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Full Length Research Paper

Renewable Energy Micrograms to Improve Electrification Rate in Democratic Republic of Congo: Case of Hydro, Municipal Waste and Solar

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ABSTRACT

Worldwide, it is imperative for citizens to have access to electricity. This applies to Congolese--rural and urban dwellers, and if possible, it should be guaranteed by government's laws and policies. However, the rural and urban areas of Democratic Republic of Congo (DRC) suffer majorly from lack of access to electricity. The major reasons are the high costs associated with connection to the national central grid and production insufficiency. Therefore, one feasible approach to electrify these areas is to use microgrids. This technology is decent and viable option for energy revolution since it incorporates energy storage systems, distributed generators, and localized loads. This paper has taken to implement this solution by firstly analysing some cities located at the borders of large rivers or watercourses (with known depth and width), such as the Congo River considered for hydrokinetic power (HKP). However, where the Congo River does not pass through, the paper will consider largest rivers passing in the area. For the case of photovoltaic electricity production, large cities are considered those with good sunshine and large population who have purchasing power for the photovoltaic electricity. The waste to energy power plans will consider the top ten densely populated cities in DRC. The proposed microgrids will operate in isolation (islanded) mode. This paper proposed 44 projects to generate 795 690 kW total energy from the microgrids. These energies are divided as 661 000 kW from solar photovoltaic, 83 790 kW from waste to energy, and 50 900 kW from hydrokinetic generation. The urban share will be 94.9% and rural area share will be 5.1% of this generation. Further work needs to include biomass as a possible renewable energy to add in the mix.

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INTRODUCTION

Rural dwellers in several places of Africa need electricity for domestic applications. However, the access to the electric grids is a major challenge. These grids are plagued by unreliability, instability, un-sustainability, poor power quality, and poor efficiency (Ahlborg & Hammar, 2014; Motjoadi et al., 2020). All over Africa and other developing nations, these problems with the centralized electricity access leaves the population in states of poverty, economic dependency, academic stagnation, and very little technological contribution to the world. That is why, a lot of technological advances don't occur in these countries forcing them to rely on technology importation. These problems are also brought about by lack of diversification of the energy sources. These problems abound in the Democratic Republic of the Congo (DRC), what with many decades of unending civil strife and wars. The DRC grid is in utter shambles denying millions of the population access to electricity.

Therefore, a decentralized electricity supply through use of microgrids could be used as a viable and lucrative solution (Al-Ammar et al., 2020; Sawle et al., 2018). These microgrids could be powered by solar photovoltaics (Justo & Mushi, 2020), other renewables (Gaslac et al., 2018; Jahangiri et al., 2018), and sometimes integrated with diesel generators (DG) (Belboul et al., 2022; Ji et al., 2022). Using right funding models and policy frameworks such as was proposed in Northeast Nigeria (Mshelia, 2021), the DRC could utilize renewable energy-powered microgrids to increase the electricity access to a larger rural population, and this could be extended to large cities at a low cost as compared to conventional grid (and generators). (Bhattacharyya & Palit, 2016; Wells et al., 2013) Microgrids are interconnections of power generators, storage devices, energy conversion devices, distribution equipment and users to enable power supply to isolated customers. The size (or number) of targeted customers differentiates the size of the microgrid, whether to be called microgrids or picogrids. Microgrids supply loads in the range of 20-500 kW, while picogrids supply loads less than 20 kW (Ighravwe & Babatunde, 2018; Winkler et al., 2009). These systems are usually designed for isolated operations, however, in some cases they are connected to the main grids to power rural loads located far from the grid (Abd El-Sattar et al., 2021; El-Sattar et al., 2021; Fungo et al., 2021). In these isolated operations, they can supply remote locations for small populations (Juma et al., 2021a; Marcel et al., 2021). Microgrids provide notable competitive benefits to customers (Motjoadi et al., 2020) and imparts considerable advantages within the entire electric power supply chain (Awan et al., 2022; Krause & Nordström, 2004; Lidula & Rajapakse, 2011; Minja & Mushi, 2021; Winkler et al., 2009). The rest of the paper is organized as follows – Section 2 discusses the site descriptions, interviews, measurements, assumptions for the design of these microgrids, and cost calculations. Section 3 presents the simulation scenarios of each proposed design power plan, and Section 4 presents the discussion of results obtained from the simulations. Finally, the Section 5 presents the conclusion of the paper, and possible future works.

METHODS AND MATERIALS

This section describes the methodology and all tools utilized in the execution of this research.

Interviews and expert consultations

This study involved conducting participatory interviews, meetings, workshops with various stakeholders at provincial, territorial, and national levels. In these sessions, the stakeholders included experts, organizations and development agencies (both public and private) who are involved in generation, transmission and distribution of electrical energy in DRC.

Measurements and selection of the study sites for hydrokinetic systems

Hydrokinetic (HKP) systems when used in hybrid mode has shown savings for the cost of total system of electricity generation in South Africa (Kusakana, 2015) and its exploitation is increasing (Behrouzi et al., 2014). Therefore, they are proposed to be used as one of the renewable sources to power the DRC microgrid. To choose the hydrokinetic sites, the authors used the Google Earth Tool, and it facilitated to identify these sites by the following procedures:

1. Identifying towns that are located nearby large rivers.
2. These rivers depths need to be about 5 m deep to be considered.
3. The rivers need to have regular flow, so that production of electricity continues even during dry seasons.
4. After river identification, Google Earth is used to measure distances, elevations and other important features for the study.

Bibliographic and documentary review

To establish the electricity needs of the DRC, this study undertook extensive bibliographic and documentary reviews.

Energy situation in the Democratic Republic of the Congo

The DRC is located at the central sub-Saharan Africa lying between latitudes 6°N and 14°S, and longitudes 12°E and 32°E, bordering the Central African Republic to the north, the Republic of the Congo to the north-west and South Sudan to the north-east (see map shown in Figure 1). On her eastern border there are Uganda, Rwanda, Burundi and Tanzania. The South Atlantic Ocean forms the western border, with Angola situated to the south-west. Zambia lies to both the south and south-east. She is the 11th largest country in the world covering a land mass equal to that of the United States east of the Mississippi, and second largest in Africa after Algeria. By the year 2020, the population of DRC was estimated to be 89 million, whereby 54% are rural dwellers documented by this website (*DR Congo Population (2022) - Worldometer*, n.d.). The DRC's potential renewable energy sources include hydropower, biomass, solar, wind and geothermal.

The DRC’s rural access to electricity stands at 1% recorded in the SDG7 website (IEA et al., 2022). This country represents one of the lowest rural electrification rates in the world (IEA et al., 2021). This has made the 94% of the population to rely using biomass for cooking and lighting (Emetere et al., 2021). The United States Agency for International Development (USAID) puts the DRC's generation capacity at 2 844 MW – hydro: 2 792 MW; gas: 2.2 MW; solar: 1 MW; and others: 48.8 MW (USAID, 2021). The International Water Activist Group called International Rivers (International Rivers, 2013) estimates an untapped generation of 100 000 MW of hydroelectricity to satisfy the DRC electricity needs which the government has geared not for the poor but for selling to the mines, abroad and rich populace. The DRC's rural electrification rate of 1% was partly brought on, by ongoing war conflicts that destroyed most of the electrical infrastructure. The current electrification rate would see the DRC with 80% population without electricity access by 2030 (World Bank, 2020). The country's energy demand forecast up to 2025 is captured in Table 1 which shows an unprecedented increment that does not get a servicing by utility.

Out of these consumption projections, the residential loads consume 77% of the DRC's electricity; industrial sector consumes 20.5%; agriculture, transport and public services consume about 2.5% (Kusakana, 2016), therefore, very little electricity is used for economic development.

Figure 1: The DRC map.
Source: (IEA et al., 2022)

The Congo River, with its basin straddling the Equator, with the mentioned potential of about 100 000 MW could be harvested from 780 sites in 145 territories and 76,000 villages. This is 37% of the total African continent potential and it comes at nearly 6% of the world's hydroelectric renewable energy potential as per the National Investment Promotion Agency's website (National Investment Promotion Agency (NIPA), n.d.). Most of this Congo River's energy is untapped, only featuring a meagre 2.5% of the total electricity in 2009 while biomass featured about 95%, and the rest was thermal (World Bank, 2020). The DRC has another untapped energy resource, that is municipal solid waste (MSW) with a potential of generating 96 MWh of electricity from 200 metric tons of MSW (Smith, 2021). In addition, the DRC has about 128 004 198 hectares (ha) of forestry that covers 54% of the total area. The forest's products could be harnessed to provide electricity if harnessed ecologically to ensure the forest's continuation and survival (Gbenga, 2019).

Despite all these potentials, the national electricity company, called Societe Nationale d'Electricite (SNEL) has a difficult time to supply electricity to the DRC's provinces as captured in Table 2. This has led to the observed low electrification rate, especially to the rural areas. Rural electrification rate has been shortened to RER by Irechukwu and Mushi in their publication of 2020 (Irechukwu & Mushi, 2020), where they talked about RER improvement focusing on using cheaper medium voltage transmission line from the grid. Differing from that method, this paper proposes to improve the DRC's RER by exploiting the available renewable energy resources such as solar, hydro (conventional and hydrokinetic), MSW, biomass, and wind to curb the deficit displayed in Table 2.

Table 1: Forecast of demand in MW by Province of the DRC from 2013–2025

Province Name	Years and power in MW						
	2013 – 2014	**2015 – 2016**	**2017 – 2018**	**2019 – 2020**	**2021 – 2022**	**2023 – 2024**	**2025**
Nord – Kivu	55 – 58	61 – 64	66 – 69	72 – 75	78 – 81	85 – 89	93
Maniema	8 – 8	8 – 9	9 – 9	10 – 10	11 – 11	12 – 13	13
Sud – Kivu	31 – 32	33 – 34	35 – 36	37 – 38	39 – 41	42 – 43	45
Equateur	21 – 22	24 – 25	27 – 29	30 – 32	34 – 36	38 – 41	43
Oriental	60 – 63	65 – 68	71 – 74	77 – 80	84 – 87	91 – 95	99
Kasai – OCC	34 – 36	38 – 40	42 – 45	48 – 51	54 – 58	62 – 66	71
Kasai – OR	46 – 49	52 – 56	60 – 64	68 – 73	77 – 83	88 – 94	101
Katanga	770 – 799	799 – 829	826 – 855	886 – 918	952 – 988	1 026 – 1 065	1 107
BAS – Congo	101 – 104	107 – 110	113 – 117	120 – 123	127 – 131	135 – 139	143
Bandundu	40 – 51	54 – 56	58 – 61	63 – 66	69 – 72	75 – 78	82
Kinshasa	751 – 784	819 – 855	893 – 933	974 – 1 017	1 062 – 1 109	1 158 – 1 210	1 263
Total demand	**1 926 – 2 006**	**2 060 – 2 146**	**2 200 – 2 292**	**2 385 – 2 483**	**2 587 – 2 697**	**2 812 – 2 933**	**3 060**

Table 2: Electricity deficit in the DRC's provinces

Province name	Total demand (MW)	SNEL supply (MW)	Deficit (MW)
Nord – Kivu	338.17	3.6	334.57
Maniema	104	1	103
Sud – Kivu	275.74	8.5	267.24
Equateur	156.19	132.65	23.54
Oriental	424.342	33.548	390.794
Kasai – OCC	165.1	6	159.1
Kasai – OR	165.802	17.505	148.297
Katanga	137.48	114.62	22.86
BAS – Congo	56.74	0.176	56.564
Bandundu	452.67	8.07	444.6
Kinshasa	852	420	432
Total demand	**3 128.234**	**745.669**	**2 382.565**

Assumptions

Since the DRC is a huge country in an unstable political state for a long time, it creates complexity in availability of important data. Therefore, authors are forced to define the following assumptions:

1. This study will analyse cities located at the borders of large rivers or watercourses for which the depth and width data are known.
2. The Congo River due to its huge potential will be the main consideration, however, where it does not pass, the study will consider large rivers passing through.
3. For the case of solar PV electricity production, this study will consider the large cities with good sunshine, with a population density and ability to purchase the power and pay for the maintenance.

4. The micro or small grids proposed in this study will operate in isolation due to the current poor situation of the DRC distribution grid. Elsewhere (Avrin et al., 2018), it was shown that the deployment of isolated microgrids leads to development and gender equity in DRC.
5. For the proposed MSW electricity production, the study will consider top ten cities with the highest population.

Design scenarios

There are meta-heuristic-based algorithms and classical algorithms that optimally size microgrids(Bouaouda & Sayouti, 2022; Ji et al., 2021; Kharrich et al., 2021; Memon & Patel, 2021), which could be used for the case of the current paper. However, authors of this paper chose the following design process – proposing different design scenarios and evaluating each one. Several possible scenarios are proposed for design based on the renewable energy potential – HEP, HKP, solar PV, and biomass from MSW, since it has been shown that combining these sources results to better electricity reliability (Heydari & Askarzadeh, 2016). The microgrid will work in isolated mode (Juma et al., 2021a; Juma et al., 2021b), and some loads such as street lights can be powered from the DC bus bar (see Figure 2).

This research proposes a future electric grid shown by Figure 3 which contains DC microgrid and AC microgrid interconnected. The DC microgrid is connected to batteries, solar PV, and DC loads. The AC microgrid is connected to DG, MSW, HEP generators, HKP generators, and AC loads.

First design scenario considers the possibility of using all the available renewable energy resources and the DGs to power the DRC's grid, shown by Figure 4.

Second design scenario considers a typical microgrid serving a rural area, depicted by Figure 5. This contains the DGs, HKP generators, the AC busbar and the loads.

Formulating the optimization problem for operation of the hybrid micro and small grids

These microgrids will operate in stand-alone (isolated) mode, therefore, there is a need to develop the problem holistically – formulating the objective function, and defining the constraints. The objective function (OF) of the total energy cost, $C_s(t)$ is denoted by

$$C_s(t) = C_{PV}(t) + C_{MSW}(t) + C_B(t) + C_L(t) + C_{DG}(t) \tag{1}$$

where, $C_{PV}(t)$ is the solar PV array's energy cost; $C_{MSW}(t)$ is the waste to energy cost; $C_L(t)$ is the total load (AC and/or DC) energy cost; $C_B(t)$ is the battery energy storage system (BESS) energy cost; and $C_{DG}(t)$ is the DG energy cost. The t within brackets signifies the continuous time. Denoting t_f as the final time of analysis, these constituent five costs contained in Equation (1) are defined in the following (2) – (6) expressions:

$$C_{PV}(t) = \sum_{t=0}^{t_f}\left[\left(P_{PV-mppt}(t) - P_{PV}(t)\right)T_{PV}(t)\right]\delta t, \tag{2}$$

$$C_{MSW}(t) = \sum_{t=0}^{t_f}\left[\left(P_{MSW-mppt}(t) - P_{MSW}(t)\right)T_{MSW}(t)\right]\delta t, \tag{3}$$

$$C_B(t) = \sum_{t=0}^{t_f}\left[\left(P_{BC}(t) - P_{BD}(t)\right)T_{BC}(t)\right]\delta t, \tag{4}$$

$$C_L(t) = \sum_{t=0}^{t_f}\left[P_L(t)T_L(t)\right]\delta t, \text{ and} \tag{5}$$

$$C_{DG}(t) = \sum_{t=0}^{t_f}\left[P_{DG}(t)T_{DG}(t)\right]\delta t. \tag{6}$$

The variables contained above are defined as follows: $P_{PV-mppt}(t)$ is the power of the maximum power point tracking (MPPT) operated solar PV system; $P_{PV}(t)$ is the power generated by the solar PV system; and $T_{PV}(t)$ is the solar PV system power tariff. The $P_{MSW-mppt}(t)$ is the power of the MPPT operated MSW to energy system; $P_{MSW-mppt}(t)$ is the power of the MSW to energy system; and $T_{MSW}(t)$ is the MSW power tariff. The $P_{BC}(t)$ is the maximum charging power of the BESS; $P_{BD}(t)$ is the maximum discharging power of BESS; and $T_{BC}(t)$ is the BESS charging power tariff. The $P_{DG}(t)$ is the DG power; and $T_{DG}(t)$ is the DG power tariff and the δt represents the time step.

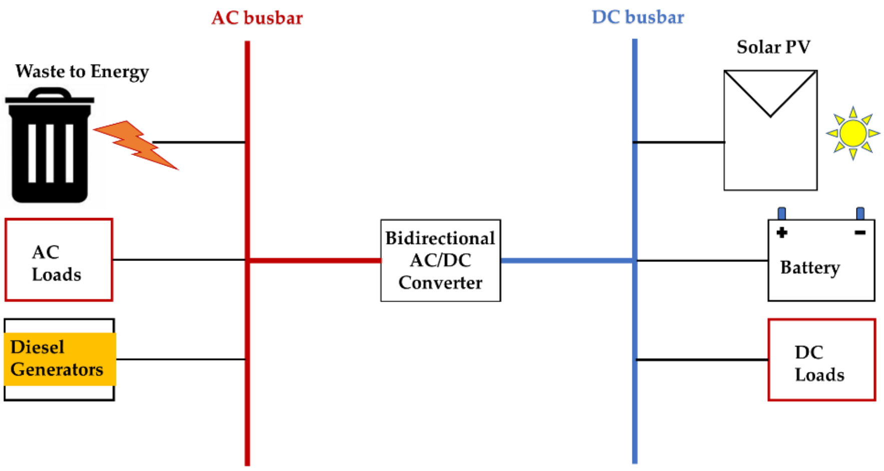

Figure 2: Isolated hybrid AC/DC microgrid.

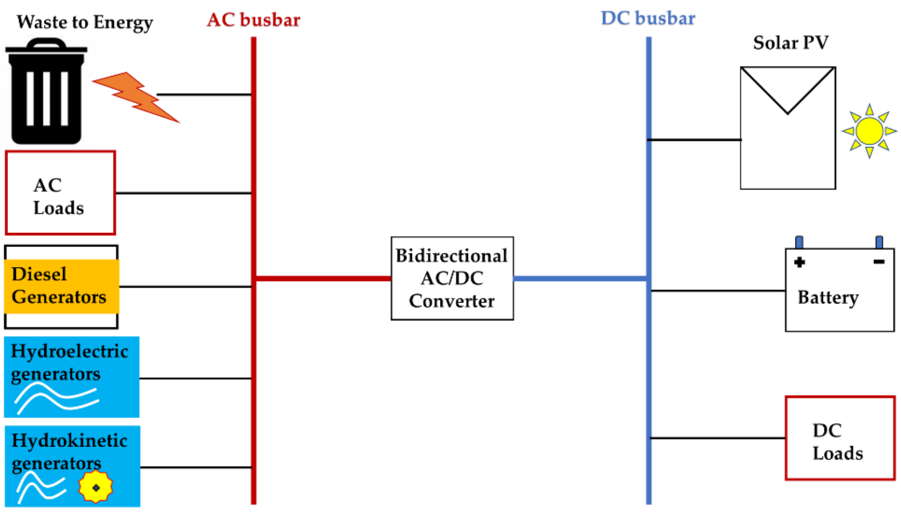

Figure 3: Future electric grid proposed for the DRC.

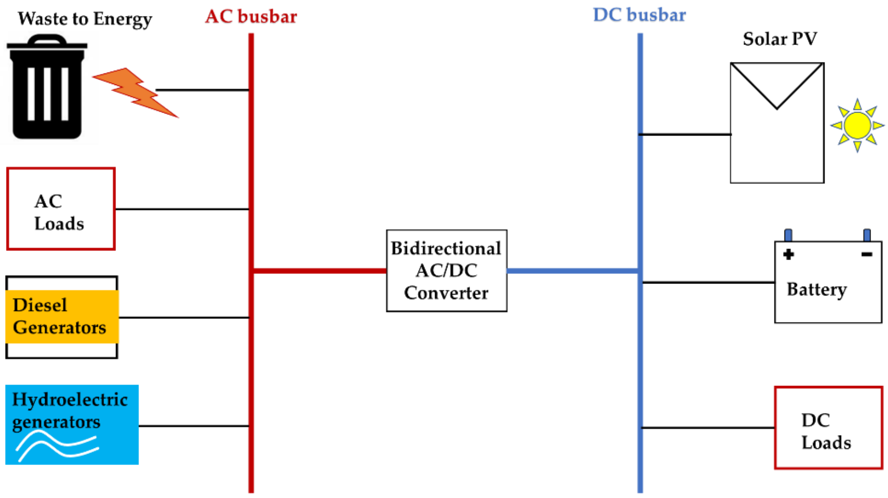

Figure 4: First design scenario of the DRC's grid.

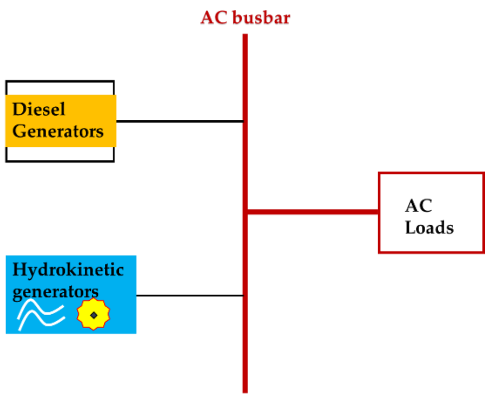

Figure 5: Second design scenario of the DRC's grid.

The OF is constrained by the generated power of the DG, solar PV, MSW with respective efficiencies; and the power consumed by the converter, load and power used to charge the BESS, as in the (7) – (8):

$$\eta_{DG}P_{DG}(t)+\eta_{PV}P_{PV}(t)+\eta_{MSW}P_{MSW}(t) = \eta_{CV}P_{CV}(t)+P_L(t)+\eta_B P_B(t), \quad (7)$$

where, $P_L(t)=P_{L-AC}(t)+P_{L-DC}(t)$, (8)

is the total load on the microgrid for which $P_{L-AC}(t)$ is the AC load power requirement, and $P_{L-DC}(t)$ is the DC load power requirement; the η_{DG}, η_{PV}, and η_{MSW} represent the efficiency of the DG, solar PV, and MSW systems. The power consumed by the converter, i.e., $P_{CV}(t)$ has an efficiency of the interlinking converter as η_{CV}. The BESS power, i.e., $P_B(t)$ has an efficiency η_B. See Table 3 for the values of the efficiency of the hybrid system of the microgrid obtained from various sources during the execution of this research.

Table 3: List of values of efficiency of hybrid system

Efficiency symbol of a system	Value (%)
η_{PV}	90
η_{MSW}	80

η_B	90
η_{DG}	85
η_{CV}	90

Furthermore, the microgrids are constrained by daylight hours production of solar PV, and available waste for the MSW system. These constraints are described as follows:

$$0 \le P_{PV}(t) \le P_{PV-\max}, \text{ and} \tag{9}$$

$$0 \le P_{MSW} \le P_{MSW-\max}. \tag{10}$$

Therefore, the OF in Equation (1) is minimized with these explained constraints, while taking care not to overcharge or drain the BESS. The BESS's state of charge ($SOC(t)$) is obtained via the expression (11):

$$SOC(t) = SOC(t_0) + \frac{1}{720}\frac{\eta_{BC-BD}}{C_N V_{DC}} \times \int_{t_0}^{t} \left(P_{BC}(t) - P_{BD}(t)\right) dt, \quad . \tag{11}$$

$$t \in \{t_0, t_0+1, \ldots, t_0 + n\Delta\tau\}$$

In here, the t_0 represents start time at 0 s; C_N represents BESS nominal storage capacity; η_{BC-BD} represents BESS charging-discharging efficiency; V_{DC} represents the DC bus voltage; n is the number of steps and $\Delta\tau$ is the time step. The BESS $SOC(t)$ overcharging limit is denoted as SOC_{MAX} , while the draining (over discharging) limit is denoted by SOC_{MIN} , such that the inequality (12) is satisfied. The BESS's power is balanced by the charging-discharging cycle (13), for which maximum power that can be contained by the BESS is P_{B-MAX} such that inequality (14) holds.

$$SOC_{MIN} \le SOC(t) \le SOC_{MAX} \tag{12}$$

$$P_B(t) = P_{BC}(t) - P_{BD} \tag{13}$$

$$0 \le P_B(t) \le P_{B-MAX} \tag{14}$$

The successful minimization of the OF in (1) by application of constraints (7), (9) – (10), (12) – (14) will result to the following **optimal states 1 – 4:**

State 1: AC microgrid supplying power from MSW while DC microgrid supplying power from solar PV with BESS, while the DG will not be used described by (15) – (18).

$$P_{L-AC}(t) \le \eta_{MSW} P_{MSW}(t) \tag{15}$$

$$P_{L-DC}(t) + \eta_B P_B(t) \le \eta_{PV} P_{PV}(t) \tag{16}$$

$$P_{CV}(t) = P_{DG}(t) = 0 \tag{17}$$

$$P_B(t) = P_B(t_0) + \eta_B \int_{t_0}^{t} \left[\eta_{PV} P_{PV}(t)\right] dt + \eta_B \int_{t_0}^{t} \left[\eta_{MSW} P_{MSW}(t) - P_{L-DC}(t)\right] dt \tag{18}$$

State 2: the AC microgrid will have higher demand than what the MSW can provide, with the DC microgrid supplied by the solar PV described by (19) – (22).

$$P_{L-AC}(t) > \eta_{MSW} P_{MSW}(t) \tag{19}$$

$$P_{L-DC}(t) \le \eta_{PV} P_{PV}(t) \tag{20}$$

$$\eta_{CV} P_{CV}(t) = \int_{t_0}^{t} \left[P_{L-DC}(t) + \eta_{PV} P_{PV}(t)\right] dt - \int_{t_0}^{t} \left[\eta_{MSW} P_{MSW}(t)\right] dt \tag{21}$$

$$P_B(t) = P_B(t_0) + \eta_B \int_{t_0}^{t} \left[\eta_{MSW} P_{MSW}(t)\right] dt - \eta_B \int_{t_0}^{t} \left[P_{L-AC}(t) + \eta_{CV} P_{CV}(t)\right] dt \tag{22}$$

State 3: the AC microgrid will be supplied by the MSW, with the DC microgrid not able to be supplied by the solar PV described by (23) – (26).

$$P_{L-AC}(t) < \eta_{MSW} P_{MSW}(t) \tag{23}$$

$$P_{L-DC}(t) > \eta_{PV} P_{PV}(t) \tag{24}$$

$$\eta_{CV}P_{CV}(t)=\int_{t_0}^{t}\left[P_{L-DC}(t)+\eta_{PV}P_{PV}(t)\right]dt - \int_{t_0}^{t}\left[\eta_{MSW}P_{MSW}(t)\right]dt \tag{25}$$

$$P_B(t)=P_B(t_0)+\eta_B\int_{t_0}^{t}\left[\eta_{MSW}P_{MSW}(t)\right]dt - \eta_B\int_{t_0}^{t}\left[P_{L-AC}(t)+\eta_{CV}P_{CV}(t)\right]dt \tag{26}$$

State 4: the AC microgrid will not be able to be supplied by the MSW, with the DC microgrid not able to be supplied by the solar PV either, denoted by (27) – (36).

$$P_{L-AC}(t)\geq \eta_{MSW}P_{MSW}(t) \tag{27}$$

$$P_{L-DC}(t)\geq \eta_{PV}P_{PV}(t) \tag{28}$$

$$P_{CV}(t)=P_{DG}(t)=0 \tag{29}$$

$$P_B(t)=P_B(t_0)+\eta_{BC-BD}\int_{t_0}^{t}\left[P_{L-DC}(t)\right]dt - \eta_{BC-BD}\int_{t_0}^{t}\left[\eta_{CV}P_{CV}(t)\right]dt - \eta_{BC-BD}\int_{t_0}^{t}\left[\eta_{MSW}P_{MSW}(t)\right]dt \tag{30}$$

$$P_B(t+1)=P_{B-MIN} \tag{31}$$

$$0\leq P_{DG}(t)\leq P_{DG-MAX} \tag{32}$$

$$P_L(t)\geq 0 \tag{33}$$

$$0\leq P_{MSW}(t)\leq P_{MSW-MAX} \tag{34}$$

$$P_{DG}(t)>0 \text{ if } SOC(t)\leq SOC_{MIN} \tag{35}$$

$$P_{DG}(t)=0 \text{ if } SOC(t)\geq SOC_{MAX} \tag{36}$$

SIMULATIONS

The four states present in Subsection 2.7 are simulated using Microsoft Excel considering the availability of respective energy resource in that particular area, i.e., electricity generation using MSW power plan; electricity generation using HKP power plan; and electricity generation using solar PV power plan; and all optimal states are considered for implementation.

RESULTS AND DISCUSSIONS

This Section presents the findings from the simulations above, and provides analysis of the suitability of each generation scenario for the DRC.

Electricity generation using Municipal Solid Waste power plan

The ten cities with potential of using MSW to power plan generation are listed in Table 4. The MSW can generate up to 83 790 kW.

Electricity generation using hydrokinetic power plan

The HKP potential of DRC can be exploited to generate electricity to about 50.9 MW for twenty-five cities situated in the path of large rivers (see Table 5), with possible minimum generation of 300 kW and maximum generation of 5 000 kW for individual HKP location (site).

Electricity generation using solar PV power plan

The DRC has lots of solar PV generation potential based on her solar insolation map, see Figure 6. This study has identified eight cities that have this potential to use solar PV and listed them in Table 6, that can use solar PV to generate electricity to the tune of 661 000 kW, where the minimum possible generation is 3 000 kW at Kananga and Kasongo and maximum generation is 400 000 kW at Kinshasa.

Summary of total renewable energy generation

Therefore, Table 7 summarises the total electricity from renewable energies totalling 795 690 kW that can power the microgrid proposed for the DRC.

Table 4: List of ten cities that can use MSW to generate electricity power plan

No.	City name	Population	MSW (tons/day)	Electricity generated (kW)
1	Kinshasa	13 265 000	9 000	50 000
2	Lubumbashi	1 786 397	1 212.03	6 733.5
3	Mbuji-Mayi	11 680 991	1 140.51	6 336.17
4	Kananga	1 061 181	719.99	3 999.94
5	Bukavu	1 012 053	686.65	3 814.72
6	Goma	1 000 000	678.48	3 769.33
7	Kisangani	935 977	635.04	3 528
8	Tshikapa	587 548	398.64	2 214.67
9	Kolwezi	453 147	307.45	1 708.06
10	Likasi	447 449	303.58	1 686.56
Total		**32 229 743**	**15 082.37**	**83 790.95**

Table 5: List of twenty-five cities that can use hydrokinetic to generate electricity power plan

No.	City name	River name	Electricity generated (kW)
1	Kinshasa	Congo	2 000
2	Kikwit	Kwilu	900
3	Idiofa	Musanga	700
4	Gungu	Kwilu	500
5	Kindu	Congo	2 000
6	Nonda	Congo	300
7	Mbandaka	Congo	5 000
8	Kalemie	Lukuga	1 000
9	Tshikapa	Kasai	3 000
10	Buta	Rubi	1 000
11	Malemba-Nkulu	Congo	2 000
12	Wamba	Congo	2 000
13	Aru	Kibali	5 000
14	Kananga	Lulua	2 000
15	Boma	Congo	2 000
16	Feshi	Feshi	5 000
17	Mwene-Ditu	Luilu and Lubilandjila	5 000
18	Bumba	Congo	2 000
19	Lisala	Congo	1 000
20	Kabanga	Lufira	1 000
21	Shabunda	Ulindi	500
22	Kisangani	Congo	2 000
23	Ubundu	Lualaba	2 000
24	Boende	Tshuapa	1 000
25	Nioki	Fimi	2 000
Total generation by HKP			**50 900**

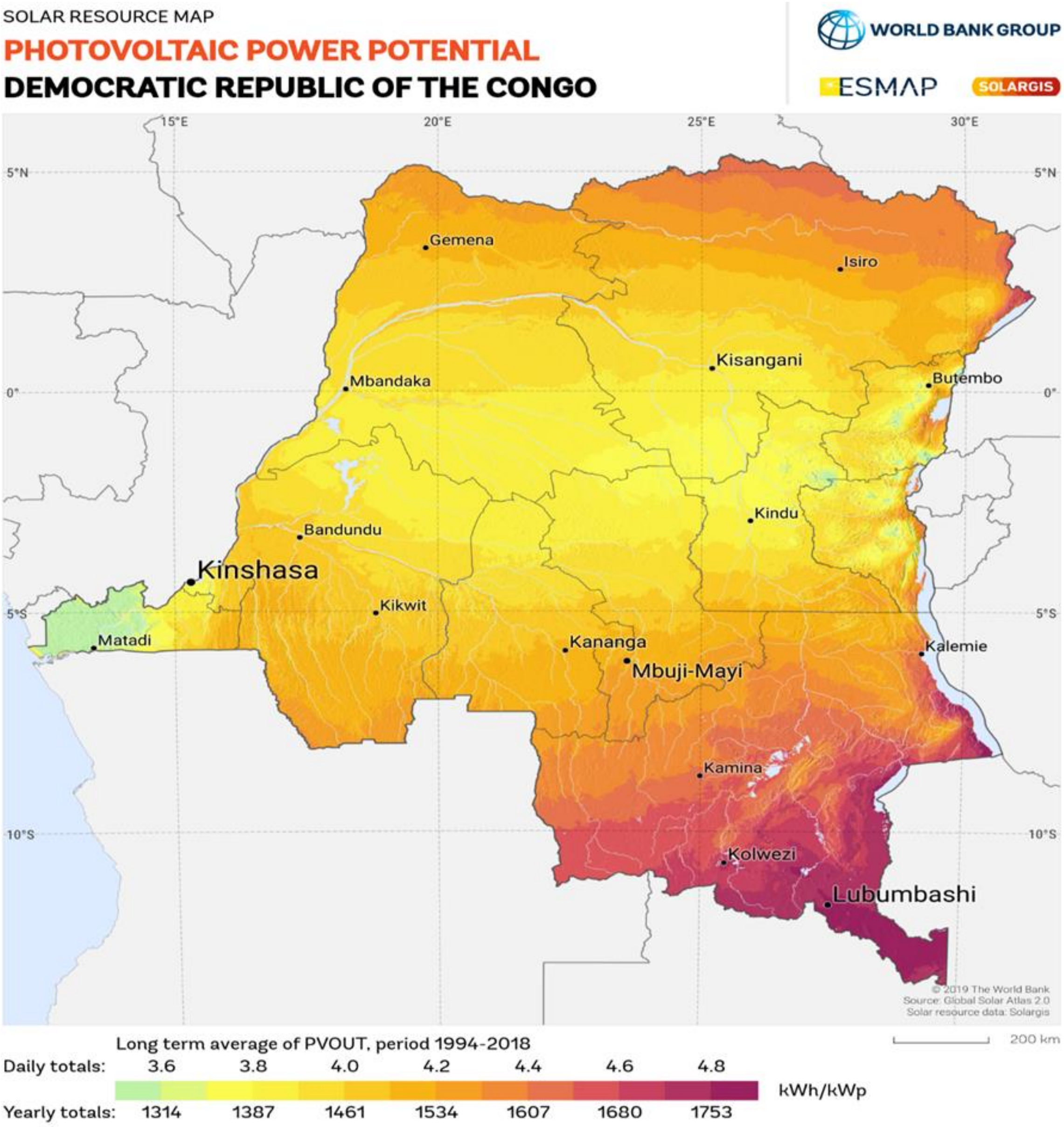

Figure 6: The DRC solar PV potential from 1994 to 2018.

Sources: (IEA et al., 2021; World Bank, 2020)

Table 6: The list of eight cities that can use solar PV to generate electricity power

City name	Insolation (kWh/m^2)	Electricity generated (kW)
Kinshasa	3.22 – 4.89	400 000
Kikwit	4.5 – 7	50 000
Mbuji-Mayi	4.4 – 5.14	50 000
Lubumbashi	6.5	100 000
Mbandaka	5 – 5.5	50 000
Kindu	3.5 – 6.75	5 000
Kasongo	3.5 – 6.75	3 000
Kananga	4.4 – 5.14	3 000
Total generation by solar PV		**661 000**

Table 7: The mix of renewable energies that can be used to power DRC's microgrid

No.	Energy type	Electricity generated (kW)
1	Solar PV	661 000
2	HKP	50 900
3	MSW	83 790
Total electricity generated		**795 690**

Further, this paper selects forty-four (44) project sites for this energy production, shown by the following distribution. The number of projects feasible for cities is 24 and for rural areas is 20 projects. The cities 24 projects will total 755 109.81 kW, i.e., 94.9% of the total proposed generation for which the energy sources are shown by Table 8. The rural areas 20 projects will total the 5.1% of the total proposed generation for which the energy sources are shown by Table 9.

Table 8: The distribution of renewable energies proposed for the cities

Type of energy resource	Number of projects
MSW	9
HKP	8
Solar PV	7

Table 9: The distribution of renewable energies proposed for the rural areas

Type of energy resource	Number of projects
MSW	1
HKP	18
Solar PV	1

CONCLUSIONS

This paper has looked at the electricity deficit of the DRC and found that despite various available renewable resources, the DRC has a deficit of 3 534 680 kW (i.e., 74% of the projected demand). This has stagnated the RER at 1%. Then, the paper explored the potential of generations using – MSW, HKP, and solar PV and found that for 44 feasible projects, there could be generated 795 690 kW. Out of this generation, 94.9% is feasible in cities, whilst 5.1% is feasible for rural areas. Further studies need to be undertaken to incorporate more sources such as the biomass from the vast forests of the DRC as a renewable energy resource and consider cheaper power transmission and distribution technologies so that the amount of energy for the rural areas is increased.

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REFERENCES

Abd El-Sattar, H., Kamel, S., Sultan, H., Tostado-Véliz, M., Eltamaly, A. M., & Jurado, F. (2021). Performance analysis of a stand-alone pv/wt/biomass/bat system in alrashda village in egypt. *Applied Sciences (Switzerland)*, *11*(21). https://doi.org/10.3390/app112110191

Ahlborg, H., & Hammar, L. (2014). Drivers and barriers to rural electrification in tanzania and mozambique - grid-extension, off-grid, and renewable energy technologies. *Renewable Energy*, *61*, 117–124. https://doi.org/10.1016/j.renene.2012.09.057

Al-Ammar, E. A., Habib, H. U. R., Kotb, K. M., Wang, S., Ko, W., Elmorshedy, M. F., & Waqar, A. (2020). Residential Community Load Management Based on Optimal Design of Standalone HRES with Model Predictive Control. *IEEE Access*, *8*, 12542–12572. https://doi.org/10.1109/ACCESS.2020.2965250

Avrin, A.-P., Yu, H., & Kammen, D. M. (2018). Supporting social and gender equity through micro-grid deployment in the DR Congo. *2018 IEEE/IAS PowerAfrica*, 646–651.

Awan, M. M. A., Javed, M. Y., Asghar, A. B., Ejsmont, K., & Zia-Ur-rehman. (2022). Economic Integration of Renewable and Conventional Power Sources—A Case Study. *Energies*, *15*(6). https://doi.org/10.3390/en15062141

Behrouzi, F., Maimun, A., & Nakisa, M. (2014). Review of various designs and development in hydropower turbines. *World Academy of Science, Engineering and Technology, International Journal of Mechanical and Mechatronics Engineering*, *8*(2). https://www.waset.org/publication/Review-of-Various-Designs-and-Development-in-Hydropower-Turbines/9997410

Belboul, Z., Toual, B., Kouzou, A., Mokrani, L., Bensalem, A., Kennel, R., & Abdelrahem, M. (2022). Multiobjective Optimization of a Hybrid PV/Wind/Battery/Diesel Generator System Integrated in Microgrid: A Case Study in Djelfa, Algeria. *Energies*, *15*(10), 3579. https://doi.org/10.3390/en15103579

Bhattacharyya, S. C., & Palit, D. (2016). Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? *Energy Policy*, *94*, 166–178. https://doi.org/10.1016/j.enpol.2016.04.010

Bouaouda, A., & Sayouti, Y. (2022). Hybrid Meta-Heuristic Algorithms for Optimal Sizing of Hybrid Renewable Energy System: A Review of the State-of-the-Art. In *Archives of Computational Methods in Engineering*. Springer Science and Business Media B.V. https://doi.org/10.1007/s11831-022-09730-x

DR Congo Population (2022) - Worldometer. (n.d.). Retrieved July 26, 2022, from https://www.worldometers.info/world-population/democratic-republic-of-the-congo-population/

El-Sattar, H. A., Sultan, H. M., Kamel, S., Khurshaid, T., & Rahmann, C. (2021). Optimal design of stand-alone hybrid PV/wind/biomass/battery energy storage system in Abu-Monqar, Egypt. *Journal of Energy Storage*, *44*. https://doi.org/10.1016/j.est.2021.103336

Emetere, M. E., Agubo, O., & Chikwendu, L. (2021). Erratic electric power challenges in Africa and the way forward via the adoption of human biogas resources. In *Energy Exploration and Exploitation* (Vol. 39, Issue 4, pp. 1349–1377). SAGE Publications Inc. https://doi.org/10.1177/01445987211003678

Fungo, L. J., Mushi, A. T., & Msigwa, C. J. (2021, November 11). Grid Connected PV-Wind Energy System for Luxmanda Village in Tanzania. *The Third Annual Conference on Research and Inclusive Development*.

Gaslac, L., Willis, S., Quispe, G., & Raymundo, C. (2018). A hybrid energy system based on renewable energy for the electrification of low-income rural communities. *IOP Conference Series: Earth and Environmental Science*, *168*(1). https://doi.org/10.1088/1755-1315/168/1/012005

Gbenga, A. M. (2019, August 23). Hydropower failures in DRC put Africa’s largest rainforest in danger. *Independent*. https://venturesafrica.com/lack-of-electricity-in-drc-puts-africas-largest-f...

Heydari, A., & Askarzadeh, A. (2016). Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept. *Applied Energy*, *165*, 601–611. https://doi.org/10.1016/j.apenergy.2015.12.095

IEA, IRENA, United Nations Statistics Division, The World Bank, ESMAP, & WHO. (2022). *Tracking SDG7: The Energy Progress Report-Democratic Republic of the Congo*. https://trackingsdg7.esmap.org/country/democratic-republic-congo

IEA, IRENA, UNSD, World Bank, & WHO. (2021). *TRACKING SDG7: The Energy Progress Report*. www.worldbank.org

Ighravwe, D. E., & Babatunde, M. O. (2018). Selection of a mini-grid business model for developing countries using CRITIC-TOPSIS with interval type-2 fuzzy sets. *Decision Science Letters*, *7*(4), 427–442. https://doi.org/10.5267/j.dsl.2018.1.004

International Rivers. (2013). *Congo’s Energy Divide Factsheet: Hydropower for Mines and Export, Not the Poor*. https://archive.internationalrivers.org/reso urces/congo%E2%80%99s-energy-divide-factsheet-3413

Irechukwu, M. E., & Mushi, A. T. (2020). Potential for Increased Rural Electrification Rate in Sub-Saharan Africa using SWER Power Distribution Networks. *Tanzania Journal of Engineering and Technology (Tanz. J. Engrg. Technol.)*, *39*(2). https://doi.org/10.52339/tjet.v39i2.707

Jahangiri, S., Haghani, A., Heidarian, S., Alidadi Shamsabadi, A., & Pomares, L. (2018). Electrification of a tourist village using hybrid renewable energy systems, Sarakhiyeh in Iran. *Journal of Solar Energy Research (JSER)*, *3*(3), 201–211.

Ji, L., Liang, X., Xie, Y., Huang, G., & Wang, B. (2021). Optimal design and sensitivity analysis of the stand-alone hybrid energy system with PV and biomass-CHP for remote villages. *Energy*, *225*. https://doi.org/10.1016/j.energy.2021.120323

Ji, L., Liu, Z., Wu, Y., & Huang, G. (2022). Techno-economic feasibility analysis of optimally sized a biomass/PV/DG hybrid system under different operation modes in the remote area. *Sustainable Energy Technologies and Assessments*, *52*. https://doi.org/10.1016/j.seta.2022.102117

Juma, M. I., Mwinyiwiwa, B. M. M., Msigwa, C. J., & Mushi, A. T. (2021). Design of a hybrid energy system with energy storage for standalone DC microgrid application. *Energies*, *14*(18). https://doi.org/10.3390/en14185994

Juma, M., Mwinyiwiwa, B. M. M., Msigwa, C. J., & Mushi, A. T. (2021). *Proposal Design of a Hybrid Solar PV-Wind-Battery Energy Storage for Standalone DC Microgrid Application*. https://doi.org/10.20944/preprints202108.0264.v1

Justo, J. J., & Mushi, A. T. (2020). Performance Analysis of Renewable Energy Resources in Rural Areas: A Case Study of Solar Energy. In *Tanzania Journal of Engineering and Technology (Tanz. J. Engrg. Technol.)* (Vol. 39, Issue 1).

Kharrich, M., Kamel, S., Hassan, M. H., Elsayed, S. K., & Taha, I. B. M. (2021). An improved heap-based optimizer for optimal design of a hybrid microgrid considering reliability and availability constraints. *Sustainability (Switzerland)*, *13*(18). https://doi.org/10.3390/su131810419

Krause, M., & Nordström, S. (2004). *Solar Photovoltaics in Africa: Experiences with Financing and Delivery Models, Lessons for the Future*.

Kusakana, K. (2015). Optimization of the daily operation of a hydrokinetic-diesel hybrid system with pumped hydro storage. *Energy Conversion and Management*, *106*, 901–910. https://doi.org/10.1016/j.enconman.2015.10.021

Kusakana, K. (2016). A Review of Energy in the Democratic Republic of Congo Battery Energy. *ICDRE Conference*. https://www.researchgate.net/publication/306380971

Lidula, N. W. A., & Rajapakse, A. D. (2011). Microgrids research: A review of experimental microgrids and test systems. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 1, pp. 186–202). https://doi.org/10.1016/j.rser.2010.09.041

Marcel, E. T., Mutale, J., & Mushi, A. T. (2021). Optimal Design of Hybrid Renewable Energy for Tanzania Rural Communities. *Tanzania Journal of Science*, *47*(5), 1716–1727. https://doi.org/10.4314/tjs.v47i5.19

Memon, S. A., & Patel, R. N. (2021). An overview of optimization techniques used for sizing of hybrid renewable energy systems. In *Renewable Energy Focus* (Vol. 39, pp. 1–26). Elsevier Ltd. https://doi.org/10.1016/j.ref.2021.07.007

Minja, M. N., & Mushi, A. T. (2021, November 11). Proposing Mixed Coupled Hybrid Renewable Energy Sources for Mwanza International Airport. *The Third Annual Conference on Research and Inclusive Development*.

Motjoadi, V., Bokoro, P. N., & Onibonoje, M. O. (2020). A review of microgrid-based approach to rural electrification in South Africa: Architecture and policy framework. *Energies*, *13*(9). https://doi.org/10.3390/en13092193

Mshelia, R. B. (2021). Assessment of Renewable Energy Potentials of The Northeast Geopolitical Region of Nigeria. *Renewable Energy Sources Energy Policy and Energy Management*, *2*(2), 24–38.

https://www.researchgate.net/publication/351946112

National Investment Promotion Agency (NIPA). (n.d.). *Energy-Agence Nationale pour la Promotion des Investissements*. Retrieved March 20, 2022, from https://www.investindrc.cd/en/Energy?lang=en

Sawle, Y., Gupta, S. C., & Bohre, A. K. (2018). Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. *Renewable and Sustainable Energy Reviews*, *81*, 2217–2235. https://doi.org/10.1016/j.rser.2017.06.033

Smith, T. (2021, August 6). *DRC to get first waste plastic to energy pyrolysis plant*. https://www.esi-africa.com/industry-sectors/future-energy/drc-to-get-firs...

USAID. (2021). *Democratic Republic of the Congo: Power Africa Fact Sheet*. https://www.usaid.gov/powerafrica/democratic-republic-congo

Wells, V., Greenwell, F., Covey, J., Rosenthal, H. E. S., Adcock, M., & Gregory-Smith, D. (2013). An exploratory investigation of barriers and enablers affecting investment in renewable companies and technologies in the UK. *Interface Focus*, *3*(1). https://doi.org/10.1098/rsfs.2012.0039

Winkler, H., Hughes, A., & Haw, M. (2009). Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios. *Energy Policy*, *37*(11), 4987–4996. https://doi.org/10.1016/j.enpol.2009.06.062

World Bank. (2020). *Increasing Access to Electricity in the Democratic Republic of Congo: Opportunities and Challenges*. www.worldbank.org