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Can cities become self-reliant in energy? A technological scenario analysis for Kampala, Uganda

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ABSTRACT

Energy self-reliance is important for economic growth and development for any nation. An energy self-reliance technological analysis for Kampala the capital city of Uganda is presented. Three renewable energy sources: Municipal Solid Waste (MSW), solar and wind are assessed for the period of 2014 to 2030. Annual MSW generation will increase from 6.2×10^5 tons in 2014 to 8.5×10^5 and 1.14×10^6 tons by 2030 at 2% and 3.9% population growth respectively. MSW energy recovery yield varies from 136.7 GWh (2014, 65% collection) to 387.9 GWh (2030, 100% collection). MSW can at best contribute 2.1% and 1.6% to total Kampala energy demands for 2014 and 2030 respectively. Wind contribution is 5.6% and 2.3% in those respective years. To meet Kampala energy demands through solar, 26.6% of Kampala area and 2.4 times her size is required for panel installation in 2014 and 2030 respectively. This study concludes that improving renewable energy production may not necessarily translate into energy self-reliant Kampala City based on current and predicted conditions on a business as usual energy utilization situation. More studies should be done to integrate improvement in renewable energy production with improvement in efficiency in energy utilization.

Keywords: Energy, Kampala, Kampala Capital City Authority, Renewable Energy, Self-reliance

1. Introduction

Sustainable Development Goal Eleven (SDG 11) calls for cities to be inclusive, safe, resilient and sustainable [1]. This requires detailed understanding of what cities are. In essence, a city can be considered as a system and properly satisfies the system theory proposed by Bertalanfy [2]. Using the system theory, a city can be seen as an organism composed of independent parts – for example people and infrastructure – that interact closely to form a complex whole. It takes in inputs and transforms them through internal processes then releases outputs outside its boundary. Inputs to a city can be in the form of energy, manufactured products, food, technology and raw materials while outputs may be in the form of manufactured goods, wastes such as Municipal Solid Waste (MSW), technology and energy. Sustainability of city system requires a balance of inputs and outputs flows and utilizations. The fact that cities are unique in terms of their composition, culture, input requirement, technology and output potential implies that scenario analysis for sustainability must be done apiece at city level.

In this work we focused on understanding the energy scenarios of Kampala City the Capital of Uganda with an interest to find out how it can be energy self-reliant. It is known that energy consumption is directly related with economic growth of a country, especially Sub-Saharan African (SSA) countries [3, 4]. Kampala is a national economic and commercial hub contributing up to 60% Uganda's GDP and accounting 80% industrial sector of the country [5, 6]. Improving energy supply in Kampala by ensuring sustainable energy self-reliance will positively impact economic growth, development and climate response at both city and national levels.

2. Energy Self-Reliance in a City Context

Morris [7] pointed out that energy and climate crises must ultimately be solved at local level. Self-reliance is the proper approach for energy and climate solution. Self-reliance is different from self-sufficiency. The latter describes a state of complete independence in which a city requires no external aid, support, or interaction to produce enough energy. The city only produces and consumes energy from its own generated raw materials using its own technology. However, a city is said to be energy self-reliant when it is not a net energy consumer. The city utilizes available raw materials and technologies from within and without its boundary to contribute equivalent amount of energy it consumes or

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net energy to the national energy mix.

The significance of energy self-reliance cannot be overestimated especially for developing-country cities such as Kampala. City energy self-reliance ensures: (1) consistency of energy supply that acts as lifeblood for domestic, commercial and industrial utilization, (2) sustainable city development through proper utilization of resources and waste disposal and (3) protection of biomass forest/tree reserves by revealing realistic alternative energy sources. Load shedding leads to industrial loss of time and money while it causes inconveniences in residential life that directly affects the general standard of living and development of communities.

3. Energy Profile of Kampala

In this paper by Kampala we mean Kampala City Center Area which consists of five urban divisions, including: Central Business District, Kawempe, Makindye, Rubaga and Nakawa. Kampala has experienced decades of significant urban growth and is currently the second-fastest-growing city in Eastern Africa [5]. By 2014 Kampala had 1,516,210 inhabitants and 418,787 households with a population growth rate of 2.0% per annum [8]. The first quantification and monitoring of energy and greenhouse gas (GHG) balance of Kampala was carried out by Kampala Capital City Authority in 2014. Annual energy consumption of Kampala was estimated at 10,000 GWh (36,000 TJ) in 2014 and it is expected to increase to 13,300 GWh (48,000 TJ) and 25,000 GWh (90,000 TJ) in 2020 and 2030 respectively on a business as usual basis [8]. Fig. 1 shows the energy mix for the three years. Petroleum currently contributes 47% to energy mix and will increase to 55% by 2030 if current trends continue. There will be a meager increase in electrical energy share rising from 17% in 2014 to contribute only about one quarter of Kampala energy mix by 2030. Biomass that currently contributes 36% will still contribute up to 19% of the energy mix by 2030. Renewable energy contribution is insignificant with solar and biogas having annual contributions of only 90 MWh and 2.6 MWh respectively [8, 9]. There is no recognizable wind energy harnessing.

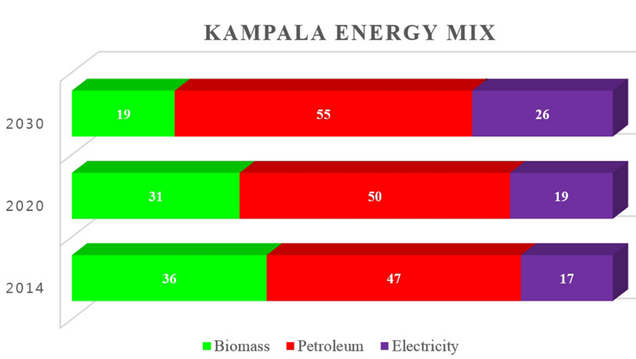

Fig. 1. Kampala energy mix on business as usual scenario. Source KCCA [8].

4. Energy Flow Map of Kampala

Kampala is a net energy consumer. Almost all the energy consumed by this city is produced from sources outside her territory. Biomass is consumed in the form of charcoal and firewood. Seventy five percent (75%) of all households in Kampala rely on firewood and charcoal to meet their cooking needs [10]. Firewood and charcoal are also used by tertiary institutions and industries for heating, cooking and industrial applications. Fig. 2 is a schematic map showing net energy flow of Kampala with access routes and directions from which the different energy sources enter into the city. The largest supply (45%) of charcoal/biomass comes from three districts Masindi, Luweero and Nakasongola and enters through Kawempe (C) [11]. Nansana (D), Bweyogerere (A) and Kyengera (F) are the next major routes allowing access to 19%, 13% and 11% of charcoal/biomass respectively to Kampala. Mpererwe (B) and Buloba (E) contribute 3.5% and 5.4% respectively while Port Bell (G) contributes 1.8% from the Islands of Lake Victoria [11]. Kampala imports all the petroleum products it consumes; about 90% come from Kenya through Bweyogerere (A) and 10% from Tanzania through Port Bell (G). Kampala's electricity comes from power generation plants outside her territory. Electricity is transmitted through 132 kV and 220 kV transmission lines entering the capital city from the east (A) [9].

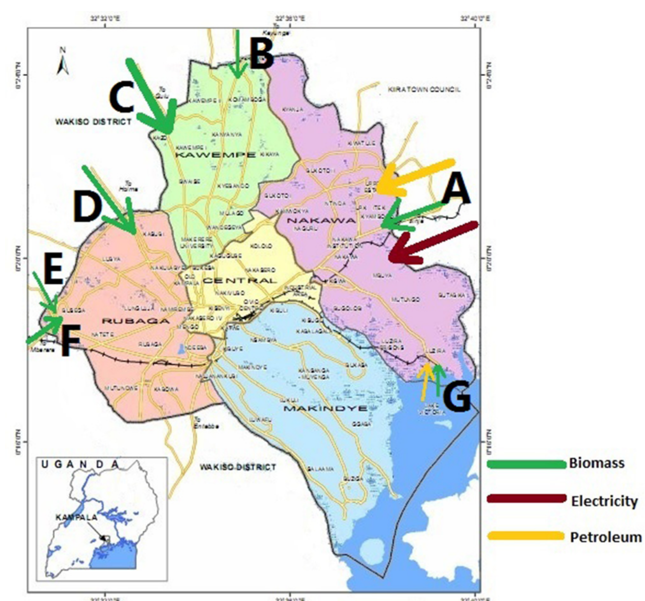

Fig. 2. Energy flow map of Kampala. Background map of Kampala from KCCA [6].

5. Technological Scenario Analysis

5.1. Alternative Energy Sources for Kampala

Despite the current energy position, with proper planning and knowledge application, can Kampala become energy self-reliant.? Potential renewable energy alternatives applicable in Kampala include energy recovery from Municipal Solid Waste (MSW), Solar and Wind energy harnessing. For city sustainability concerns in accordance with SDG 11, this paper gives priority to energy recovery from MSW before considering solar and wind energy harnessing. Kampala MSW is landfilled at Kiteezi built in 1996. However the existing centralized landfill facility at Kiteezi is close to maximum capacity with limited working area and space for expansion. Planned expansion on 6 acres is expected to provide only two additional years of capacity [5]. Kampala should take a new approach, different from disposal, in order to manage MSW in a sustainable way. Kampala MSW is 92.1% organic [12]. Recycling and reuse are not applicable to this fraction of MSW. Again, given the prevailing culture, prevention and reduction efforts will take time to have recognizable effects [6]. Energy recovery is currently the best management approach to solve Kampala MSW problems.

5.2. Waste Energy Scenario, Anaerobic Digestion

Nyakaana [13] pointed out that alternative means to waste disposal need to be developed with population growth and economic development in mind. Bingh [14] did an estimation of electricity production from combustion of Kampala MSW to be at a practical potential of 98 GWh in 2004 with a collection rate of 40% and 430,000 tons/year waste generation rate. At 100% collection rate, a theoretical potential of 250 GWh was expected. However times have changed. Kampala organic fraction of MSW (OFMSW), 92.1%, has a moisture content of 71.1% [12]. At such high average waste moisture content, incineration is uneconomical [15]. Komakech [16] advised that claims for successful design for incinerators suitable for wastes generated in SSA cities [17] needed more investigations. Furthermore, air emissions from incinerators contain several carcinogens and soil, water and food pollutants such as dioxins, heavy metals and other volatile organic compounds [16]. Therefore our analysis was based on waste energy recovery by the method of Anaerobic Digestion (AD).

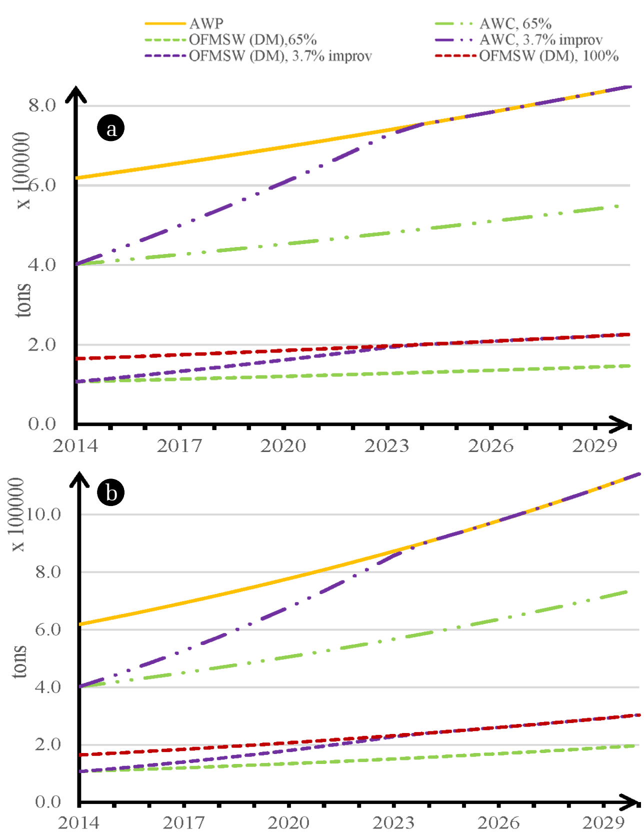

Fig. 3. Estimated Kampala annual MSW production, collection and corresponding landfill organic fraction, (A) at 2% population growth rate, (B) at 3.9% population growth rate.

The practicability and process of energy recovery from OFMSW using AD is well documented. Many plants around the world are successfully using AD to recover energy from OFMSW. The aim of this paper is to theoretically estimate the amount of energy recoverable from OFMSW of Kampala using this technology. In AD technology, biogas generated from anaerobic digestion of waste can be used to fuel a gas turbine to produce electricity.

Fig. 3, 5, 6 are a graphical representations of waste energy recovery analysis from Kampala OFMSW under two population growth scenarios – 2% [8] and 3.9% [5]. The following assumptions were used during the analysis: (1) daily per capita waste production for Kampala is 1 kg [6, 14], (2) 65% waste collection rate [5] starting with 33,500 tons per month in 2014 [6], (3) annual improvement in waste collection rate continue in the trend of 2010 to 2013 at 3.7% [5], (4) 92.1% OFMSW [12] with 0% recycling and reuse for this fraction and (5) 592 m^3 biogas generation per ton dry matter of OFMSW with 35% electricity production [18].

The percentage for GHG avoidance by the use of AD was estimated from:

$$Percent_{avoidance} = \frac{GHG_{avoidance}}{GHG_{emission}} \times 100\%$$

Annual GHG emission for Kampala was based on estimations of KCCA [8] and assumed to increase linearly between 2014 to 2020 and 2020 to 2030. Annual GHG avoidance was estimated in CO_2-equivalent to be $\frac{20}{21} \times Landfill_{emission}$

Where $Landfill_{emission}$ is the estimated emission from Kiteezi landfill in CO_2 – equivalent.

$$Landfill_{emission} = Q_{biomass} \times CH_4\_IPCC_{decay} \times GWP\_CH_4$$

$$CH_4\_IPCC_{decay} = MCF \times DOC \times DOC_F \times F \times \frac{16}{12}$$

MCF (Methane Correction Factor) = 0.8 (default value for Kampala) [19].

DOC (Degradable Organic Carbon) = $0.4A \pm .17B + 0.15C + 0.3D$

DOC percentages were based on characterization of Kampala MSW by Komakech et al. [12].

DOC_F (Actual DOC Fraction that Degrades) = 0.5 (IPCC default value).

5.3. Solar Energy Scenario

The potential for solar power generation in Kampala is very promising. Kampala lies close to the Equator on coordinate 0.3136°N, 32.5811°E with average solar radiation of 5.21 kWh/m^2/d [20]. If well implemented, solar power can prove to be a good source of renewable energy which can be utilized locally within the city or fed into the national grid in order to supply other parts of the country. Through the technology of net metering resi

Table 1. Number of Solar Panels Required to Meet Kampala Energy Demands

Year	Number of Solar Panels Required		
	Electricity	Electricity and Biomass	Electricity, Biomass & Petroleum
2014	4,561,023	14,219,660	26,829,547
2020	24,468,547	64,390,913	128,781,826
2030	62,781,140	108,659,666	241,465,924

dential and commercial customers who produce electricity from solar power can feed it into the national grid. Net metering also reduces distribution losses in long-distant electric transmission and distribution systems.

Table 1 shows the number of 245 W (1.675 × 1.001 m) solar panels required to meet Kampala energy demand in 2014, 2020 and 2030. The number of solar panels required was determined through the following procedure; (1) daily city energy need in KWh was determined by dividing the annual energy demand (in KWh) by 365, (2) a 25% cushion was added to the daily average energy demand to offset inefficiencies in hardware and shading, (3) the cushioned daily average energy demand was divided by the average number of daily peak sunlight hours (solar radiation) to get hourly energy production requirements from the panels in kilowatts, (4) the hourly requirements were converted to watts by multiplying by 1000 and (5) the hourly requirements in watts were divided by solar panels' wattage to determine the required panels. Table 1 shows the number of solar panels required to satisfy electricity, electricity and biomass and full energy demands in Kampala for 2014, 2020 and 2030.

5.4. Wind Energy Scenario

The average wind speed of Uganda is about 3 $m \cdot s^{-1}$. However previous studies have revealed that areas on the shores of Lake Victoria have wind speeds reaching up to 6 $m \cdot s^{-1}$ sufficient for wind energy generation [21]. The wind energy potential could be higher given that the reported wind speeds are recorded at lower metrological heights and not the standard 10 m [21]. Kampala has 20 square km of Lake Victoria water [5]. Wind farms can be installed along lake shores. This analysis considers a case where wind towers are installed partly in lake water and partly on lake-shores for wind energy harnessing.

Fig. 4 is a graph showing wind energy potential from Kampala Lake Victoria shorelines. Analysis was performed for five installation area scenarios 5, 10, 15, 20 and 30 km^2 with three different rotor diameters. Tower installation spacing of 5 by 9 rotor diameter was used. From the wind power Eq. (1), Eq. (2) was utilized in accordance with Celik [22] after assuming that wind speed along Lake Victoria shoreline follow Rayleigh distribution. A power coefficient of 0. 4, air density of 1.225 $kg \cdot m^{-3}$ and wind speed of 6 $m \cdot s^{-1}$ were used.

$$P = \frac{1}{2} \rho_{air} A_r V_m^3 \quad (1)$$

$$P = \frac{3}{\pi} \rho_{air} A_r V_m^3 \quad (2)$$

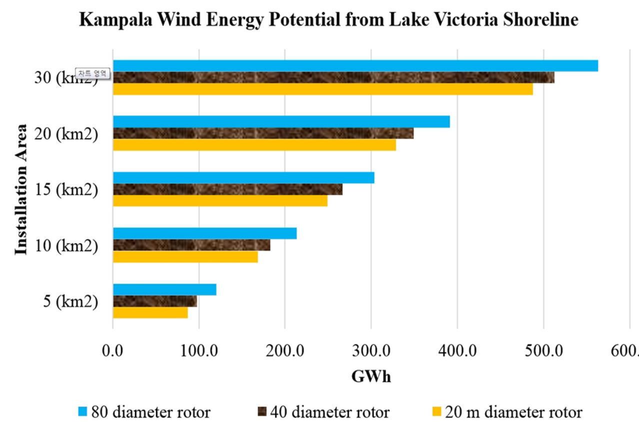

Fig. 4. Kampala wind energy potential from Lake Victoria shoreline.

6. Discussion

Waste energy recovery through AD can provide a significant contribution to Kampala energy. With 2% population growth rate and 65% collection rate, electricity from waste energy recovery is estimated at 136.7 and 187.7 GWh in 2014 and 2030 respectively, see Fig. 5a. This amounts to about 1.37% and 0.75% of their respective annual Kampala energy demands. At 100% collection rate with the same population growth rate, electricity generation from waste is estimated at 210.3 and 288.7 GWh in 2014 and 2030 respectively. This amounts to 2.1% and 1.15% of their respective annual Kampala energy demands. For 3.9% population growth rate [5], the potential of electricity from waste energy recovery is slightly higher. At 65% collection rate electricity generation potential is estimated at 136.7 and 252.2 GWh in 2014 and 2030 respectively, see Fig. 5b. This amounts to 1.37% and 1% of respective annual Kampala energy demands. At 100% collection rate with 3.9% population growth rate, electricity generation from waste is estimated at 210.3 and 387.9 GWh in 2014 and 2030 respectively. This amounts to 2.1% and 1.55% of their respective annual Kampala energy demands.

The result reveals that though waste energy recovery is a significant source of energy, it is not sufficient to satisfy Kampala energy demands. Theoretically (100% collection rate), waste energy will at best contribute 2.1% of the energy requirements. This does not however imply that waste energy recovery should be ignored. In fact as mentioned before in accordance with SDG 11 [1] waste management in cities should be priority. This is especially applicable to Kampala where uncollected waste normally dumped in open areas, streams, open drainage channels and other areas are creating environmental and public health disaster for the inhabitants [16]. Kampala MSW is also the biggest city contributor to emission contributing 34% [23].

From the results obtained, motivation for waste energy recovery from Kampala MSW should largely be based on emission reduction. Through AD technology GHG avoidance of 8.8 and 13.5% could be achieved in 2014 at 65% and 100% waste collection rates respectively, see Fig. 6. The percentage of GHG avoidance at 65% waste collection rate will still be as high as 5.1 and 6.8% in 2030 for 2% and 3.9% population growth rates respectively. While at 100% collection rate percentage of GHG avoidance will still be even higher at 7.5 and 10.5% in 2030 for 2% and 3.9% population growth rates respectively. This implies that implementation of an AD technology for Kampala OFMSW will be a long-term solution to GHG emission especially given the context of high dependence (55%) on petroleum by 2030.

The second motivation for establishing an AD is the financial implication. At the present domestic electricity tariff [24], with $1 = UGX 3,480 (rate as of January 28 2016), the gross annual waste electricity energy potential is estimated at $25.5m and $39.4m in 2014 at 65 and 100% collection rates respectively. At 2% population growth rate this is expected to increase to $35.1m and $54m by 2030 at 65 and 100% collection rates respectively. While at 3.9% population growth rate it is expected to increase to $47.2 m and $72.6 m by 2030 at 65 and 100% collection rates respectively.

KCCA has installed 170 solar panels on street lighting with average capacity of 250 W producing about 90 MWh annually [8]. However results from solar power potential analysis show that in order to satisfy electrical energy demand for Kampala in 2014 about 4.6 million solar panels (245 W) would be required. This needs about 7.6 km^2 of area of land and is possible given that Kampala has 169 km^2 of land [5]. In order to meet the full energy demand for Kampala through solar power in 2014, about 26.8 million panels were required covering about 45 km^2 (26.6%) area of land. In 2030 to meet Kampala electricity energy demand through solar power about 62.8 million panels will be required covering an area of 105.2 km^2 (62.2%). The pragmatism of this is questionable given that land utilization in the city takes many forms. In order to meet the full energy demand for Kampala in 2030 through solar power about 241.5 million panels are required covering about 404.9 km^2 area of land. This is practically impossible given that Kampala is only 169 km^2. It is therefore not possible to meet future Kampala energy demands through solar power only. With the understanding that waste energy recovery will contribute less than 2% of energy demand, the required areas for solar power will not have significant decrease. It follows that both waste energy recovery and solar power are unable to meet future Kampala needs.

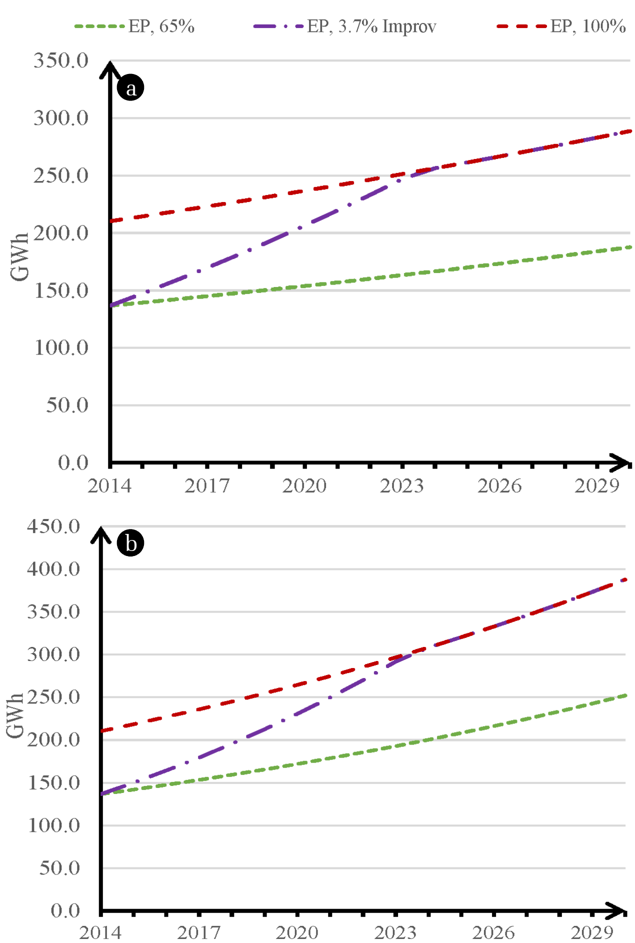

Fig. 5. Estimated annual electricity production from Kampala MSW, (A) at 2% population growth rate, (B) at 3.9% population growth rate.

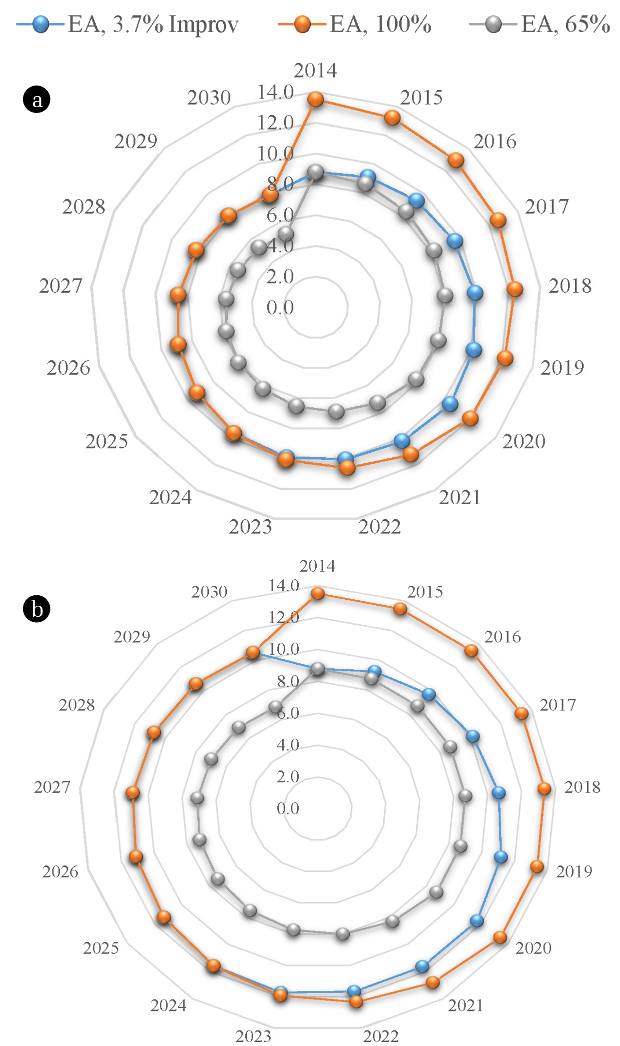

Fig. 6. Percentage of annual GHG emission avoidance from Kampala MSW by AD technology, (A) at 2% population growth rate, (B) at 3.9% population growth rate.

Wind can provide notable amount of energy to Kampala. As shown in Fig. 4 the maximum annual energy that can be harnessed from wind is 562.8 GWh when 80 m diameter rotors are installed on an area of 30 km^2. When 20 m diameter rotors are utilized energy generation is expected to be 487.6 GWh for the same installation area. On a 5 km^2 installation area, wind energy generation is expected to be 120.4 and 87.2 GWh for 80 m and 20 m rotor diameter scenarios respectively. The maximum value of 562.8 GWh from 30 km^2 accounts for only 5.6 and 2.3% of Kampala energy needs in 2014 and 2030 respectively. Wind may provide a reasonable quantity of energy but cannot ultimately solve Kampala energy generation issues. It is therefore impossible to sustainably meet Kampala energy demand through AD energy recovery of MSW, solar and wind energy harnessing now and in the future.

7. Conclusions

Energy scenario analysis for Kampala city was performed for the period of 2014 to 2030 on a business as usual basis. Three renewable energy sources in Kampala were technically analyzed. These included waste energy recovery through anaerobic digestion of Kampala OFMSW, solar energy and wind energy harnessing. Our analysis shows that waste energy recovery and wind energy harnessing could contribute at best 2.1% and 5.6% to total Kampala energy demand in 2014 respectively. Their contributions will drop to about 1.55% and 2.3% respectively by 2030. Motivation for installation of AD should largely be based on reduction of GHG emissions. For the scenarios considered GHG avoidance by the use of AD for MSW management was estimated to vary from 5.1% to 13.5%. Kampala city cannot be energy self-reliant through renewable energy production by AD, solar and wind only. Integrating increase in renewable energy production and improving efficiency in energy utilization should be promoted. About half of Kampala energy is from petroleum consumption. This can be attributed to traffic congestions and lack of an integrated and affordable public transport system in the city. Most public transport is by 14-seat minibuses (taxies). Implicitly, this implies that sustainable transportation significantly affects the state of energy self-reliance of a city, especially developing SSA cities.

Acknowledgments

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Nomenclature

A	Percent of paper and textile in MSW (%)
A_r	Swept area of rotor (m^2)
AWP	Annual waste production (tons)
AWC	Annual waste collection (tons)
B	Percent of garden and yard waste in MSW (%)
C	Percent of food waste in MSW (%)
D	Percent of wood in MSW (%)
EA	Emission avoidance (%)
EP	Electricity production (GWh)
F	Fraction of methane in landfill gas = 0.5 (Default value)
GWP_CH_4	Global warming potential of methane = 21 (Default value)
$OFMSW$	Organic fraction of municipal solid waste (Dry matter) (tons)
$Q_{biomass}$	Annual OFMSW landfilled at Kiteezi landfill (tons)
UGX	Uganda shillings (/=)
V_m	Daily mean wind speed ($m{\cdot}s^{-1}$)
ρ_{air}	Density of air (kg m^{-3})

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