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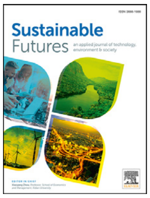

A practical approach for increased electrification, lower emissions and lower energy costs in Africa

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ABSTRACT

The limited access to affordable, reliable and sustainable energy in sub-Saharan Africa could inhibit the region's realisation of the United Nations Sustainable Development Goals by 2030. The intermittency and unreliability of power supply in the region has led countries, especially in the eastern sub-region, to implement sustainable energy solutions for rural electrification, thereby improving electricity supply access to underserved and unserved communities. With this focus on rural electrification, a deficit in electricity supply to urban settlements could arise, owing to the economic feasibility of extending the power grid towards securing electricity access for a growing population and the increasing number of rural-urban migrators. This paper reviews existing literature on electrifying sub-Saharan Africa, highlighting the prescriptions for deploying energy solutions in the region. Consequently, a country-level case study on grid defection solutions for Nigerian commercial centres assessing 14 different designs of Integrated Power Systems' (IPS) operations against the three impact metrics of cost implication ($/lifetime), greenhouse gas (GHG) emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.), is presented. The systematic analysis demonstrates that an integrated hybrid-solar-photovoltaics (PV)-based system (IHSS) without battery storage, serving 56% of its load from solar-PV and 44% from fossil-fuelled generators provides the lowest cost power supply option. The modelled system generated 25 MWh/yr. in surplus energy and emitted 53% fewer GHG emissions than the largest emitter. A compelling case is made whereby augmenting existing infrastructure with an appropriately sized PV plant will significantly reduce costs and simultaneously have a significant impact on GHG emissions. The generation of surplus energy also presents an opportunity to augment urban electrification through custom-fit sustainable energy solutions and the formation of a transactive electricity market.

1. Introduction

Sub-Saharan Africa's (SSAs) electric power supply-to-demand shortfall has been widely documented [1–3]. The electrification rate of most countries in SSA excluding South-Africa is less than 30% with an average electrification rate of 16% in rural communities [3]. The paucity of electricity supply in the region is quite alarming, with the World Bank estimating that over 50% of the 1 billion people without access to electricity reside in SSA [2,3]. Consequently, over 70% of primary energy is sourced from traditional biomass (fuelwood and charcoal), with more than half of SSA's electricity generated from large hydropower [4].

In the eastern sub-region, electricity consumption in 2015 for the EA-8 (Burundi, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda including South-Africa) stood at 261 TWh, with South-Africa consuming 227 TWh of the total figure [6]. In comparison, Italy consumed 310 TWh within the same period, despite having a fifth of the EA-8′s total population [6]. At the country-level, Nigeria – the most populous nation on the continent – still has to electrify over half its population [5] and improve the quality of power delivered to electrified areas. According to the World Bank, Nigerians with power supply access experience 33 power outages a month at an average outage duration of 8 h [2]. The need for reliable power has resulted in the proliferation of small-medium scale fossil-fuel generators of different models and capacities, giving rise to electricity costs and air pollution in the multi-sectors (commercial, industrial and residential) [7,8]. The region's limited access to an affordable, reliable and sustainable source of power has inhibited its socioeconomic development, with attendant consequences on quality of life, public health, climate change, economic growth and prosperity.

Public health in SSA is of concern on two fronts: in rural communities and settlements where indoor air pollution is a growing prob-

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Nomenclature

BOS	balance of system
C&I	commercial and Industrial
DG	diesel generator
DisCo	distribution companies
EA-8	East Africa [8]
GHG	greenhouse gas
GHI	global horizontal irradiance
GS	generator system
HVDC	high voltage direct current
IHGS	integrated hybrid generator based system
IHSBS	integrated hybrid solar and battery based system
IHSS	integrated hybrid solar based system
IPS	integrated power system
kW	kilowatt
kWh	kilowatt hour
LCCA	Life-cycle cost analysis
MW	megawatt
MWh/yr.	megawatt hour per year
NEM	net energy metering
NWA	non-wire alternative
PG	petrol generator
PV	photovoltaic
RE	renewable energy
RES	renewable energy system
RET	renewable energy technology
SDG	sustainable development goal
SHS	solar home system
SSA	sub-Saharan Africa
TEM	transactive electricity market

lem, with 65% of primary energy (cooking, heating and lightning) in the EA-8 sourced from solid biomass [6], and in urban regions where diesel/petrol fuelled generators are employed in ameliorating the effect of electric power supply unreliability on the quality of life. The air quality impacts from both situations could adversely impact human health [6,9,20,26]. SSA's electricity crisis presents an opportunity to address the electricity access deficit in tandem with climate change. The region is already considered a non-significant contributor to global greenhouse gas (GHG) emissions with its global contributions at 2–3% attributed to energy related and industrial activities [10]. Furthermore, about 60% of the countries on the continent have committed to climate change mitigation by ratifying the "Paris Climate Accord" [1,11]. However, South-Africa with an electrification rate of approximately 88% is looking to bring about 12 GW of coal-powered plants online, with Malawi and Zimbabwe also making considerable investments in coal-power generation capacities [3].

Climate policies and an enabling regulatory environment will be required in realising country-level and regional climate change mitigation commitments. The transition to a low-carbon economy has garnered some level of success in the eastern sub-region [16], with countries implementing sustainable energy solutions for rural electrification [3]. A notable industry leader in SSA is M-Kopa – a Kenyan solar energy company, serving Kenya, Tanzania and Uganda. According to the company, they have been able to develop solar home systems (SHSs) for over 600,000 low-income households in these countries, providing them with affordable and cleaner access to energy [12]. They have also been able to pioneer a pay-as-you-go mobile payment system for collecting returns on their services and in remotely monitoring (communicating with) their physical asset.

As the discourse on SSA's electricity paucity centres on providing electricity supply access to underserved and unserved communities particularly in rural areas, urban regions could experience an electricity supply deficit resulting from natural population growth and rural-urban migration. With over 50% of the African population predicted to be living in cities by 2030 and 60% by 2050, urbanisation is a social phenomenon that could influence access to electricity by putting pressure on energy resources and infrastructure [3]. At the country-level, Nigeria is predicted to add about 212 million people to its urban population between 2014 and 2050 [1]. The success recorded so far through the deployment of low-carbon technology for rural electrification in eastern Africa, presents an opportunity for exploring sustainable energy solutions in extending power supply access, improving power quality and sustaining the duration of electricity supply to a growing urban region (commercial, industrial and residential) in SSA.

In light of these conditions, further discussions in this paper are structured as follows: Section 2 covers a review of the literature on the energy solutions and drivers to energy access in SSA. Section 3 presents the method adopted, outlining the case study on Nigerian commercial centres and defining system operations design. Section 4 covers the results of the case study analysis with Section 5 discussing the implications of the results. Section 6 concludes the paper.

2. Review of relevant studies

The literature on SSA's electricity supply paucity and the energy solutions that could bridge the power supply to demand deficit is extensive, with discussions highlighting power supply access and reliability as a nexus to the region's socioeconomic development. Documented energy solutions for electrifying SSA's unserved and underserved communities favour sustainable energy solutions due to their minimal to zero adverse impact on public health and the environment, amongst other factors. Consequently, literature on SSA's electric power supply unreliability is reviewed accounting for the western, eastern and southern Africa sub-regions, with discussions split into energy solutions for increasing electrification and the drivers for improving electricity supply access.

2.1. *Energy solutions*

With the electrification rate of most countries in SSA excluding South-Africa below 30% and an average electrification rate of 16% in rural communities [3], existing literature on energy solutions for the region mainly focus on implementing sustainable solutions for rural settlements towards meeting their primary energy needs i.e. cooking, heating and lighting. Okoye and Oranekwu-Okoye [14] advocated the economic viability of solar-photovoltaic (PV) systems for rural electrification in SSA, using rural Gusau, Nigeria as a case study. Other studies by Azimoh *et al.* [23] on rural Namibia and Boamah and Rothfub [19] on Ghana analysed the successes of the hybrid (solar-diesel) mini-grid system in operation and the government-led solar home system (SHS) initiative respectively. Considering the wider benefits of "electrification beyond lighting", Schwerhoff and Sy [20] identified large-scale renewable energy developmental projects requiring substantial capital as integral to electrifying SSA and accelerating the transition to sustainable energy solutions. Barasa *et al.* [21] demonstrated the cost suitability of renewable energy (RE) systems delivering power through a high voltage direct current (HVDC) grid and their potential in increasing regional electrification through interconnected grid systems. Presley *et al.* [13] disputed the immediate focus on deploying sustainable solutions for electrification by arguing that the transition should only occur once conventional energy has been scaled up and utilised in achieving the "benchmark" of reducing energy poverty and accelerating economic growth and development. Adhekpukoli [29] presented the democratisation of Nigeria's electricity industry by further deregulating the sector to accommodate disparate electric power producers as a solution to the 'decades-long' electricity supply deficit. There is a need for sharing the emphasis on Africa's electrification agenda between the rural deficient and increasing electricity supply access to urban regions, particularly economic drivers like the commercial and industrial (C&I) sectors. A cost-benefit analysis by Olówósejéjé *et al.* [25] on Nigeria's industrial sector realised that industries could make significant cost savings if they transitioned to solar-PV based systems instead of complementing unreliable grid power with diesel generation. Sustainable energy solutions are being favoured for narrowing the electricity supply shortfall in rural SSA because they address the global issue of climate change. Chakamera and Alagidede [16] emphasised the need to mitigate the adverse effect of climate change by decreasing electricity production from non-renewable energy sources and increasing production from renewable energy sources in the long term. Ouedraogo [17] stated that the economic, social and environmental benefits of deploying renewable energy technology and infrastructure outweighed its capital-intensive nature.

Rose *et al.* [35] evaluated the potential of solar-PV (combined with reservoir hydropower) grid connected systems in displacing diesel generation in Kenya. They suggested that these large-scale RE systems are more impactful investments in providing sustainable energy solutions and significantly reducing carbon emissions. The United Nations 2030 target of ensuring access to affordable, reliable, sustainable and modern energy for all might have to be revised due to the rate at which SSA is being electrified. To support this point, Bazilian *et al.* [22] considered regional electrification targets in line with that of the Sustainable Development Goals (SDGs) as quite ambitious, stating that power generation capacity has not kept pace with population growth. They also put forward the contrasting level of commitment to power development projects amongst countries in the region as a significant issue in realising the SDGs within the stipulated time period.

2.2. Energy access drivers

The unavailability of and inaccessibility to data on the energy sector in SSA critically inhibits effective electricity supply planning and implementation. Trotter *et al.* [15] identified a major problem of electricity planning as the lack and unreliability of data. Bazilian [24] in discussing the role of international institutions in fostering SSA's electrification, implored the establishment of an information sharing mechanism towards improving the delivery of financial instruments and initiatives to the region. Ateba and Prinsloo [33] in identifying an effective approach towards electricity supply sustainability in South Africa, recommended the development of an integrated strategic management framework for sectoral planning informed by the holistic and comprehensive analyses of grid operations. The necessity for accessible energy data cannot be overemphasised as energy policies are informed by available data on the production, distribution and consumption of energy. Trotter *et al.* [15] listed the enabling factors for sustaining SSA's electrification drive as adequate policy design, sufficient finance, securing social benefits, a favourable political situation, community engagement together with human capital development. Azimoh *et al.* [23] listed government support, involvement of the local community, capacity development of same, sensitisation towards energy efficient practices, prepaid metering and the adoption of a progressive electricity tariff system as factors that have sustained the operation of the mini-grid system in Tsumkwe village, Namibia. In another study, Jain and Jain [32] presented political instability, contrasting energy strategies, technical ineptitude and grid infrastructure modification/integration as issues to be addressed in electrifying rural localities through renewable energy technology (RET). Adesanya and Schelly [26] concluded that renewable energy uptake in Nigeria is subject to supporting energy policies and an awareness drive through synergies amongst the government, financial institutions, private investors and stakeholders.

It is imperative that the renewable energy industry in SSA is de-risked to promote investments in renewable energy technology (RET) by private investors, multilateral financial organisations and international development partners. Obeng-Darko [28] in discussing the impeding factors to Ghana utilising renewable energy and energy efficient technologies in achieving a 10% penetration of national electricity production by 2020, highlighted deficiencies in legislative and regulatory frameworks as risk escalators deterring investments in renewable energy development projects and initiatives. Consolidating discussions in [28], Aliyu *et al.* [30] highlighted the importance of renewable energy policy mechanisms such as feed-in-tariffs and net energy metering in promoting and incentivising investments in renewable energy technology. Moner-Girona *et al.* [34] recommended the implementation of RET-specific tariffs for incentivising national and international investments in RETs. Social factors and societal behaviours have to be considered in the deployment of energy solutions and more particularly innovative solutions and new technology. Boamah and Rothfub [19] stated that the inter-relationship between energy and society is an important factor in implementing energy development projects. Wojuola and Alant [27] inferred the integration of sustainable development in education, science and technology policies towards fostering a national sustainable development culture, after realising a low level of knowledge on RETs in their survey of Ibadan, Nigeria. They also recommended that energy education should encompass all knowledge delivery systems. Misplacing priorities on energy development projects could scupper the rate at which continent-wide social and economic development is achieved. Trotter and Abdullah [18] proposed that international involvement in Africa's energy sector be redirected towards focussing on making public aid available for rural electrification, promoting local content through dissemination of technology and relaxing the conditions on foreign aid in order to support state-driven leadership. Simone and Bazilian [24] also proposed that international institutions channel their efforts into supporting the development of sound energy policies, sectoral reforms, corporate governance and ensuring transparency best practices. Renewably-powered systems for rural electrification could be faced with sustainability challenges, if the after services are not functional. Azimoh *et al.* [31] surveyed rural households in South Africa to investigate the impact of the SHS programme on the community. They argued that although the programme had facilitated the illumination of households thereby increasing study and business hours, it was not sustainable in the offing. This was due to the inadequacies of the fee for service payment model, the system's limited power supply, improper system use, equipment theft and the rising cost of doing business for the energy service companies.

2.3. Gaps in the literature

A review of the literature shows solar-power based systems as the preferred energy solution (due to a continent-wide resource abundance) in facilitating SSA's electrification. Their deployment either in standalone configurations or in complementarity with fossil-fuel based systems were consistent in the discourse. Also consistent in the literature was the mode in which these RETs were implemented (SHSs and mini-grid systems).

Following the extensive literature review, we present three stages/enablers to energy supply access. The first stage encompasses a politically stable environment, reliable data that is readily accessible and energy policies, with policy actions supported by an enabling legislative and regulatory infrastructure. Access to RE development finance, mechanisms incentivising RET investments, dissemination of RET, energy sector reforms and effective payment models for collecting returns on RET services constitute the second stage. The third stage focusses on community engagement in determining the best-fit innovative solutions as well as in inculcating a community-wide technology sustenance culture post-project implementation. The first stage serves as the building blocks for the successful implementation of the second stage with the final stage ensuring the sustenance of the project after completion.

Throughout the breadth of the literature, discussions have centred on implementing grid defection solutions (small-scale SHSs and mini-grid systems) for the electrification of rural SSA. With an electrification rate of less than 30% in most SSA countries [3], it is important that

Table 1
Summary of the IPS' system capacities.

IPS	Capacity (kW)			Capacity (kWh)
	Solar-photovoltaic (PV)	Diesel generator (DG)	Petrol generator (PG)	Battery array
RES	100	–	–	82
GS	–	15.5	2.2	–
IHSS	30	15.5	2.2	–
IHSBS 1	20	15.5	–	12
IHSBS 2	30	15.5	–	12
IHSBS 3	40	15.5	–	12
IHSBS 4	50	15.5	–	12
IHSBS 5	60	15.5	–	28
IHSBS 6	70	15.5	–	42
IHSBS 7	80	15.5	–	42
IHSBS 8	90	15.5	–	42
IHGS 1	10	15.5	2.2	–
IHGS 2	10	15.5	2.2	12
IHGS 3	10	15.5	–	12

electrifying rural areas is in tandem with extending and improving the quality of power delivered to urban regions. It is also important that electrification goes beyond lighting and provides the quality of power required in meeting the operational demands of urban-domiciled commercial centres and industries. This study seeks to address this gap in literature by analysing the economic and environmental viability of hybrid scalable PV-centric grid defection solutions for urban commercial centres (with urban regions comprising of commercial, industrial and residential sectors) towards a collective electrification drive i.e. increasing urban electrification and sustaining rural electrification efforts. A systematic analysis is carried out on 14 stand-alone integrated power system designs in meeting the electricity demand of urban commercial sectors and by extension, augmenting electricity supply access to the residential sector. There is an opportunity for surplus energy generated from these hybrid systems to power the residential sectors through industrial and commercial coalition formations. As a sustainable approach in terms of economic viability, the non-essentiality of energy storage systems in these hybrid configurations based on regional location is also elicited. The focus on the commercial sector stems from the fact that small and medium scale enterprises are the mainstay of an economy.

3. Method

This study was guided by three fundamental pillars: affordability, reliability and sustainability. Commercial centres in Abuja's (Nigeria) metropolis were surveyed to establish their most commonly-occurring commercial activities, which informed load demand projections. Subsequently, Olowos Plaza, a model single commercial centre housing the commercial outlets that cater to these activities was created and modelled in detail as a case study. A systematic analysis was performed on 14 different integrated power systems (IPSs): (a renewable energy system (RES); a fossil-fuel generator system (GS); an integrated hybrid solar-based system (IHSS); eight integrated hybrid solar and battery-based systems (IHSBS); and three integrated hybrid generator-based systems (IHGS)). In realising a viable solution, the power systems were analysed against three impact/performance metrics: cost implication ($/lifetime over 20 years), GHG emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.). Table 1 summarises the system capacities of the 14 IPS' operations designs.

3.1. *Survey on commercial centres*

Forty commercial centres in Abuja were surveyed to establish the most commonly-occurring commercial activities in these centres. A checklist was designed with 31 out of the 40 centres surveyed accommodating commercial outlets that engage in three or more of its listed activities, namely: cyber café businesses, boutiques, salons, tailoring businesses and grocery shops. These results informed the creation of Olowos Plaza, located in Abuja and housing a cyber café, boutique, salon, tailoring and grocery shop. See Supplementary material 1 for the survey checklist.

3.1.1. *Load demand projection/determination*

The weekly load demand of Olowos Plaza was realised based on the power requirements of the five commercial outlets. Olowos Plaza is open for business seven days a week with reduced business hours on Sundays. Some commercial outlets (cyber café, boutique and tailoring shops) are not operational on Sundays. Business operations are from 9 a.m. to 10 p.m., Mondays to Saturdays, and from noon to 5 p.m. on Sundays. Business times are representative of most commercial centres in Nigeria. Fig. 1 indicates the hourly load demand (kW) for Olowos plaza for a typical weekday, Saturday and Sunday. See Supplementary material 2, 3 and 4 for the typical week (weekdays and weekend) power consumption breakdown, equipment model and power rating, as well as business operation assumptions.

3.2. *Power system selection and cost consideration*

The three main power system components (although with different system compositions, and in different capacities and operations configuration) analysed in meeting Olowos Plaza's load demand were a solar-photovoltaic (PV) system, a battery storage system and a fossil-fuel generator system.

3.2.1. *Solar-PV system*

The Solar-PV system operations was designed using Abuja's global horizontal irradiation (GHI) data for year 2017 sourced from Copernicus Atmosphere Monitoring Service [36]. 100W$_p$ (V_{oc} – 22.3 V; I_{sc} – 6A; V_{mp} – 18 V; I_{mp} – 5.56A; η – 19.2%) monocrystalline solar-PV panels (considering the technical data specific to the panel's power rating) were selected and sized for every 10 kW capacity increment, for systems' operation design in the 10 kW$_p$–100 kW$_p$ capacity range. For practicality, "48V" string array configurations were considered i.e. to limit the systems' current-carrying capacity, thereby limiting the systems' protection sizing. See Supplementary material 5 for a full listing of operations design assumptions and considerations.

Solar-PV system cost consideration: A 20 year operational lifetime was considered when determining system cost prices. The PV panels' costs were based on wholesale prices [37]. The other costs taken into account for the PV system include the land costs, balance of system (BOS) costs (excluding battery storage costs) and PV panel maintenance costs. Maintenance costs (cleaning schedules) were considered due to the location of Olowos Plaza and its susceptibility to seasonal dust accumulation

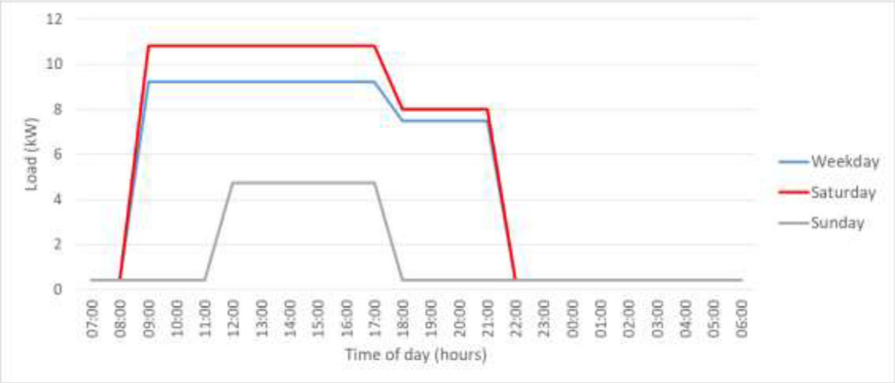


Fig. 1. Olowos plaza hourly load demand for a typical weekday, Saturday and Sunday.

[38]. Eq. (1) was used in determining the lifetime (Lt) costs for the solar-PV systems' capacities. See Supplementary material 6 for a full listing of the systems' cost assumptions and considerations.

$$\text{Total Cost} = \text{Capital} + \text{Maintenance} + \text{Replacement Costs} + \text{Land Cost} \tag{1}$$

3.2.2. Battery storage system

Flooded, deep-cycle, lead-acid batteries (the industry workhorse) were selected as the technology for the battery storage system. "Rolls" batteries were selected due to capacity and cost considerations. We employed brute-force search in determining the battery capacity for our system array. The search compared 6 V and 12 V battery types from three battery manufacturers (others being "Trojan" and "Crown" batteries) against possible application "C-rates" (10hr, 13hr and 15hr) and depth of discharge (10%, 20%, 30% and 40%). We opted for a 48 V system and limited an array to three parallel connections, with reference to the "Rolls" battery manual [39]. Also referencing the manual [39], we employed a multi-stage (bulk, absorption and float) battery charge for the "charging" phase in the battery array's operation cycle. See Supplementary material 5 for further details on the battery storage system's operation design.

Battery storage system cost consideration: The capital, replacement and maintenance costs for a 20 year operational lifetime were considered for the battery storage systems. Eq. (2) was employed in realising the lifetime costs for the different battery storage capacities. See Supplementary material 6 for further details on battery storage system costs.

$$\text{Total Cost} = \text{Capital} + \text{Maintenance} + \text{Replacement Costs} \tag{2}$$

3.2.3. Generator system

The fossil-fuelled generator system consists of one "19.3kVA/15.5kW" diesel-fuelled and one "2.8kVA/2.2kW" petrol-fuelled generator installed at the canopy level operating in prime power mode. 3-phase, direct-injection generators with a rotation speed of 1500 rpm were considered for the system. Pertaining to system lifetime, we were guided by "HOMER" – a software on distributed generation power system design and optimisation [40], whilst considering the system's mode of operations. See Supplementary material 5 for further details on the generator system's operation design.

Generator system cost consideration: The capital, replacement, fuel and maintenance costs for a 20 year operational lifetime were considered for the generator system. Eq. (3) was used in determining the generator system's lifetime costs. See Supplementary material 6 for further details on these costs.

$$\text{Total Cost} = \text{Capital} + \text{Maintenance} + \text{Replacement Costs} + \text{Fuel} \tag{3}$$

A life-cycle cost analysis (LCCA) was carried out on the different IPS for their operational lifetime. The real discount rate was calculated considering inflation at 11.4% and nominal interest rate at 14% [41,42].

For the calculations, we employed the equation:

$$r = \left(\frac{1+i}{1+n}\right) - 1 \tag{4}$$

where:

r = real discount/interest rate;
i = nominal interest rate; and
n = inflation rate, taken as 2% representative.

This rate was used in calculating the present value of the maintenance, operations and replacement costs for the lifetime of the 14 IPS analysed. Diesel and petrol costs [43,44] were considered for the generator system. The solar-PV system cost accounts for the BOS components costs, as well as the charge controllers and inverter capital and replacement costs. Supplementary material 7 details the LCCA on the IPSs.

3.3. System operations of the different IPS

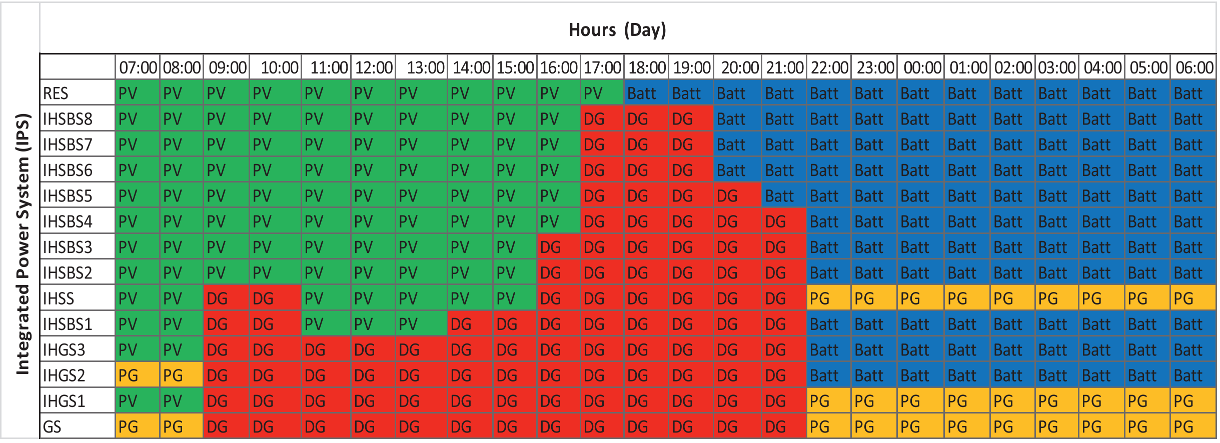
Figs. 2, 3 and 4 indicate the hourly system operations of the different IPS for a typical weekday, Saturday and Sunday, respectively. In these representations, the following codes are used to indicate the main power source for each hour of the day: Photovoltaic – PV; Battery – Batt; Diesel Generator – DG and Petrol Generator – PG.

4. Results

From our analysis, the "IHSS" variant is the cheapest ($162,225) IPS of the 14 power systems analysed. Olowos Plaza will make power system cost (capital, replacement, operations and maintenance) savings of up to 55% when compared to the average power system costs ($358,578) for its operational lifetime. The plaza will make further power system cost savings of up to 26% when compared to the "RES" – the most costly ($867,436) power system for the analysis. Fig. 5 represents the various IPS' costs.

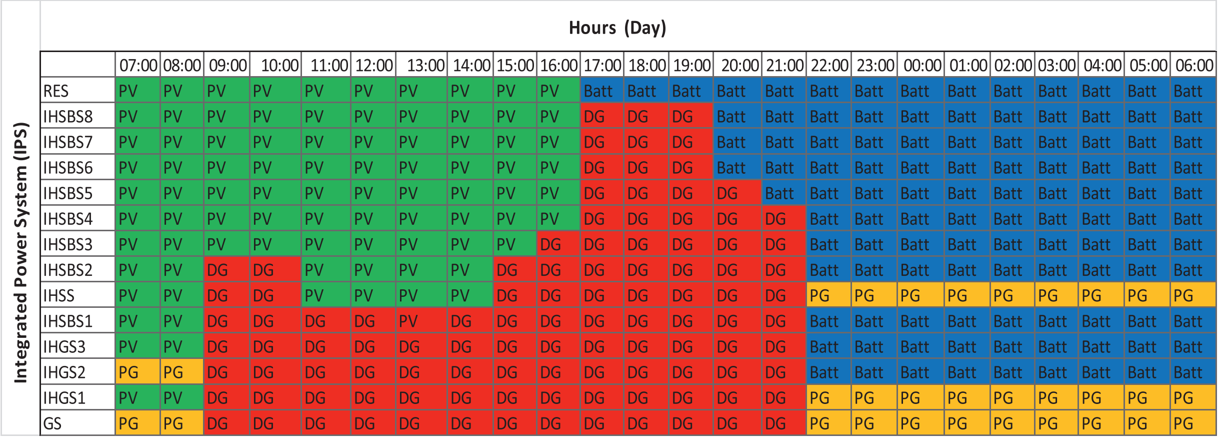
Informed by power distribution companies' (DisCos) unwillingness to transact with embedded generators (with proferred excuses of network maintenance and rehabilitation), and with all but one of the power systems generating surplus energy (MWh/yr.), we factored in the surplus energy performance metric. We hypothesise that the inability to capitalise on the surplus energy generated by Olowos Plaza power systems' operations would be more impactful to the systems at the upper limit of the surplus energy metric. The plaza is also permitted to operate without a power distribution license in all the power system capacities considered [45]. Fig. 6 represents the IPS' costs and surplus energy relationship.

The "GS" is the only power system of the 14 analysed that generated no surplus energy through its operations. As an outlier it was not included in calculations determining the average surplus energy (56 MWh/yr.). The "RES" through its operations, generated the most surplus energy (126 MWh/yr.) of the systems'. With no operational



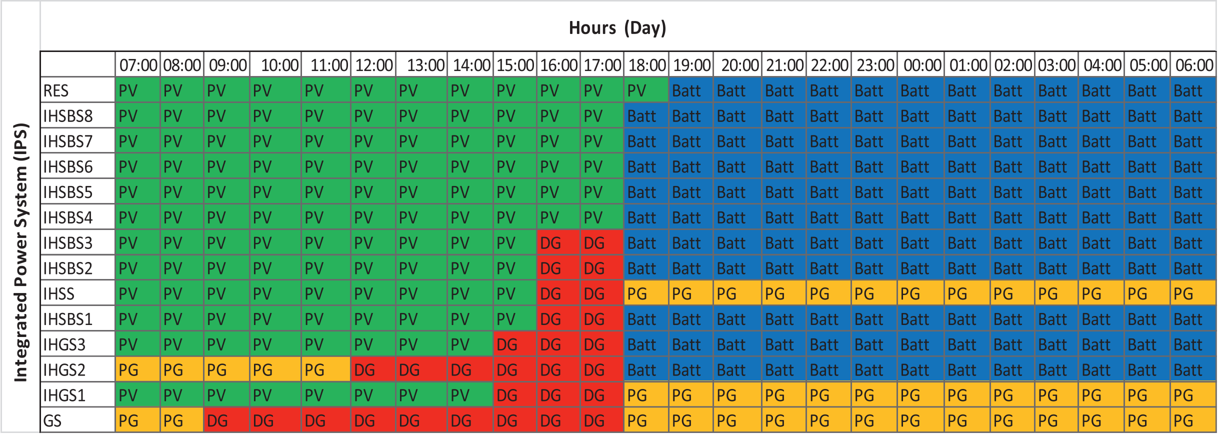
Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	DG	DG	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	DG	DG	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Fig. 2. Hourly system operations of the different IPS for a typical weekday.



Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	DG	DG	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	DG	DG	PV	PV	PV	PV	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	DG	DG	DG	DG	PV	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Fig. 3. Hourly system operations of the different IPS for a typical Saturday.



Integrated Power System (IPS)	Hours (Day)																							
	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00	04:00	05:00	06:00
RES	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS8	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS7	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS6	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS5	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS4	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	PV	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS3	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSBS2	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHSS	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG
IHSBS1	PV	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS3	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS2	PG	PG	PG	PG	PG	DG	DG	DG	DG	DG	DG	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt	Batt
IHGS1	PV	PV	PV	PV	PV	PV	PV	PV	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG
GS	PG	PG	DG	DG	DG	DG	DG	DG	DG	DG	DG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG	PG

Fig. 4. Hourly system operations of the different IPS for a typical Sunday.

transactive electricity market (TEM) in place, we considered the systems with surplus energy generation above average as non-feasible with precedence set on system operations efficiency i.e. closely matched supply-demand ratio (systems generating below the average surplus energy). In light of these, eight of the fourteen IPS analysed were found to generate surplus energy below the average.

In determining the CO_2 (tonnes/year) value for the different IPS, we worked with the assumption of diesel fuel emitting 2.68 kg per litre consumption and petrol emitting 2.31 kg per litre consumption [46]. Fig. 7 (hockey stick graph) represents the IPS' costs and GHG emissions relationship.

The "RES" is the only power system of the 14 analysed that emitted no greenhouse gases through its operations. As an outlier it was not included in calculations determining the average GHG emissions (22 CO_2 tonnes/year). The "GS" through its operations, generated the most GHG emissions (47 CO_2 tonnes/year) of the systems. Furthermore, and with emphasis on GHG emissions, the following power systems were feasible: *IHSS, IHSBS 2, IHSBS 3, IHSBS 4, IHSBS 5, IHSBS 6, IHSBS 7, IHSBS 8*

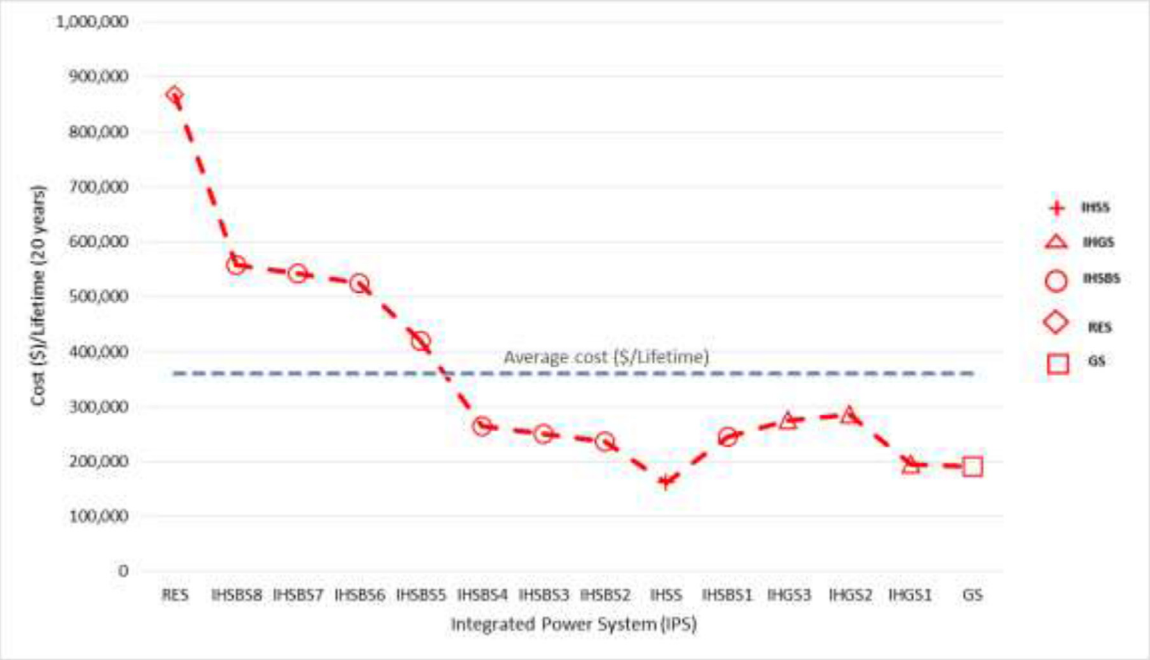


Fig. 5. Total lifetime cost of all IPS, in descending order of percentage renewable contribution.

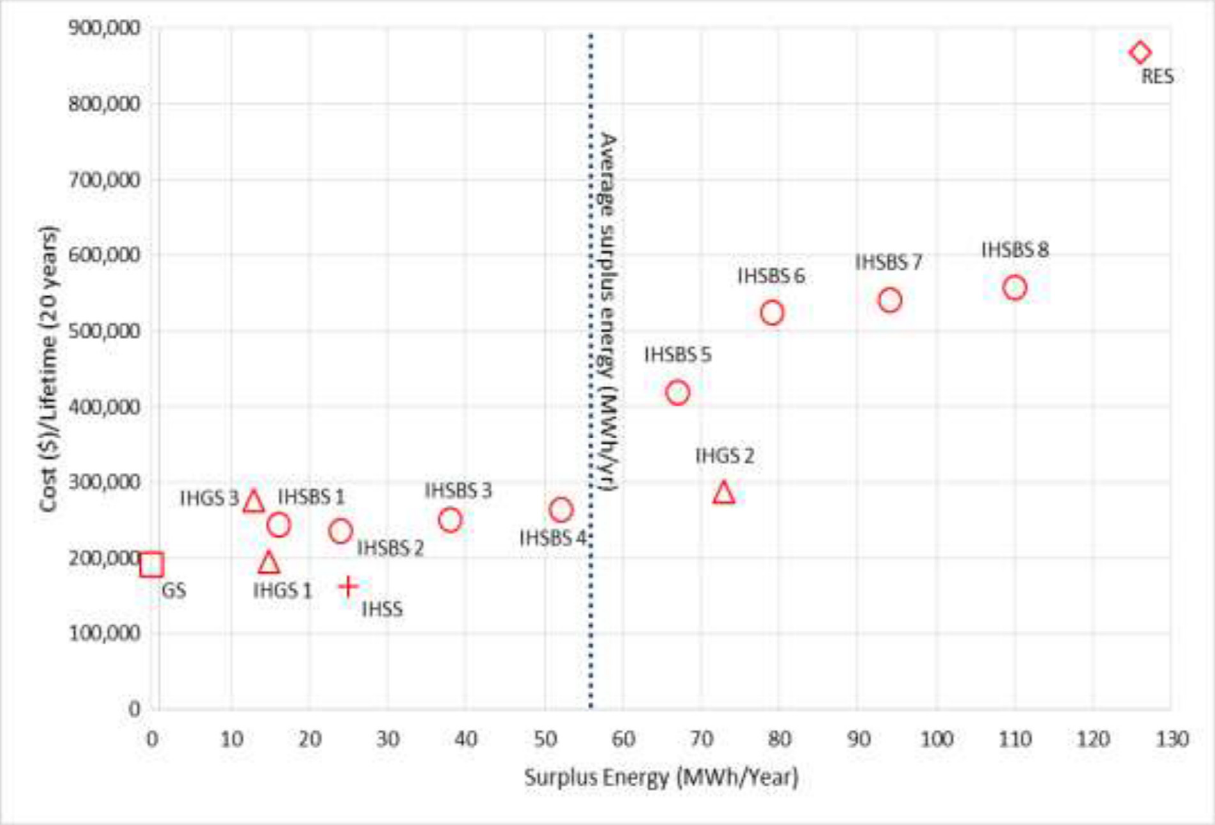


Fig. 6. IPS' costs and surplus energy relationship in ascending order of surplus energy generated.

and RES. The following were also feasible when assessing the systems for cost implication: *GS, IHGS 1, IHGS 2, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4*, with a review on the systems' surplus energy returning these: *GS, IHGS 1, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4,* as practicable.

Considering all impact/performance metrics, we realised a feasible solutions ("sweet spot") region for Olowos Plaza. The region comprises hybrid power systems, with one solar-PV based system (IHSS) and three solar-PV and battery based systems (IHSBS 2, IHSBS 3 and IHSBS 4). In light of these, the "IHSS" is the most viable power system solution of

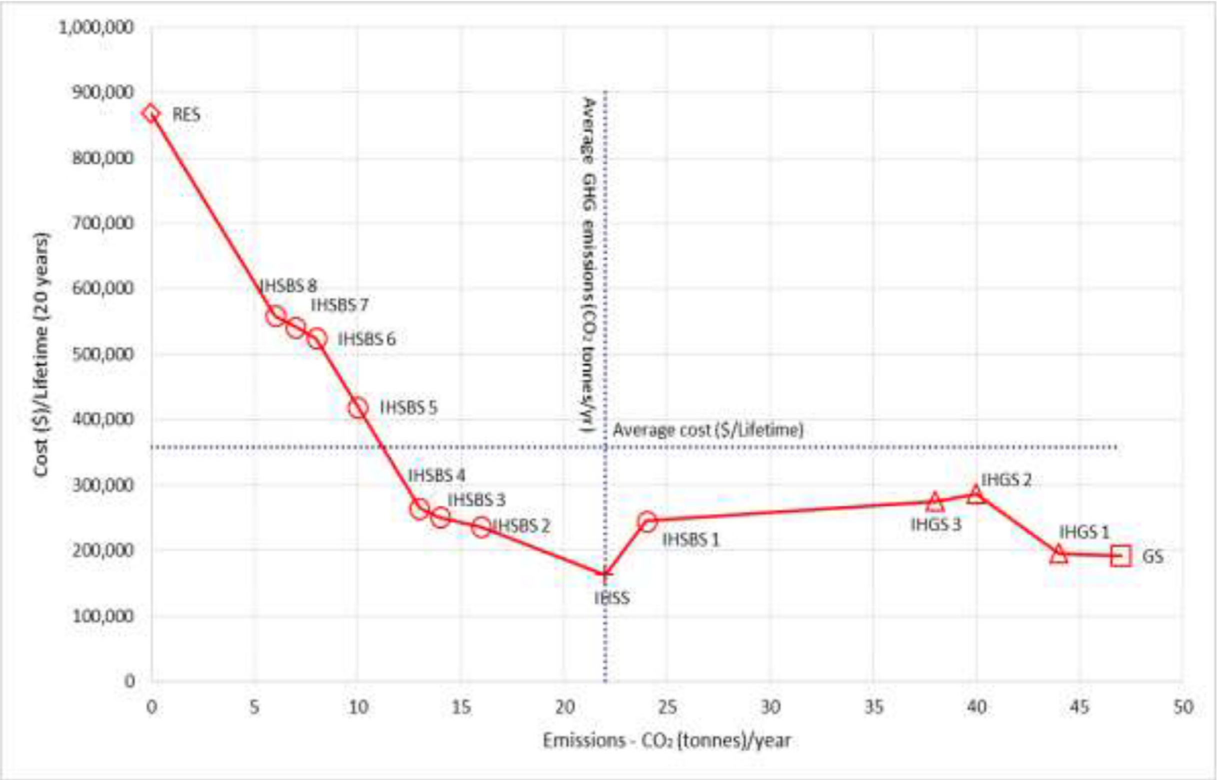


Fig. 7. IPS' costs and GHG emissions relationship in descending order of percentage renewable contribution.

the 14 integrated power system operations analysed. It best satisfied the conditions of the impact assessment defined by the three impact metrics of; cost implication ($/lifetime (20 years)), GHG emissions (CO_2 tonnes/yr.) and surplus energy (MWh/yr.) – Figs. 5, 6 and 7, respectively.

Summarising the result of our analysis, we present the following salient points:

i. The "IHSS" is the cheapest power system option, with surplus energy of 25 MWh/yr., 80% less than the largest surplus energy generator and emitting 53% less GHG emissions than the largest emitter.
ii. With a tariff of $0.12/kWh for commercial (single and 3-phase) customers [47], an average of 35.8 h of electricity per week [48] and commercial centre residents incurring an extra $0.20 – 0.30/kWh on generators for security of supply [48], the *GS, IHGS 1, IHGS 2, IHGS 3, IHSS, IHSBS 1, IHSBS 2, IHSBS 3 and IHSBS 4* all provide off-grid power solutions that are reliable with cheaper-to-similar costs as the commercial centres' current power systems. (See Supplementary material 6 for conversion rates.)
iii. The choice of a petrol generator over a battery storage system led to significant lifetime cost savings for the "IHSS" to the sum of $74,446 when compared with the "IHSBS 2″. Although, the "IHSBS 2″ performed slightly better than the "IHSS" against the other impact metrics i.e. generated approximately 1 MWh/yr. less surplus energy, emitting 6 tonnes fewer CO_2 emissions.
iv. Focussing on the IHSBS' and referring to Fig. 7, we observe a distinct transition from IHSBS 4 – IHSBS 5, an inflection point in our systems analysis with feasibility ramifications. The marginal cost of increasing the renewable percentage contribution begins to increase at the transition from IHSBS 4 – IHSBS 5.
v. Guided by Luckow et al.'s [49] report, we introduced a carbon tax ($25) on the generator (GS) and hybrid generator-based systems (IHGS 1, IHGS 2 and IHGS 3) and still found them cost-competitive (average increase of $0.03/kWh in levelised cost of energy (LCOE)) when compared to commercial centres' current power systems.
vi. The design and installation of a generator system at the canopy level for commercial centres allows for easier monitoring of air quality and implementing carbon air filter technologies. It also addresses the proliferation of small-scale petrol generators from shop to shop and floor to floor, improving air quality and mitigating the adverse effect of generator fumes on the health [6,9,20].
vii. Renewably-powered commercial centres, vanguard a transition to smart energy systems that ensures commercial centre residents energy consumption and usage are cost-reflective. For Olowos Plaza, this would result in commercial outlet 1 paying 47% of the Plaza's total yearly electricity costs, outlet 3–41%, outlet 5–10% and outlets 2 and 4 paying 1%, respectively. Refer to Supplementary material 4 for the commercial outlets activities.

5. Discussion

Results from our case study analysis demonstrate beneficial electrification for the commercial sector through PV-centric grid defection solutions. Total grid defection solutions also present an opportunity for the DisCos to increase the duration and improve the quality of electricity supply to the residential sector by reducing the number of energy intensive C&I customers connected to their network. These non-wire alternatives (NWA) could also be explored in partial grid defection configurations by incentivising surplus energy generation through policy mechanisms like net energy metering (NEM). It would mean electricity is made available during periods of peak demand and in emergencies.

In bolstering economic development, surplus energy generation could yet be pivotal in propelling the formation of a transactive electricity market (TEM) through C&I coalition formations that could further develop into hubs, clusters and villages. Reiterating recommendations by Adhekpukoli [29], further deregulation of the electricity sector to accommodate more independent power producers, embedded and captive power generators could be pivotal to increasing urban and rural electrification. As such, TEM would have to be backed by policy and an adequate regulatory infrastructure. The democratisation of the electricity sector to involve more nonconventional power producers by introducing different pathways (generation to consumers) as opposed to the traditional power delivery structure (generation to transmission to distribution to utilisation) increases business competition (through direct competition or partnerships) with the DisCos that could drive customers electricity supply costs down.

We posit that the C&I sectors transitioning to prosumers generating excess electricity could by extension electrify the residential sectors provided adequate legislative and regulatory frameworks are in place. We refer to this initiative as "*Commercial Electrification of the Residential Sector (Comtridential)"*. This could be in partnership with the DisCos (requiring further investments in revamping and modifying their electricity infrastructure/networks) or directly with the residential sector focussing on residential estates. The latter would require significant investments in the deployment of power distribution infrastructure. The potential for this energy solution could be measured by the willingness of residential estates (middle to high income earners) in maintaining access to an electricity supply network and increasing the duration of supplied hours. Given the electricity supply situation, an example of customer willingness in remaining electrified draws from the collective efforts of estate residents in funding the replacement of damaged service transformers resulting from power surges due to grid unreliability and intermittency.

The transition to sustainable solutions as a means in electrifying the various sectors that contribute to the socioeconomic development of a nation is possible and is being exemplified in Nigeria through a public sector led initiative. The Nigerian government through its rural electrification agency (REA), in partnership with private investors and multilateral finance institutions (The World Bank and African Development Bank) are deploying solar-PV powered utility-scale (stand-alone) systems in improving electricity supply to the commercial, industrial, education and health sectors [50]. These solutions are being implemented under two initiatives (Energising Economies and Energising Education), underscoring the importance of non-fragmented finance by international donor organisations and multilateral institutions as elicited by Simone and Bazilian [24].

6. Conclusions

The results of this analysis show that a practical approach of adopting hybrid systems with PV, batteries and fossil fuel generation in urban commercial settings in Nigeria will greatly reduce lifetime energy costs and deliver reliable power to loads. These would be achieved while simultaneously contributing to decarbonisation and improving air quality by reducing overall reliance on fossil fuel self-generation. It also elicited the non-essentiality of energy storage systems (high cost considerations) in regions of abundant solar energy resource especially for hybrid energy systems that also incorporate non-renewable sources of power generation. The IHSS evidenced this, by best satisfying the economic and environmental metrics of our analysis i.e. being the cheapest power system option and emitting 53% less GHG emissions than the largest emitter. Also, from this study, we realised that disparate energy solutions would have to be explored in meeting country-level and regional electrification targets in the medium to long term. Our case study results further highlighted total to partial sustainable grid defection solutions as practicable solutions for urban electrification. A unique case was presented for the commercial electrification of the residential sector (comtridential) through commercial and industrial coalition formations taking advantage of the generation of surplus energy from hybrid renewable energy systems operating in a liberated transactive electricity market.

Our case study on commercial centres informed the reality that most project developers assess their project feasibility solely on its cost implication, disregarding its social and environmental effects. Therefore without adequate climate policies, the generator and three generator-based hybrid systems (GS, IHGS1, IHGS2 and IHGS3) emitting 47, 44, 40 and 38 CO_2 tonnes/year respectively, would have been considered feasible. Focussing on the issue of climate change, sustainable energy solutions are being favoured in electrifying rural SSA. The deployment of sustainable energy solutions addresses the regional electrification crisis in tandem with mitigating the effect of climate change. Energy policy formulation that serves as a proper deterrent to carbon-intensive processes of the commercial, industrial and power sectors present a more impactful approach in reducing carbon emissions and mitigating the effect of climate change beyond small-scale, PV-centric, grid defection solutions. Consequently, the role of individual nation's government in improving regional electrification rates, both in urban and rural areas, cannot be overemphasised. Government support through policy actions and ensuring an enabling regulatory environment are essential in driving the energy transition through the implementation of sustainable energy solutions. These precursors form the bedrock to improving access to finance, implementing policy mechanisms, dissemination of information & technology, initiating sectoral reforms and community engagement. Ready access to reliable data across the region is also important in informing financial investments and implementing sustainable development projects.

In light of these, if the United Nations SDGs are to be met by 2030, it is important that SSA's rural electrification agenda goes beyond lighting and provides the required energy that could stimulate socioeconomic activities towards the collective development of communities, broader countries and the wider region. Sustainable electrification targeting core urban sectors (commercial, industrial and residential), are channelled measures in addressing the attendant consequences of urbanisation and spurring economic development through industrialisation. Therefore, it is critical that rural electrification is sustained alongside efforts of extending electrification, improving the quality of power delivered and increasing the duration of electricity supply access to urban areas.

Declaration Competing of Interest

No conflict of interest to be declared.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2020.100022.

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