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RESEARCH ARTICLE

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The scope for low-carbon development in Kigali, Rwanda: An economic appraisal

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Abstract

Urban plans and infrastructure investments in sub-Saharan Africa need to support human and economic development, while also helping countries and cities stay within the global carbon budget. To date, however, no analyses have focused on the economic costs and benefits of pursuing less carbon-intensive urban growth in sub-Saharan African cities. This is significant as the perception that low-carbon urban development is more expensive than higher-carbon alternatives can be enough to preclude consideration of opportunities for more sustainable development, especially in highly resource-constrained contexts. This paper examines the validity of this perception through an economic appraisal of the scope for low-carbon development in Kigali, Rwanda. We find that the city of Kigali could theoretically invest 0.6% of its GDP each year for 10 years in economically attractive mitigation measures. This would generate annual energy savings equivalent to 1.5% of its GDP and reduce city-scale emissions by 39% by 2032 (relative to business-as-usual trends). The economic case for urban climate action is therefore substantial, and although the city is in some ways unique, this suggests that promising opportunities also exist in other sub-Saharan African cities. However, few national or local governments in the region have the political will and institutional capabilities necessary to realise this mitigation potential. We also find that although potentially significant in the short to medium term, these economically attractive measures would not be sufficient to decouple economic development and greenhouse gas emissions in Kigali in the longer term.

KEYWORDS

cities, climate change, climate change mitigation, environmental economics, greenhouse gas emissions, sub-Saharan Africa

1 | INTRODUCTION

The Paris Agreement aspires to limit the global temperature rise this century to no more than 1.5°C above pre-industrial levels. This will require greenhouse gas emissions to reach net zero in the second half of the century, with a strong likelihood of net negative emissions being required thereafter (Rogelj et al., 2016). Urgent and ambitious climate action is therefore essential to avoid dangerous climate change. Much of this climate action must take place in urban areas, which account for 71–76% of carbon emissions from global final energy use (Seto et al., 2014). However, like nation states, towns and cities face common but differentiated responsibilities. Average per capita carbon emissions embodied in the infrastructure of industrialised countries are five times larger than those in developing countries (Müller et al., 2013). In these high-income contexts, carbon emissions from final energy use have begun to decline, and decision-makers must find ways to accelerate decarbonisation (Chavez & Sperling, 2017).

By comparison, most towns and cities in developing countries face severe infrastructure deficits and rapidly growing GHG emissions.

In sub-Saharan Africa, for example, 24.0% of the urban population lacks access to electricity (World Bank, 2018a), and for those with access, power outages are regular and prolonged (Murphy, Twaha, & Murphy, 2014). GHG emissions are currently less than one sixth of the global average (per capita), but are on track to more than double through 2050 (WRI, 2018).

At the same time, urban areas are expanding fast in many developing countries: A 2.3% growth rate will see urban populations approximately double in the next 30 years (UN DESA, 2014). Towns and cities in sub-Saharan Africa alone are projected to expand by 777 million people by 2050, equating to a more than threefold increase (UN DESA, 2014). Urban plans and infrastructure investments over the next few decades need to support human and economic development across the region, while also ensuring that countries and cities stay within the global carbon budget.

There is therefore a need to understand what low-emission urban development might entail and the economic implications of pursuing a less carbon-intensive path in sub-Saharan Africa. Low-carbon development is widely regarded as more expensive than high-carbon development (Granoff, Hogarth, & Miller, 2016). Many low-carbon investments carry higher upfront costs because they are very capital-intensive compared with high-carbon options. This also means that financing costs can be more expensive, because construction risks become more significant. The cost of capital may also be increased due to the real and perceived risks associated with new technologies (Schmidt, 2014). Low-carbon measures can also be susceptible to market failures arising from imperfect information, split incentives, and externalities (of which climate change is but one). Many low-carbon infrastructure projects are more complex than conventional options and therefore demand additional technical and institutional capacities. District cooling schemes, for example, are not only more complicated in engineering terms than individual air conditioners but also require the consent and coordinated action of large numbers of homeowners and businesses.

Many of these constraints are particularly pronounced in sub-Saharan Africa, where endemic poverty limits the availability of both human and financial capital. For instance, local governments in Africa have very small municipal budgets, often equating to less than $20 per person (Cabannes, 2015). Most of these resources are dedicated to operational costs such as salaries, rather than capital expenditure. Few sub-Saharan African cities outside South Africa have the creditworthiness to access capital markets (Gorelick, 2018). Even where local governments can secure private finance, they typically face very high interest rates due to real and perceived risks associated with weak public administration capacities, limited own-source revenues and the challenges of cost recovery where end users have very low per capita incomes. As a result, African local governments may find it harder than their counterparts in other regions to justify the higher capital and financing costs associated with low-carbon options. In many cases, perceptions of higher cost or lack of familiarity may mean that low-carbon options are not even considered as an investment alternative.

On the other hand, there is a growing body of work highlighting the economic potential of low-carbon investment. There is strong evidence to suggest that more efficient appliances, buildings, lighting, and vehicles could pay for themselves through energy savings (IEA, 2017). Technological learning and scale economies are rapidly reducing the costs associated with decentralised renewables: The price of rooftop solar panels, for example, fell up to 85% between 2009 and 2016 (IRENA, 2017). These kinds of measures look likely to generate substantial economic returns to private investors. In other cases, the economic benefits of low-carbon development are significant but diffuse. Investments in public transport, for instance, improve access to jobs, services, and amenities, whereas investments in solid waste management reduce the incidence of water/vector-borne disease. Interventions of this kind may yield significant economic returns at the city scale, although it can be difficult for investors to recover their costs. It is also worth noting that emissions reduction is rarely the primary motivation for such projects. In other cases, low-carbon innovations may have the potential to address critical challenges that the reason is facing: For example, the modular nature of renewables means that electricity systems can be constructed in a more incremental way than conventional generation options have allowed.

To date, there are no any publicly available analyses of the costs and benefits of low-carbon urban development in any African cities. There is some evidence on the economic and environmental implications of specific low-carbon measures that can be deployed in cities, including energy-efficient lighting in Cameroon (Enongene, Murray, Holland, & Abanda, 2017), bus networks in Nigeria (Gujba, Mulugetta, & Azapagic, 2013), solar photovoltaics in Kenya (Ondraczek, 2014), and waste-to-energy technologies in Ghana (Oteng-Ababioa, Arguello, & Gabbay, 2013). However, there are no appraisals of the wider economic case for low-carbon investments in sub-Saharan African cities as there are for several middle-income countries (Gouldson et al., 2015). This paper seeks to address this gap.

In this study, we focus on the economic opportunities for climate action available to the city of Kigali, Rwanda. This case study is presented in Section 2. We calculate the investment needs, payback periods, and mitigation potential of a wide range of low-carbon measures in this city. We then evaluate their aggregate impact on energy use, energy bills, and greenhouse gas emissions, relative to business-as-usual trends. Our methodology is explained in Section 3. We adopt an economic lens to this analysis to reflect the financial realities in sub-Saharan Africa, where projects face significant fiscal constraints and opportunity costs. The results of this research, presented in Section 4, can help to identify policy and investment priorities for Kigali. In Section 5, we consider the economic implications for low-carbon investment across sub-Saharan African cities, as well as the opportunity costs of prioritising climate mitigation in a context of widespread poverty and deprivation.

2 | CASE STUDY: KIGALI, RWANDA

2.1 | The national context

Rwanda is a small, landlocked country in East Africa, with a population of 12.2 million people (World Bank, 2018b). The average per capita income in Rwanda was estimated to be USD 748.39 in 2017, which means that the country is among the poorest 20 nations in the world alongside its neighbours, Burundi (USD 320.09) and Uganda (USD 604.04; World Bank, 2018c). Rwanda remains predominately rural, with only 28.8% of the population living in urban areas in 2015. This is close to the average in East Africa, but well below the average of 37.9% across sub-Saharan Africa (UN DESA, 2014).

For some, Rwanda remains synonymous with the 1994 genocide. Yet in recent years, the country has recently been internationally acclaimed for its technocratic governance, performing better than most African countries on control of corruption, rule of law, competence of public service delivery, and ease of doing business (Ansoms & Rostagno, 2012). Public agencies in Rwanda have repeatedly demonstrated their planning and delivery capabilities (Dhillon & Phillips, 2015), which contributed to the country's real GDP growth of about 8% per annum between 2000 and 2015 (World Bank, 2018d). This economic growth has translated effectively into urban poverty reduction, as evident across a range of human development indicators (Figure 1). Although Rwanda may be admired for its administrative efficiency, some observers have noted that the country has not performed well on indicators of voice, accountability, and civic and political liberties (Ansoms & Rostagno, 2012; Reyntjens, 2011).

Rwanda's relatively well-developed institutional and technical capacities mean that it is well positioned to plan and deliver ambitious climate action. The central government has committed to mainstreaming environmental objectives into all its activities, as outlined in the *National Strategy for Climate Change and Low Carbon Development*. Rwanda established one of the world's first national climate funds (FONERWA), commissioned the first utility-scale solar farm in East Africa and replaced 800,000 incandescent light bulbs with energy-efficient compact fluorescent ones.

Rwanda has a tiny carbon footprint: The average Rwandan is responsible for 74 kg of CO_2-e a year. For reference, the average for least developed countries is 314 kg and the average for high-income countries is 10.7 metric tonnes (World Bank, 2018e). These low emissions are primarily a function of widespread poverty, which also means that the lives and livelihoods of many Rwandans are vulnerable to environmental hazards. The Government of Rwanda has highlighted that climate change will increase the probability of higher temperatures and prolonged droughts, interspersed with torrential rains (Ministry of Lands, Environment, Forestry, Water and Mines, 2006). These conditions will have multiple negative consequences, including reduced agricultural productivity due to erosion, silting, and water scarcity; poor health due to increased malnutrition and a proliferation of mosquitoes; diminishing power supplies due to low production of hydroelectricity; and the destruction of economic infrastructure such as roads, schools, and houses during floods and landslides (Byamukama, Carey, Cole, Dyszynski, & Warnest, 2011; Ermert, Fink, & Paeth, 2013). The loss of food security, productivity, and well-being creates significant social and political risk. The anticipated impacts of climate change help to explain Rwanda's ambitious commitments to mitigation in both domestic and international fora.

2.2 | The city context

With a population of 1.1 million people, the capital of Rwanda—Kigali—accommodates 10% of the Rwandan population. The city nearly doubled in size in the decade between the 2002 and 2012 censuses (NISR, 2002, 2012). Rapid population growth, coupled with rising affluence, has put the city's public services and infrastructure under increasing stress. This is illustrated by increasing congestion as the stock of private cars soars from 11,096 registered vehicles in 2005 to 161,925 registered vehicles in 2015 (NISR, 2009, 2016).

Kigali is the political, economic, and logistics hub of Rwanda. Around 40% of small and medium enterprises in the country are located in the city, as are around half the large firms (Kamarudeen & Söderbom, 2013). Most of the country's construction industry is based in the capital, and light manufacturing firms (primarily processing agricultural goods) are also significant employers (MINICOM et al., 2011).

Looking forward, continued economic growth offers the hope that Kigali will build upon its human development gains. More than 87% of Kigali residents are below 40, and are therefore either a member of, or are soon to join, the workforce (NISR, 2012). As with cities

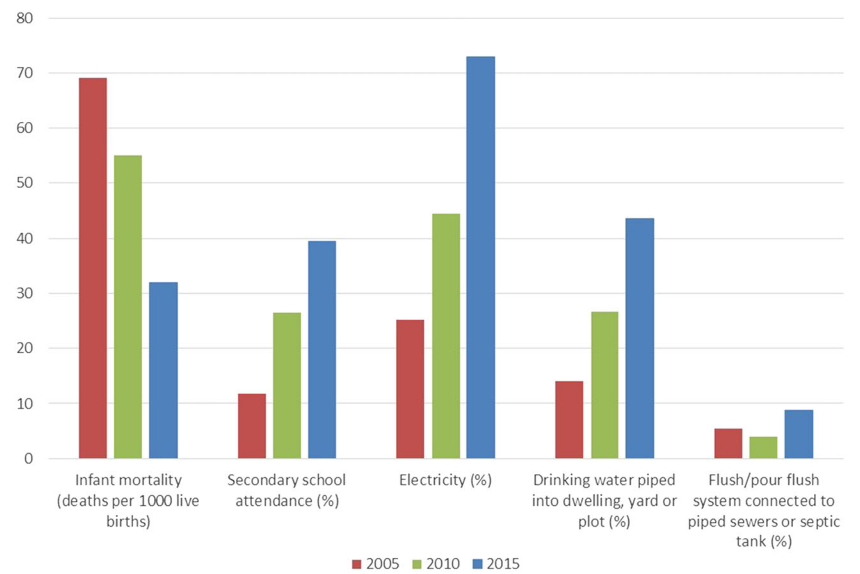

FIGURE 1 Key human development indicators for the urban population of Rwanda between 2005 and 2015. Data sources: INSR and ORC Macro (2006), NISR, Ministry of Health [Rwanda], and ICF International (2012; 2015) [Colour figure can be viewed at wileyonlinelibrary.com]

around the world, the higher population densities associated with urban areas permit more efficient provision of basic infrastructure, higher returns to scale and reduced transaction costs (Turok & McGranahan, 2013). At the same time, poorly managed urbanisation can lead to the growth of informal settlements and their associated economic, social, and environmental problems.

Kigali seems to be able to mobilise the resources and capacities for exemplar policies and projects that influence decision-makers throughout the country and wider region. Local government agencies have already constructed an extensive network of paved and segregated pedestrian sidewalks, established car-free zones, and introduced a smart fare collection system on public transport. A host of successful government programmes, including a plastic bag ban, improved public waste disposal, and beautification initiatives, have earned Kigali a reputation as one of the world's cleanest cities (UN-Habitat, 2008).

Two “master plans” have been developed to conceptualise future growth in Kigali, the first prepared by Oz Architecture (2007) and a second, more detailed iteration by Surbana International Consultants (2013). These share a strong focus on environmental sustainability, but have been criticised for their disconnect from the realities of informality, poverty, pollution, and inadequate service delivery (Watson, 2014). In light of the city's pressing development needs, it is necessary to identify climate-compatible interventions and pathways that do not entail significant opportunity costs and may ideally free up resources for more socially and economically productive investment.

3 | METHODS

3.1 | Predicting business-as-usual trends

We collected data that enabled us to understand the levels and composition of energy demand in Kigali between 2000 and 2015, looking at commercial, public, and residential buildings and transport. We also evaluated the electricity sector, which substantially influences the carbon intensity of energy supply, and the waste sector, as it both generates greenhouse gas emissions and has the potential to generate energy.

We used these historical data, as well as information on recent policy changes and planned infrastructure investments, to develop “business-as-usual” baselines predicting energy use and energy intensity through to 2032. This target year was chosen in consultation with stakeholders to align with the *Kigali Transportation Master Plan*. The baselines were reviewed by sectoral focus groups (see Table 1) to ensure they were as realistic as possible. The focus groups were assembled by the City of Kigali and the International Growth Centre (which funded this study).

In our analysis of commercial, public, and residential buildings, data on electricity consumption in Kigali by private customers (excluding industry) and public sector customers were provided by the Rwanda Energy Group. Annual per capita consumption of kerosene, charcoal, and fuelwood were held constant at 52 L, 194 kg, and 366 kg, respectively (Drigo, Munyehirwe, Nzabanita, & Munyampundu, 2013; Lights for Life, 2011), as demand for these goods is unlikely to increase with higher incomes. The number of households using these fuels were obtained from the Integrated Households Living Conditions Survey (NISR, 2006, 2011, 2015a). Commercial and public consumption of fuelwood and charcoal in Kigali was projected to increase at a constant rate, based on levels of consumption in 2009 and 2020 (Drigo et al., 2013), as demand for these goods increases with industrial development and economic growth. Estimates of liquefied petroleum gas (LPG) consumed in Rwanda between 2003 and 2007 (MARGE, 2009) was assumed to have been consumed in Kigali, and city-scale data were subsequently available for 2009 and 2020 (Drigo et al., 2013). Historical growth rates between 2010 and 2015 were projected to continue through to 2032 at the same rate.

In the transport sector, planned infrastructure investments in Kigali are drawn from the Kigali City Master Plan (City of Kigali, 2013a) and Rwandan Transport Development Authority (Van Zyl, Swanepoel, & Bari, 2014). Transport mode share in Kigali in 2011 was drawn from a revealed preference dataset (SSI Engineers, 2011a), whereas the number of trips per day, average vehicle speed, occupancy rates, travel time, and walking distances by travel mode were drawn from a hierarchical multimodal transport model (SSI Engineers, 2011b). These models were initially prepared for, and shared with us by, the Rwanda Transport Development Authority. The number of trips by private transport is assumed to grow in proportion to vehicle ownership, and the number of trips by bus is assumed to increase with the expected number of buses (holding occupancy constant). The proportion of trips made on foot and by heavy transport was held constant, and trips by motos was considered the residual.

In the electricity sector, data from the Rwanda Environment Management Authority (REMA, 2014) and Bloomberg New Energy Foundation (BNEF, 2015) were used to calculate historical generation, capacity factors, and generation efficiency. The baseline scenario was developed based on planned capacity expansions, investment costs, and anticipated technical losses through 2017/2018, drawn from the Rwandan Ministry of Infrastructure (MININFRA, 2011) and Japan International Cooperation Agency (JICA, 2015).

The composition of waste in 2012 was food waste (67%), paper waste (16%), garden waste (7%), industrial waste (4%), wood waste (3%), textiles (2%), and plastics/metal (1%; Bazimenyera, Qiang, & Karangwa, 2012a). This was assumed to remain constant through

TABLE 1 Organisations that participated in the expert workshops

Private sector	Public sector	Other
Ampersand	City of Kigali	Cooperation for Urban Mobility in the Developing World (CODATU)
BESS	Environment and Climate Change Fund	Global Green Growth Institute
COPED	Ministry of Local Government	Rwanda Federation of Transport Cooperatives
Kigali Bus Services	Ministry of Natural Resources	University of Rwanda
Mobisol	Ministry of Infrastructure	
Rwanda Energy Group	Rwanda Environment Management Authority	
	Rwanda Housing Authority	

2032. Per capita waste production is projected to rise from 1.8 kg per day in 2011 to 2.0 kg per day in 2030 (UN, 2013). Waste disposal methods were drawn from the population and housing censuses (NISR, 2002, 2012). The cost of waste disposal was drawn from the Kigali City Master Plan (City of Kigali, 2013a) and the characteristics of landfills serving Kigali from Bazimenyera, Qiang, and Ntakirutimana (2012b).

Data on electricity prices were obtained from the Statistical Yearbooks (NISR, 2013, 2014; 2015b, 2016). Data on the price of charcoal and fuelwood were obtained from the Global Environmental Facility (GEF, 2005), the Biomass Energy Strategy (MARGE, 2009), the Rwanda Natural Resources Authority (Drigo et al., 2013), and Safari (2010). Data on the prices of kerosene, LPG, and gasoline were obtained from the Biomass Energy Strategy (MARGE, 2009), the World Bank (2015a), United Nations agencies (Kazoora, 2010), and regional media outlets such as The New Times (Mukaaya, 2008) and allAfrica (Businge, 2015). Nominal energy prices were converted into real energy prices at 2014 levels using a consumer price index (World Bank, 2015b). An annual increase of 2% in real terms was assumed for all energy prices from 2015 to 2032.

We compare all future activities against these baselines.

3.2 | Identification and assessment of measures

We reviewed the academic and grey literature to develop a long list of all the energy efficiency, renewable energy, and other low-carbon measures that could potentially be adopted in the city, including both technological and behavioural measures. This long list was then reviewed to remove any low-carbon options that are not applicable in a Rwandan context or that lacked sufficient data on their energy performance. The shortlist of measures is presented in Table 2.

We determined the net present value of each measure, assuming real price increases of 2% per annum and using a real interest discount rate of 5%. We considered the capital, running, and maintenance costs, focusing on the marginal or extra costs of adopting a more energy efficient or lower-carbon alternative. We then calculated the energy, financial, and carbon savings of each option over its lifetime. As each measure could be in place for many years, we accounted for the changing carbon intensities of electricity (based on planned investments in the electricity sector) and assumed an average annual rise of 2% in real prices (including energy).

We then calculated the potential for deploying each measure in Kigali between 2015 and 2032. Our assessment of realistic levels of uptake took into account anticipated rates of economic development, planned infrastructure investments, and the lifespans of existing measures that could be replaced with lower-emission alternatives.

Our method can be illustrated with a specific low-carbon measure: replacing sodium high-pressure bulbs in street lights with more efficient light emitting diodes (LEDs). Fixtures and lamps for sodium bulbs cost USD 250, whereas LEDs cost USD 475 (Silsby, 2013). There are 7,066 fixtures across the city, so the upfront cost of installing sodium bulbs would be RWF 1.2 billion (USD 18.15 million) compared with an upfront cost of RWF 2.3 billion (USD 34.48 million) for LEDs. Sodium bulbs have a lifespan of 10,000 hr, whereas LEDs have a lifespan of 50,000 hr. Street lights are turned on for 12 hr a night in Kigali (City of Kigali, 2013b). We therefore calculate that sodium bulbs will have a lifespan of 2.28 years, whereas LEDs have a lifespan of 11.4 years.

There are three different levels of power required for street lights in different parts of the city.

- Fifteen lamps with low wattage: 150 W bulbs will be replaced with 80 W LED bulbs. We calculate that each LED bulb will save 306.6 kWh per year, which collectively equates to 4.6 MWh.
- Six thousand two hundred fifty-one lamps with medium wattage: 250 W bulbs will be replaced with 120 W LED bulbs. We calculate that each LED bulb will save 569.4 kWh per year, which collectively equates to 3.6 GWh.
- Eight hundred lamps with high wattage: 400 W bulbs will be replaced with 200 W LED bulbs. We calculate that each LED bulb will save 876 kWh per year, which collectively equates to 700.8 MWh.

To calculate the emission reductions each year, we multiply the energy savings by the carbon intensity of electricity. In 2016, this was 0.41 tCO_2-e/MWh, so the total emission reductions from replacing the street lamps that year would be 1.8 $ktCO_2$-e. To calculate the economic returns each year, we multiply the energy savings by the commercial price of electricity. In 2016, this was 164.4 RWF/kWh, so the total economic returns from replacing the street lamps that year would be RWF 701.05 million (USD 10.5 million). We calculate the carbon and economic savings for the lifespan of the low-carbon measure.

These figures are then used to calculate the net present value, that is, the value of future cash inflows and outflows from the perspective of an investor. We find that, although the capital requirements for LEDs are significantly higher, the almost biennial cost of

TABLE 2 Lists of the low-carbon measures considered in the evaluation of the commercial and public, residential, transport, and waste sectors

Sector	Measures
Commercial and public buildings	Replacing incandescent bulbs with compact fluorescent (CFL) bulbs; replacing incandescent bulbs with light emitting diodes (LEDs); replacing CFL bulbs with LEDs; building energy efficiency standards; solar panels (1.5 kWp and 2.5 kWp models); solar water heaters (300 L models); street lighting: replacing sodium high pressure bulbs with LEDs.
Residential buildings	Replacing incandescent bulbs with CFL bulbs; replacing incandescent bulbs with LEDs; buildings energy efficiency standards—training workshops; improved cookstoves (SAVE80 and JICO models); replacing charcoal cookstoves with LPG stoves; solar home systems (200, 120, 80, and 30 W models); solar water heaters (200 and 300 L models).
Transport	Bus network expansion; bus network expansion with hybrid vehicles; bus rapid transport (BRT) system—Central Business District (CBD) to Rususoro; BRT system—CBD to Gahanga; cycle lanes; electric motorbikes; Euro IV vehicle standards; import age restrictions (<15 years and < 10 years); parking metres in the CBD.
Waste	Anaerobic digestion; biogasification; home composting; landfill gas flaring; landfill gas utilisation; recycling; centralised (windrow) composting.

replacing the sodium bulbs combined with the additional energy expenditure means that the net present value of choosing LEDs over sodium bulbs is worth RWF 8.4 billion (USD 126.2 million). This is at a discount rate of 5%, that is, assuming that future cash flows are worth 5% less every year relative to current cash flows.[1] In short, investing in LEDs seems like a much more economically attractive option than investing in sodium bulbs—and would also generate total emission reductions of 35.2 ktCO_2-e.

The inputs for each low-carbon measure were subjected to review by the local groups of sectoral experts, whose institutional affiliations are listed in Table 1. Details of the data sources and assumptions used in the appraisal of all other low-carbon options are presented in Appendix A.

3.3 | Aggregation of investment needs and mitigation potential

We drew together our estimates of the performance and scope for deployment of each measure to determine the aggregate impact on the city. This allowed us to estimate overall investment needs and payback periods, as well as impacts on energy expenditure and greenhouse gas emissions. The resulting economic case is presented from the perspective of the city as a unit, rather than from the perspective of individual or institutional investors.

Some of the measures interact with each other, so their performance depends on whether/to what extent another option is also adopted. For example, the carbon savings from increasing use of bicycles depend on whether commuters are moving from diesel or hybrid cars, whereas the mitigation potential of more efficient air conditioners depends on the emission intensity of the grid. The league tables present the impacts of individual low-carbon measures. The city-scale scenarios present the impacts of bundles of low-carbon measures.

3.4 | Limitations

One of the major challenges facing decision-makers across sub-Saharan Africa is the absence of robust, detailed, publicly available data. Rwanda is an exception to this trend in many ways: Most notably, the National Institute of Statistics of Rwanda (NISR) prepares an annual statistical yearbook, conducts a population census every five years, and prepares thematic reports on a wide range of topics (including amenities and utilities) every 5 years. However, there is still extremely limited information available on the composition of energy supply, levels of energy consumption, the price of energy, the capital costs of different measures, or the potential energy savings. This analysis therefore draws on a wide range of data sources, including academic and grey literature, newspaper articles, product advertisements, project reports, and datasets published by government and multilateral agencies.

Data on energy use by industry are not available at the city scale in Rwanda. The country has only completed one industrial survey (MINICOM et al., 2011), and this does not clearly break down where different firms are located or provide any data on their energy consumption. It was therefore not possible to include this sector in this analysis.

4 | RESULTS

4.1 | Business-as-usual trends in Kigali

Population and economic growth in Kigali are driving a significant increase in energy consumption. The city's total energy consumption is projected to increase by 187.0%, from 2.1 TWh in 2015 to 6.1 TWh in 2032. When coupled with rising energy prices, total expenditure on energy will rise by 249.7% in the same period of time, increasing from RWF 206.1 billion (USD 301.0 million) to a forecast level of RWF 720.8 billion (USD 1.1 billion). However, economic growth is outstripping rising energy demand: Energy use per unit of GDP will fall by over a third in the same period of time. This similarly means that the proportion of city-scale GDP spent on energy will fall from 10.1% in 2015 to 7.7% in 2032.

Although diesel generation remains common and consumption of peat is expected to rise, the increasing share of natural gas and hydropower (including regional imports) will lead to a decline of 11.4% in the emission intensity of electricity. Despite this fall, the average carbon intensity of energy is projected to remain constant due to rising demand for liquid fossil fuels.

Higher per capita energy consumption and a growing population will lead to an increase in the city's carbon emissions. Total emissions are forecast to increase nearly threefold, from 1.0 MtCO_2-e in 2015 to 2.8 MtCO_2-e in 2032 (Figure 2).

In 2015, waste is responsible for nearly 40% of emissions in Kigali. This is because per capita waste production approaches levels seen in high-income countries much earlier than other sources of greenhouse gas emissions (such as private vehicle ownership or cooling energy demand). By 2032, however, transport is likely to become the primary source of greenhouse gas emissions as dependence on moto-taxis and private vehicles increases (Figure 3). Under business-as-usual conditions, emissions associated with transport are projected to increase by 170%. Residential, commercial and public buildings will see an even greater increase of 237% in the same timeframe.

4.2 | The scope for a low-carbon urban transition in Kigali

We find that emissions could be reduced by 39.0%, relative to business-as-usual trends, through cost-effective investments that would more than pay for themselves on commercial terms over their lifetime (see Figure 4). This would require investment of RWF 630.6 billion (USD 920.7 million), generating annual savings of RWF 118.6 billion (USD 173.2 million). The measures would collectively pay for themselves in 5.3 years and continue to generate savings throughout their lifetimes.

[1]At a discount rate of 1%, the net present value rises to RWF 12.2 billion (USD 183.2 million); at a discount rate of 10%, it falls to RWF 5.6 billion (USD 83.9 million). The choice of discount rate therefore significantly affects the estimated net present value.

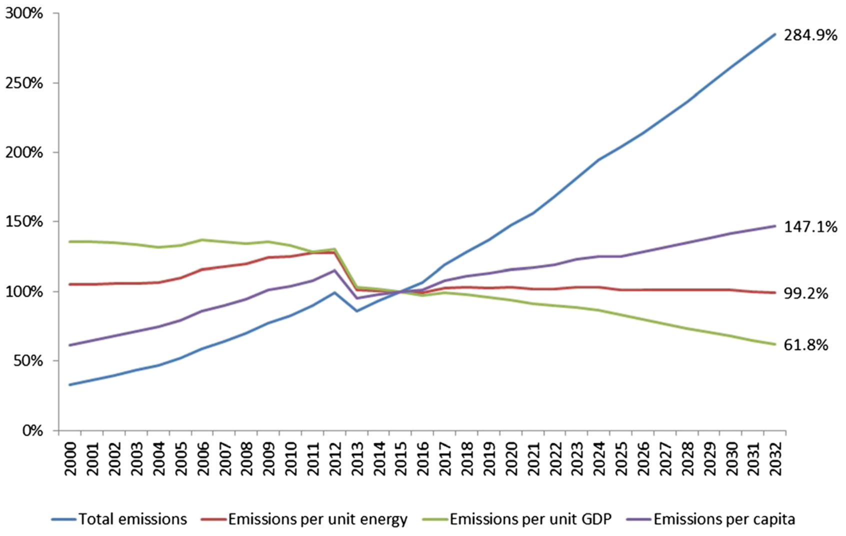

FIGURE 2 Indexed emissions—total, per unit of energy, per unit of GDP and per capita, 2000–2032 [Colour figure can be viewed at wileyonlinelibrary.com]

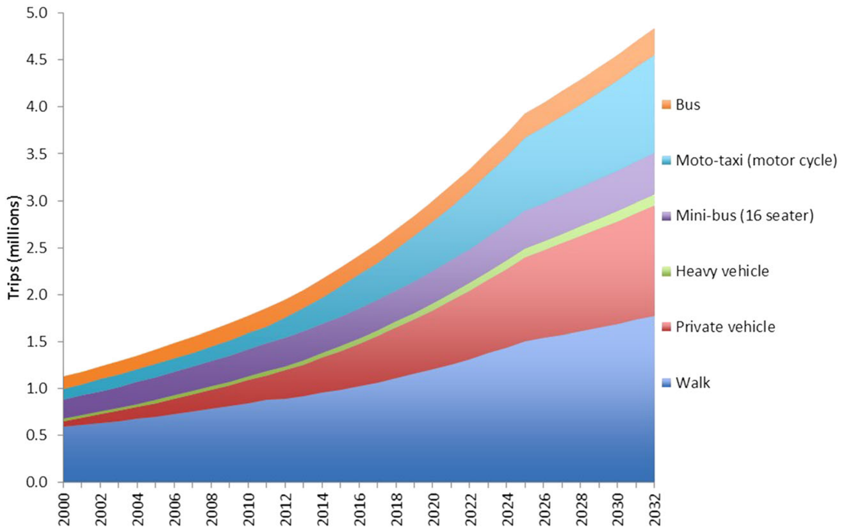

FIGURE 3 Trips by mode share in Kigali in the business-as-usual scenario, 2000–2032 [Colour figure can be viewed at wileyonlinelibrary.com]

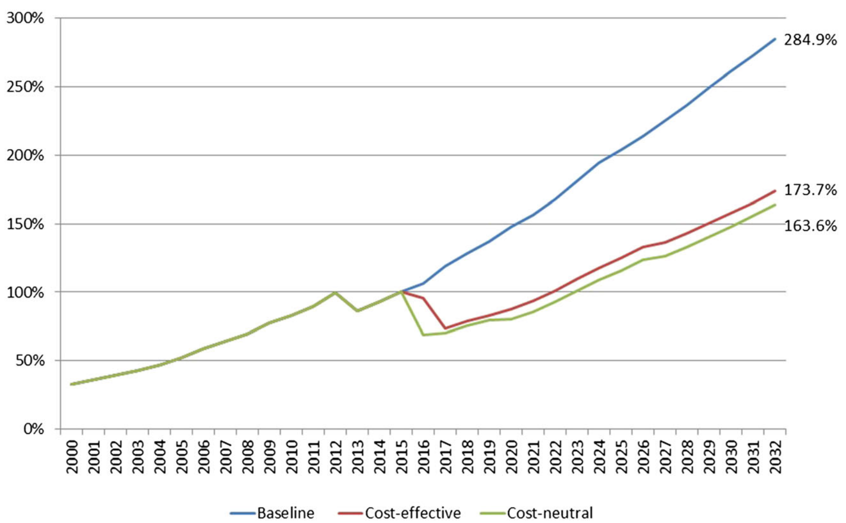

FIGURE 4 Emissions from Kigali under three different investment scenarios, indexed against 2015 emissions, 2000–2032 [Colour figure can be viewed at wileyonlinelibrary.com]

Greenhouse gas emissions could be reduced by 43%, relative to business-as-usual trends, through re-investing the income generated from the cost-effective measures into additional low-carbon measures. This would require net investment of RWF 1.0 trillion (USD 1.5 billion), generating annual savings of RWF 138.8 billion (USD 202.6 million). The measures would collectively pay for themselves in 7.5 years.

The waste sector contains 74% of the economically attractive mitigation potential in Kigali (see Table 3). This is in part because of the

TABLE 3 League table of the most cost- and carbon-effective measures available in the city of Kigali

Sector	Cost-effective measures (USD/tCO2-e)		Carbon-effective measures ($ktCO_2$-e)[a]	
Commercial and public buildings	Replacing incandescent light bulbs with compact fluorescent bulbs	405	Replacing compact fluorescent tubes with LED tubes—100,000 tubes	72
	Street lighting: replacing high pressure sodium bulbs with LED bulbs	349	Replacing incandescent light bulbs with LED bulbs—100,000 bulbs	60
	Replacing incandescent light bulbs with light emitting diodes (LEDs)	346	Building energy efficiency standards	48
			2.5 kWp solar panel—3,000 installed	39
	2.5 kWp solar panel	231	Street lighting: replacing high pressure sodium bulbs with LED bulbs	35
	Replacing compact fluorescent tubes with LED tubes	192	300-L solar water heater—3,000 installed	29
	300 L solar water heater	160		
Power generation	Geothermal (200 MW)	369	Geothermal (200 MW)	10,137[b]
Residential buildings[c]	Building energy efficiency—training workshops	1,860	200 L solar water heaters (50,000 installed by 2032)	321
	Replacing kerosene lamps with solar lamps		Replacing incandescent light bulbs with LED bulbs	
	Replacing incandescent light bulbs with compact fluorescent bulbs	1,784	Replacing incandescent light bulbs with compact fluorescent bulbs	281
	Replacing incandescent light bulbs with LED bulbs	405	Improved cookstoves	258
	200 L solar water heaters		200 W solar home system—15,000 installed by 2032	
	Improved charcoal cookstoves	346		90
			Replacing charcoal cookstoves with LPG stoves	
		255		18
		113		
				11
Transport	Parking metres in Central Business District	691	Doubling bus network capacity with Euro IV standards	1,340
	Bike lanes			
	Electric motorbikes	676	Doubling bus network capacity	1,300
	Import age restrictions on private vehicles (<15 years)	650	Euro IV standards for private vehicles	865
		360	Electric motorbikes—5% of all trips	355
	Euro IV standards for private vehicles		Bus Rapid Transit line—CBD to Gahanga	256
	Doubling bus network capacity	234	Bus Rapid Transit line—CBD to Rusosoro	233
	Doubling bus network capacity with Euro IV standards	71	Import age restrictions on private vehicles (<15 years)	201
		70		
Waste	Landfill gas utilisation	5	Centralised anaerobic digestion to electricity	12,736
	Centralised anaerobic digestion to electricity	0	Landfill gas utilisation	
				9,133

Note. Measures in red do not yield a positive net present value, although their incremental costs could be paid for by re-investing the profits generated from the cost-effective measures [Colour table can be viewed at wileyonlinelibrary.com]

[a]These are estimates of the total carbon savings between 2016 and 2032, assuming phased deployment. However, most of these mitigation options would continue to generate emissions reductions beyond 2032.

[b]This is an estimate of the total carbon savings associated with this measure, only a small proportion of which could be attributed to Kigali.

[c]Subsidies are available for compact fluorescent light bulbs and solar water heaters, which further improve their cost-effectiveness.

energy generation potential of the waste treatment measures, whereby electricity generated would displace emissions that would have otherwise been released in the power generation sector: The waste sector can therefore potentially be a carbon sink (Papargyropoulou, Colenbrander, Sudmant, Gouldson, & Tin, 2015). The remaining carbon savings are distributed among the transport sector (13%), the residential sector (6%), the commercial and public sector (1%), and the electricity sector (6%).

Reducing the carbon intensity of power generation (Figure 5) generates relatively few direct emission reductions for the city. However, the provision of low-carbon electricity can significantly broaden the range of mitigation options that could be adopted in Kigali. For example, the growing mode share of private vehicles and moto-taxis will lead to growing demand for diesel and gasoline. Increasing the reliability of the power supply can improve the feasibility of electric cars and electric motorbikes, while reducing the greenhouse gases produced during those trips. By 2032, we find that investments in geothermal energy could reduce the emission factor of electricity by 36.6% (from 0.41 tCO_2 to 0.26 tCO_2 per megawatt hour) and the levelised cost of electricity[2] by 22.5% (from RWF 85.1 [USD 0.12] to RWF 109.8 [USD 0.16] per kilowatt hour).

Although these mitigation measures will reduce city-scale emissions relative to business-as-usual trends, it is clear from Figure 4 that they do not stop overall emissions from rising in absolute terms. With exploitation of all cost-effective options, emissions would still be 73.7% above 2015 levels by 2032.

5 | DISCUSSION AND CONCLUSIONS

Our research suggests that a lower-carbon development path is both technically and economically feasible for Kigali. The city could profitably invest 0.6% of its GDP (USD 17 million) per year for 10 years in low-carbon measures. This would reduce the city's greenhouse gas emissions by 39.0% by 3032, relative to business-as-usual trends. The measures would collectively generate energy savings equivalent

[2]The average total cost to build and operate electricity-generating infrastructure over its lifetime, divided by the total power output over its lifetime.

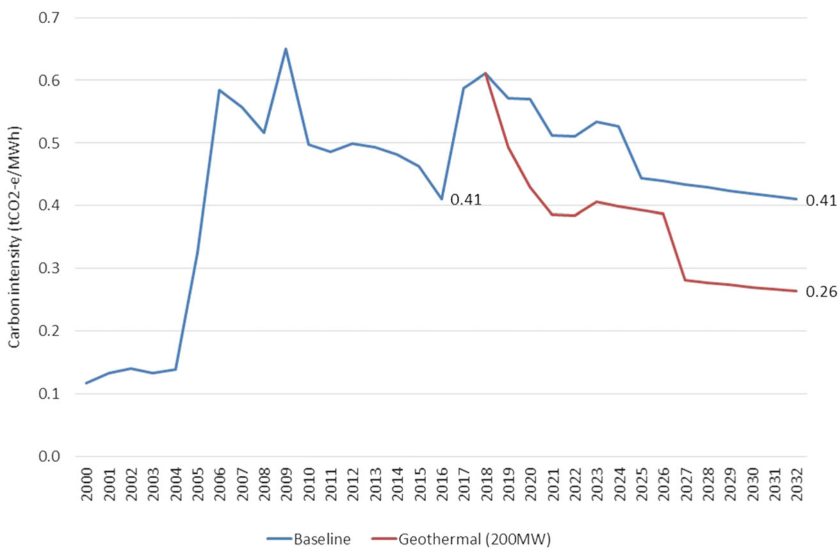

FIGURE 5 Emissions factor of electricity in Rwanda under two different investment scenarios, 2000–2032 [Colour figure can be viewed at wileyonlinelibrary.com]

to 1.5% of city-scale GDP in 2032 (USD 203 million). As a share of total city-scale emissions, these findings indicate that the cost-effective mitigation potential in Kigali is much higher than that that available for cities in middle-income countries. In Palembang in Indonesia (Colenbrander, Gouldson, Sudmant, & Papargyropoulou, 2015), Kolkata in India (Colenbrander et al., 2016), and Recife in Brazil (Colenbrander et al., 2017), for example, economically attractive measures would only deliver emission reductions of 20–25% relative to business-as-usual trends.

It is also important to note that these investments would cumulatively offer two further economic benefits through improving energy efficiency and increasing the share of electricity generated from decentralised renewables. First, the Government of Rwanda would not have to construct as much new power generation infrastructure in the near-term. Under business-as-usual conditions, planned investment in the electricity sector will reach RWF 2.2 trillion (USD 3.1 billion) between 2015 and 2032. This bundle of investments would reduce total demand for, and increase the supply of, electricity, thereby reduce total investment needs in the power sector. Second, Kigali would reduce its dependence on fossil fuel imports, which currently account for 38.6% of domestic electricity generation as well as almost all the energy consumed in the transport sector. These low-carbon investments would therefore help to insulate the city against volatile fossil fuel prices.

Although this analysis seems to offer a number of “win-win” opportunities, two important qualifications are necessary.

First, the upfront investment needs to realise these benefits are implausibly large considering Rwanda's economic context. We estimate that RWF 630.6 billion (USD 920.7 million) would be required to cover the incremental costs of lower-carbon options, which equates to just over 10% of national GDP in 2017 (World Bank, 2018f). For some measures, public and private investors may consider the higher upfront cost to be worthwhile where there is an attractive rate of return: for example, more efficient lighting, improved cookstoves, landfill gas utilisation, solar home systems, or solar water heaters. Where cost recovery is difficult, international development assistance or climate finance might be available to cover the additional investment needs: for example, for the construction of cycle lanes or expansion of bus networks. However, many households, firms, and government agencies in Rwanda would have much higher discount rates than we have used in this study and therefore would not regard these measures as economically attractive.

Second, this bundle of measures is not sufficient to shift Kigali on to a low-emission development pathway. Even if the city were to adopt the large and cross-sectoral bundle of measures identified in this study, per capita emissions would continue to rise. This suggests that more ambitious and possibly costly climate action will be required if cities like Kigali are to decouple economic development and greenhouse gas emissions in the long-term. It is difficult to argue that countries like Rwanda should aggressively prioritise low-carbon investments when they face so many other pressing development needs. However, low-carbon measures should undoubtedly be considered as feasible and sometimes attractive options as urban populations and economies grow.

Rwanda may be able to realise some of the immediate economic opportunities identified in this study and even lay the foundations for more ambitious climate action. The country has exceptionally well-developed technical, institutional, and financial capacities relative to its level of economic development, as outlined above. It also has an increasingly centralised state (Gaynor, 2014) with a single political party holding power at all levels. This reduces the probability of tension between central and municipal governments, which has curtailed urban development in other sub-Saharan African nations (Resnick, 2011).

For the most part, however, it seems plausible that low-carbon urban development in Kigali and similar cities will be constrained by the same institutional, technical, and financial constraints that have hindered more conventional forms of urban development in sub-Saharan Africa. Fiscal shortfalls mean that African governments struggle to finance large infrastructure in ways that balance social and private returns (Parnell & Pieterse, 2014). The civil service has limited experience with urban planning, budgeting, accounting, and finance and is not able to draw on either a sufficiently skilled workforce or established procurement processes (UN Habitat, 2013). Governance arrangements are typically fragmented and contested among public, private, traditional, and community organisations (Dodman, Leck, Rusca, & Colenbrander, 2017). Weak and exclusionary governance systems have resulted in widespread informality, with much physical and economic development occurring outside official spatial plans, regulation, or land property markets (Watson, 2009). Taken together, these characteristics will make it difficult for decision-makers to design and implement climate-compatible urban plans, policies, and investments in sub-Saharan African cities.

Kigali may be able to shift on to a lower-carbon development path in the short to medium term, generating economic returns that inspire other municipalities across the region to emulate its efforts. However, it is unlikely that many other towns and cities in sub-Saharan Africa would be able to realise the full economic opportunity outlined in this paper. Even if they did, the evidence suggests that this would not necessarily lead to a deeper decoupling of economic growth from carbon emissions in the longer term. Yet without ambitious climate action in the fast-growing cities of sub-Saharan Africa, it will be difficult to achieve the Paris Agreement. The tragedy, of course, is that urban residents in Africa will bear some of the most severe impacts of global climate change.

INFORMATIVE

What is the economic case for African cities to pursue more sustainable modes of development? An analysis of low-carbon measures in Kigali, Rwanda, finds significant scope for emissions reduction through the deployment of measures that generate a commercial return. However, these investments are not sufficient to decouple economic growth and greenhouse gases. This is significant as the perception that low-carbon urban development is more expensive than higher-carbon alternatives can be enough to preclude action, especially in highly resource-constrained contexts.

AUTHOR CONTRIBUTIONS

Sarah Colenbrander managed this project, conducted the analysis for the commercial, public, and residential buildings sectors, and drafted this article. Andrew Sudmant conducted the analysis of the power generation and transport sectors, collated the findings from across sectors to produce the city-level findings, and contributed paragraphs to this article. Natasha Chilundika conducted the analysis of the waste sector. Andy Gouldson originally developed the bottom-up approach to assessing the investment needs, returns, and carbon savings of urban mitigation options and provided constructive comments on this article.

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REFERENCES

Ansoms, A., & Rostagno, D. (2012). Rwanda's Vision 2020 halfway through: What the eye does not see. *Review of African Political Economy*, *39*(133), 427–450. https://doi.org/10.1080/03056244.2012.710836

Bazimenyera, J. D., Qiang, F., & Karangwa, A. (2012a). Solid waste management in Kigali City, Rwanda. *East African Journal of Science and Technology*, *2*, 46–58.

Bazimenyera, J. D., Qiang, F., & Ntakirutimana, T. (2012b). Assessment of the characteristics of Nyanza Landfill leachate, Rwanda. *Advanced Materials Research (Trans Tech Publications).*, *599*, 618–621. https://doi.org/10.4028/www.scientific.net/AMR.599.618

BNEF (2015). *Bloomberg Rwandan electricity generation database*. London: Bloomberg New Energy Finance.

Businge, J. (2015). Fuel dealers or profiteers? allAfrica. Published 18 January 2015. Retrieved from http://allafrica.com/stories/201501190074.html [retrieved 03/08/2015]

Byamukama, B., Carey, C., Cole, M., Dyszynski, J., & Warnest, M. (2011). *Baseline report: National strategy on climate change and low carbon development for Rwanda*Smith School of Enterprise and the Environment, University of Oxford. Retrieved from http://www.greengrowthknowledge.org/resource/baseline-report-national-strategy-climate-change-and-low-carbon-development-rwanda [retrieved 02/08/2018]

Cabannes, Y. (2015). The impact of participatory budgeting on basic services: Municipal practices and evidence from the field. *Environment and Urbanization*, *27*(1), 257–284. https://doi.org/10.1177/0956247815572297

Chavez, A., & Sperling, J. (2017). Key drivers and trends of urban greenhouse gas emissions. In S. Dhakal, & M. Ruth (Eds.), *Creating low carbon cities* (pp. 157–168). Springer International Publishing. https://doi.org/10.1007/978-3-319-49730-3_14

City of Kigali. (2013a). *Kigali City Analysis Benchmarking and Vision Report*. Retrieved from http://www.masterplan2013.kigalicity.gov.rw/downloads/Docs/RWF1101_02_Kigali%20City_Analysis%20Benchmarking%20and%20Vision%20Report_03062013-s.pdf [retrieved 28/05/2015]

City of Kigali. (2013b). *Request for expression of interest for replacement of sodium high pressure bulbs with the energy efficient light emitting diode on the existing street lights on the urban roads of the City of Kigali*. Retrieved from http://www.kigalicity.gov.rw/IMG/pdf/Expression_of_Interest_-_Public_Lights-_a_draft.pdf [retrieved 21/08/2015]

Colenbrander, S., Gouldson, A., Roy, J., Kerr, N., Sarkar, S., Hall, S., … McAnulla, F. (2016). Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization*, *29*(1), 139–158.

Colenbrander, S., Gouldson, A., Sudmant, A. H., & Papargyropoulou, E. (2015). The economic case for low-carbon development in rapidly growing developing world cities: A case study of Palembang, Indonesia. *Energy Policy*, *80*, 24–35. https://doi.org/10.1016/j.enpol.2015.01.020

Colenbrander, S., Sudmant, A. H., Gouldson, A., Reis de Albuquerque, I., McAnulla, F., & Oliviera de Sousa, Y. (2017). The economics of climate mitigation: exploring the relative significance of the incentives for and barriers to low-carbon investment in urban areas. *Urbanisation.*, *2*(1), 38–58. https://doi.org/10.1177/2455747117708929

Dhillon, R. S., & Phillips, J. (2015). State capability and Rwanda's health gains. *The Lancet Global Health.*, *3*(6), e308–e310. https://doi.org/10.1016/S2214-109X(15)00008-X

Dodman, D., Leck, H., Rusca, M., & Colenbrander, S. (2017). African urbanisation and urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, *26*, 7–15. https://doi.org/10.1016/j.ijdrr.2017.06.029

Drigo, R., Munyehirwe, A., Nzabanita, V., & Munyampundu, A. (2013). *Update and upgrade of WISDOM Rwanda and Woodfuels value chain analysis as a basis for the Rwanda Supply Master Plan for fuelwood and* *charcoal*. Rwanda Natural Resources Authority and the Department of Forestry and Nature Conservation. Retrieved from http://rnra.rw/fileadmin/user_upload/Final_Report_SMP_Rwanda.pdf [retrieved 14/02/2018]

Enongene, K. E., Murray, P., Holland, J., & Abanda, F. H. (2017). Energy savings and economic benefits of transition towards efficient lighting in residential buildings in Cameroon. *Renewable and Sustainable Energy Reviews*, *78*, 731–742. https://doi.org/10.1016/j.rser.2017.04.068

Ermert, V., Fink, A. H., & Paeth, H. (2013). The potential effects of climate change on malaria transmission in Africa using bias-corrected regionalised climate projections and a simple malaria seasonality model. *Climatic Change*, *120*(4), 741–754. https://doi.org/10.1007/s10584-013-0851-z

Gaynor, N. (2014). 'A nation in a hurry': The costs of local governance reforms in Rwanda. *Review of African Political Economy*, *41*(S1), S49–S63. https://doi.org/10.1080/03056244.2014.976190

GEF. (2005). *Sustainable energy development project: Financing plan*. Global environment facility. Retrieved from http://documents.worldbank.org/curated/en/2014/07/19904831/rwanda-sustainable-energy-development-project-rwanda-sustainable-energy-development-project [retrieved 14/02/2018]

Gorelick, J. (2018). Supporting the future of municipal bonds in sub-Saharan Africa: The centrality of enabling environments and regulatory frameworks. *Environment and Urbanization*, *30*(1), 103–122. https://doi.org/10.1177/0956247817741853

Gouldson, A., Colenbrander, S., Sudmant, A., McAnulla, F., Kerr, N., Sakai, P., … Kuylenstierna, J. (2015). Exploring the economic case for climate action in cities. *Global Environmental Change*, *35*, 93–105. https://doi.org/10.1016/j.gloenvcha.2015.07.009

Granoff, I., Hogarth, J. R., & Miller, A. (2016). Nested barriers to low-carbon infrastructure investment. *Nature Climate Change*, *6*, 1065–1071. https://doi.org/10.1038/nclimate3142

Gujba, H., Mulugetta, Y., & Azapagic, A. (2013). Passenger transport in Nigeria: Environmental and economic analysis with policy recommendations. *Energy Policy*, *55*, 353–361. https://doi.org/10.1016/j.enpol.2012.12.017

IEA (2017). *Energy efficiency 2017*. Paris: International Energy Agency. Retrieved from: http://www.iea.org/publications/freepublications/publication/Energy_Efficiency_2017.pdf [retrieved 21/07/2018]

INSR and ORC Macro (2006). *Rwanda demographic and health survey 2005*. Calverton, Maryland, USA: Institut National de la Statistique du Rwanda and ORCD Macro.

IRENA (2017). *IRENA cost and competitiveness indicators: Rooftop solar PV*. Abu Dhabi: International Renewable Energy Agency. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Dec/IRENA_Cost_Indicators_PV_2017.pdf [retrieved 21/07/2018]

JICA (2015). *The project for preparation of electricity development plan for sustainable geothermal energy development in Rwanda*Japanese International Cooperation Agency.

Kamarudeen, S., & Söderbom, M. (2013). *Constraints and opportunities in Rwanda's industrial sector*. London: International Growth Centre. Retrieved from https://www.theigc.org/project/constraints-and-opportunities-in-rwandas-industrial-sector-evidence-from-firm-level-data/

Kazoora, C. (2010). Final report on four economic instruments. UNDP-UNEP poverty environment initiative. Retrieved from http://www.unpei.org/sites/default/files/e_library_documents/rwanda-finalreport-ECONOMICINSTRUMENTS.pdf [retrieved 14/02/2018]

Lights for Life. (2011). *The impact of lighting poverty on children*. Retrieved from http://www.lightsforlife.org/impact_of_lighting_poverty_on_children [accessed 14 February 2018]

MARGE. 2009. *Rwanda: Biomass energy strategy: Volume 2: Background and analysis*. European Union Energy Initiative on behalf of Ministry of Infrastructure, Ministry of Environment and Natural Resources. Retrieved from http://cleancookstoves.org/resources_files/best-volume-2background.pdf [retrieved 14/02/2018]

MINICOM, NISR, BNR and RDB (2011). *Rwanda industrial survey 2011*. Kigali: The Ministry of Trade and Industry, the National Institute of Statistics Rwanda, the National Bank of Rwanda and the Rwanda Development Board. Retrieved from: http://www.minicom.gov.rw/fileadmin/minicom_publications/Reports/minicomIndustrialSurveyUpdated_opt1.pdf

MININFRA (2011). *National energy policy and strategy*Ministry of Infrastructure. Retrieved from https://energypedia.info/images/7/77/ENERGY_POLICY_and_STRATEGY.pdf [retrieved 14/02/2018]

Ministry of Lands, Environment, Forestry, Water and Mines (2006). *National adaptation programmes of action to climate change*. Republic of Rwanda. Kigali. Retrieved from https://unfccc.int/resource/docs/napa/rwa01e.pdf

Mukaaya, E. (2008). *Kerosene prices fall by 3.3 percent*. The New Times. Published 17 October 2008. Retrieved from http://www.newtimes.co.rw/section/read/40553/

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H. (2013). Carbon emissions of infrastructure development. *Environmental Science & Technology*, *47*, 11739–11746. https://doi.org/10.1021/es402618m

Murphy, P. M., Twaha, S., & Murphy, I. S. (2014). Analysis of the cost of reliable electricity: A new method for analysing grid connected solar, diesel and hybrid distributed electricity systems considering an unreliable electric grid, with examples in Uganda. *Energy*, *66*(1), 523–534. https://doi.org/10.1016/j.energy.2014.01.020

NISR (2002). *Third general census of population and housing of Rwanda*. Kigali, Rwanda: National Institute of statistics of Rwanda. Retrieved from http://www.statistics.gov.rw/publication/third-general-census-population-and-housing-rwanda-final-results-statistical-tables [retrieved 14/02/2018]

NISR (2006). *EICV2 thematic report: Utilities and amenities*National Institute of statistics of Rwanda. Retrieved from http://www.statistics.gov.rw/survey-period/integrated-household-living-conditions-survey-2-eicv-2 [retrieved 14/02/2018]

NISR (2009). *Statistical yearbook 2009*. Kigali, Rwanda: National Institute of Statistics of Rwanda. Retrieved from: http://www.statistics.gov.rw/publication/statistical-yearbook-2009 [retrieved 14/02/2018]

NISR (2011). *EICV3 thematic report: Utilities and amenities*National Institute of statistics of Rwanda. Retrieved from http://www.statistics.gov.rw/survey-period/integrated-household-living-conditions-survey-3-eicv-3 [retrieved 14/02/2018]

NISR (2012). *Fourth population and housing census—2012*. Kigali, Rwanda: National Institute of statistics of Rwanda. Retrieved from http://statistics.gov.rw/survey-period/fourth-population-and-housing-census-2012 [retrieved 14/02/2018]

NISR (2013). *Statistical yearbook 2012*. Kigali, Rwandad: National Institute of statistics of Rwanda. Retrieved from http://statistics.gov.rw/publications/statistical-yearbook-2012 [retrieved 14/02/2018]

NISR (2014). *Statistical yearbook 2013*. Kigali, Rwanda: National Institute of Statistics of Rwanda. Retrieved from http://statistics.gov.rw/publications/statistical-yearbook-2013 [retrieved 14/02/2018]

NISR (2015a). *Rwanda integrated households living conditions survey [EICV] 2013/2014: Main indicators report*National Institute of statistics of Rwanda. Retrieved from: http://statistics.gov.rw/publications/main-indicators-report-results-eicv-4 [retrieved 14/02/2018]

NISR (2015b). *Statistical yearbook 2014*. Kigali, Rwanda: National Institute of Statistics of Rwanda. Retrieved from http://statistics.gov.rw/publications/statistical-yearbook-2015 [retrieved 14/02/2018]

NISR (2016). *Statistical yearbook 2016*. Kigali, Rwanda: National Institute of statistics of Rwanda. Retrieved from http://www.statistics.gov.rw/publication/statistical-yearbook-2016 [retrieved 14/02/2018]

NISR, Ministry of Health [Rwanda] and ICF International (2012). *Rwanda demographic and health survey 2010*. Calverton, Maryland, USA: National Institute of Statistics of Rwanda, Ministry of Health [Rwanda], and ICF International.

NISR, Ministry of Health [Rwanda], and ICF International (2015). *Rwanda demographic and health survey 2014–2015*. Rockville, Maryland, USA: National Institute of Statistics of Rwanda, Ministry of Health [Rwanda], and ICF International.

Ondraczek, J. (2014). Are we there yet? Improving solar PV economics and power planning in developing countries: The case of Kenya. *Renewable and Sustainable Energy Reviews*, *30*, 604–615. https://doi.org/10.1016/j.rser.2013.10.010

Oteng-Ababioa, M., Arguello, J., & Gabbay, O. (2013). Solid waste management in African cities: Sorting the facts from the fads in Accra, Ghana. *Habitat International*, *39*, 96–104.

Oz Architecture, Kigali Conceptual Master Plan, Bolder Colorado, United States. (2007). Retrieved from http://ozarch.com/portfolio/kigali-master-plan/[retrieved 03/08/2018].

Papargyropoulou, E., Colenbrander, S., Sudmant, A. H., Gouldson, A., & Tin, L. C. (2015). The economic case for low-carbon waste management in rapidly growing cities in the developing world: The case of Palembang, Indonesia. *Journal of Environmental Management*, *163*, 11–19.

Parnell, S., & Pieterse, E. (2014). *Africa's urban revolution*. London: Zed Books.

REMA (2014). *Rwandan grid emissions factor stabilized baseline*. Kigali: Rwandan Environment Management Authority. May 20, 2014. Retrieved from: https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20140625122845372/Rwanda_GEF_SB_May-14.pdf [retrieved 14/02/2018]

Resnick, D. (2011). In the shadow of the city: Africa's urban poor in opposition strongholds. *The Journal of Modern African Studies.*, *49*(1), 141–166.

Reyntjens, F. (2011). Constructing the truth, dealing with dissent, domesticating the world: Governance in post-genocide Rwanda. *African Affairs*, *110*(438), 1–34.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, *534*(7609), 631–639.

Safari, B. (2010). A review of energy in Rwanda. *Renewable and Sustainable Energy Reviews*, *14*, 524–529.

Schmidt, T. S. (2014). Low-carbon investment risks and de-risking. *Nature Climate Change*, *4*, 237–239.

Seto, K. C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G. C., Dewar, D., … Ramaswami, A. (2014). Human settlements, infrastructure and spatial planning. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al. (Eds.), *Climate change 2014: Mitigation of climate change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Silsby, S. L. (2013). *HPS to LED conversion—A city of phoenix experience*. City of Phoenix. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/silsby_msslc-phoenix2013.pdf [retrieved 14/02/2018]

SSI Engineers (2011a). *Revealed preference dataset*. Kigali, Rwanda: SSI Engineers.

SSI Engineers (2011b). *Development of a hierarchical multi-modal transport model: Model development task specific technical report*. Kigali, Rwanda: SSI Engineers.

Surbana International Consultants. (2013). *Kigali master plan 2013*. Retrieved from https://surbanajurong.com/sector/kigali-city-master-plan/ [retrieved 14/10/2015].

Turok, I., & McGranahan, G. (2013). Urbanization and economic growth: The arguments and evidence for Africa and Asia. *Environment and Urbanization*, *25*(2), 465–482.

UN Environment (2013). *Rwanda: State of environment and outlook report 2013*. Nairobi, Kigali: United Nations Environment Programme. Retrieved from http://na.unep.net/siouxfalls/publications/Kigali_SOE.pdf [retrieved 14/02/2018]

UN DESA (2014). *2014 Revision of world urbanization prospects*. New York, USA: United Nations Department of Economic and Social Affairs.

UN-Habitat. (2008). UN-Habitat scroll of honour award. Retrieved from http://mirror.unhabitat.org/content.asp?typeid=19&catid=827&cid=6586 [retrieved 03/08/2018].

UN-Habitat (2013). *Planning and design for sustainable urban mobility: Global report on human settlements 2013*. Abingdon, UK: Earthscan/UN HABITAT.

Van Zyl, N. J. W., Swanepoel, L., & Bari, M. (2014). *Planning of a public transport system for the city of Kigali, Rwanda*. 33rd Southern African Transport Conference. Pretoria, South Africa. Retrieved from https://repository.up.ac.za/handle/2263/45589 [retrieved 14/02/2014].

Watson, V. (2009). The planned city sweeps the poor away…': Urban planning and 21st century urbanisation. *Progress in Planning*, *72*, 151–193.

Watson, V. (2014). African urban fantasies: Dreams or nightmares? *Environment and Urbanization*, *26*(1), 215–231.

World Bank. (2015a). *Pump price for gasoline (US$ per litre)*. Retrieved from http://data.worldbank.org/indicator/EP.PMP.SGAS.CD/countries?page=2 [retrieved 14/02/2018].

World Bank. (2015b). *Consumer price index (2010 = 100)*. Retrieved from http://data.worldbank.org/indicator/FP.CPI.TOTL [retrieved 14/02/2018].

World Bank (2018a). *Access to electricity, urban (% of urban population)*. Washington, DC, USA. Retrieved from https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS

World Bank (2018b). *Population, total*. Washington, DC, USA. Retrieved from http://data.worldbank.org/indicator/SP.POP.TOTL?locations=RW

World Bank (2018c). *GDP per capita (current US$)*. Washington, DC, USA. Retrieved from: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

World Bank (2018d). *GDP growth (annual %)*. Washington, DC, USA. Retrieved from http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?page

World Bank (2018e). *CO_2 emissions (metric tons per capita)*. Washington DC, USA. Retrieved from https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

World Bank. 2018f. *GDP (current US$). Washington DC, USA*. Retrieved from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

World Resource Institute. (2018). *Explore historic GHG emissions*. Retrieved from http://cait.wri.org/profile/Sub-Saharan%20Africa

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APPENDIX A

Electricity sector

Through an iterative participatory process involving representatives of the Rwandan Ministry of Infrastructure, Bloomberg New Energy Finance, and energy developers in Rwanda, six scenarios were developed for the electricity sector through 2032. Each scenario produces a minimum of 4,500 GWh in 2032 with 1,036 MW of dispatchable supply. The geothermal scenarios were ultimately found to be the most cost-effective, albeit for investors with higher risk appetites and longer time horizons. The economic and carbon impacts of each scenario were calculated using the technology-specific factors detailed below.

Energy generation scenarios (MW)

Technology	Baseline	Thermal scenario	JICA low cost	Solar 1	Solar 2	Geothermal 1	Geothermal 2
Hydro	285.15	113.15	293.15	285.15	190.15	190.15	173.15
Solar	10.75	10.75	10.75	60.75	260.75	10.75	10.75
Peat	145	195	145	145	145	145	95
Natural gas	203.6	253.6	278.6	203.6	203.6	128.6	128.6
Diesel	73.3	73.3	313.75	73.3	69.3	45.3	45.3
Geothermal	0	0	0	0	0	100	200
Imports	493.5	493.5	3.5	493.5	493.5	493.5	493.5

Key technology-specific values (2015–2032 averages)

Technology	Capacity factor	Capital cost (USD million/ MW)	Operating and maintenance costs (cents per KWh)
Hydropower	0.75	4.00	0.80
Methane gas	0.85	3.70	8.80
Solar	0.16	3.00	0.00
Peat	0.42	3.20	5.50
Geothermal	0.85	3.00	0.50
Diesel	0.61	3.00	27.00
Imports	—	*Case specific*	7.50

Sources:

- AfDB. 2013. *Rwanda Energy Sector Review and Action Plan*. African Development Bank. Available from: http://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Rwanda_-_Energy_Sector_Review_and_Action_Plan.pdf [retrieved 06/09/2015]
- BNEF, 2015. *Rwandan Electricity Generation Database*. Bloomberg New Energy Finance.
- JICA, 2015. *The Project for Preparation of Electricity Development Plan for Sustainable Geothermal Energy Development in Rwanda*. Japan International Cooperation Agency.
- MININFRA, 2011. *National Energy Policy and Strategy*. Ministry of Infrastructure. Available from: https://energypedia.info/images/7/77/ENERGY_POLICY_and_STRATEGY.pdf [retrieved 14/02/2018]
- REMA, 2014. *Rwandan Grid Emissions Factor Stabilized Baseline*. Rwandan Environment Management Authority. Kigali. May 20, 2014. Available from: https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20140625122845372/Rwanda_GEF_SB_May-14.pdf [retrieved 14/02/2018]

Commercial and public sector

(Continued)

Measure	Costs	Savings
Building energy efficiency—training workshops	The incremental costs of improving new commercial and public buildings in a moderate efficiency scenario cost USD 886/m^2.[1] These are sub-Saharan Africa wide estimates, refined by climate zone: We consider Rwanda to fall into the zone of "Only cooling (low and moderate cooling demand)."	The economic savings are based on avoided investment in, and energy consumption by, air conditioners. We assume the cost of a 5-kW air conditioner is RWF 707,143, that is, proportionate to those of a 3.5-kW air conditioner.[c] The total number of air conditioners by 2032 is based on cooling needs of 5 W/m^2. This is low level of cooling reflects Kigali's temperate climate. Total amount of retail, office and hotel floor space is based on projections from the City of Kigali's Master Plan.[2]
More efficient lighting	Incandescent bulbs cost RWF 630.62. Compact fluorescent lamps (CFL) cost RWF 2,541. CFL tubes cost RWF 4,109. Light emitting diodes (LED) cost RWF 22,671. LED tubes cost RWF 44,521.[4] The price of a subsidised CFL bulb is RWF 200. [5]We assumed that CFL bulbs and tubes would entirely replace incandescent options by 2030 without policy interventions. We assume 0% LED market penetration in Kigali in 2015.	Incandescent bulbs have an average input power of 60 W and a life span of 1,200 hr. Compact fluorescent lamps (CFL) have an average input power of 14 W and a life span of 10,000 hr. CFL tubes have an average input power of 25 W and a life span of 8,000 hr. Light emitting diodes (LED) have an average input power of 10 W and a life span of 50,000 hr. LED tubes have an average input power of 8 W and a life span of 40,000 hr.[6]
Solar panels	A 250-Wp solar panel cost RWF 276,000, [7] so we assumed a 2.5-kWp solar panel cost 10 times as much. We assumed 3,000 could be deployed by 2032.	Solar panels are assumed to have a conversion efficiency of 14.5% and life span of 20 years.
Solar water heaters	A 300-L solar water heater has an average cost of USD 1,600. The subsidy for a 300-L solar water heater is RWF 279,000, less an application fee of RWF 30,000. [8]We assumed 3,000 could be deployed by 2032, in light of scope for substantial uptake in the hospitality industry.	Installing 12,000 solar water heaters would save 23,328 MWh per year.[9] We assumed this was based on equal deployment of 200 L and 300 L solar water heaters, that is, a 300-L solar water heater would save 2,332.8 kWh per year. We assumed a lifespan of 15 years.
Street lighting	There are three levels of power required in Rwandan street lights[10]:	Traditional sodium high pressure bulbs have a lifespan of 10,000 hr. LED bulbs have a

(Continued)

Measure	Costs	Savings
	• 15 poles with low wattage: 150 W bulbs will be replaced with 80 W LED bulbs • 6251 poles with medium wattage: 250 W bulbs will be replaced with 120 W LED bulbs • 800 poles with high wattage: 400 W bulbs will be replaced with 200 W LED bulbs Fixtures and lamps for high pressure sodium bulbs cost USD 250, with an annualised replacement cost of USD 14.4. Fixtures and lamps for LED bulbs cost USD 475, with an annualised replacement cost of USD 7.2. [11]	lifespan of 50,000 hr. Street lights are turned on for 12 hr per night. [12]

[1]Ürge-Vorsatz D, Reith A, Korytárová k, Egyed M, Dollenstein J. 2015. Monetary Benefits of Ambitious New Building Energy Policies. Global Buildings Performance Network. Available from: http://www.gbpn.org/sites/default/files/Low_C_MBABEP.pdf

[2]Kaymu. 2015a. LG air conditioner. Available from: http://www.kaymu.rw/lg-air-conditioner-39037.html [retrieved 07/07/2015]

[3]City of Kigali. 2013. Kigali City Analysis Benchmarking and Vision Report. Available from: http://www.masterplan2013.kigalicity.gov.rw/downloads/Docs/RWF1101_02_Kigali%20Cit_Analysis%20Benchmarking%20and%20Vision%20Report_03062013-s.pdf [retrieved 28/05/2015]

[4]Fabien M. 2013. Application of LED type lamps in domestic and public utilities and gain capabilities to run new small investments in Rwanda. Engineering. 5 775--778 doi: 10.4236/eng.2013.510093

[5]World Bank. 2014. Raising Awareness of Energy Efficient Light Bulbs Pays off in Rwanda. Available from: http://www.worldbank.org/en/news/feature/2014/11/06/raising-awareness-energy-efficient-light-bulbs-pays-off-rwanda [retrieved 14/02/2018]

[6]Fabien M. 2013. Application of LED type lamps in domestic and public utilities and gain capabilities to run new small investments in Rwanda. Engineering. 5 775--778 doi: 10.4236/eng.2013.510093

[7]Kaymu. 2015. Solar Panel 250w/24v. Available from: http://www.kaymu.rw/solar-panel-250w-24v-51634.html [retrieved 07/07/2015]8=

[8]REG. 2014. Residential Solar Water Heating Program. Rwanda Energy Group (REG), Rwanda Utilities Regulatory Authority (RURA). Available from: http://www.reg.rw/images/pdf/Description%20of%20SolaRwanda%20Program%20Updated%202014%2002%2011.pdf [retrieved 14/02/2018]

[9]REG. 2014. Residential Solar Water Heating Program. Rwanda Energy Group (REG), Rwanda Utilities Regulatory Authority (RURA). Available from: http://www.reg.rw/images/pdf/Description%20of%20SolaRwanda%20Program%20Updated%202014%2002%2011.pdf [retrieved 14/02/2018]

[10]City of Kigali. 2013. Request for expression of interest for replacement of sodium high pressure bulbs with the energy efficient light emitting diode on the existing street lights on the urban roads of the City of Kigali. Available from: http://www.kigalicity.gov.rw/IMG/pdf/Expression_of_Interest_-_Public_Lights-_a_draft.pdf [retrieved 21/08/2015]

[11]Silsby SL. 2013. HPS to LED Conversion – A City of Phoenix Experience. City of Phoenix. Available from: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/silsby_msslc-phoenix2013.pdf [retrieved 14/02/2018]

[12]City of Kigali. 2013. Request for expression of interest for replacement of sodium high pressure bulbs with the energy efficient light emitting diode on the existing street lights on the urban roads of the City of Kigali. Available from: http://www.kigalicity.gov.rw/IMG/pdf/Expression_of_Interest_-_Public_Lights-_a_draft.pdf [retrieved 21/08/2015]

Residential sector

Measure	Costs	Savings
Building energy efficiency training workshops	Kigali City Council currently holds training workshops at RWF 11 million per workshop. We assume no additional costs associated with constructing green residential buildings as passive cooling levels can be achieved by, for example, optimising building orientation or window-to-wall ratios.	Economic savings are based on avoided investment in, and energy consumption by, air conditioners. A 3.5-kW air conditioner cost RWF 495,000.[1] We assume 2 hr of use per day 100 days per year, and savings enjoyed by 1% of households in Kigali.
Improved cookstoves	An improved SAVE80 cookstove costs USD 100 and has a lifespan of 10 years. [2]	The quantity of woody biomass saved per year is 0.495 tonnes. 88.6% of the woody biomass saved is from nonrenewable sources.[3]
More efficient lighting	Incandescent bulbs have an average input power of 60 W, a life span of 1,200 hr and cost RWF 630.62. Compact fluorescent lamps (CFL) have an average input power of 14 W, a life span of 10,000 hr, and cost RWF 2,541. Light emitting diodes (LED) have an average input power of 10 W, a life span of 50,000 hr, and cost RWF 22,671. [4]The price of a subsidised CFL bulb is RWF 200. [5]	The average household has approximately six light bulbs.[6] For future growth, we assumed that social housing would have two bulbs, affordable housing would have four bulbs, mid-range housing would have 10 bulbs, and premium housing would have 20 bulbs per household. We assumed that CFL bulbs have not achieved market penetration independent of World Bank support,[7] but would be entirely replaced with CFL bulbs by 2030 without policy interventions. We assume 0% LED light bulbs in Kigali in 2015.
Solar home systems	A 200-Wp solar home system requires a down payment of USD 86 and monthly payments of USD 47 for 3 years. [8]	We assume a conversion efficiency of 17%, life span of 20 years and deployment of 15,000 units by 2032.
Solar lamps	The kerosene lamps cost USD 1. Solar lamps cost USD 30 and have a lifespan of 5 years. [9]	Solar lamps replace kerosene lamps, which would consume approximately 1 L per week.
Solar water heaters	A 200-L solar water heater has an average cost of USD 1,300, although it enjoys a subsidy of RWF 186,000 (less an application fee of RWF 30,000). [10]	A 200-L solar water heater would save 1,555.2 kWh per year.[11] We assume a lifespan of 15 years and deployment of 50,000 units by 2032.

[1]Kaymu. 2015. LG air conditioner. Available from: http://www.kaymu.rw/lg-air-conditioner-39037.html [retrieved 07/07/2015]

[2]Hogarth R. 2011. "Finance Sector Working Paper". Smith School of Enterprise and the Environment, University of Oxford. Supplement to Green Growth and Climate Resilience: National Strategy for Climate Change and Low Carbon Development. Available from: http://rema.gov.rw/climateportal/IMG/pdf/finance-swp-final_proofed-2.pdf [retrieved 14/02/2018]

[3]Hogarth R. 2011. "Finance Sector Working Paper". Smith School of Enterprise and the Environment, University of Oxford. Supplement to Green Growth and Climate Resilience: National Strategy for Climate Change and Low Carbon Development. Available from: http://rema.gov.rw/climateportal/IMG/pdf/finance-swp-final_proofed-2.pdf [retrieved 14/02/2018]

[4]Fabien M. 2013. Application of LED type lamps in domestic and public utilities and gain capabilities to run new small investments in Rwanda. Engineering. 5 775--778 doi: 10.4236/eng.2013.510093

[5]World Bank. 2014. Raising Awareness of Energy Efficient Light Bulbs Pays off in Rwanda. Available from: http://www.worldbank.org/en/news/feature/2014/11/06/raising-awareness-energy-efficient-light-bulbs-pays-off-rwanda [retrieved 14/02/2018]

[6]MININFRA. 2008. Residential Customer Lighting Survey of Kigali. Ministry of Infrastructure. Kigali. Available from: https://www.esmap.org/sites/esmap.org/files/27.%20Rwanda_BASELINE_SURVEY_FINAL_REPORT.pdf [retrieved 05/07/2015]

[7]Sarkar A. 2008. Large Scale CFL Deployment Programs; Mainstreaming Carbon Finance and Clean Development Mechanism. World Bank. Available from: http://www.energyrating.gov.au/wp-content/uploads/Energy_Rating_Documents/Library/Lighting/Lighting/2008-phase-out-session4-sarkar.pdf [retrieved 11/07/2015]

[8]Sprenger R. 2013. Mobile Enabled Offgrid Electrification. Mobisol GmbH. Available from: https://www.giz.de/fachexpertise/downloads/2013-de-pep-fachveranstaltung-direktvermarktung-sprenger.pdf [retrieved 10/06/2015]

[9]Disch D, Bronckaers J. 2012. An analysis of the off-grid lighting market in Rwanda: sales, distribution and marketing. Global Village Energy Partnership. Available from: http://www.gvepinternational.org/sites/default/files/rwanda-solar-study-v1.6_small4.pdf [retrieved 03/07/2015]

[10]REG. 2014. Residential Solar Water Heating Program. Rwanda Energy Group (REG), Rwanda Utilities Regulatory Authority (RURA). Available from: http://www.reg.rw/images/pdf/Description%20of%20SolaRwanda%20Program%20Updated%202014%2002%2011.pdf [retrieved 10/06/2015]

[11]REG. 2014. Residential Solar Water Heating Program. Rwanda Energy Group (REG), Rwanda Utilities Regulatory Authority (RURA). Available from: http://www.reg.rw/images/pdf/Description%20of%20SolaRwanda%20Program%20Updated%202014%2002%2011.pdf [retrieved 10/06/2015]

Transport sector

(Continued)

Measure	Costs	Savings
Bike lanes (40 km)	Capital costs and maintenance costs are estimated using the Bogota Cicloruta as a case study [1] and the "Share the Road" cycling project in Nairobi. [2]	Impacts on transport modal share are informed by regional studies[3] and case studies of Bogota[4] and Cape Town. [5]
Parking meters in CBD	350 m are installed and operate 12 hr per day. Cost for installation and maintenance are informed by academic literature. [6]	The occupied rate (50%) and cost per hour (RWF 100) were determined by consultation.
Import restrictions on private vehicles: • <15 years old • <10 years old • Euro IV performance standards	Data on vehicle imports, prices, import taxes, vehicle efficiencies, and the elasticity of demand for vehicles were drawn from previous work completed by the Rwandan Transport Development Agency. [7]	The economic case compares lost tax revenue from vehicles not imported against additional revenue from purchases of younger vehicles. We assume that after 3 years, the total number of vehicles purchased returns to the baseline number as the elasticities provided by RTDA are not viable more than 3 years into the future.
Bus Rapid Transit (BRT) lines: • CBD to Rusororo • CBD to Gahanga.	Construction costs are drawn from the Rwandan Transport Development Authority. [8]	Operating days, operating hours and tariffs are drawn from the Ministry of Infrastructure [9] and the Rwandan Transport Development Authority.[10] The fuel efficiency of vehicles is assumed to be 2.5 km/L. Fuel costs are assumed to be 35% of total operating costs. [11]
Electric motorbikes	Electric bike costs were provided by a private company, Ampersand, at $1176 each including the cost of a replacement battery and local taxes.	Bike efficiencies, annual kilometres and lifetimes were provided by a private company, Ampersand. We assume that electric motorbikes reach 5% of total passenger trips by 2032 by taking modal share from moto transport. Individuals can finance their electric bike at an annual interest rate of 34.5% over 2 years.
Doubling bus network capacity: • Standard buses • Euro IV buses	Capital cost, operating costs, fuel efficiencies, operating days, operating hours, vehicle lifespans, and travel tariffs are drawn from the Kigali Masterplan [12] and the Ministry of Infrastructure.[13] We assume that Euro IV buses cost 40% more than conventional buses based on consultation with transport providers in Kigali.	We assume that bus occupancy remains constant through 2032 and that Euro IV buses operate at 20% higher efficiency than the existing vehicle stock based on consultation with transport providers in Kigali.

[1]C40. 2013. Bogotá''s CicloRuta is one of the Most Comprehensive Cycling Systems in the World. Available from: http://www.c40.org/case_studies/bogot%C3%A1%E2%80%99s-cicloruta-is-one-of-the-most-comprehensive-cycling-systems-in-the-world [retrieved 28/11/2015]

[2]UNEP. 2015. Share the Road: Increased investment in Walking and Cycling Infrastructure. Available from: http://www.unep.org/transport/sharetheroad/ News_info/news_archive_details.asp [retrieved 05/07/2015]

[3]Sietchiping R, Permezel MJ, Ngomsi C. 2012. Transport and mobility in sub-Saharan African cities: An overview of practices, lessons and options for improvements. Cities. 29(3) 183--189.

[4]C40. 2013. Bogotá''s CicloRuta is one of the Most Comprehensive Cycling Systems in the World. Available from: http://www.c40.org/case_studies/bogot%C3%A1%E2%80%99s-cicloruta-is-one-of-the-most-comprehensive-cycling-systems-in-the-world [retrieved 28/11/2015]

[5]Jennings G. 2014. Finding our balance: Considering the opportunities for public bicycle systems in Cape Town, South Africa. Research in Transportation Business & Management. 15 6--14

[6]Litman T. 2009. Transportation cost and benefit analysis. Victoria Transport Policy Institute. 31.

[7]RTDA. 2012. Planning & Design of Public Transport System for Kigali City. Rwandan Transport Development Authority. Available from: http://www.mininfra.gov. rw/uploads/media/Public_Transport_Policy_and_strategy_for_Rwanda_02.pdf [retrieved: 05/06/2015]

[8]RTDA. 2012. Planning & Design of Public Transport System for Kigali City. Rwandan Transport Development Authority. Available from: http://www.mininfra.gov.

[9]MINIFRA. 2011. Final Draft on Public Transport Policy and Strategy for Rwanda. Ministry for Infrastructure.

[10]RTDA. 2012. Planning & Design of Public Transport System for Kigali City. Rwandan Transport Development Authority. Available from: http://www.mininfra.gov.

[11]SSI Engineers. 2011. Revealed Preference Dataset. And Development of a Hierarchical Multi-Modal Transport Model: Model Development Task Specific Technical Report.

[12]City of Kigali. 2013. Kigali City Analysis Benchmarking and Vision Report. Available from: http://www.masterplan2013.kigalicity.gov.rw/downloads/Docs/RWF1101_02_Kigali%20City_Analysis%20Benchmarking%20and%20Vision%20Report_03062013-s.pdf [retrieved 28/05/2015]

[13]MINIFRA. 2011. Final Draft on Public Transport Policy and Strategy for Rwanda. Ministry for Infrastructure.

Waste sector

Measure	Costs	Savings
Landfill gas flaring and utilisation	Capital costs, operational costs, and flaring efficiencies are based on data from the World Energy Council,[1] the International Renewable Energy Agency, [2] and Clean Development Mechanism projects in South Africa[3] and Ghana [4]	We assumed 75% landfill gas collection efficiency [5] and a 10% oxidation factor due to landfill cover. [6] Emission reductions are estimated using data from the Environmental Protection Agency[7] and European Communities. [8] For landfill gas utilisation, we assume that 10% of the electricity generated is used on site and revenue from the remainder is sold at 10 US cents/Kwh.

(Continued)

Measure	Costs	Savings
Composting: - Centralised (windrow) - Home (recycled receptacles)	Capital and operational costs are based on CDM composting projects in Uganda [9] and comparative studies on composting.[10] We assumed a participation rate of 30%, based on targets established by the City of Kigali. [11]	Emissions savings are calculated using data from the IPCC [12] and European Communities. [13] The centralised composition option assumes revenue from the sale of compost, with current prices obtained from local stakeholders involved in composting.
Energy-from-waste using anaerobic digestion	Capital and operational costs for a 15-MW plant are based on case studies in Europe.[14] Emissions resulting from the construction of the plant are derived from academic literature. [15]	It is based on an electricity-only recovery scenario. Calculations of electricity generation potentials and avoided carbon emissions from energy displaced are calculated using data from the IPCC [16] and European Communities. [17]
Recycling	Capital and operation costs are based on European case studies.[18] We assume that waste is separated at source, but goes through additional sorting at the recycling facility.	The yield of recycling material is based on consultations with local stakeholders. The revenue from the sale of paper is assumed to be 36 USD/tonne, whereas sale of plastic is assume to be 150 USD/tonne. [19] Additional emissions from extra transportation of recycled materials are accounted for.
Biogas production	Biodigester construction costs are derived from case studies in Rwanda[20] and India. [21] A conservative yield of 10% of commercial food waste is targeted.	Gas produced is assumed to be used in-house by restaurants, hospitals, prisons, and schools, so savings are derived from avoided purchase costs. Emissions savings are calculated using data from the IPCC [22] and European Communities.[23]

[1]WEC. 2013. World Energy Perspectives: Cost of Energy Technologies. World Energy Council. Available at: http://www.worldenergy.org/wp-content/uploads/2013/09/WEC_J114 3_CostofTECHNOLOGIES [retrieved 07/05/2015]

[2]IRENA. 2012. Renewable Energy Technologies: Cost Analysis Series. International Renewable Energy Agency. Available from: http://www.irena.org/DocumentDo wnloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf [retrieved 07/05/2015]

[3]CDM. 2009. Durban Landfill-Gas Biasar Road. United Nations Framework Convention on Climate Change. Clean Development Mechanism. Available from: http://cdm.unfccc.int/filestorage/M/L/N/MLNVZQAWH8REBSD0CTUO26JIG9FKP7/Revised%20final%20PDD.pdf?t=Qkt8bnJvdWlhfDDx1ZQJaFrSewHjaY91US9y [retrieved 05/07/2015]

[4]CDM. 2012. Oti Landfill Gas Capture, Flaring and Utilization at Kumasi (Ghana). United Nations Framework Convention on Climate Change. Clean Development Mechanism. Available from: https://cdm.unfccc.int/filestorage/A/I/E/AIE47N59BTFQYGOD2RXS0V3KZPL6CH/CPA-DD.pdf?t=a3J8bnM1bWZufDA_Qw0A8tZso_KYm7jZF2Sp [retrieved 05/07/2015]

[5]EPA. 2013. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills. United States Environmental Protection Agency. Available from: http://www3.epa.gov/nsr/ghgdocs/landfills.pdf [retrieved 15/10/2015]

[6]Manfredi S, Scharff H M, Tonini D, Christensen T H. 2009. Landfilling of Waste: Accounting of Greenhouse Gases and Global Warming Contributions. Waste Management & Research. 27: 825–836. DOI: 10.1177/0734242X09348529

[7]EPA. 2013. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills. United States Environmental Protection Agency. Available from: http://www3.epa.gov/nsr/ghgdocs/landfills.pdf [retrieved 15/10/2015]

[8]Smith A, Brown K, Ogilvie S, Rushton K, Bates J. 2001. Waste Management Options and Climate Change. European Commission. Luxembourg. Available from: http://ec.europa.eu/environment/waste/studies/pdf/climate_change.pdf [retrieved 14/02/2018]

[9]CDM. 2014a. Uganda Municipal Waste Compost Programme. United Nations Framework Convention on Climate Change. Clean Development Mechanism. Available from: https://cdm.unfccc.int/ProgrammeOfActivities/poa_db/JL4B8R2DKF90NE6YXCVOQ3MWSGT5UA/view [retrieved 14/02/2018]

[10]Hareem R V, Nikolas J, Morton B. 2009. Large Scale Aerobic Composting of Source Separated Organic Wastes: A Comparative Study of Environmental Impacts, Costs, and Contextual Effects. Department of Earth and Environmental Engineering, Columbia University.

[11]City of Kigali and BTC Rwanda. 2012. Data collection and analysis on Solid Waste Management in the City of Kigali. City of Kigali.

[12]Pipatti R, Svardal P, Silva Alves JW, Gao Q, López Cabrera C, Mareckova K, Oonk H, Scheehle E, Sharma C, Smith A, Yamada M. 2006. Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Intergovernmental Panel on Climate Change. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf . [retrieved 30/10/2015]

[13]Smith A, Brown K, Ogilvie S, Rushton K, Bates J. 2001. Waste Management Options and Climate Change. European Commission. Luxembourg. Available from: http://ec.europa.eu/environment/waste/studies/pdf/climate_change.pdf [retrieved 14/02/2018]

[14]IRENA. 2012. Renewable Energy Technologies: Cost Analysis Series. International Renewable Energy Agency. Available from: http://www.irena.org/DocumentDo wnloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf [retrieved 07/05/2015]

[15]Brogaard LK, Riber C, Christensen TH. 2013. Quantifying capital goods for waste incineration. Waste Management. 33(6) 1390−-1396.

[16]Pipatti R, Svardal P, Silva Alves JW, Gao Q, López Cabrera C, Mareckova K, Oonk H, Scheehle E, Sharma C, Smith A, Yamada M. 2006. Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Intergovernmental Panel on Climate Change. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf . [retrieved 30/10/2015]

[17]Smith A, Brown K, Ogilvie S, Rushton K, Bates J. 2001. Waste Management Options and Climate Change. European Commission. Luxembourg. Available from: http://ec.europa.eu/environment/waste/studies/pdf/climate_change.pdf [retrieved 29/10/2015]

[18]Dawkins E, Roelich K, Barrett J, Baiocchi G. 2010. Securing the future: The role of resource efficiency. Waste and Resources Action Programme. Durham, UK. Available from: http://www.wrap.org.uk/sites/files/wrap/Securing%20the%20future%20The%20role%20of%20resource%20efficiency.pdf [retrieved 14/02/2018]

[19]Tabaro I. 2017. Rwandans take on solid waste recycling. The New Times Rwanda. Available from: http://www.newtimes.co.rw/section/read/63596/ [retrieved 14/02/2018]

[20]SNV. 2008. Financing of Domestic Biogas Plants (Rwanda). Netherlands Development Organisation. Available from: http://www.snvworld.org/fr/publications/financing-of-domestic-biogas-plants-3 [retrieved 29/10/2015]

[21]Agrahari RP, Tiwari GN. 2013. The production of biogas using kitchen waste. International Journal of Energy Science. 3(6) 408−-413

[22]Pipatti R, Svardal P, Silva Alves JW, Gao Q, López Cabrera C, Mareckova K, Oonk H, Scheehle E, Sharma C, Smith A, Yamada M. 2006. Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Intergovernmental Panel on Climate Change. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf . [retrieved 30/10/2015]

[23]Smith A, Brown K, Ogilvie S, Rushton K, Bates J. 2001. Waste Management Options and Climate Change. European Commission. Luxembourg. Available from: http://ec.europa.eu/environment/waste/studies/pdf/climate_change.pdf [retrieved 14/02/2018]