-age technologies, such as robotics, AI, 3D printing, blockchain, the Internet of Things (IoT) and quantum computers, with interdisciplinary sciences such as biotechnology and social, cognitive and humanitarian sciences, 4IR can be harnessed to create more effective socio-technical systems that may ultimately lead to the SDGs being met (UNIDO, 2024). The question remains: *what can be done?*

The Opportunities of the Fourth Industrial Revolution (4IR) for Sub-Saharan Africa in Addressing Poverty, Education and Infrastructure Challenges

When analysing poverty, it becomes clear that Africa is not the only continent that struggles with this pervasive issue. To illustrate this, baseline projections indicate that around 6% of the worldwide population will still be living in extreme poverty by 2030, falling short of the first SDG's target to eradicate poverty by that year (Mhlanga, 2021: 5). Individuals experiencing extreme poverty continue to endure embedded deprivation, often compounded by their vulnerability, violent conflicts and natural disasters, especially now as the effects of climate change are felt more intensely. The situation is particularly dire in SSA, where poverty is highly concentrated, and approximately 38% of the working poor remained in extreme poverty in 2018 (as compared to only 8% elsewhere in the world) (Mhlanga, 2021: 5). So how can the 4IR assist in this?

Conde and Twinn (2019; cited in Mhlanga, 2021: 8) assert that one of the 4IR technologies, AI, is reshaping the global economy, with advancements in AI projected to contribute approximately $13 trillion to the 2030 global economic output. To illustrate this, the global market for AI-related technologies in the transport sector was valued at approximately 1.2 to 1.4 billion US dollars in 2017, with estimates suggesting growth to $3.1–$3.5 billion by 2023, representing a 12–14.5% increase. This indicates how much potential AI interventions have to enhance infrastructure across various sectors, including transport and agriculture, facilitating progress toward achieving the SDGs in general and alleviating poverty in particular (Mhlanga, 2021: 8).

When examining education, poverty reduction is closely linked to this aspect. The African Futures and Innovation programme, which is part of the Institute for Security Studies, reported that improved education levels in Africa have the potential to bring approximately 47 million out of poverty by the year 2043 and contribute an additional 368.4 billion US dollars (equal to 4.3%) to GDP (Aikins, 2024). This also relates to a higher GDP per capita of about US$240, and each additional year of schooling is linked to a nearly 0.6% rise in long-term GDP growth rates.

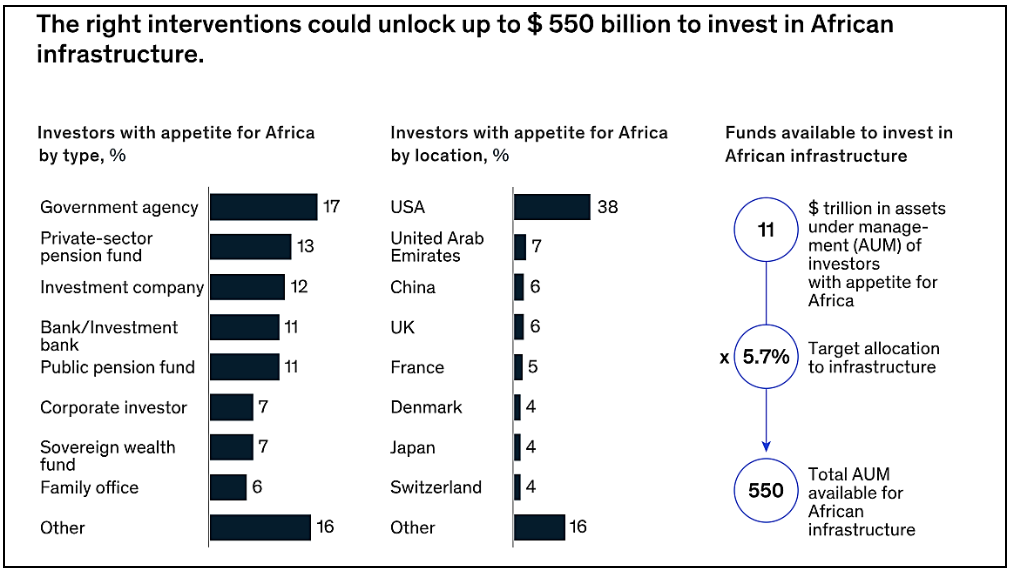
A possible opportunity for African education is solving the mismatch between what companies require and the skills being delivered by the African education systems (Morsy, 2020). For instance, several countries are already making notable progress in advancing education and digital access. For example, Egypt introduced 'interactive classrooms' by giving their students 1.5 million tablets preloaded with an electronic encyclopaedia accessible through school networks/youth centres. Additionally, around 2,500 Egyptian schools were equipped with high-speed internet, while novel solar-powered 'smart' classrooms are being established in remote areas utilising progressive mobile technologies (Morsy, 2020).

Similarly, the African Development Bank (AfDB) has implemented the 'Coding for Employment' initiative as part of its *Jobs for Youth in Africa* strategy (Morsy, 2020). This program is aimed at young people aged 15–35 and endeavours to equip training centres and universities with computers and other needed resources, to deliver demand-driven training in collaboration with leading technology firms, and to provide soft skills development alongside direct employment opportunities. Moreover, the AfDB is working with academic institutions to research ways of creating more adaptive African education systems that are more responsive to future demands (Morsy, 2020).

When it comes to infrastructure, Klaus Schwab (as cited in Maule, 2019) highlights the rapid advancements in renewable energy as one of the most significant achievements of Industry 4.0. For a continent where 69% of the global population without electricity resides—amounting to over 590 million people in 2018—and where electrification rates in many African countries remain below 50%, with some as low as 20%, the severe energy access challenges are evident (Lakmeeharan et al., 2020). These advancements are particularly critical, coupled with the continent's rising energy demands and the urgent need to expand its energy infrastructure (Smith, 2019, 2023). Renewable energy allows Africa to access clean, reliable, and climate-compatible energy sources, reducing dependence on fossil fuels. Moreover, innovations in renewable energy, fuel efficiency, and energy storage foster more profitable investment opportunities, driving business growth and contributing to GDP expansion in SSA (Maule, 2019; Smith, 2023). This progress could enable economically disadvantaged African states to develop more effectively while addressing the needs of millions across the continent who still lack access to electricity.

Furthermore, one fascinating study by McKinsey and Company (Lakmeeharan et al., 2020) underscores the significant potential for unlocking up to $550 billion in investment for African infrastructure through targeted interventions (see Figure 5). With $11 trillion in assets under management (AUM), international investors could allocate 5.7% to infrastructure, chief amongst them government agencies with 17%, private-sector pension funds with 13%, and investment companies with 12%. The US dominates geographically, contributing 38% of potential funding, followed by the UAE (7%), China (6%), and the UK (6%). Despite rising debt-to-GDP ratios in many African nations—exceeding 50% in SSA—international investors remain committed to both high-return greenfield projects and stable brownfield assets. In this regard, Africa's infrastructure pipeline, valued at $2.5 trillion and projected for completion by 2025, underscores growing momentum, although over half remain in feasibility stages. Concentrated in six countries, with Nigeria leading (17%), this pipeline reflects Africa's ability to attract transformative investment with the right policies and partnerships. (Lakmeeharan et al., 2020).

Figure 5 Unlocking Africa's Infrastructure Potential: Investor Appetite and Funding Opportunities



(Source: Lakmeeharan et al., 2020).

The Case Study of South Africa: 4IR and Digital Infrastructure Development

To analyse how the SDGs and countries in SSA overlap and how the obstacles to attaining these goals can be overcome, the article utilises the case study of South Africa. South Africa was chosen to represent the real-world context of how poverty, education and infrastructure development affect countries in SSA. Furthermore, this particular case study is utilised because South Africa has the most developed economy on the continent with a reasonably stable and diversified mixed economy, which consists of a mining, agriculture, and services sector, which can be applied as a representative instance in a pragmatic manner (Wisevoter, 2023).

However, as highlighted by prior studies and the recently introduced African Transformation Index (ATI) datasets done by the African Center for Economic Transformation (ACET), South Africa faces significant challenges in preparing for and capitalising on the 4IR (*African Center for Economic Transformation (ACET)*, 2023; Brown et al., 2023). Among these difficulties are a stagnating economy, a debilitating energy crisis, extensive transport inefficiencies, significant education challenges, the highest income inequality in the world (intrinsically linked to poverty), and deep-seated structural constraints (African Development Bank Group, 2023; Brown et al., 2023: 4–10; *Inequality, Poverty, and Jobs: South Africa's relationship to the Fourth Industrial Revolution*, 2018: 2; *MK Party*, 2024; Valodia, 2023; World Bank, 2023a). Thus, South Africa is no different than other SSA countries in this regard. How did South Africa apply 4IR technology to overcome some of its poverty, education and infrastructure challenges?

Regarding the first SDG of 'no poverty', the South African government started using AI to salvage an estimated R210 billion during the first eleven months of the 2024 tax year (Moodley, 2024a). Due to South Africa's current high unemployment and inflation climate, many taxpayers are prioritising other expenses, leading to a rise in the South African Revenue Service's (SARS) debt, now at R300 billion. This debt comprises amounts owed by individuals who do not dispute their liability but cannot pay or have de-prioritised their SARS obligations.

One key area where SARS has integrated AI is in debt propensity modelling, which uses machine learning algorithms to identify taxpayers with the highest likelihood of repaying debts efficiently (Moodley, 2024a). For instance, SARS prioritises contacting profitable, active businesses over dormant or insolvent entities to maximise recovery with minimal resources. Despite these challenges, the salvaged R210 billion was accomplished through the following interventions:

- AI and Debt Propensity Modelling (R70 billion): AI algorithms resolved 2.1 million debt cases, issued over 100,000 final demand letters, and facilitated nearly 24,000 civil judgements.
- Data Science Applications (R67 billion): Evaluating around 14 million tax returns, SARS flagged 1.5 million as high risk. Using a team of 550 auditors, SARS conducted verifications that improved compliance and collections.
- Refund Risk Management (R57 billion): SARS prevented fraudulent or impermissible refunds, including R34 billion in VAT, R13 billion in personal income tax, and R10 billion in corporate tax.
- Customs Fraud Interventions (R9 billion): SARS stopped 5,500 instances of cargo fraud, detecting and preventing R8 billion in customs fraud and leakage.
- Illicit Trade Interventions (R5 billion): SARS conducted 850 operations targeting illicit tobacco and alcohol trade, resulting in 550 detentions and 160 seizures (Moodley, 2024a).

The use of AI at SARS to achieve these goals is linked to poverty alleviation as Commissioner Edward Kieswetter noted: SARS has issued R22.5 billion in refunds to approximately 2.6 million taxpayers so far, equating to an average refund of over R8,000 per taxpayer (Moodley, 2024b). Also, the increased revenue can now be channelled into social spending like welfare programmes, education and infrastructure, thereby addressing poverty and inequality. Furthermore, by targeting high-net-worth individuals and corporations that evade taxes, these new AI-driven tax enforcement measures can promote fairness and ensure a more equitable distribution of the tax burden. Finally, it can also free up more resources to increase the support of the poor and vulnerable populations in South Africa (Fall, 2022; Howlett, 2012).

In terms of SDG 4, quality education through new technology has been in the spotlight since the advent of COVID-19 in 2020 (Donald et al., 2023: 427–429; Gastrow, 2021: 161). Suddenly, technology became essential as students no longer had the option of face-to-face or contact classes. Since then, technology has increasingly become integral to education, especially to the 'vanguards' of the 4IR: universities. In higher education, academics had to master literacy in technology to incorporate digital tools into their teaching practices. Some of these tools mentioned by Donald *et al.* (2023: 427–429) are:

- Online Learning and Massive Open Online Courses (MOOCs): The proliferation of these online platforms for learning and MOOCs has revolutionised access to education by offering flexibility and overcoming geographical barriers. Historically, the University of South Africa led this approach through its distance learning model.
- Virtual and Augmented Reality (VR and AR): These technologies are reshaping experiential learning as we know it. For instance, simulations and simulated field trips are being used to enhance comprehension and employability, while augmented reality overlays digital content onto the physical environment, revolutionising traditional teaching methods. An example is the University of the Witwatersrand (Wits), which utilises VR to deliver immersive surgical simulations for medical students, enhancing their practical skills and comprehension. Additionally, AR is employed in disciplines like engineering and architecture to provide interactive, hands-on learning experiences, bridging the gap between theory and practice (*Technological Higher Education Network South Africa*, 2024).
- AI and Machine Learning (ML): AI and ML have introduced personalised learning pathways, with AI-driven platforms such as ChatGPT enabling customised feedback and enhanced student interaction. The University of Johannesburg (UJ) has launched the Institute for Intelligent Systems, which is dedicated to AI research and its application in critical sectors such as healthcare, finance, and transportation. Big Data analytics is also being leveraged to tackle pressing issues, including climate change, disease outbreaks, and urban planning, driving evidence-based solutions (*Technological Higher Education Network South Africa*, 2024).

- The Internet of Things (IoT) and Smart Campuses: IoT technology has fostered the rise of smart campuses, where sensors and devices improve operational efficiency, optimise infrastructure, and provide actionable insights into student performance. These systems have facilitated the shift to online administrative processes, including applications and registrations (Donald et al., 2023: 427–429). An example is the Centre for High-Performance Computing (CHPC) in Cape Town, which offers researchers across South Africa access to advanced computational resources. Through collaborations with CHPC, universities can perform complex simulations, data analysis, and modelling, greatly strengthening their research capabilities and capacity for innovation (*Technological Higher Education Network South Africa*, 2024).

Regarding SDG 9, with a focus on infrastructure, South Africa is a founding member of the Square Kilometre Array Observatory (SKAO), and it has been involved in the Square Kilometre Array (SKA) project for over two decades (*Square Kilometre Array Observatory (SKAO)*, 2022). After nine years of bidding, South Africa and its eight African partner states were selected as the designated co-hosts of the SKA telescopes in 2012 alongside Australia. This is significant because the SKA will be the world's principal radio telescope, with a collecting area of one million square metres, enabling frequency coverage from 70 MHz to 10 GHz (Barradas, 2024). It comprises two arrays: SKA-Mid in South Africa with 197 dishes (including MeerKAT) and SKA-Low in Australia with 131,072 dipole antennas. Construction will occur in phases, allowing early operations by July 2028. The €2 billion project involves 500 engineers and over 1,000 scientists globally, aiming to revolutionise radio astronomy and generate significant scientific and economic benefits (Barradas, 2024).

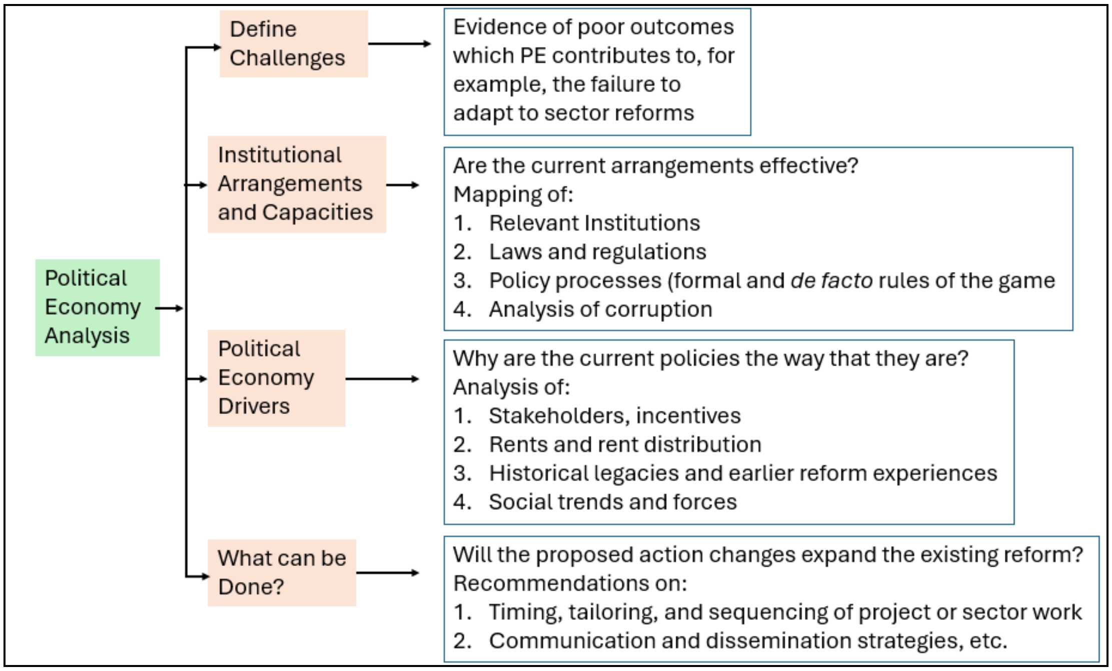
Some of these benefits to South Africa are that the SKA project will include two cutting-edge supercomputers, each with a processing speed of 135 petaFLOPS, making them among the fastest in the world (*South African Radio Astronomy Observatory (SARAO)*, 2023). The SKA-Mid supercomputer in Cape Town will process a maximum of 8.9 terabits of data per second which comes from 197 dishes transmitted via extensive fibre-optic networks. Construction of the SKA-Mid supercomputer will begin this year, with completion expected within the next three years, while the SKA-Low processor in Australia is set for 2027. Regional data centres, essential for storing and accessing processed data, will be operational by the decade's end. With construction underway, the SKA telescope is already generating data, paving the way for early operations to unravel cosmic mysteries and advance scientific theories by 2028 (South African Radio Astronomy Observatory (SARAO), 2023).

From a development perspective, the SKA project is poised to generate significant job opportunities during its construction, operation, and maintenance phases (Omarjee, 2022). It is also projected to stimulate greater interest in engineering, mathematics and astrophysics as fields of study in the country. Research shows the South African project component has already provided over 700 bursaries and grants to support education and skill development. After the hosting agreements were signed in October 2021, Dr Phil Mjwara, Director General of the Department of Science and Innovation, emphasised the project's numerous potential socio-economic benefits, which include industrial growth, job creation and capacity-building initiatives (Omarjee, 2022). In line with this, by early 2019, around R136 million had already been spent on local contractors for constructing MeerKAT (a radio interferometer), R162 million on salaries in the Northern Cape, R3 million on catering and accommodation, R4 million on transport, and R5 million on materials from local suppliers (*BusinessTech*, 2019; *South African Radio Astronomy Observatory (SARAO)*, 2024). KAT-7 (the first global radio telescope array made up of composite antenna structures and with 7×12m antennae), MeerKAT (with 64×13.5m antennae), and associated projects have created nearly 8,000 jobs, including employing over 100 local women by the South African Radio Astronomy Observatory (SARAO) between 2015 and 2017 and nearly 1,300 by subcontractors (*BusinessTech*, 2019; Carignan, 2017).

Applying the Steps in a Problem-Driven Political Economy Analysis to SSA and South Africa

When applying the findings of this article to the Problem-Driven Political Economy Analysis (PEA) framework in Figure 6, interesting patterns emerge. First, in terms of *defining the challenges*, it is clear that SSA suffers from poor outcomes. This is largely due to structural issues such as technological inequality, limited digital literacy, inadequate infrastructure and 4IR-readiness (see Figure 1) hinder the ability to harness 4IR technologies fully. For example, SSA's poor access to electricity (over 590 million people lack electricity) and low youth literacy rates (77% compared to the global average of 95%) severely constrain digital transformation efforts and sustainable development. These challenges are further compounded by the levels of extreme poverty on the continent (40% of SSA's population are living on a level of less than $1.90 a day) and persistent educational disparities (low tertiary enrolment rates of 9% in SSA versus the global average of 38%).

Figure 6: The Steps in a Problem-Driven Political Economy Analysis



(Source: Poole, 2011: 3).

Second, when examining the *institutional arrangements and capacities,* institutions such as those started by South Africa called the Institute for Intelligent Systems at UJ, focusing on AI applications and technical training centres to address skills deficits, come to the fore. The laws and regulations that play a role are South Africa's policies supporting 4IR technologies, such as tax reform powered by AI to recover R210 billion and the SKA project worth billions, showcasing initial efforts to align institutional frameworks with technological adoption. The efforts to expand the use of AI, IoT, and renewable energy are important for the policy processes. Here, the lack of robust and coordinated policies across SSA to fully support infrastructure development and educational reform can be identified and must be addressed to capitalise on the changing modern world. Finally, while this paper does not directly address corruption, existing research highlights that organised crime and corruption are pervasive and deeply entrenched across Sub-Saharan Africa (SSA), a region characterised by some of the highest levels of poverty and inequality globally (Global Investigative Journalism Network, 2022). This may explain why Africa is the second-highest region for criminality worldwide, following Asia. Alarmingly, violent crime has escalated significantly since 2000, with attacks targeting civilians reaching an unprecedented 9,024 incidents in 2022, compared to 1,206 recorded in 2000.

Third, regarding *political economy drivers*, the first aspect is SSA's key stakeholders. Regarding development, these stakeholders include governments, international organisations, universities, and private investors. However, a significant misalignment remains between educational systems and industry demands, with skills taught often failing to meet labour market requirements. Also, historical underinvestment in these areas has left a persistent backlog, compounded by rapid population growth that continues to outpace efforts to achieve universal secondary education and develop sustainable infrastructure. Encouragingly, social trends do highlight a growing momentum towards adopting 4IR technologies, such as renewable energy, IoT-enabled smart campuses, and AI in education as mentioned in the South African case study. Nevertheless, societal inequalities, particularly the digital divide, remain a critical barrier to ensuring equitable progress across the region.

The last aspect of the PEA is the question: What can be Done? To aid in SSA getting ready for the 4IR and benefitting from its technology for better sustainable development, the continent has to expand on its existing reforms. These extensions include those discussed in the South African case study, such as AI-driven tax systems and IoT-enabled smart campuses, that can be prioritised across SSA. Also, governments must concentrate on investing in critical energy infrastructure and internet connectivity to establish the foundational conditions necessary for successful digital transformation (Figure 1). For this to be implemented effectively, infrastructure gaps such as reliable electricity and widespread internet access have to be addressed as prerequisites for advanced 4IR solutions. Furthermore, initiatives such as coding programmes and renewable energy projects can help foster investment, participation, and equitable progress across the region, which have significant untapped potential, as seen in Figure 5.

Conclusion

In conclusion, adopting 4IR technologies presents a transformative and even a leapfrog opportunity for sustainable development across SSA. This is illustrated by South Africa's efforts in integrating AI into their tax systems, establishing smart campuses, and technical training initiatives, demonstrating the capacity of 4IR technologies to address systemic issues like poverty and unemployment. These developments also highlight the critical role of governments, educational institutions, and international partnerships in fostering innovation and aligning policies with technological advancements. The construction of the SKA project also holds numerous development benefits for South Africa, generating jobs, income and scientific infrastructure.

However, as Figure 1 highlighted, SSA faces critical challenges in attaining the necessary infrastructural preconditions for the region to capitalise on the 4IR effectively (Oosthuizen and Mkhize, 2024). Some key challenges include those discussed here, such as persistent poverty and education combined with infrastructure challenges, but also include high unemployment rates, inequality, crime and low economic competitiveness. To address these issues, SSA nations require a comprehensive approach that aligns with the prerequisites for 4IR readiness in Figure 1. These comprise developing robust digital IT infrastructure, fostering digital literacy, upskilling citizens to meet technological demands, and ensuring macroeconomic stability through structural reforms. Furthermore, economic growth and enhanced state capabilities are essential to create an enabling environment for technological adoption, alongside targeted measures to mitigate poverty and crime, particularly cybercrime. By meeting these preconditions, SSA can benefit from the transformative capability of the 4IR for greater sustainable development and global competitiveness.

The application of the PEA framework further emphasises the need to address key drivers of reform, such as institutional arrangements, stakeholder incentives, and historical legacies, to ensure the successful implementation of 4IR technologies. By addressing institutional inefficiencies, aligning education systems with labour market demands, and tackling the digital divide, SSA can harness 4IR technologies for socio-economic transformation and accelerate progress toward achieving the SDGs. Leveraging the insights from the PEA framework, fostering stakeholder collaboration, and scaling these reforms are essential steps for SSA to position itself as a leader in the global advancement of technology-driven solutions while meeting the SDG goals.

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