International Journal of Smart Sensor Technologies and Applications
Volume 2 • Issue 1

The Circular Economy, Big Data Analytics, and the Transformation of Urban Slums in Sub-Saharan Africa

Darrold Cordes, Curtin University, Australia*
Gregory Morrison, Curtin University, Australia

ABSTRACT

Sub-Saharan Africa is currently experiencing growth in the number of people living in poverty, and the situation is worsening due to climate change and the COVID-19 pandemic. Cities are increasingly under stress because of urbanization and the demand for low-cost housing. Slum dwellers face daunting social, environmental, and economic challenges. Geospatial analysis of remote sensing, demographic, economic, social, and environmental data is being used to delineate slums. The application of circular economy guidelines for an intelligent transformation of slums combines technical and social innovation that reaches beyond the slums to the whole urban ecosystem. Examples of contributions to the circular economy are provided. Finally, some ideas are introduced on how the internet of things can improve access to goods and services and strengthen interconnectedness through the ability to participate more readily in the social dialogue of the city. The city of Accra in Ghana, West Africa, is discussed as a potential slum city to functional intelligent city transformation.

KEYWORDS

3D Printing, Aquaponics, Big Data, Biomass, Blockchain, Data Analytics, Developing Countries, Geospatial, Intelligent City, Machine Learning, Sanitation, Smart City, Social Wellbeing

1. INTRODUCTION

The UN-Habitat (2016) World Cities Report 2016 provides comprehensive insights into the challenges facing urban slum dwellers, policy makers, and urban planners. Slums exist everywhere, but they are more evident in developing countries exacerbated by rural-urban migration, poor urban planning, and weak governance (UN-Habitat, 2016). Slums are highly correlated with poverty (UN-Habitat, 2016).

Mahabir et al. (2016) provide an historical account of the tried and failed policy initiatives to eradicate slums over the past 50 years. They refer to the *sites and services* approach during the 1970s that led to the relocation of slum dwellers to new sites and to the former slums being demolished. Displaced people were required to pay for the new infrastructure developments and housing. Without adequate resources, the slums continued to flourish. For example, the Brazilian government effort in the 1970s to forcibly displace favela (slum) dwellers into public housing without adequate planning

DOI: 10.4018/IJSSTA.319720 *Corresponding Author

and support resulted in the creation of new favelas (Brown University, 2019). Mahabir et al. (2016) describe the policy initiative of the 1980s to redevelop the slums in-situ. This approach also failed primarily because of the lack of financial commitment and the failure to recognize the importance of addressing the economic conditions of the slum dwellers, governance issues, and land tenure issues (Mahabir et al., 2016). The next policy initiative was to bestow land ownership on the slum dwellers based on the assumption that the structure within which they lived was owned by the occupier. This assumption proved to be incorrect, and occupiers could still be evicted. Mahabir et al. (2016) discuss the more recent Nelson Mandela inspired Cities Without Slums initiative which acknowledges the link between poverty and slums. It appears that this initiative has given way to the United Nations Sustainable Development Goal (SDG) 11 which was revised extensively in 2018 to *make cities and human settlements inclusive, safe, resilient, and sustainable* (United Nations, 2019b).

The United Nations (2019a) and World Bank (2019b) aim to eliminate poverty by 2030, but efforts to reduce poverty are being hampered by climate change, the emergence of the COVID19 pandemic during 2020, and persistent problems in Sub-Saharan Africa (S-SA) (World Bank, 2021b). A study by Kedir et al. (2017) reveals that Africa requires an economic growth rate of 16.6 per cent per year between 2015 and 2030 to meet this goal. The United Nations Development Programme (UNDP) estimated the growth elasticity of poverty reduction in S-SA to be -0.7 (Bhorat & Naidoo, 2014). Hence, for every 1% increase in gross domestic product (GDP) a 0.7% reduction in poverty is gained. The task of poverty reduction in S-SA is daunting. Bhorat and Naidoo (2014) note that inequality will act to the reduce the impact that GDP growth has on poverty.

West African countries are facing a poor investment climate and insufficient technical capacity to take advantage of increased foreign direct investment (FDI) (Eregha, 2015). S-SA suffers profound and abject poverty in many areas (Beegle et al., 2016) and Patel (2018) estimates that in 2015 there were 413 million extremely poor people in S-SA living off less than $1.90 per day. The World Bank (2019b) estimates that by 2030, nine out of ten extremely poor people in the world will live in that region, and that the number of people living in extreme poverty in S-SA is increasing. The United Nations (2019c) estimate that the two central African nations of Nigeria and the Democratic Republic of Congo will be among the ten most populous countries in the world by 2050. The diversity of nations on the African continent stands in the way of a uniform approach to poverty eradication. The problems in S-SA have triggered an elevated sense of urgency among the African Union which is aiming to reduce poverty to below 3% by 2063 (African Union, 2019) under the African Union Agenda 2063 initiatives for the eradication of poverty (Institute for Security Studies, 2019).

Ghana is a country of 31,072,945 (2020) million people (World Bank, 2021a) in West Africa. Its main exports are oil, cocoa, and gold (UNCTAD, 2019). The World Bank (2019a) predicts economic growth of 7.6% for Ghana in 2019 while acknowledging problems with fiscal consolidation, currency depreciation, and the energy sector. Ghana ranks high in Africa for freedom of speech and press freedom but ranks 75/180 in the world for corruption, where a ranking of 1/180 denotes the least corrupt country (Transparency International, 2020). Ghana has been a model among the Economic Community of West African States (ECOWAS) for its social programs to reduce poverty and for economic growth. However, the World Bank (2020) Ghana Country Environmental Analysis report states that economic growth has come at a significant cost to the environment and to the health and wellbeing of its population. They claim that, as of 2017, 10.7% of Ghana's gross domestic product (GDP) is being lost annually because of the decline in its natural resources and the impact on human health.

Accra is the capital city and main political and commercial center of Ghana. The population of the Accra Metropolitan Assembly (AMA) was 1,665,086 at the 2010 census (AMA, n.d.). The Greater Accra Region population growth rate is 3.1% per annum (AMA, n.d.). When this growth rate is applied to the AMA 2010 census population, an estimated 2,259,557 people lived in the AMA in 2020. The World Bank (2018) estimate that 38.4% of the AMA or approximately 867,670 people live in slums.

Much of the literature on intelligent cities focuses on cities in the developed world and, while there have been many studies on slums, little attention has been given to the transformation of slums as the pivotal initiative leading to intelligent cities in the developing world. The World Economic Forum (2018) outlines the concept of a slum area being designated as a microcity or special development zone to be developed as the *framework for urban reform*. The pathway for the transformation of slum cities in developing countries presented in this article share the core concept of the microcity and expand on it as the genesis for intelligent cities of the future. At the centre of this approach is the recognition that sustainable economic development is the primary motivator for slum dwellers to engage in the transformation process.

The following section discusses the identification of slums in Accra using a combination of inputs to produce maps of likely slum neighborhoods. This highlights the complexity of the slum environments and profiles the physical challenges to redevelopment. Mapping of slum areas helps to delineate land areas in a country where land ownership can be contested because no accurate records exist. An integrated environmentally sustainable circular economic model that combines commercial activities and associated community infrastructure is then introduced. This is followed by discussions on imperatives within this model for manufacturing, energy production, food production, housing construction, water, sanitation and health, transport, and education. Finally, an insight is provided into the types of data that could be collected through a variety of techniques, the processing of the data, and the reporting of information to households and businesses as the first increment towards a functionally intelligent city.

2. DEFINING A SLUM CITY

There does not appear to be any formal definition of a slum city. One simple approach is to calculate the percentage of the total population within the metropolitan area that are slum dwellers and then establish a threshold above which the city may be deemed a slum city. At a nominal threshold of 50%, slum dwellers comprise 50% of the total metropolitan population. UN Habitat (2020) World Cities Report 2020 claims that 60.7% of all urban populations in S-SA live in slums. All cities in S-SA would exceed the 50% population threshold and are hence slum cities. The AMA has 38.4% of its population living in slums occupying 29.6% of the land area (World Bank, 2018). While not exceeding the nominal 50% threshold, the extent and degradation of conditions in slums in Accra in terms of land area, environmental impact, and population would deem it to be a slum city.

2.1 Identifying Slums

Mahabir et al. (2016), when referring to the UN Habitat (2018) report, state that approximately 1 billion people globally are slum dwellers, and they project that this will grow to 2 billion by 2030 and to 3 billion by 2050. The UN-Habitat (2018) report defines a slum household as a group of individuals living under the same roof in an urban area and who lack one or more of the following:

- Durable housing of a permanent nature that protects against extreme climate conditions.
- Sufficient living space which means not more than three people are sharing the same room.
- Easy access to safe water in sufficient amounts at an affordable price.
- Access to a private or public toilet that is not demand overburdened.
- Security of tenure that prevents forced evictions.

Mahabir et al. (2016) state that work undertaken in slums has been mainly concentrated in the following areas:

- Socio-economic and policy.
- Methods for determining the physical characteristics of slums using remote sensing.
- Modelling of slums using machine learning and agent-based modelling to gain a more complete understanding of the extent of the slums in urban areas.

Kuffer et al. (2016) undertook a review of literature for the period 2000 – 2015 of space-based observations of slum mapping techniques. They concluded there is limited understanding of the nature and diversity of slums globally and that further research was required to describe slum environments more accurately. Taubenbock et al. (2018) investigated the spatial structure of a selection of arrival cities worldwide. They used a combination of earth-observation remote sensing data, street view imagery, and field surveys to develop an index of morphologies for these cities and concluded that no single morphology identifies all urban slums. Arrival cities are those areas of the urban environment that may otherwise be referred to as *slums* or *informal settlements* that offer the lowest cost housing alternatives for arriving immigrants (Taubenbock et al., 2018).

Engstrom et al. (2015), Engstrom et al. (2019), and Mahabir et al. (2016) acknowledge that two-dimensional remote sensing needed other information from household surveys, census data, other aerial maps, and boundary maps to obtain a more detailed view of slums. Large slum areas are not easy to hide in the urban landscape, but smaller pockets of slums with different spatial characteristics make them harder to discern. For instance, Figure 1 shows a small part of the well-known Agbogbloshie slum in Accra, Ghana, which has a population of between 25,000 and 40,000 people over 146 hectares Owusu-Ansah et al. (2016). To illustrate the difficulty of determining the population and area of slums, The Rockefeller Foundation (2019) estimated the population of Agbogbloshie to be 80,000 occupying only 35 hectares. Other areas of Accra that are deemed slums do not have the same appearance and crowding of homes.

Mobile phone metadata was used to predict poverty and map wealth distributions in Rwanda (Blumenstock et al., 2015). Phone data was combined with targeted survey data to predict wealth, social connections, travel patterns, and other expenditures. Njuguna and McSharry (2017) confirmed that mobile phone meta-data, night illumination data, and population data could provide an estimator of poverty. Xie et al. (2016) trained a convolutional neural network (CNN) using night illumination data to delineate areas of poverty. They claimed poverty prediction results approaching that of survey

Figure 1. Image of Sodom and Gomorrah (Agbogbloshie, Accra, Ghana) Attribution: atcmask.com

data. However, while night illumination data is available from the National Oceanic and Atmospheric Administration, accurate census and survey data is not readily available in S-SA (Blumenstock et al., 2015; Njuguna & McSharry, 2017; Xie, 2016)

2.2 Locating the Slums of Accra

Every city and its slums are different. The UN-Habitat (2018) definition of slums requires extensive household surveys and census data to correctly classify localities as slums. This is an expensive process and the infrequency of these surveys and censuses does not support continuous monitoring of any slum transformational efforts. Continuous self-reporting or crowdsourcing of data can contribute additional inputs to remote sensing or satellite imaging of cities. Data analytics plays a big role in the monitoring and evaluation of the slum city transformation. Data analytics may be used to develop comprehensive understandings of the slum environments, social structures, and the wellbeing of the slum population. These understandings are crucial to redevelopment plans and in the creation of opportunities for community involvement in such plans. Geospatial data and economic data may be combined with data sourced from the slum populations on issues ranging from food, transport, health, education, and access to government services to create visualizations to aid social, economic and infrastructure programs. Data analytics will continue to play an on-going role in the monitoring of the progress of redevelopment, social engagement, economic growth, and contributions to environmental rehabilitation.

2.3 Mapping of Accra Metropolitan Assembly

The AMA (n.d.) state that the population of the AMA is growing at a rate of 3.1% per annum. Using the 2020 estimate of 867,670 people living in slums in Accra this would mean that the slum population would swell to about 2,168,276 by 2050, unless mitigating interventions are adopted immediately. The growth in slum populations comprises the normal population increase and the rural-urban migration rate. Engstrom et al. (2019) utilized household survey data, high resolution geospatial imagery, census data, and multiple methodologies to produce a machine learning slum index and a consumption poverty map. They observed that household size, elevation, and population density were the most significant variables in the creation of a slum index. Figure 2 is the machine learning slum index where the higher index values indicate areas of higher slum incidence (Engstrom et al., 2019).

Figure 3 is a consumption-based map from which Engstrom et al. (2019) concluded that the low variability of building orientation is more likely to be correlated with higher consumption. Slum areas are often characterized by random building orientations. They observed that occupancy in slum dwellings is for relatively long periods from which it may be concluded that other factors such as linkages to business opportunities and jobs, social networks, and cultural/religious associations may contribute more to longevity of stay than monetary considerations. This is an important observation when considering any redevelopment plans for slums.

2.4 Enumeration Areas

Ghana undertook its last census in 2010 and recent completed the 2021 census. For these censuses, the country is divided into enumeration areas which are the largest spatial units that a single census officer can cover during the period of the census. These areas each contain approximately 600 people in 150 households. The number of enumeration areas for the Ghana 2021 census was 82,000. Extensive household data is collected during the census. Figure 4 is a map of the enumeration areas in the Ashanti Region showing population density for the 2010 census (Ghana Statistical Service, 2019). The dark area near the center of the map is the city of Kumasi which had an estimated metropolitan area population of 2,010,000 people in 2010 (Macrotrends, n.d.).

The enumeration areas are an ideal spatial unit for testing slum and other low-income sustainable development initiatives and the alignment with census data in the future will help develop a comprehensive understanding of community wellbeing.

Figure 2. Machine Learning Slum Index of Accra, Ghana Attribution: Engstrom et al. (2019)

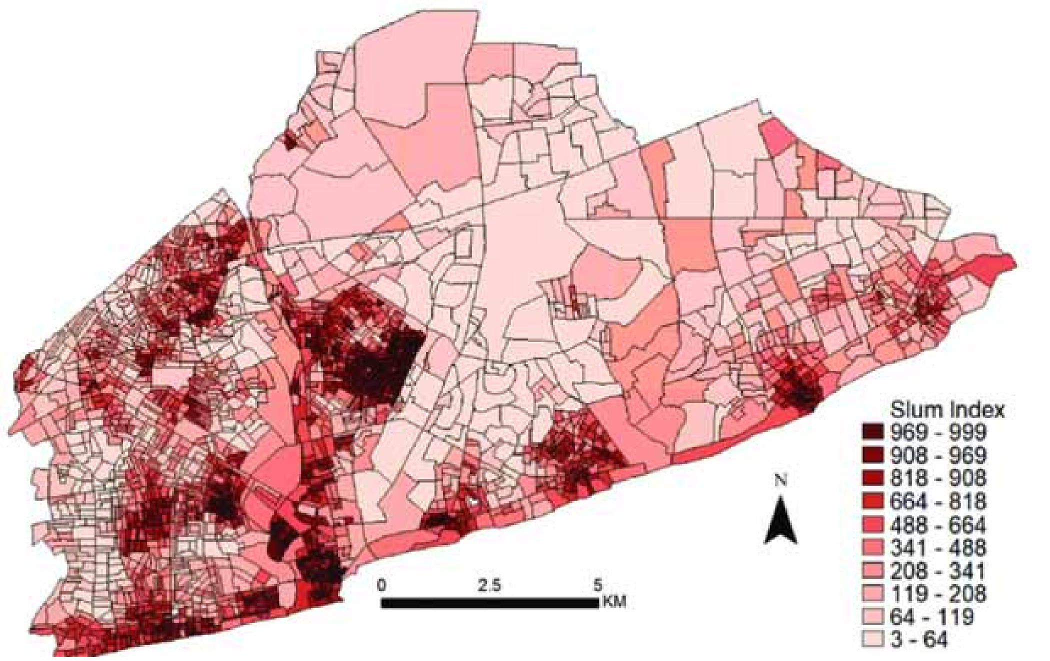


Figure 3. Poverty Map by Consumption for Accra, Ghana Attribution: Engstrom et al. (2019)

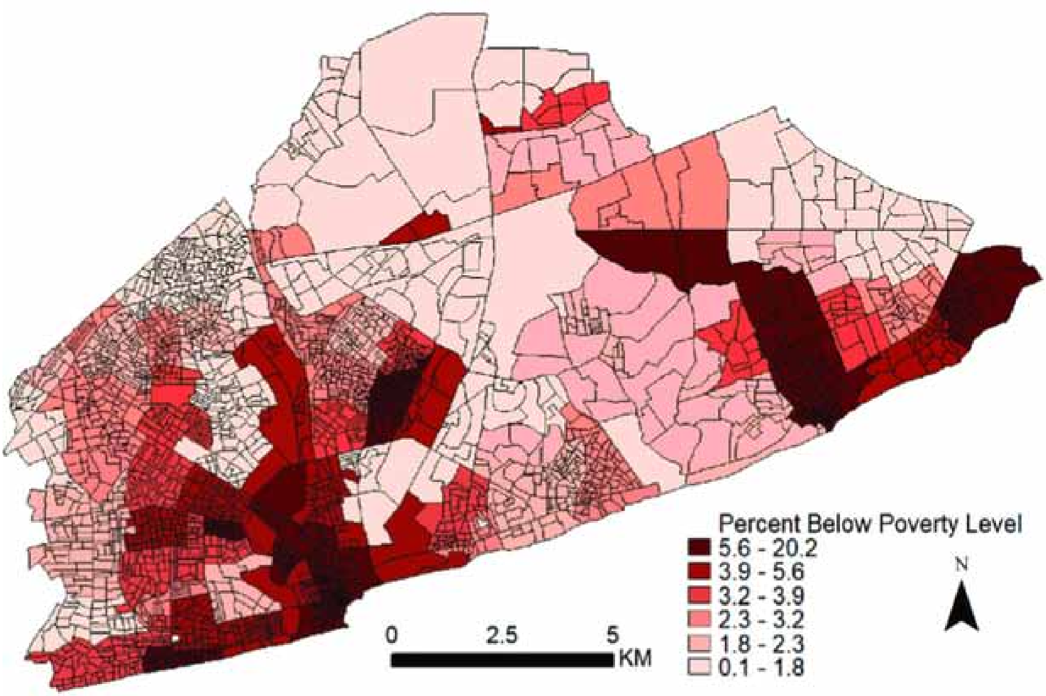
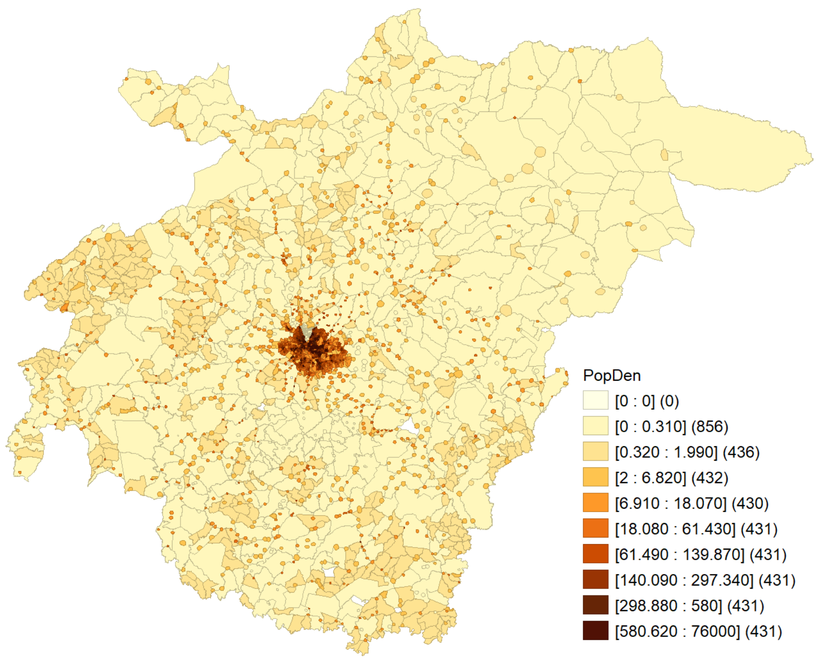


Figure 4. Ashanti Region - 2010 Enumeration Areas - Population Density Attribution: Ghana Statistical Service (2019)



2.5 Slum Land Ownership

Land rights in Ghana are distributed between traditional owners and the government on an 80:20 ratio (Stacey, 2018). Traditional land is referred to as skin or stool land and is often subject to disputes over who has authority or delegation over its use or disposal (Stacey, 2018). The processes for the administration of land entitlements in Ghana are not working well and this is further exacerbated when dealing with slum land because of the presence of squatters (Stacey, 2018). Traditional land is often not registered with the Land Title Registry and disputes over the demarcation of boundaries occur (Stacey, 2018). Issues of land ownership and occupancy entitlements must be resolved prior to redevelopment of the slums. This will instill confidence in all stakeholders that slum city transformations can proceed with the establishment of a built environment that provides affordable housing, small business facilities, and community infrastructure without the need for relocation.

3. SLUM CITY TRANSFORMATION (SCT)

The transformation of a slum city is a *function accompanying intelligent* process that strives to meet the multi-dimensional needs of the population while positioning for regional and global relevance. These needs are encapsulated in the concept of wellbeing which can be expressed as levels of consumption of commodities, health, education, freedom, self-esteem, access to services, and transport above which a person, family, or a community can equitably function in the broader society (Haughton & Khandker, 2009). A classification of wellbeing goes way beyond monetary considerations to embrace the emotional capital associated with social identity, equality, belongingness, freedom of speech, and security (Haughton & Khandker, 2009). Wellbeing is difficult to define, and it varies considerably across regions and countries. Measures of wellbeing in developing countries are local or regional and bear no comparison with the developed world. Wellbeing in a developing world may be significantly enhanced with relatively simple improvements to daily routines. For instance, the daily collection of water for household use may take hours. Provision of community wells have the potential to improve a sense of wellbeing in the community.

While an absolute measure of wellbeing is difficult to define, it is possible to quantify some characteristics of human ecosystems that contribute to wellbeing. For the purposes of this article, the objective is to attempt to show that everything that is observable can provide highly nuanced insights to the human condition. This is a big data concept that continuously informs the condition of the natural environment, the built environment, and human behavior. With sophisticated data collection and computational tools, social scientists can model and develop strategies to inform policy decisions on a wide range of public health, safety, economic, social, and environmental initiatives in near real time. Table 1 identifies 5 broad factors contributing to wellbeing measured on a 0 – 5 scale. Each factor contributes on a scale of 0 – 1.

Each of the 1 – 4 contributing factors in Table 1 are composites of reasonably quantifiable elements that can be reported consistently at the local level. Currently, many of these factors are derived from census, surveys, and other independent analysis including the World Bank, aid agencies, research organizations, and government reports. There are significant limitations to these sources of data. Censuses are taken every ten years in developing countries, if at all. Survey data is a sample of the population, and other reports tend to be a macro level view of the population. For example, Gross Domestic Product (GDP) per capita does not reflect the inequality across all sectors of the population. With the Internet of Things (IoT), much of the data collection can be automated, or at least granulated to the enumerations areas of the censuses and reported semi-automatically in near real time. Reporting entities can be individuals with smartphone apps, businesses, government agencies, schools, clinics, and other community organizations. Hence, the assessment of the contributing factors is endogenous to each community. The standards used for assessing factors that contribute to wellbeing in developed countries may not be applicable for developing countries. For instance, a suburban street in a city in a developing country does not have to be paved to serve the access requirements of a community, just reasonably well maintained.

Mahabir et al. (2016) and Bettencourt (2014) present the idea that cities are a collection of self-organizing social structures and that the cities are shaped by these structures and the individuals who live and work there. Prior to the age of the Internet and intelligent mobility devices, print media disseminated local, regional, and global news. Interpersonal communications were facilitated by written exchanges delivered by the postal service, print media, or verbally via the telephone (Bettencourt, 2014). These large interconnected social networks benefited from information sharing which gave voice to community ideas and guidance to the shaping of the environment by urban planners. New technologies for information collection and sharing are supportive enablers of these *social dynamics* (Bettencourt, 2014). The transformation to an intelligent city is a potential contributor to social capital. Internet social media forums, talk-back radio, print media, and public forums can

Table 1. Measure of Wellbeing

#	Contributing Factor	Scale	Description
1	Public Infrastructure	0 - 1	Roads, public transport, energy, telecommunications, security, water supply.
2	Social Infrastructure	0 - 1	Schools, clinics/hospitals, recreation, culture.
3	Environmental Infrastructure	0 - 1	Water quality, sanitation, waste management.
4	Economic Infrastructure	0 - 1	Business activities, jobs, incentives, financing.
5	Social Capital	0 - 1	Combination of other factors that reflect a sense of societal connectedness, belonging, and empathy.
	Wellbeing	**0 - 5**	**0 = extreme depravity, 5 = utopia**

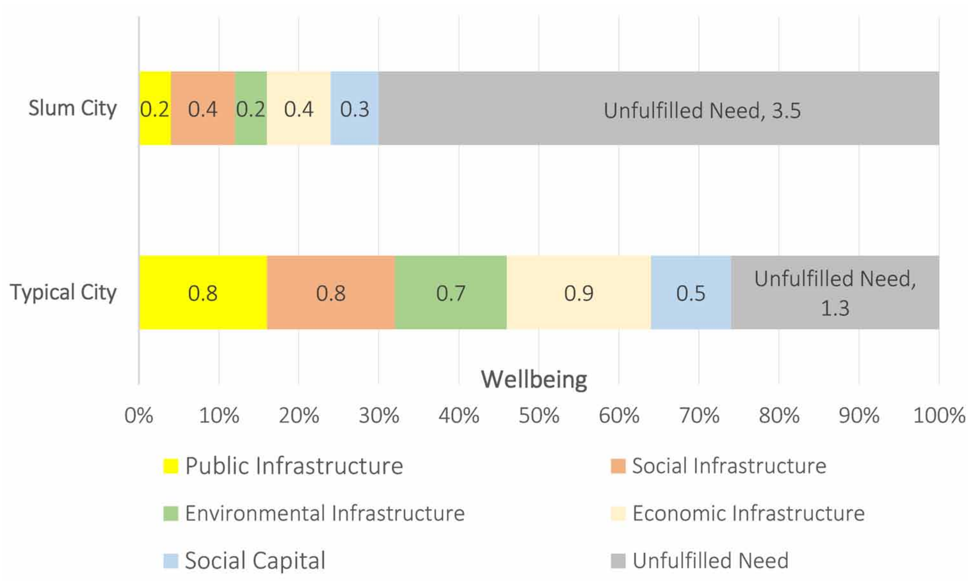
provide a rich continuous stream of data that can be analyzed using big data analytic techniques to better understand the structure of social capital. The social capital component in Table 1 is illustrated in Figure 5. The intelligent city contributes to social capital. Cities assume a character that is reflective of its culture and shared beliefs, which also includes a voice from slum dwellers. Figure 5 depicts a wellbeing scale that is a simple combination of the contributing factors in Table 1. The unfulfilled need is the accumulated shortfall of all contributing factors in Table 1. No single contributing factor in Table 1 can compensate for shortfalls in the other contributing factors. However, the contributing factors are not uncorrelated. Improvements in social infrastructure, for instance, could have arisen because of an investment of social capital (collective voice, election results). A successful outcome of this investment may have not only resulted in improved social infrastructure (hospitals, schools) but also an increase in social capital through a sense of collective achievement and empowerment.

The pathway for slum cities to become functional intelligent cities begins with the urban slums and the enduring issues that are at the core of the people who inhabit them. It is not a simple matter of rebuilding them with better quality houses (World Economic Forum, 2019). Housing is an important issue but any attempt to improve the quality of life of slum dwellers must recognize the broader social, economic, and environmental conditions of the people. This means that basic infrastructure such as transport, roads, water and electricity supply, appropriate housing, and other services enjoyed by the more affluent sectors of society must also be made available to the slums. Economic opportunities must be integrated into slum development initiatives to encourage innovation and entrepreneurial initiatives, and to create job opportunities while preserving and enhancing the social fabric. Slum dwellers have formed social networks and other support structures, and redevelopment should take place in-situ. Environmental factors should address the need to improve physical and emotional health, including access to clean water, proper sanitation, health care, and a quality education. Air quality and resilience to climate change are important markers of a more secure environment.

3.1 Circular Economy - Conceptual Model for Slum Transformation

Central to the transformation of a slum city to an intelligent city is the restorative and regenerative design concepts of the circular economy (Marchesi et al., 2020). Successful transition to an intelligent

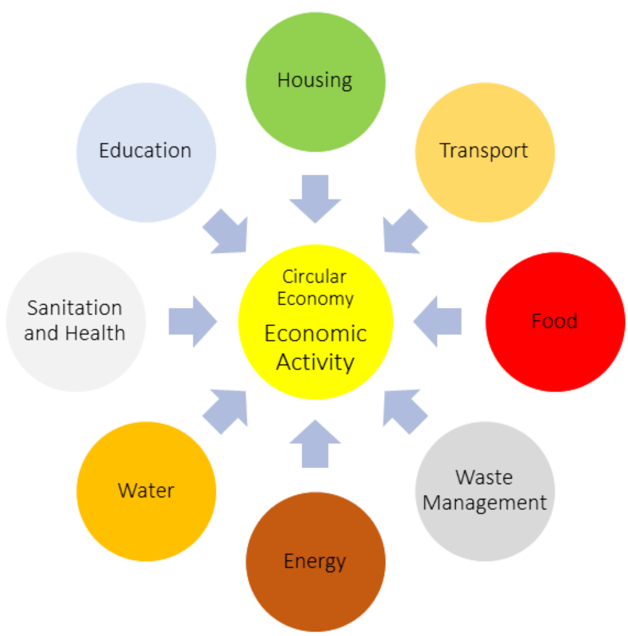
Figure 5. Wellbeing Index – Conceptual Comparison of Slum City and Typical City



city must build technical and social innovation into the broad fabric of the socio-technical systems (Marchesi et al., 2020). Technical innovation is the physical infrastructure that provides for housing, places of work, and interconnecting linkages for the movement of goods and services (Marchesi et al., 2020). Social innovation is less obvious, but it is linked to social capital and comprises a collective approach to the development of new paradigms for the management of natural capital and for product design, recycling, and behaviors to meet social needs for housing, food, energy, water, waste treatment, and sanitation. Figure 6 illustrates this concept with the economy at the nucleus that draws in the social and environmental needs of society to inform and direct the restorative and regenerative use of assets and resources. In developing countries there are unsustainable demands on natural capital and the goal of the circular economy is to reduce these demands and to contribute returns to the biosphere (Marchesi et al., 2020). Education and health are included in Figure 5 because social innovations will ultimately arise out of generational perceptions of the fragile ecosystems and out of ideas on how to best manage coexistence. Health contributes to the circular economy through measures of productivity, resilience to disease, and the importance of nutrition. According to Marchesi et al. (2020) there is no theoretical underpinning of the influence of social innovation on socio-technical systems. However, it is conceivable that the multi-level perspective of socio-technical transition theory might be useful as an explanatory model for social innovations as it does for technical innovations (Geels, 2002). In S-SA there is evidence of a growing presence of social entrepreneurs who combine people, resources, and innovations to address poverty alleviation (Foy Connor & Bent-Goodley, 2016). These social entrepreneurs are working in communities to maximize social value and to engender empowerment.

Technology plays a vital role in every element of the conceptual framework in Figure 6. Technology is evident in industrial machinery, agribusiness, transport, construction, food processing, health, education, and public utilities. New fabrication technologies offer potential for decentralization of manufacturing using locally sourced materials (All3DP, 2019). Information and communication technology (ICT) is present in almost everything that is encountered in daily routines. A vast array of devices may be connected to the Internet to collect and process data, to control machinery, and to interact with humans. The Internet can be viewed as a fragile system of communication nodes that

Figure 6. Circular Economy - Conceptual Model for Slum Transformation



facilitates this connectivity and the combination is commonly referred to as the IoT. There is practically no limit to the amount of data that can be collected and directed to vast data lakes or processed in real time for immediate visualization. The collection and processing of data from sources within a city can provide insights into the performance of social innovations and potentially contribute to the social capital of the city. This concept is not new. The systems are already in place to exploit capitalistic market opportunities for goods and services. Considerable knowledge on consumer needs and behavioral patterns is being rapidly accumulated as business intelligence. This very same technology can just as easily be deployed to describe and quantify social capital.

The following section discusses each element of Figure 6 in more detail and how they contribute to the development of slums as vibrant and strongly engaged participants in the transformation of slum cities to intelligent cities. Process technology and ICT are foundationally embedded into each element and generate continuous streams of data for processing and visualization as discussed in the last section.

3.2 Economic Activity

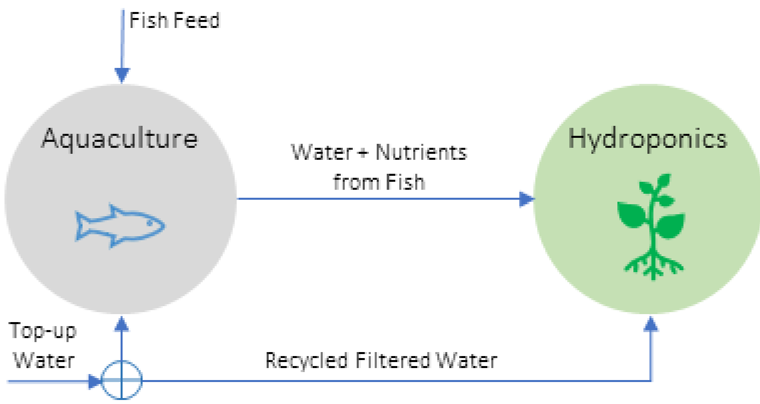
Economic activity is at the core of the transformation of slums and incorporates everything that improves the wealth and wellbeing of slum dwellers through job creation and small business opportunities. Urban farms (aquaponics) are capable of intensive fish and vegetable production in a significantly compressed footprint using much less water than other farming techniques (Nelson & Pade, 2019b). Another manufacturing opportunity is in paper products (toilet paper, paper towels, tissues, and sanitary products) which are consumed daily. Both initiatives provide employment and street vendor opportunities for residents. Other areas are in construction materials distribution (cement, building materials, electrical components, plastics, timber, and steel products), and fresh produce processing and distribution.

3.3 Food Production

USAID (2019) notes that West Africa is one of the world's most impoverished regions despite a richness in natural and human resources. USAID (2019) claim 60% of the labour force and approximately 35% of the region's GDP are attributed to the agriculture sector in West Africa. However, agricultural productivity suffers from the inability of farmers to connect with markets, the cost and availability of high-quality seeds and fertilizer, and insufficient information on new technologies and farming best practices (USAID, 2019). High transportation costs and the lack of support for regionally agreed policies on cross-border trade further exacerbate sector growth (USAID, 2019). According to USAID (2019), the region experiences low per hectare crop yields and an estimated 13.5% of the regional population is undernourished. This makes the agricultural sector in West Africa extremely vulnerable to the effects of climate change. Sultan et al. (2019) found that there is already evidence of crop losses from global warming and conclude that further losses will be experienced unless crop adaptation measures are implemented. In a study by Asante and Amuakwa-Mensah (2015), it was observed that temperatures across Ghana are rising, and that rainfall is becoming more erratic and variable. Naab et al. (2019), in a field study through focus group discussions and key informant interviews, concluded that climate change was manifesting in shorter rainy seasons and loss of soil fertility. Asante and Amuakwa-Mensah (2015) forecast dire consequences of climate change in Ghana with periods of extremely high temperature and low rainfall, increasing desertification, and increased sea-surface temperatures affecting Ghana marine fisheries. They also predict a narrowing of the range of suitable weather for cocoa production and lower yields from rice, cassava, and other rooted crops.

Aquaponics combines hydroponics and aquaculture in a single integrated system as shown in Figure 7. The fish are grown in one or more tanks and are fed with a blend of essential nutrients optimized for the type of fish being farmed. The fish waste contains nutrients which then becomes food for the plants. The plants absorb these nutrients, and the water is filtered and recycled to the fish tanks. The main inputs to the system are fish fingerlings, fish feed (which can be organic) (Nelson &

Figure 7. Aquaponics System



Pade, 2019a), plant seedlings, water (to top up the recycled water to a constant level), and electricity to drive pumps, conveyors, and lighting. The recirculating system depicted in Figure 7 is energy efficient and can be adapted to different fish species and a wide range of plant types to suit market needs (Jena et al., 2017). The environmental impact can be minimized when renewable energy is used.

According to Nelson and Pade (2019b), yield is 8 times greater than traditional agriculture with 1/6th of the water usage. These are significant benefits in dry climates and in areas facing degradation due to climate change. Aquaponics systems can be introduced as viable urban farms producing fresh fish and vegetables near the consumers. Storage and transportation requirements are minimized. There is no need for herbicides, pesticides, antibiotics, and growth hormones. No manufactured or mined fertilizers are required. The aquaponics system is non-seasonal, and food can be grown year-round in a stable environment.

Commercial aquaponics in urban slum areas creates employment for people with diverse skills. They can be focal points for food processing, packaging, and marketing of local traditionally grown produce as well as the aquaponics output. The creation of a food hub also improves logistics, product quality, branding, and reputation. Solar energy can power the production system as well as the greenhouse environment to maintain a consistent climate. The aquaponics production may be electronically monitored, and sales are e-commerce enabled to support business-to-customer (B2C) and business-to-business (B2B) transactions. All production and business data can be automatically uploaded to Internet cloud storage for processing and reporting.

3.4 Renewable Energy

The demand for energy grows rapidly as urban regions expand due to population growth. This impacts on the centralized generation capability and on the capabilities of the distribution networks. Ghana has a relatively high access rate for electricity with potentially 100% of the population having access by 2022 (Kumi, 2017). Ghana's energy generation profile is approximately 57% thermal with the balance provided by hydro-electric power from the Akosombo Dam facility on the Volta River and other locations (Kumi, 2017). However, the national distribution grid contributes to a high level of loss and the poor tariff structure provides financial uncertainty for electricity service providers. The installed capacity is approximately 4,650MW but availability is limited to about 2,400MW because of aging and failing infrastructure, seasonal rainfall variations affecting hydro-electric power generation, and unreliable fuel supplies for thermo-electric power generation (Power Africa, 2019a).

The energy sector in Ghana is in crisis. Under the current contract structure, payment must be made for the full capacity of 4,650MW even though peak demand in 2019 was only 2,400MW. This results in a sector shortfall and an annual payment of $1,268 million for unused capacity (Ministry of Energy, 2019). Furthermore, the energy sector has an accumulated debt backlog of approximately $2,748 million. The Ministry of Finance (2019) reports that this is an unsustainable burden on the emerging Ghanaian economy. The Energy Sector Reform Program aims to overhaul the energy sector, to renegotiate current contracts, and to increase emphasis on renewable sources (Ministry of Energy, 2019). Initiatives were also announced to increase demand, but the delivery infrastructure needs a significant overhaul to increase efficiency. One such initiative is the revival of the aluminium industry under the Ghana Integrated Aluminium Development Corporation (Ghanaweb, 2019a). This was the industry that was used to justify the building of the Akosombo Dam hydro-electric power facility in the early 1960s. Almost 60 years later, the Ghanaian government now see this as an industry that can contribute to economic growth (Ghanaweb, 2019a). Aluminium production requires significant energy, and this will contribute to the increase in demand, and the reduction of the supply/demand deficit.

The consequences of the crisis in the energy sector do not bode well for the redevelopment of urban slums and low-income communities across Ghana. Access to low-cost renewable energy is vital for the redevelopment of these communities. In this section, microgrids delivering energy from solar and biomass offering greater developmental autonomy, lower costs, economic opportunities under energy trading schemes, and lower carbon footprints for a more sustainable environment are discussed.

3.4.1 Microgrids

Microgrids were mainly used in remote rural settings that had no access to the electricity grid. They have now emerged as an integral component of urban planning strategies. Microgrids servicing groups of households and businesses within the slum environment can facilitate near autonomous operation of shared renewable energy sources. Microgrids can be monitored for the supply and demand for electricity, the environmental impact of energy use, and usage patterns. These can be built into new urban developments to complement grid supply during peak times, and they can be operated in island mode (off grid) during extended outages.

3.4.2 Solar Energy

Advances in solar photovoltaic panel technology have resulted in a dramatic drop in the capital cost of domestic installations. While solar photovoltaic panels are popular for small installations, solar thermal systems are viable for a wide range of commercial and utility scale electricity generation. An excellent example of the use of solar thermal for hydroponics is the Sundrop Farms installation in South Australia (Sundrop Farms, 2019). In this example, solar power provides the energy to maintain a uniform greenhouse environment to produce vegetables and fruit, and to generate freshwater from seawater. There are many applications for solar energy supporting SCT initiatives including:

- Powering essential 24/7 services.
- Powering all manufacturing and other production systems.
- Street vendor stands and small business operations.
- Recharge points for all electric vehicles.
- Street lighting and other community lighting.
- Community Wi-Fi.
- Shared energy sources for high density community housing in urban areas.

These systems range in power output of a few watts to many kilowatts but become a part of an integrated energy delivery system in the SCT. Solar, even with battery storage, has low entry-level costs compared with other forms of renewable energy. They can be monitored and managed to provide information on usage, and to optimize the delivery of electricity on demand.

3.4.3 Waste to Energy

Municipal solid waste (MSW) comprises organic and inorganic material disposed of by households, businesses, and industry. The organic component of MSW includes food, plastics, paper, municipal tree trimmings, construction waste, packaging materials, biomass waste from food manufacturing and processing, and sludge from municipal sewerage treatment, domestic septic, and industrial wastewater systems. It has high energy content and can be used as a feed stock for electricity generation (Seo et al., 2018). It is estimated that one ton of organic MSW can produce up to 1,000 KWh of electricity using gasification technology (Global Syngas, 2019). Downdraft gasification converts organic material into a synthetic gas under extreme temperature in an oxygen starved environment. The minimal residue from this process can be easily disposed of. Small community-based gasification systems are modular and can be scaled to suit community needs. This is an environmentally superior solution to landfill and incineration. The oxygen deficient downdraft gasification process prevents the formation of contaminants such as highly toxic dioxins and furans (Waste to Energy Systems, n.d.). The processing of the inorganic component of MSW is discussed later in this article. Waste to energy (W2E) systems perfectly complement solar on autonomous microgrids. Data from these systems can provide markers for the economic activities of the communities they serve.

3.4.4 Peer-to-Peer Energy Trading

Peer-to-Peer (P2P) energy trading enables small producers/consumers (or prosumers) to trade their excess energy to local and external consumers (IRENA, 2020). P2P trading platforms are suitable for domestic consumers and for businesses (IRENA, 2020). Blockchain is a type of distributed ledger technology that can be used to securely store payment transactions between consumers and prosumers without the need for a central billing authority. Payments can be made more frequently, in contrast to the more common monthly or bi-monthly billing periods. Energy micro-payments and pay-as-you-go solutions are beneficial to consumers and to utilities (Andoni et al., 2019). The creation of a time-stamped trading transaction is verifiable and transparent. Energy trading transactions are recorded in the multi-location data structure of blockchain, providing resilience and robustness. Security of energy supply can be achieved by increasing the volumes of renewable energy and implementing efficient and flexible electricity trading markets (Mylrea & Gourisetti, 2017). These benefits offer considerable potential for slum redevelopment and the establishment of economic centers for energy trading within the SCT.

3.5 Housing

The provision of affordable functional housing is essential for the wellbeing of its inhabitants. The United Nations Sustainable Development Goal 11 acknowledges the urgent need for affordable housing to address the challenges of rapid urbanization (United Nations, 2019a). The government of Ghana estimated a shortfall of 2 million homes in Ghana by 2020 (Ghanaweb, 2019b). On the conservative assumption that each household comprises 5 people, this equates to 10 million people, or about 1/3 of the population of Ghana that are without adequate housing. Ghanaweb also reported a government initiative to raise $3.1 billion to finance 200,000 new homes at about $15,500 each using conventional building techniques. On the same assumption for occupancy, this investment would provide housing for about 1 million people at a total cost of ownership of more than $15,500 per home. These homes would not be affordable by low-income slum dwellers and an alternative approach to redevelopment of slum housing is required. It was earlier estimated that approximately 867,670 people live in slums in Accra. This would require 173,534 new home constructions in Accra at a substantially reduced total cost of ownership.

One potential solution to lowering housing costs is the 3D printing of homes. 3D printing can quickly construct a variety of dwellings to suit single and multiple families, and for other purposes. Claims that a single-family home can be constructed within 24 hours for less than $4,000 need to be tested and the cost verified (CNBC, 2018). New Story, a USA non-profit organization, has focused on ending global homelessness, and claim that they can produce low-cost housing that is affordable for people living on less than $200 per month. The 3D printing of large structures such as homes and commercial buildings has been proven viable and will become more affordable under economies of scale (All3DP, 2019). This is a significant improvement over conventional construction techniques and opens opportunities for lower cost subsidized housing. The cost of construction also benefits from the ability to use locally sourced construction materials. These homes can be equipped with sensors to report air quality, fire detection, water consumption, electricity consumption and generation, emergency service alerts, and security alerts. Each home can be equipped to provide access to the whole range of intelligent city services. High speed access to the Internet provided by 5G telecommunications services can provide access to interactive education, entertainment, and information services.

3.6 Water Supply and Management

The supply of clean water in slum districts is a major issue. In Accra, many areas are not serviced with piped water. This means that water must be transported by truck to homes and businesses where it is pumped into poly tanks. This is not possible in slums because of access difficulties and the cost of poly tanks. People must carry water from delivery points to maintain daily fresh supplies in their homes. The extension of the city water supply from the Akosombo dam to slum communities would be costly, and water levels in the Volta are declining because of climate change (Ndehedehe et al., 2017).

Well-water in S-SA is often problematic because of potential pollution effects from inadequate water protection practices (Grönwall & Oduro-Kwarteng, 2017). Well-water remediation or desalination using developing technologies such as carbon nanotubes (Ihsanullah, 2018) may be economically viable in the future.

In high humidity regions, atmospheric water can be harvested to further reduce the environmental impact. Fog harvesting has proven to be viable at high altitudes (Klemm et al., 2012). Atmospheric Water Generation (AWG) requires only air and electricity to produce potable water after filtration (Aboueleta, 2019). AWG systems are highly portable and can be located anywhere but are currently limited to small quantities of potable water. Cost is the current limiting factor for widespread use of AWG. AWG systems may be digitally printed into building structures and utilize existing solar or other renewable energy to lower costs.

The average annual rainfall in Accra is 809mm (WorldData, 2019). Rainwater capture may be viable for domestic use when homes are digitally printed to incorporate roof drainage and tank storage. For industrial buildings that have significant roof area, storage tanks can supply water for building operations and with appropriate water recycling strategies they can reach self-sustainability. Commercial buildings that are air-conditioned use systems that dehumidify the input air stream and generate water. This water can also be collected and stored and used for toilets, and for general use after treatment. High quality potable water is a scarce commodity. Careful management of the various sources in conjunction with recycling is integral to intelligent city objectives and to the circular economy. Data on water quality, usage rates, and recycling efficiencies can be continuously collected and processed in near real time.

3.7 Sanitation and Health

Owusu-Ansah et al. (2016) researched access to health care in slums in the Agbogbloshie district in Accra and observed that malaria and diarrheal diseases linked to poor sanitation conditions in the district were most prevalent. In the slum areas of Accra, pay-per-use public toilets are the main facility but open defecation is common, especially among children (Emory, 2016).

Owusu-Ansah et al. (2016) observed that slum dwellers who were enrolled in the National Health Insurance Scheme (NHIS) in Ghana were more likely to seek medical attention. Others sought advice and treatment from pharmacists and other sources. They also noted that the cost of the initial joining fees was the main deterrent to NHIS membership registration. There is a public health issue in the slums that requires the development of greater awareness of available health care services. The SCT can provide information on health risks, preventative measures, and community health service providers. New homes in the SCT can be printed with in-house toilet facilities, and public toilets under trial in Durban, South Africa, hold great promise for wider community access to safe environmentally sustainable toilets (Bill and Melinda Gates Foundation, 2020) that can also contribute to the circular economy (van Welie et al., 2019).

3.8 Transportation and Access

Accra is a city that has experienced considerable growth, but it lacks an efficient integrated transport structure with it regional centers and the seaport of Tema. Road access into Tema is congested and the movement of goods in and out of the port is slow and inefficient. The AMA (n.d.) reports that more than 2 million people enter Accra each day for work, leisure, or other activities. This creates significant traffic congestion on the arterial links to the surrounding regions, and pollution levels are high.

Slums are typically highly dense configurations of randomly oriented buildings. The ability to move around is limited by the space between buildings and by accumulated trash. The design of the SCT is limited by the amount of land available and the density of the population. Some separation can be achieved with multi-level buildings, but the wide suburban streets of modern urban planning are not possible.

This suggests an opportunity to encourage the use of other forms of transport. Improved walking paths will make it easier to move in and out of more delineated housing layouts, and bicycle paths encourage pedal-powered transport. All motorized vehicles are prohibited and only electric vehicles for people movement, deliveries of bulky items, and service vehicles are permitted. The objective is to provide a fast and less strenuous means to arrive at transport hubs for longer journeys or to escort children to and from school. Power poles connected to community microgrids will be accessible for vehicle recharging. All community vehicle assets can be managed and safeguarded using the global positioning system (GPS) to track movements.

3.9 Education

School absenteeism is much higher for children living in slums in Ghana than for children not living in slums (Glenn, 2014). The main reason is usually economic. Children often miss school to assist parents in the marketplace (Glenn, 2014). They are given a choice of going to school and not having food or going to the market where they can help their parents. Schooling in Ghana has been free for all students since the 2017 introduction of the free secondary high school program. However, the costs of uniforms, books and other materials, and various fees must be paid by parents. This places economic stress on families and even if donor funds are available these funds may not necessarily be used for the intended purpose (Maslin Nir, 2019). It is noted that there are exceptions with evidence that some children from slums are enrolled in private preschools (Felsman, 2014). There is insufficient evidence to conclude that this results from the parent's ability to pay or if there is some external donor source. There is a high correlation between poverty and slums. Improvement of slum conditions must not only lead to improved economic circumstances but also to integrative local partnerships and social programs to ensure that no child is left behind. School attendance and dropout rates of boys and girls can inform policy decisions on school programs.

3.10 Waste Management

According to CCAC (n.d.), Accra generates about 900,000MT of mainly organic waste per year. Accra does not have any landfill sites, has limited collection services, and transports any collected waste to a landfill site near Tema. The disposal of MSW to landfill or to various forms of incineration or other processing is problematic (Crowley et al., 2003; Lisk, 1991). There are significant environmental concerns over air pollution and surface and ground water integrity. The accumulation of MSW due to inadequate recovery and disposal systems poses serious health hazards. Recycling can recover approximately 25% of household waste with the remainder going to landfill (EPA, 2019). The organic component of MSW has high energy content and which can be recovered using W2E systems (Seo et al., 2018). These systems are appealing for low-income urban areas for the following reasons:

- **Urban clean-up:** Urban waste including recyclable materials have economic value. Collection can be achieved at low cost while providing a source of income for residents. Transportation costs are minimized resulting in further reduction of greenhouse gas emissions.
- **Environmental impact:** Unprocessed organic material releases methane gas and can cause pollution of surface and ground water. Urban clean-up results in a healthier environment.
- **Renewable energy:** A clean syngas can be used in combined heat and power systems to reduce reliance on fossil fuel electricity generation, and to contribute to a carbon neutral environment.

Recyclable materials can be recovered, sorted, and packaged for sale, hence adding another revenue stream. W2E systems can also be configured to extract chemicals, fertilizers, transportation fuels, and hydrogen. Data can be collected from the waste collection, processing, and recycling stages. This is integral to circular economy strategies. Machine learning can be used to visualize and guide urban waste management planning.

4. IOT AND DATA ANALYTICS

IoT, big data and data analytics are terms that refer to the data collection, storage, processing, and visualization of information. Technology has made it possible to collect and process vast amounts of data quickly. The following sections present an overview of the information framework, basic data classifications for the SCT, data collection methods, and cloud processing platforms.

4.1 Information Framework

The transition from a slum city to a functional intelligent city is an incremental one. Careful consideration should be given to the establishment of the data sharing structures so that government agencies, industry and individuals can submit data for processing, and then receive information in a variety of visualizations. In this sense, transforming of slum cities to functional intelligent cities can have significant advantages because the intelligent systems are being built progressively upon existing infrastructure. The fundamental structure of identifying the appropriate data types, the collection of data, storing and processing, disseminating information to the community, and interacting with the community should be the basic goal of intelligent city strategies in developing countries.

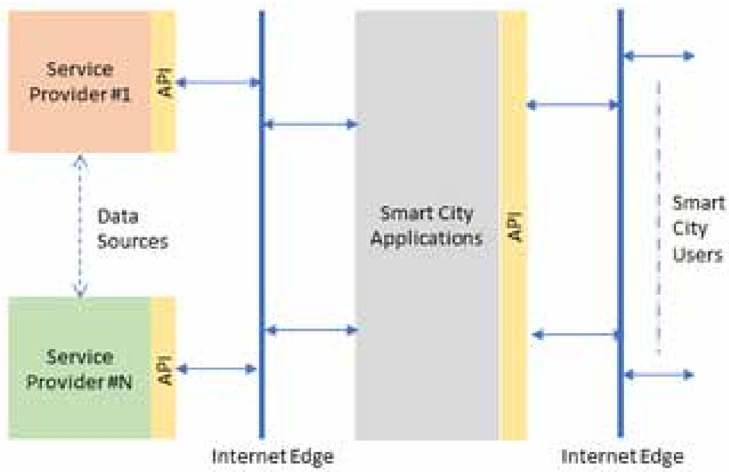
While the data collection, storage, processing, and visualization is relatively straightforward for some data streams, problems arise when integrating the dataflows from different sources. Common cross-platform semantics will enable consistent interpretation of the data and ease of processing. Data exchange models are being tested in different cities globally (Russo and Feng, 2020). Alternatively, as depicted in Figure 8, information can be accessed through well-defined application programming interfaces (APIs) to various entity platforms, such as government agencies. This then enables the compilation of dashboard presentations for mobility devices and computers to suit the intelligent city end-user.

4.2 Data Classifications

There are six broad classifications of data that relate to the intelligent city model:

- **Economic Data:** Generated from commercial and household income data.
- **Social Data:** Relates to the general wellbeing of the community and includes both quantitative (such as school attendances, and clinic visits) and qualitative data (social structures, interest groups, and cultural events).

Figure 8. API between Service Provider Systems and Smart City Applications



- **Environmental Data:** A wide range of critical data including weather, air quality, water quality, sanitation, and land usage.
- **Structural Data:** Is from energy sources and distribution, road types and quality, transport systems, food sources and supply, schools, and clinics.
- **Institutional Data:** Relates to the presence and engagement of institutions such as those agencies involved in welfare, health, education, aid agencies, non-government organizations (NGOs), and research programs.
- **Remote Sensing Data:** Is from satellite and other aerial views of the city metropolitan area, including the slums under transformation.

Each entity within the SCT is capable of collection of a diverse range of data. Table 2 in the Appendix provides a broad view of the types of data that can be collected under each classification and the entity primarily responsible for the collection. Table 3 in the Appendix shows the sources of such data and how these sources are accessed.

4.3 Data Processing

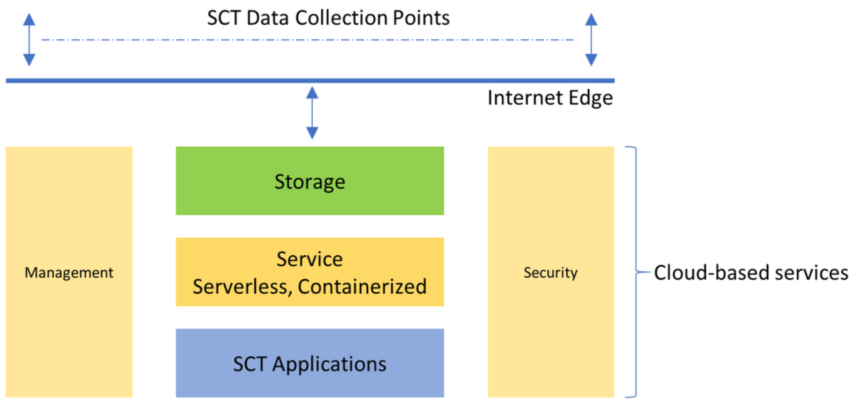
The Internet Cloud has made it possible to access vast storage capabilities and serverless computing. This allows all SCT data to be stored in the cloud and processed on demand for minimal cost. Furthermore, the cloud-based environment eliminates the cost of in-house servers, their upgrades, and operational management. Data backup and data integrity are managed within the cloud for minimal cost. Several providers charge only for the time it takes to run each application. High speed Internet is the minimal requirement for SCT to perform well.

Ghana has several service providers with international fiber capacity (Submarine Cable Networks, n.d.). There are several well-established cloud-based service providers to choose from including Microsoft Azure, Google BigQuery, Alibaba, IBM Cloud, and Amazon Web Services. Figure 9 illustrates the general structure of the cloud-based platforms. These cloud-based service providers offer similar services including fast database queries, machine learning capabilities, data analytics, website hosting, and pay-as-you-use application processing.

4.4 Smart City User Dashboards

Smart city users comprise all registered participants of the SCT including individuals, government agencies, registered businesses, street vendors, and all other service provider nominees. Each dashboard

Figure 9. General Structure of Cloud-Based Platforms



is tailorable to the requirements of each participant. Individuals can monitor their home environment, including electricity consumption, water usage, security status, and financial transactions from their smartphones, tablets, or computers. Businesses may report total sales by product and price, and employee or agent payments. It is possible to determine the extent of cash generated and distributed to slum dwellers. Government agencies can perform highly nuanced studies to help formulate future policies.

5. CONCLUSION

Slums are a persistent and increasingly serious problem for cities in the developing world. Linked with poverty, slums have resisted attempts to eliminate them through resettlement, redevelopment, forced eviction, and other tried and failed approaches. There is no clear definition for a slum city, but the magnitude of the problem requires major policy initiatives to provide alternatives to the deprivation of living in slums. However, policy initiatives may not be the most efficient approach in countries where there is weak governance, corruption, autocracy, or regime instability. Any rehabilitation activity must address the economic prospects for slum dwellers with a new livelihood paradigm offering employment and small business opportunities arising from products and services produced from within the slum communities. This economic process is highly interactive with the slum communities while being conscious of the social fabric and broader community environment. There is necessarily a cost to all stakeholders. However, the benefits are improved wellbeing through better living conditions, better incomes, and a cleaner and safer environment. This, in turn, has a positive impact on the GDP of the city.

Several income-generating ideas have been introduced. Aquaponics, as an urban farm, provides a connection with the previous rural livelihoods of many of the slum dwellers. The collection of organic waste, which is a visible marker of the slum environment, and its conversion to electricity or other products has both environmental and economic benefits. Many daily in-use commodity products are imported. Local manufacture of these products serves to replace imports and offers employment and other economic opportunities.

Functional homes can be digitally printed. While this process is in its early development phase, it offers great promise for customizing homes that meet the needs of people emerging from poverty. They can be configured to provide improved sanitation and to include income-earning systems. As rehabilitation progresses, the home designs can be adjusted based on lessons learned from the initial constructions. Ownership of the land being redeveloped is also an issue in many S-SA countries and some insights into the challenges of land ownership in Ghana are provided. It will take a major policy effort to redefine urban land entitlements to give confidence to homeowners and business developers that their investments are secure and are protected under the law.

The slum city transformation is a partnership between government, private investors, landowners, and the slum dwellers. Each stakeholder has an equally important role to play to bring success to the project. Data collection and processing provides an on-going measure of performance. The IoT is introduced to highlight the ease of attaching a wide range of sensors and other Internet edge devices. Remote sensing imagery, combined with other near-terrestrial data and survey data, can be useful in providing spatial and temporal visualizations of the slum city transformation, and to monitor impacts outside of the slum areas. Big data and the IoT are the stimulus for the implementation of broader intelligent city strategies. All stakeholders are provided with insights to the conditions of their household, community, and city through easy to access data dashboards that are tailored to their needs. This open transparent access to information helps define and organize social structures in the city and allows the city to develop under its own unique culture and vision to become a future functional intelligent city.

REFERENCES

Aboueleta, M. (2019). *Atmospheric water harvesting: Our one environmental chance against a water crisis*. https://www.quantumrun.com/article/atmospheric-water-harvesting-our-one-environmental-chance-against-water-crisis

African Union. (2019). *Our aspirations for the Africa we want*. https://au.int/en/agenda2063/aspirations

All3DP. (2019). *About Us*. https://all3dp.com/about/

AMA. (n.d.). *Population*. https://ama.gov.gh/theassembly.php

Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, G., Jenkins, D., McCallum, P., & Peacock, A. (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable & Sustainable Energy Reviews*, *100*, 143–174. doi:10.1016/j.rser.2018.10.014

Asante, F. A., & Amuakwa-Mensah, F. (2015). Climate change and variability in Ghana: Stocktaking. *Climate (Basel)*, *3*(1), 78–99. doi:10.3390/cli3010078

Beegle, K., Christiaensen, L., Dabalen, A., & Gaddis, I. (2016). *Poverty in a rising Africa*. https://www.un.org/africarenewal/sites/www.un.org.africarenewal/files/Poverty%20in%20a%20Rising%20Africa%20Overview.pdf

Bettencourt, L. (2014). The uses of big data in cities. *Big Data*, *2*(1), 12–22. doi:10.1089/big.2013.0042 PMID:27447307

Bhorat, H., & Naidoo, K. (2014). *Drivers of inequality in the context of the growth-poverty-inequality nexus in Africa: An overview of key issues*. https://www.undp.org/content/dam/rba/docs/Reports/undp-rba_Income%20Inequality%20in%20SSA_Chapter%203.pdf

Bill and Melinda Gates Foundation. (2020). *Reinventing the toilet*. https://gcgh.grandchallenges.org/article/reinventing-toilet

Blumenstock, J., Cadamuro, G., & On, R. (2015). Predicting poverty and wealth from mobile phone metadata. *Science*, *350*(6264), 1073–1076. 10.1126/science.aac4420

Brown University. (2019). *Favelas in Rio de Janeiro, past and present*. https://library.brown.edu/create/fivecenturiesofchange/chapters/chapter-9/favelas-in-rio-de-janeiro-past-and-present/

CCAC. (n.d.). *Solid waste management in Accra*. https://www.waste.ccacoalition.org/sites/default/files/files/city_fact_sheet/Accra_MSW_FactSheet_0.pdf

CNBC. (2018). *New Story is a nonprofit that hopes to use 3-D printers to build homes in poor communities*. https://www.cnbc.com/2018/03/15/new-story-nonprofit-will-3-d-print-homes-in-poor-communities.html

Crowley, D., Staines, A., Collins, C., Bracken, J., Bruen, M., Fry, J., Hrymak, V., Malone, D., Magette, B., Ryan, M., & Thunhurst, C. (2003). Health and environmental effects of landfilling and incineration of waste - A literature review. *Reports,* Paper 3. http://arrow.dit.ie/schfsehrep/3

Emory. (2016). *Should public toilets be part of urban sanitation solutions for poor families living in slums*? School of Public Health. https://sanipath.org/wp-content/uploads/2016/04/SaniPath-Public-Latrin-Policy-Brief.pdf

Engstrom, R., Pavelesku, D., Tanaka, T., & Wambile, A. (2019). Mapping poverty and slums using multiple methodologies in Accra, Ghana. *JURSE*, *2019*, 1–4. Advance online publication. doi:10.1109/JURSE.2019.8809052

Engstrom, R., Sandborn, A., Yu, Q., Burgdorfer, J., Stow, D., Weeks, J., & Graesser, J. (2015). Mapping slums using spatial features in Accra, Ghana. *JURSE*, *2015*, 1–4. Advance online publication. doi:10.1109/JURSE.2015.7120494

EPA. (2019). *Facts and figures about materials, waste, and recycling*. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Eregha, P. B. (2015). Foreign direct investment inflow, volatility, and domestic investment in West Africa. *Journal of Developing Areas*, *49*(2), 273–294. doi:10.1353/jda.2015.0018

Felsman, C. (2014). *Schools in slums: A surprising number of the poorest kids are enrolled in private preschools*. https://educationinnovations.org/blog/schools-slums-surprising-number-poorest-kids-are-enrolled-private-preschools

Foy Connor, R., & Bent-Goodley, T. B. (2016). Zanzibari social entrepreneurs and poverty alleviation strategies: Understanding efforts to build local community sustainability. *Journal of Community Practice*, *24*(3), 302–318. doi:10.1080/10705422.2016.1201784

Geels, F. W. (2002). Technological transitions as evolutionary configuration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8/9), 1257–1274. doi:10.1016/S0048-7333(02)00062-8

Ghana Statistical Service. (2019). *Shapefiles of enumeration areas of Ashanti region*. https://www.statsghana.gov.gh/regionalpopulation.php?population=MTI5MzE3OTU5OC40NDg1&&Ashanti&regid=1

Ghanaweb. (2019a). *Akufo-Addo wants vibrant Ghana aluminium industry*. https://www.ghanaweb.com/GhanaHomePage/business/Akufo-Addo-wants-vibrant-Ghana-aluminium-industry-727527

Ghanaweb. (2019b). *Ghana's housing deficit hits two million – Housing Minister*. https://www.ghanaweb.com/GhanaHomePage/business/Ghana-s-housing-deficit-hits-two-million-Housing-Minister-739235

Glenn, G. (2014). *In Ghana, school absenteeism and poverty go hand-in-hand*. https://news.wypr.org/post/ghana-school-absenteeism-and-poverty-go-hand-hand#stream/0

Global Syngas. (2019). *Waste to energy gasification*. https://www.globalsyngas.org/syngas-production/waste-to-energy-gasification/

Grönwall, J., & Oduro-Kwarteng, S. (2017). Groundwater as a strategic resource for improved resilience: A case study from peri-urban Accra. *Environmental Earth Sciences*, *77*(1), 6. Advance online publication. doi:10.1007/s12665-017-7181-9

Haughton, J., & Khandker, S. R. (2009). *Handbook on poverty and inequality*. The World Bank. doi:10.1596/978-0-8213-7613-3

Ihsanullah, I. (2018). Carbon nanotube membranes for water purification: Developments, challenges, and prospects for the future. *Separation and Purification Technology*, *209*, 307–337. doi:10.1016/j.seppur.2018.07.043

Institute for Security Studies. (2019). *Reducing poverty in Africa: Huge potential, but more realistic goals needed*. https://issafrica.org/about-us/press-releases/reducing-poverty-in-africa-huge-potential-but-more-realistic-goals-needed

IRENA. (2020). *Innovation landscape brief: Peer-to-peer electricity trading*. International Renewable Energy Agency.

Jena, A. K., Biswas, P., & Saha, H. (2017). Aquaponics - a step towards urban agriculture. Innovative farming. *International Journal of Agriculture*, *1*, 163–167. http://www.innovativefarming.in/index.php/innofarm/article/view/167

Kedir, A., Elhiraika, A., Chinzara, Z., & Sandjong, D. (2017). Growth and development finance required for achieving sustainable development goals (SDGs) in Africa. *African Development Review*, *29*(S1), 15–26. doi:10.1111/1467-8268.12230

Klemm, O., Schemenauer, R. S., Lummerich, A., Cereceda, P., Marzol, V., Corell, D., van Heerden, J., Reinhard, D., Gherezghiher, T., Olivier, J., Osses, P., Sarsour, J., Frost, E., Estrela, M. J., Valiente, J. A., & Fessehaye, G. M. (2012). Fog as a fresh-water resource: Overview and perspectives. *Ambio*, *41*(3), 221–234. doi:10.1007/s13280-012-0247-8 PMID:22328161

Kuffer, M., Pfeffer, K., & Sliuzas, R. (2016). Slums from Space—15 Years of slum mapping using remote sensing. *Remote Sensing*, *8*(6), 455. doi:10.3390/rs8060455

Kumi, E. N. (2017). *The electricity situation in Ghana: Challenges and opportunities*. CGD Policy Paper. Washington, DC: Center for Global Development. https://www.cgdev.org/sites/default/files/electricity-situation-ghana-challenges-and-opportunities.pdf

Lisk, J. (1991). Environmental effects of landfills. *The Science of the Total Environment*, *100*, 415–468. doi:10.1016/0048-9697(91)90387-T

Macrotrends. (n.d.). *Kumasi, Ghana Metro Area Population 1950-2021*. https://www.macrotrends.net/cities/21108/kumasi/population

Mahabir, R., Crooks, A., Croitoru, A., & Agouris, P. (2016). The study of slums as social and physical constructs: Challenges and emerging research opportunities. *Regional Studies, Regional Science*, *3*(1), 399–419. doi:10.1080/21681376.2016.1229130

Marchesi, M., Tweed, C., & Gerber, D. (2020). BEYOND 2020 – World sustainable built environment conference, IOP conference series. *Earth and Environmental Science, 588*. doi:10.1088/1755-1315/588/5/052065

Maslin Nir, S. (2019). *In Ghana, free high school brings opportunity and grumbling*. https://www.nytimes.com/2019/06/15/world/africa/ghana-free-senior-high-school-brings-chaos.html

Ministry of Energy. (2019). *Energy sector recovery program*. https://energycom.gov.gh/files/2019%201111%20ESRP%20ESTF_Clean_v3.0redacted%20final.pdf

Ministry of Finance. (2019). *Mid-year fiscal policy review of the 2019 budget statement and economic policy & supplementary estimates of the government of Ghana for the 2019 financial year.* https://mofep.gov.gh/sites/default/files/budget-statements/2019-Mid-Year-Budget-Statement.pdf

Mylrea, M. E., & Gourisetti, S. N. G. (2017). Blockchain for smart grid resilience: Exchanging distributed energy at speed, scale, and security. *Resilience Week (RWS)*, 18-23. 10.1109/RWEEK.2017.8088642

Naab, F. Z., Abubakari, Z., & Ahmed, A. (2019). The role of climate services in agricultural productivity in Ghana: The perspectives of farmers and institutions. *Climate Services*, *13*, 24–32. doi:10.1016/j.cliser.2019.01.007

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta River basin using in-situ data and satellite observations. *Journal of Hydrology. Regional Studies*, *12*, 88–110. doi:10.1016/j.ejrh.2017.04.005

Nelson & Pade. (2019a). *A non-gmo fish food for aquaponics*. https://aquaponics.com/product-category/aquaponic-growing-supplies/fish-food/

Nelson & Pade. (2019b). *Aquaponics*. https://aquaponics.com/

Njuguna, C., & McSharry, P. (2017). Constructing spatiotemporal poverty indices from big data. *Journal of Business Research*, *70*, 318–327. doi:10.1016/j.jbusres.2016.08.005

Owusu-Ansah, F. E., Tagbor, H., & Togbe, M. A. (2016). Access to health in city slum dwellers: The case of Sodom and Gomorrah in Accra, Ghana. *African Journal of Primary Health Care & Family Medicine*, *8*(1), e1–e7. doi:10.4102/phcfm.v8i1.822 PMID:27247151

Patel, N. (2018). *Figure of the week: Understanding poverty in Africa*. https://www.brookings.edu/blog/africa-in-focus/2018/11/21/figure-of-the-week-understanding-poverty-in-africa/

Power Africa. (2019a). *Ghana. Energy sector overview*. https://www.usaid.gov/sites/default/files/documents/1860/Ghana_-_November_2018_Country_Fact_Sheet.pdf

Russo, M., & Feng, T. (2020). *The risks and rewards of data sharing for smart cities*. https://www.bcg.com/publications/2020/smart-cities-need-to-understand-the-risks-and-rewards-of-data-sharing-part-3

Seo, Y., Alam, M. T., & Tang, W. (2018). *Gasification of municipal solid waste*. 10.5772/intechopen.73685

Stacey, P. (2018). Urban development and emerging relations of informal property and land-based authority in Accra. *Africa*, *88*(1), 63–80. doi:10.1017/S0001972017000572

Submarine Cable Networks. (n.d.). *Submarine cable systems connecting West Coast of Africa to Asia, Europe, and South America*. https://www.submarinenetworks.com/euro-africa

Sultan, B., Defrance, D., & Iizumi, T. (2019). Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific Reports*, *9*(1), 12834. Advance online publication. doi:10.1038/s41598-019-49167-0 PMID:31492929

Sundrop Farms. (2019). *Innovation. Sundrop is the future*. https://www.sundropfarms.com/innovation/

Taubenböck, H., Kraff, N. J., & Wurm, M. (2018). The morphology of the arrival city - A global categorization based on literature surveys and remotely sensed data. *Applied Geography (Sevenoaks, England)*, *92*, 150–167. doi:10.1016/j.apgeog.2018.02.002

The Rockefeller Foundation. (2019). *Accra*. https://nextcity.org/informalcity/city/accra

Transparency International. (2020). *Ghana*. https://www.transparency.org/en/cpi/2020/index/gha

UN-Habitat. (2016). *World Cities Report 2016. Urbanization and development: Emerging futures*. https://unhabitat.org/sites/default/files/download-manager-files/WCR-2016-WEB.pdf

UN-Habitat. (2018). *SDG Indicator 11.1.1 Training module: Adequate housing and slum upgrading*. United Nations Human Settlement Programme (UN-Habitat). https://unhabitat.org/wp-content/uploads/2019/04/Indicator-11.1.1-Training-Module.pdf

UN-Habitat. (2020). *World cities report 2020*. https://unhabitat.org/sites/default/files/2020/10/wcr_2020_report.pdf

UNCTAD. (2019). *State of commodity dependence 2019*. https://unctad.org/system/files/official-document/ditccom2019d1_en.pdf

United Nations. (2019a). *Sustainable development goals*. https://sustainabledevelopment.un.org/sdgs

United Nations. (2019b). *Sustainable Development Goal 11. Make cities and human settlements inclusive, safe, resilient, and sustainable*. https://sustainabledevelopment.un.org/sdg11

United Nations. (2019c). *Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100*. https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html

USAID. (2019). *Agriculture and food security*. https://www.usaid.gov/west-africa-regional/agriculture-and-food-security

van Welie, M. J., Truffer, B., & Yap, X. S. (2019). Towards sustainable urban basic services in low-income countries: A technological innovation system analysis of sanitation value chains in Nairobi. *Environmental Innovation and Societal Transitions*, *33*, 196–214. doi:10.1016/j.eist.2019.06.002

Waste to Energy Systems. (n.d.). *Why is gasification better then incineration?* https://www.wastetoenergysystems.com/why-is-gasification-better-than-incineration/

World Bank. (2018). *Greater Accra clean, resilient, and inclusive development project (P164330)*. https://ewsdata.rightsindevelopment.org/files/documents/30/WB-P164330.pdf

World Bank. (2019a). *Overview*. www.worldbank.org/en/country/ghana/overview

World Bank. (2019b). *Poverty overview*. https://www.worldbank.org/en/topic/poverty/overview

World Bank. (2020). *Ghana country environmental analysis*. https://documents1.worldbank.org/curated/en/419871588578973802/pdf/Ghana-Country-Environmental-Analysis.pdf

World Bank. (2021a). *Population 2020*. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=GH

World Bank. (2021b). *Poverty and shared prosperity. Reversals of Fortune*. World Bank Group. https://openknowledge.worldbank.org/bitstream/handle/10986/34496/9781464816024.pdf

World Economic Forum. (2018). *Slums could inspire the cities of the future. Here's how*. https://www.weforum.org/agenda/2018/01/this-startup-is-turning-slums-into-microcities/

World Economic Forum. (2019). *What slums can teach us about building the cities of the future*. https://www.weforum.org/agenda/2019/03/why-slums-could-provide-the-housing-inspiration-of-the-future/

WorldData. (2019). *Climate for Greater Accra (Ghana)*. https://www.worlddata.info/africa/ghana/climate-greater-accra.php

Xie, M., Jean, N., Burke, M., Lobell, D., & Ermon, S. (2016). *Transfer learning from deep features for remote sensing and poverty mapping*. Paper presented at the 30th AAAI Conference on Artificial Intelligence, AAAI 2016. doi:10.1609/aaai.v30i1.9906

APPENDIX

Table 2. Data to be Collected and Collection Entities

Data Classification	Description	Reporting Entity(s)
Economic	Total revenues	SCT Commercial Enterprise
	Number, age, and gender of employees	SCT Commercial Enterprise
	Household incomes	Households
	Household members, gender, and age	Households
	Mobile phone credit top-ups1	Households/Individuals
	Mobile money transfers/receipts1	Households/Individuals
Social	School attendance	Schools
	Gender of attendees	Schools
	Age of attendees	Schools
	Number of health clinic visits	Clinics
	Gender of patients	Clinics
	Type of treatment sought	Clinics
	Population	Ghana Statistical Service
Environmental	Water source and usage	SCT
	Electricity source and usage	SCT
	Weather and air quality	SCT Weather Stations
	Field observations (flora and fauna)	Schools
Structural	Energy supply and distribution	SCT
	Road types and quality	SCT
	Transport systems	SCT
	Food sources and supply	SCT
	Schools and facilities	SCT
	Clinics	SCT
Institutional	Number of institutions	SCT
	Location of each institution	SCT
	Number of people in each institution	SCT
	Primary activity of each institution	SCT
Remote Sensing	Satellite image data	Maxar (https://www.maxar.com)

Note: The automatic collection of mobile phone credits and mobile money transfers/receipts requires the permission of the account owner to automatically report this data using a downloaded purpose-built App.

Table 3. Methods of Data Collection

Data Classification	Description	Source	Accessed
Economic	Revenues and costs	API	On-demand
	Number, age, and gender of employees	API	On-demand
	Household incomes	App/Kiosk	On-demand
	Household members, gender, and age	App/Kiosk	On-demand
	Mobile phone credit top-ups	App	Automatic/event
	Mobile money transfers/receipts	App	Automatic/event
Social	School attendance	App	As available
	Gender of attendees	App	As available
	Age of attendees	App	As available
	Number of health clinic visits	App	As available
	Gender of patients	App	As available
	Type of treatment sought	App	As available
	Population	API	When available
Environmental	Water source and usage, electricity source and usage	App	As available
	Weather and air quality	SCT Weather Station	Streaming data
	Field observations (flora and fauna). School programs.	App	As available
Structural	Energy supply and distribution	App	Scheduled
	Road types and quality	App	Scheduled
	Transport systems	App	Scheduled
	Food sources and supply	App	Scheduled
	Schools and facilities	App	Scheduled
	Clinics	App	Scheduled
Institutional	Number of institutions	App	Scheduled
	Location of each institution	App	Scheduled
	Number of people in each institution	App	Scheduled
	Primary activity of each institution	App	Scheduled
Remote Sensing	High resolution imagery	Download	Biannually
	Mosaic imagery	Download	Biannually
	Infrared imagery	Download	Biannually
Legend			
API	Application Programming Interface.		
App	A purpose-built application for mobility devices (smartphones, tablets, and notebook computers) that collects the designated data and sends it automatically, scheduled, or on-demand to the SCT for processing.		
Kiosks	At SCT facilities that enable input of data as a convenience/alternative to mobility Apps.		
SCT Weather station	A comprehensive weather station collecting temperature, humidity, rainfall, wind speed and direction, solar radiation, and air pollutant information.		
On-demand	Data collection is initiated as required for processing.		
Automatic/event	Details of each event are transmitted as they happen.		
As available	Data is sent by the person collecting the information when it is available.		
Streaming data	Data, such as from weather stations and video sources are streamed in real-time.		
When available	Data is collected from external sources when a notice of availability has been received.		

Darrold Cordes is currently undertaking a Doctor of Sustainable Development degree with Curtin University in Australia. His research thesis is on the role of electronic commerce in providing pathways to sustainability for poverty alleviation in Sub-Saharan Africa. He holds a Bachelor of Technology Degree (Electronic Engineering) from the University of Adelaide, a Graduate Diploma in Mathematics from the University of South Australia, a Master of Business Administration from the University of Nevada, Las Vegas, a Master of Science in Management Information Systems from the University of Nevada, Las Vegas, and a Master of Science in Applied Economics and Data Analysis from the University of Nevada, Las Vegas.

Gregory Morrison is currently the Lang Walker Chair in Urban Transformation at Western Sydney University.