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## Research paper

## Optimising photovoltaic-centric hybrid power systems for energy autonomy

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## ABSTRACT

In recent years, emphasis has been placed on the design and implementation of sustainable energy system solutions to combat the adverse environmental impact of emissions from the power and transportation sectors. This study applies a systems elimination method using numerical simulation to validate and optimise recently-reported results demonstrating the benefits of photovoltaic (PV)–diesel – battery hybrid integrated power systems (IPS) for commercial centres, with Abuja in Nigeria used for the case study. An optimal IPS was identified from 20,200 candidate solutions analysed by assessment against environmental (1st priority) and economic (2nd priority) metrics. Although environmental conditions were prioritised, the optimal system was economically viable. The environmentally optimal system emitted 33% less greenhouse gas (GHG) emissions (CO<sub>2</sub> tonnes/yr.) than the economically optimised solution (PV–diesel) over their operational lifetimes (\$/20 years), and was 4% costlier than same. The results demonstrate that carbon taxation or outright bans on independent fossil fuel systems (IFFSs) in emerging economies might not be effective policies in mitigating the impact of climate change on our environment. This study contributes to the body of knowledge on energising unserved and underserved communities in sub-Saharan Africa, considering the case study country of Nigeria. It decries the common practice of prioritising economic factors over environmental factors in optimising the operations of grid defected power system solutions as continental and regional electrification efforts are being ramped up. This is particularly of importance (an environmental responsibility), as immediate economic gains could have far-reaching environmental and social implications that elicits the limitations of economically prioritised power development projects in the offing.

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## 1. Introduction

In attaining global electrification, human efforts must be multidimensional; in other words, ensuring access to affordable, reliable, sustainable and modern energy for all is central to the realisation of the United Nations' sustainable development goals (SDGs) (International Bank for Reconstruction and Development, 2017). As such, it is imperative that a synergy of both renewable and other power sources (Avila et al., 2017) are implemented for the multiple sectors that contribute substantially to the economy. Also integral to the electrification agenda are enablers in the form of financial support from public/private institutions and consolidated governmental and inter-governmental policy actions (IRENA, 2018).

The electrification drive adopts different forms at both ends of the economic development spectrum. The developed world is investing human, technical and financial resources in studying and re-engineering the power systems that service their sectors (with notable interest in the transportation sector) (EY, 2020). They are becoming more energy, process and resource efficient – as countries drive their transition to sustainable solutions (IRENA, 2018; Cucchiella et al., 2018). At the other end, the developing world (low-middle income countries) still grapples with the reliability and resiliency of their power grid systems and securing electricity supply access for the unserved and underserved communities (Murugaperumal et al., 2020; The Economist Intelligence Unit, 2016). This situation has led to the continued investment in conventional power systems (coal power generation) in countries like South-Africa, Malawi and Zimbabwe, for example (Oxford Institute for Energy Studies, 2018), thus posing a challenge to the energy transition.

The paucity of power supply in emerging economies which needs to focus on poverty reduction, food security, economic

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## Nomenclature

BOS	balance of system
$C_{ESS}$	energy storage system's lifetime costs (\$/20 years)
$C_{GS}$	generator system's lifetime costs (\$/20 years)
$C_{solar-PV}$	solar-PV system's lifetime costs (\$/20 years)
C&I	commercial and industrial
DCF	discounted cash flow
DG	diesel generator
$\epsilon_{GS}$	the generator system's yearly GHG emissions (CO <sub>2</sub> tonnes/yr.)
$\epsilon_{IHSBS}$	the integrated hybrid solar-PV and battery based systems' yearly GHG emissions (CO <sub>2</sub> tonnes/yr.)
$\epsilon_{IHSS}$	the integrated hybrid solar-PV based systems' yearly GHG emissions (CO <sub>2</sub> tonnes/yr.)
ESS	energy storage system
GHG	greenhouse gas
GS	generator system
HPVPS	hybrid photovoltaic-centric power system
HRES	hybrid renewable energy system
IFFS	independent fossil fuel system
IHSBS	integrated hybrid solar-PV and battery based system
IHSS	integrated hybrid solar-PV based system
IPS	integrated power system
kW	kilowatt
kWh	kilowatt hour
LCOE	levelised cost of energy
LEAP	long-range energy alternatives planning
LF	load factor
NEM	net energy metering
NPC	net present cost
PG	petrol generator
PV	photovoltaic
RE	renewable energy
RES	renewable energy system
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SDG	sustainable development goal
TEM	transactive electricity market
TOP	technical operating parameter

growth and development, presents an opportunity in implementing sustainable energy solutions towards addressing the power supply deficit. This is exacerbated by deficient electricity infrastructure which struggles to keep pace with a growing population (Oxford Institute for Energy Studies, 2018). As these countries industrialise towards stimulating their economic activities, greenhouse gas (GHG) emissions will inevitably rise (Colenbrander et al., 2015) if the primary sectors (commercial and industrial (C&I)) spurring industrialisation and urbanisation remain heavily dependent on unreliable conventional grid power systems. It becomes an environmental and health issue when the deficiency of the centralised power grid is ameliorated by cost-prohibitive (Olówósejé et al., 2019; Arowolo et al., 2019) and unsustainable independent fossil fuel solutions (e.g. petrol and diesel generators).

The tendency to analyse the economic viability of power systems development projects in isolation or as a priority over

socio-environmental factors, has long-term implications on the environment and people's social well-being. GHG emissions and fumes from independent fossil fuel systems (IFFS) would inevitably contribute to climate change with adverse effects on the environment (IRENA, 2018) and human health (Ifegwu et al., 2013). Adopting a reactive culture in addressing the problems that could arise from implementing conventional power systems (coal power generation) and/or IFFS in bridging the power supply deficit gap in emerging economies, could prove costlier in the long-term than rolling out renewable energy system (RES) or hybrid renewable energy system (HRES) solutions. Considering the equal importance of socio-environmental factors with economic factors in optimising HRESs design (Diemuodeke et al., 2016) is a more impactful approach towards realising holistic power system solutions for emerging economies.

Therefore implementing third generation HRESs that includes solar-photovoltaic (PV) generation and diesel generators, could drive the transition to sustainable energy system solutions for the developing world. The HRES's operations could be supported by interactive devices (e.g. remote monitoring systems and energy consumption metres) (ESMAP, 2019), and optimised to satisfy economic, environmental and social metrics. These could be more effective than carbon taxation (based on the current pricing structure) (Luckow et al., 2015) and outright bans on IFFS in access-deficient regions. In this paper, Section 2 highlights the findings from a review of recent literature and outlines the gaps in the research this study seeks to address. Section 3 presents the method adopted for the study. Section 4 sheds light on the results from the operations analysis of hybrid integrated power systems, with Section 5 discussing the implications of the results. Section 6 concludes the study.

## 2. Review of relevant studies

The review of literature was undertaken to highlight the emphasis placed on economic over environmental factors in power systems design and operations analysis. Where economic metrics continue to be prioritised, social actions/responsibilities could be key in tipping the scale and advancing the transition towards a sustainable environment.

### 2.1. The viability of grid defected power system solutions

Studies have found that grid defected integrated power system (IPS) solutions could be more affordable than conventional power grid systems both in the developing (Peffley and Pearce, 2020) and developed (Arowolo et al., 2019) world. Supporting these findings, Olówósejé et al. (2020) adopted a systematic quantitative analysis in evaluating the techno-economic and environmental viability of grid defected power system solutions for commercial centres in Abuja, Nigeria. The integrated hybrid solar-PV based system (IHSS) in the study, was the most viable power system of the 14 power system solutions analysed. Olówósejé et al.'s study prioritised economic viability in selecting an optimal power system solution for commercial application. Arowolo et al. (2019) utilised an energy modelling software — Hybrid Optimisation Model for Electric Renewables (HOMER) in analysing the techno-economic viability of hybrid solar-PV systems for the commercial sector (small and medium enterprises) in the Upper Peninsula of Michigan, USA. They concluded that a solar-PV hybrid system (including energy storage and natural gas power generators) is technically and economically viable for all scales of commercial utility customers. Their study also laid emphasis on the techno-economic viability of decentralised solutions. For both studies, environmental benefits were incidental to economic considerations and their benefits.

Across the literature, grid defected IPSs in different power system mixes and configurations have been documented to be viable particularly for remote locations i.e. the rural underserved/unserved and critical sectors. Ali and Jang (2020) modelled an optimum hybrid renewable energy system (with solar and wind as the main energy sources) in HOMER considering techno-economic (comparing levelised cost of energy and net present cost) parameters for the remote island of Deokjeok-do, South Korea. Their study also evaluated the economic viability of the supporting energy storage system (ESS) technology (battery against pumped hydro storage). The solar-wind-pumped hydro storage system was more economically viable than the solar-wind-battery storage system based on their results. This study focused on optimising power system solutions for techno-economic viability. Babatunde et al. (2019a) performed a techno-economic analysis in HOMER to determine the feasibility of implementing a hybrid renewable energy system (HRES) for hypothetical rural healthcare centres in the six geo-political zones of Nigeria. The PV and diesel generator (DG) and battery HRES was economically feasible for all locations studied with some locations considered more feasible than others. The net present cost (NPC) for the power system solutions considered in their analysis was sensitive to fluctuations in the fuel pump price. Their study realised economically viable power system solutions with environmental benefits. All of these studies identified economically optimal grid defected solutions, but the environmental impact of the various solutions were not independently determined i.e. the extent of environmental benefits were limited to economically viable solutions.

Franco et al. (2017) reviewed energy production and storage technologies based on a multi-criterion and multidisciplinary method defined by the EssentialTech programme. Their goal was to realise the most suitable power system solution for healthcare centres in the global south. They presented the hybrid renewable energy system solution (renewable source plus battery storage and DG) as the optimal power system solution for medium to large scale healthcare facilities, particularly those situated in remote areas. The economic implications of the power system solution were the primary consideration of the study. This begs the question, to what extent are the environmental impacts of power system solutions truly considered?

## 2.2. The factors considered when designing grid defected power system solutions

When deploying renewable energy (RE) and HRES solutions, energy storage systems (ESSs) usually contribute significant costs to the total power system costs. The sub-optimisation of ESSs could impact the economic viability of grid defected IPS solutions. The choice of integrating ESSs for energy autonomy in advanced economies are usually assessed solely by their economic implications. This is especially the case when a reliable and affordable grid connection is available. Grid defection could yet offer environmentally cleaner power system solutions with economic viability if ESSs are optimised and integrated for longer lifetimes. Optimising the ESS component of the power system solution, taking into consideration the choice of storage technology, capacity sizing and the operation strategies implemented could realise environmentally cleaner IPS with economic viability. An aggregation of autonomous power systems could contribute to decarbonising the environment especially as base load power plants that offer energy access to grid connected energy consumers are usually gas or coal powered. Veilleux et al. (2020) applied HOMER in remodelling the current rural micro-grid (integrating more PV modules and replacing lead-acid batteries with lithium ion batteries) solution implemented for the case study island of Koh Jik in Thailand. In assessing the techno-economic viability of their remodelled

solution, they presented an economic argument for lithium ion ESSs over lead-acid alternatives. Although lithium ion ESS are more expensive than lead-acid ESS, the capacity of lead-acid batteries required to attain the same RE fraction that the lithium ion ESS provided in the off-grid system, drove the total cost of the lead-acid ESS to almost cost parity with the lithium ion ESS. The power system remodelling exposed an environmental lapse in their initial power system design and implementation that had economic implications over the long-term. This reinforces the point that optimising the ESS configuration in IPS design could present environmentally viable power systems with economic benefits over the long-term. Foles et al. (2020) employed Matlab in evaluating the techno-economic viability of solar-PV and solar-PV plus energy storage systems for the residential sector in three representative Portuguese locations. They considered four power system configuration scenarios (solar-PV, solar-PV + grid connection, solar-PV + battery storage and solar-PV + battery storage + grid connection). The locations considered were characterised by differing solar resource potential. Their results elicited the unviability of the scenarios with energy storage systems for residential applications. Their study did not highlight the fact that the prioritisation of economic factors in the choice of power system solutions has an impact on the environmental benefits that a grid defected solution with ESSs could offer.

Cucchiella et al. (2018) applied a discounted cash flow (DCF) method in analysing the practicality of solar-PV plus lead-acid ESSs in four case study scenarios for the residential sector in Italy. Their conclusions infer that solar-PV plus ESSs is practical when the share of self-consumption is increased through the installation of solar-PV plants in regions with high levels of solar insolation. Although they present a condition for the practicality of solar-PV plus ESSs, their study does not go further to advance the environmental importance of integrating optimised ESSs. Förstl et al. (2020) applied SimSES – simulation of stationary energy storage systems, an open source software tool in evaluating the techno-economic feasibility of residential solar-PV and battery storage systems. The study presented two case studies with one focusing on the profitability and lifetime of battery storage systems under different energy management and tariff regimes in New South Wales, Australia and Germany. The other placed emphasis on the profitability and degradation impact of three different operation strategies for the residential sector in Australia. Results from case study one highlighted the unprofitability of solar-PV and battery storage systems in both regions with case study two highlighting the beneficial impact of operation strategies on the economic feasibility of solar-PV and battery storage systems. This was at the cost of increased battery degradation. Their study's principal focus considering both case studies, was in optimising the lifetime and performance of the integrated ESS for economic viability. Environmental benefit was not prioritised.

Considering economic factors as a priority over environmental and social factors could have long-term economic implications that are not apparent when the immediate economic case is prioritised. This is the case especially when optimising grid defected IPSs design and operations. In an attempt to highlight the neglect of social parameters (job creation and social acceptance) which constitutes an important factor in the implementation of HRESs for small communities, Cuesta et al. (2020) performed a methodological review of studies that had applied energy modelling software (HOMER, RETScreen, DER-CAM, iHOGA, EnergyPRO) in optimising the design of HRESs. They concluded that except for the latest version of iHOGA, these commercial or open source software tools had not incorporated social parameters into their models. Their review did not draw the link between social and environmental factors i.e. how GHG emissions can have an adverse effect on the environment and in turn impact jobs in the



agricultural sector over the long-term or how environmental pollution can impact an individual's health and/or quality of life. Babatunde et al. (2019b) followed a multi-criteria (technical, economic, environmental, social and policy) decision making approach in selecting the most suitable HRES for a typical low-income household in Lagos, Nigeria. Their analysis in HOMER was based on two energy demand scenarios – consumer demand with energy efficient devices and consumer demand without. They found the PV-Gen-Batt system to be the most suitable HRES for low-income households when implemented in the energy efficient devices scenario. Although their study considered multiple factors in selecting a power system solution, the economic viability of the power system solution was prioritised over the other factors considered i.e. socio-environmental benefits were incidental to the most economically viable solution.

In some emerging economies, governmental policy actions still present a gap in increasing electrification and spurring a rise in economic activities. The paucity of power supply and the limitation of the grid infrastructure in access-deficient regions positions the developing world at the fore in realising sustainable electrification and creating a sustainable environment. Considering metrics of levelised cost of energy (LCOE) and NPC, Agyekum and Nutakor (2020) applied HOMER in assessing the economic viability of two hybrid renewable energy systems (PV-Wind-DG-Battery and Wind-DG-Battery) for the commercial sector in southern Ghana. They concluded that governmental effort was imperative in creating an enabling environment that would ensure the economic viability of HRES for sustainable development. Their study did not particularly emphasise the environmental benefits of these systems in application. Emodi et al. (2017) employed the energy policy modelling and climate change mitigation assessment tool – Long-Range Energy Alternatives Planning (LEAP) in exploring the most sustainable electrification pathway in meeting Nigeria's future energy demand based on four study scenarios. They carried out an energy system analysis and cost-benefit analysis in evaluating the practicality of the scenarios presented. Their results elicited the importance of policy formulation in driving Nigeria's energy transition. It is important that the economic viability of environmentally optimised sustainable energy solutions are clearly presented to adequately inform climate policies.

Rasheed et al. (2020) argued the case for RE solutions in addressing Pakistan's energy crisis. They supported their argument by carrying out a cross-country comparative study (Pakistan vs rest of South Asia). Their conclusions highlighted effective policy implementation and institutional cooperation as requirements in harnessing Pakistan's renewable energy potential. Their study highlights feed-in-tariff schemes that are already operational in advanced economies as a policy mechanism in driving RE solutions. For emerging markets, this policy instrument might not be effectual due to the underdevelopment of the electricity market. Energy policies that incentivise the proliferation of environmentally optimised HRESs could be more effectual in decarbonising the energy sector, driving sustainable development and developing the electricity market. Ensuring access to affordable, reliable, sustainable and modern energy for all is central to the realisation of the SDGs. Adenle (2020) carried out a meta-analysis of the literature on the performance of solar energy technologies in three African countries (Ghana, Kenya and South Africa) to explore the role of solar energy in realising the SDGs by 2030. The author concluded that appropriate policy instruments such as feed-in-tariff schemes, incentive programs and renewable energy laws would drive the uptake of solar energy in African energy markets, thereby contributing to the achievement of the SDGs by 2030. Opposing the author's view and proposing a paradigm shift from a top-down to bottom-up approach in sub-Saharan

Africa's electrification agenda could yet present a solution to improving its electrification rate. The uptake of environmentally focused HRESs in this region's critical and economic sectors could be more impactful in realising the SDGs by 2030. The approach of deploying these energy solutions in the critical and economic sectors would simultaneously decarbonise the environment and improve electrification. This strategy could better inform energy (and specifically climate) policies by evidencing the impact of these systems in operation.

### 2.3. How the choice of power system solutions explains the difference between the energy landscape of advanced economies and emerging economies

The energy landscape of the developed world differs from the developing world. As such, models in increasing electrification cannot be directly replicated. Studies that analyse grid defected IPS solutions primarily for the residential sector in the developed world provide evidence that electricity consumers still favour grid-connected power systems over grid defected IPSs. Their preference is based on power supply reliability and cost implications. Liu et al. (2019) used mixed-integer linear programming in determining the techno-economic (parameters of reliability and LCOE) viability of grid defected (solar-PV + battery storage) power systems over grid-connected power supply for 300 homes in Australia. They presented the grid-connected power supply option as the more reliable and lower cost option. Their study reinforces the discourse that in the developed world where reliable grid connection is available, the cost implication of energy access is the primary and possibly sole concern of the energy consumer. Hittinger and Siddiqui (2017) considered 1020 locations in the USA when analysing the economic viability of grid defected power systems (solar-PV and battery storage) using their energy system model (ESM) developed in Matlab. They concluded that grid defected power systems are not economically viable for most locations in the USA with the exception of Hawaii and California where policy mechanisms like net energy metering (NEM) could incentivise their consideration. Even in locations where grid defected power systems can take advantage of policy mechanisms like NEM, mechanisms that reward environmentally cleaner grid defected systems are elusive.

In assessing the effect of electricity tariff structure on an electricity customer's decision to maintain connection or defect from the utility grid, Gorman et al. (2020) employed linear optimisation in calculating a range of off-grid power system costs (considering customer type, location and minimum reliability). These electricity costings were then compared against unique rate tariff structures for over 2000 utilities in the USA. Results highlight the possibility of grid defection beyond current load defection levels. This is subject to a continual fall in solar-PV and ESS technology costs. It is also contingent on tariff structures not being favourable to the electricity consumer in the offing i.e. utility companies increasing fixed charges and lowering variable charges. Their study sheds light on the fact that grid defection comes second to grid connection in advanced economies, therefore buttressing the point that in the developed world, the onus is on utility companies to decarbonise the power sector.

Whereas, in the developing world, grid defected power system solutions are considered viable in assuaging the impact of grid power unavailability and unreliability on the rural underserved. In emerging economies, the onus to decarbonise the power sector could yet be on energy-autonomous critical/economic sectors. Murugaperumal et al. (2020) applied HOMER in the optimum design and techno-economic assessment of a HRES for rural electrification in the remote district of Korkadu, India. Their results

evidence that the HRES can be a cost-effective sustainable alternative to conventional grid power system solutions. The study highlighted the emphasis placed on economic over environmental metrics. Fodhil et al. (2019) implemented a particle swarm optimisation (PSO) and  $\epsilon$  constraint method in optimising the design of a HRES towards concurrently minimising total system cost, unmet load and CO<sub>2</sub> emissions. The HRES (PV-battery-diesel) rural electrification solution realised for the remote village of Tiberkatine in southern Algeria was able to satisfy the aforementioned optimisation conditions. Furthermore, the study highlighted that its PSO approach was more cost-effective with a larger PV penetration fraction than the power system solution realised using HOMER. Although their results realised a solution that satisfied affordable, reliable and sustainable metrics, environmental benefits were limited to economic conditions.

Oyewo et al. (2020) applied a linear optimisation tool model in projecting a cost optimal power system solution for the West African region. Their analysis (for the period 2015 to 2050) evaluated the viability of the transition to fully RE systems based on six policy scenarios considered for the region studied. Their results present the fully RE system as the least cost and least GHG emitting power system solution for the West African region. The study also highlighted solar-PV as the principal energy resource and technology in driving the transition to a sustainable future. Although their study presents an all-RE system as the most economic and environmentally optimal power system solution in the long-term, economic considerations were still prioritised. There is a case to be argued on the extent to which an economically prioritised power system can be environmentally acceptable. In addition, their results are projections for the long-term and not the near to middle term this study seeks to address.

#### 2.4. The knowledge gap

Evaluating the practicality of prioritising techno-environmental factors over techno-economic factors in power system operations analysis is a knowledge gap identified in the literature this study intends to address. The particular gap this study seeks to fill is in prioritising emissions reduction over cost savings when implementing power development projects in regions with electricity supply deficit. This is particularly important as immediate cost savings on power development projects could have long-term adverse effects with an environmental and social bearing. The long-term costs that would be required to ameliorate social (job loss from climate change and adverse health conditions from polluted air) and environmental (mitigating climate change) impacts resulting from prioritising cost implications from power development projects, could be significant, with the economic, social and environmental damage irreparable. Studies reviewed evidenced the importance of hybrid renewable energy systems in bridging the power supply and demand gap in emerging markets considering cost savings and emissions reduction. None of the studies paid attention to the importance of social action (environmental responsibility) in implementing power system solutions. Especially pertinent to prioritising environmental over economic gains.

Secondly, with the knowledge that the viability of power system solutions against techno-economic, environmental and social metrics is closely aligned to the optimisation of their designs and/or operations, a significant portion of HRESs design and operations analyses in the literature review, applied the energy systems modelling software HOMER for their analysis. This study intends to diversify the methods adopted in the power systems design optimisation reviewed in the literature, by implementing a numerical simulation method in comprehensively and rigorously validating results obtained in a previous study on HRES

solutions (Olówósejé et al., 2020). This supports the transfer of knowledge, especially in emerging markets where the cost of securing an academic (or personal) license for energy modelling and analysis software could be prohibitive.

### 3. Method

A systems elimination method was adopted for this study. Numerical simulation in Matlab was applied using equations Eqs. (1)–(6). The cost function equations have been deduced from the equations of the straight line graph of solar-PV and energy storage system capacities (in the range of 0 – 100 kW and 0 – 82 kWh respectively) quantitatively determined in Olówósejé et al. (2020)'s study. The generator system cost and emissions reduction function were based on iterative computations of the systems' capacities and frequency of usage, assuming a fixed reduction in costs per decrease in capacity size (0 – 15.5 kW). In this study, a search space of 20,200 IPS solutions was defined. This provides a comprehensive validation of results obtained from a recent study on hybrid PV-centric power system solutions for commercial centres, as well as varies the methods adopted for power systems operations analysis. The numerical simulation in this study is performed considering the solar resource for Abuja and the load profile of the commercial centre in Olówósejé et al. (2020)'s study. A limitation to this approach i.e. using a static solar resource and load profile in analysing the commercial centre's operations and in realising a suitable power system solution that meets energy demand, is the inability to capture day-to-day or seasonal resource variation experienced in a typical year. As such, the optimality (best performing system) of the solution realised in this study is limited to the implementation of the approach.

#### 3.1. Design consideration for power systems' performance analysis

##### 3.1.1. Solar resource

The solar irradiation data used in this study was from Copernicus Atmosphere Monitoring Service (CAMS) at latitude – tilt angle (0°), specific to Copernicus Atmosphere Monitoring Service (2018). Abuja is positioned at geographical coordinates: latitude – 10°N and longitude – 8°E. This study worked with a single day (24 hr) solar irradiation data based on the average daily solar irradiation for each month of the year for 2017. The solar-PV system sizing for the capacity range considered, was guided by working with the lowest average daily irradiation (4.45 kWh/m<sup>2</sup>/day) for the year (August), against the commercial centre's peak load day (Saturday).

##### 3.1.2. Load demand determination

The load profile is that of Olowos plaza, a hypothetical commercial centre situated in Abuja, Nigeria, and is based on survey data of similar centres. The plaza has a weekly variable load demand, with the same total load demand from Monday–Friday (117 kWh per day), increased demand on Saturday (134 kWh) and reduced demand on Sunday (36 kWh). The total weighted average daily and weekly energy demand are 108 kWh and 757 kWh respectively. Average hourly energy demand is 4.5 kWh, base load is 0.4 kWh and weekly peak demand is 10.8 kWh. The base load cycle is from 22:00 h to 8:00 h (Mondays–Saturdays) and from 18:00 h to 11:00 h on Sundays. Fig. 1 represents the weekly load demand for Olowos plaza.

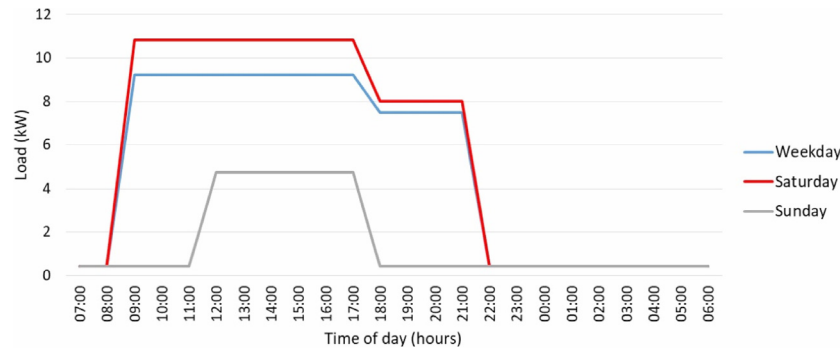


Fig. 1. Olowos plaza hourly load demand for a typical week (Olówósejé et al., 2020).

### 3.1.3. Technologies considered

The systems technologies and operating conditions are captured in bullet points:

- Solar-Photovoltaic (PV) system – monocrystalline modules in 48 V string array configurations were considered i.e. to limit the systems' current-carrying capacity, thereby limiting the systems' protection sizing.
- Energy storage system (ESS) – Rolls flooded, deep-cycle, lead-acid batteries were considered for the storage system technology (Rolls Battery Engineering, 2019). A 50% depth of discharge, with a 13 h c-rate and multi-stage charging regime were also considered.
- Independent fossil fuel system (IFFS) – Diesel generators (DG) operating in prime power (indefinite running time) mode were considered for the generator system (GS).
- Balance of system (BOS) – that include (switchgears/system protection, charge controllers, inverters) supporting technologies for the solar-PV system and ESS were not independently considered. Although, their technical operating parameters, degradation, frequency of replacement and numerical efficiencies were considered for analysis.

### 3.2. Metrics considered for power systems' performance assessment

The numerical simulation process, explored a search space defined by three power system variables i.e. solar-PV, battery and DG capacities with maximum values of 100 kW, 82 kWh and 15.5 kW respectively. At one apex of the search space, the all renewable energy system (RES) implemented a solar-PV array design (100 kW) supported by battery storage (82 kWh) while at the other apex, the fossil fuel system (GS) was solely operating on a 15.5 kW DG. The search space was populated by implementing a step size iteration sequence (1%–100%) from zero to the maximum capacities of the RES, GS, integrated hybrid solar-PV based system (IHSS = solar-PV + GS) and integrated hybrid solar-PV and battery based system (IHSBS = RES + GS). A search space of 20,200 (202 × 100) IPS solutions was realised by simulating all possible solutions (feasible and non-feasible) of the power system configurations (RES, GS, IHSS and IHSBS) considered. Feasible solutions were defined as the solutions that meet the commercial centres daily peak load demand, are within technical operating parameters (TOPs) and satisfy the metrics of affordability and sustainability i.e. cheapest lifetime costs (\$/20 years) and lowest yearly CO<sub>2</sub> emissions. The non-feasible solutions are all solutions that do not meet the aforementioned conditions.

The systematic search implemented three orders of elimination in realising an optimum solution. The first order eliminated 15,250 IPS solutions for not meeting the commercial centre's average daily and peak load demand (basic power system operating requirements), reducing the search space to 4950 IPS solutions.

The second order eliminated a further 4929 IPS solutions for not meeting TOPs, reducing the solutions in consideration to 21. The final order eliminated 20 IPS solutions in realising an optimum solution assessed against lifetime costs (\$/20 years) and yearly GHG emissions (CO<sub>2</sub> tonnes/yr.).

#### 3.2.1. Technical assessment (Reliability)

The technical assessment of power systems' performance - being the second order of systems elimination, considered TOPs in realising solutions that satisfied reliability metrics. TOPs are practical real-life considerations that aim to limit the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) to zero. Planned interruptions i.e. refuelling times and maintenance schedules are assumed to occur during non-commercial hours and do not interfere with the outcome of these reliability indexes (SAIDI and SAIFI). Therefore TOPs are:

- The minimum solar-PV capacity that is practical for a hybrid IPS (IHSS and IHSBS) mix;
- Diesel generator operating intensity;
- Maximum load demand in relation to diesel generator operating capacity;
- Duration of diesel generator operation at base load;
- Battery array configuration/matrix for the battery technology implemented (Rolls lead-acid battery).

Power system solutions are considered reliable if they can meet the conditions for TOPs i.e. ensuring the commercial centre's operation is seamless with no unmet load.

#### 3.2.2. Economic assessment (Affordability)

The economic assessment was the third order of systems elimination but second priority level when assessed in tandem with the sustainability metric. Solutions in the power systems' search space (20,200 solutions), that returned lifetime costs lower than or equal to the base IFFS ( $\leq \$189,000$ ) and also satisfied technical operating parameters were considered. The equations applied for the economic assessment in this study were realised from power systems capacity sizing deduced from graphical representations and iterative computations. These equations encompass lifetime costs (\$/20 years) implications for all IPS solutions evaluated. The equations are:

*Economic cost as a function of power system capacity*

$$C_{\text{solar-PV}} = 1937.1x + 2895.9 \quad (1)$$

$$C_{\text{ESS}} = 8171.4y + 1177.9 \quad (2)$$

$$C_{\text{GS}} = (189 \times 10^3)z \quad (3)$$

Where:

$C_{\text{solar-PV}}$ : solar-PV system's lifetime costs (\$/20 years);



$C_{ESS}$ : energy storage system's lifetime costs (\$/20 years);  
 $C_{GS}$ : generator system's lifetime costs (\$/20 years);  
 $x$ : solar-PV system capacity;  
 $y$ : energy storage system capacity; and  
 $z$ : is the percentage increment (1%–100%) in the iteration sequence that corresponds

to an IPS system capacity in the range i.e. 1% = least cap, 100% = max cap.

In light of the above, the economic element for the four categories of power system solutions considered were realised based on the following combination of equations:

- RES = Eqs. (1) + (2)
- GS = Eq. (3)
- IHSS = Eqs. (1) + (3)
- IHSBS = Eqs. (1) + (2) + (3)

### 3.2.3. Environmental assessment (Sustainability)

The environmental assessment was also the third order of systems elimination, but first priority level when assessed in tandem with the affordability metric. Solutions in the power systems' search range (20,200) greater than or equal to 0 CO<sub>2</sub> tonnes/yr. – baseline GHG emissions were considered. Also considered, were solutions less than 46 CO<sub>2</sub> tonnes/yr. – baseline GHG emissions of the primary GS.

That is,  $0 \leq \text{emissions target} < 46$ . The equations applied for the environmental assessments were predicated on the capacities in the GSs' range and the frequencies of their daily usage. The equations formulated applied to all power system solutions under the GS, IHSS and IHSBS umbrella, excluding those under the RES category i.e. 0 CO<sub>2</sub> tonnes/yr. The equations for the IPS solutions analysed are:

*Emissions reduction as a function of frequency of system usage*

$$\epsilon_{GS} = 46z \quad (4)$$

$$\epsilon_{IHSS} = 46z \times 0.75 \quad (5)$$

$$\epsilon_{IHSBS} = 46z \times 0.5 \quad (6)$$

Where:

$\epsilon_{GS}$ : the GS's yearly GHG emissions (CO<sub>2</sub> tonnes/yr.);

$\epsilon_{IHSBS}$ : the IHSBS's yearly GHG emissions (CO<sub>2</sub> tonnes/yr.);

$\epsilon_{IHSS}$ : the IHSS's yearly GHG emissions (CO<sub>2</sub> tonnes/yr.);

$z$ : is the percentage increment (1%–100%) in the iteration sequence that corresponds

to an IPS system capacity in the range i.e. 1% = least cap, 100% = max cap;

0.75: avg. frequency of usage i.e. the GS meets  $\frac{3}{4}$  of daily load demand; and

0.5: avg. frequency of usage i.e. the GS meets  $\frac{1}{2}$  of daily load demand.

The flowchart in Fig. 2 illustrates the search sequence implemented in realising an optimal IPS solution based on all the power system assessments described in this section.

## 4. Results

### 4.1. Categorisation of theoretical solutions

Table 1 represents the theoretical power system solutions, i.e. the power system solutions that meet the average/hr daily load demand and/or peak load demand but do not satisfy TOPs. The theoretical solutions are categorised according to their lifetime costs (\$/20 years) and yearly GHG emissions (CO<sub>2</sub> tonnes/yr.). Supplementary Materials 1 and 2 capture all the power system solutions categorised according to their lifetime cost (\$/20 years) implications and their yearly GHG (CO<sub>2</sub> tonnes/yr.) emissions.

### 4.2. Categorisation of practical solutions — 2nd order of systems elimination

Table 2 breaks down the technical composition, environmental and economic implications of the practical IPSs. Although, the base RES and GS systems are unviable when evaluated against economic and environmental factors in tandem, they are included in Table 2 as reference systems.

### 4.3. Optimum power system solution — 3rd order of systems elimination (1st priority level)

Table 3 highlights the optimal IPS solution (with a lifetime cost of \$166,000 and 16 CO<sub>2</sub> tonnes in yearly GHG emissions) amongst the practical and reference power system solutions. The table accounts for the 21 practical solutions assessed against the reference systems — GS (with lifetime cost of \$189,000 and 46 CO<sub>2</sub> tonnes in yearly GHG emissions and the RES (with lifetime cost of \$867,000 and zero yearly emissions), at both ends of the table. The metric for assessing affordability (economic viability) is represented on the vertical axis with that of sustainability (environmental viability) on the horizontal axis. The optimum power system solution is highlighted in Table 3.

### 4.4. Summary of results

Results from this study have demonstrated the IHSBS (solar-PV — 11 kW<sub>p</sub>; battery storage — 9 kWh and DG — 11 kW) as the best performing system (against the impact metrics of sustainability, affordability and reliability) in meeting the load demand of commercial centres in Nigeria. This evidences the viability of implementing an environmentally focused hybrid renewable energy system in bridging the electrification gap in access-deficient regions. This brings to the fore, the role of social action/responsibility in driving environmentally cleaner power system solutions. This is of particular importance as economic cost savings are still considered priority when implementing power system solutions.

The IHSBS was the optimum power system solution i.e. the lowest cost power system under priority level 1. It was more economically viable than 67% of power system solutions under priority level 2. The IHSBS had a comparative advantage of 81% and 12% in cost savings over the RES and GS respectively, for their operational lifetime (20 years). The system recorded a 65% reduction in yearly GHG (CO<sub>2</sub> tonnes/yr.) emissions over the GS. When compared to its closest competitor — the IHSS (solar-PV — 27 kW<sub>p</sub> and DG — 11 kW), the IHSBS was 6% costlier than the IHSS over their operational lifetime (20 years) but recorded a 33% reduction in yearly GHG emissions over same. It also had a better system's operations efficiency over the IHSS (closely matched supply–demand ratio). The IHSBS had a load factor (LF) of 90%, 24% more than the IHSS with a LF of 66%.

Introducing a carbon tax of \$25 per tonne of CO<sub>2</sub> emitted (Luckow et al., 2015) and unifying the metrics of affordability and sustainability, the IHSBS was still 4% costlier than the IHSS for their operational lifetime. These results evidence that carbon taxation (based on the current pricing structure) is not an effectual policy in mitigating the impact of climate change on our environment. Results infer that lifetime cost implications are sensitive to an increase in the percentage share of RE contribution (particularly the ESS capacity) in the hybrid mix. The increase in RE contribution also significantly reduces the yearly GHG (CO<sub>2</sub> tonnes/yr.) emissions by reducing the operating intensity of the GS. This also establishes the link between lifetime cost implications and a reduction in yearly GHG emissions.



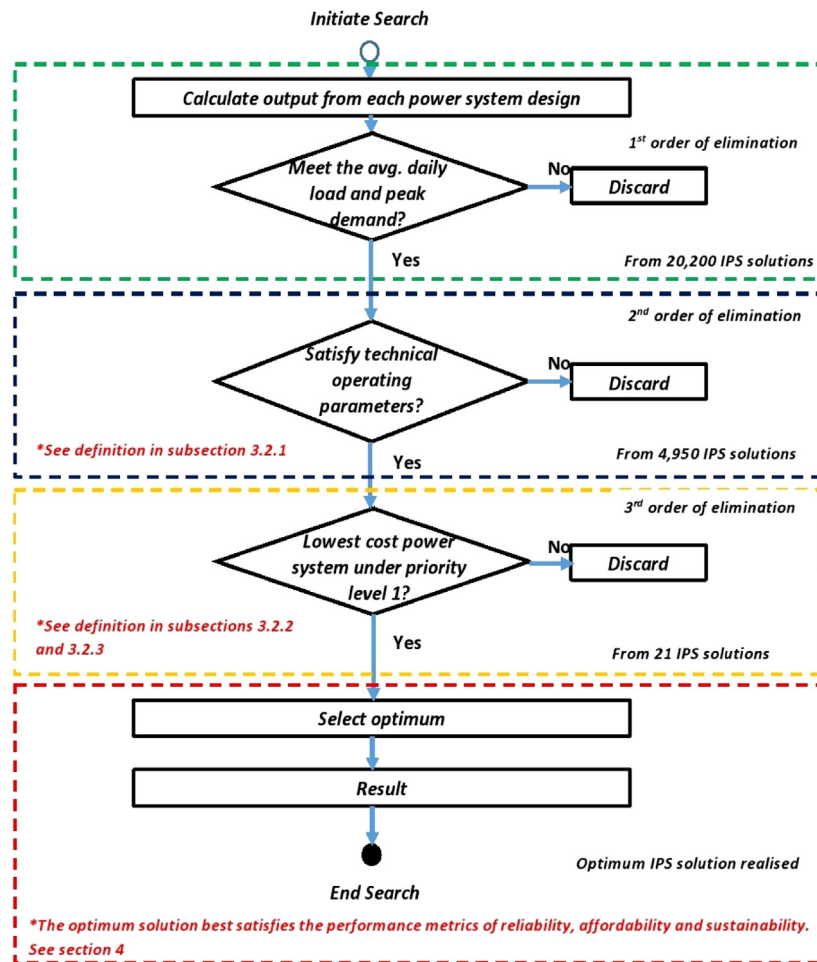


Fig. 2. Flowchart of the systematic search implementation on IPS solutions.

Table 1

The 4950 theoretical IPS solutions categorised by their lifetime cost implications (\$/20 years) and yearly GHG emissions (CO<sub>2</sub> tonnes/yr).

	Emissions - CO2 (tonnes/yr)																																
	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15 to 1	0
> 850k																								39	52	51	60	47	44	54	10		3
800-849k																								18	24	22	30	22	24	28	6		5
750-799k																								18	23	23	29	23	24	29	6		6
700-749k																								18	22	24	28	24	23	29	6		6
650-699k																								17	23	24	28	24	21	30	6		4
600-649k																								16	24	23	30	23	24	29	6		
550-599k																								18	24	22	30	22	24	27	5		
500-549k																								18	23	23	29	23	24	29	6		
450-499k																								18	22	24	28	23	21	30	6		
400-449k																								17	23	24	28	24	23	30	6		
350-399k																								16	24	22	30	22	24	28	6		
300-349k												18	37	46	40	36	30	24	18	12	6	1		18	24	22	30	22	24	28	6		
250-299k												26	52	77	77	78	78	78	77	77	79	52	25	18	22	23	28	24	23	29	6		
200-249k												26	52	77	77	78	78	78	77	77	78	52	27	18	22	24	28	24	23	30	6		
150-199k	2	2	2	2	2	2	3	2	2	2	2	2	6	15	22	28	34	41	48	56	60	46	18	4	8	8	14	12	14	20	3		
100-149k												2	3	2	2																		
< 100k																																	
Total IPS	2	2	2	2	2	2	3	2	2	2	2	75	149	217	216	220	220	221	220	222	223	151	70	271	360	359	450	359	360	450	90	0	24
Legend:		GS	RES	IHSS	IHSBS																												

The findings of this study consolidates the viability of strategically electrifying commercial centres through hybrid photovoltaic-centric power systems (HPVPSs). Fig. 3 illustrates the benefits of a HPVPS option amidst grid unreliability and implementing IFFS alternatives. The illustration highlights the current system of grid power supply complemented with the sub-optimal operation of IFFS. It also elicits the unviability of IFFS in sole operation due

to cost implications and adverse environmental impact. Finally, the ideal power system configuration for the energy consumer is presented as the optimised operation of a PV system and IFFS in a hybrid system. This solution would offer the consumer lifetime benefits of reliability, affordability, sustainability and power system autonomy.

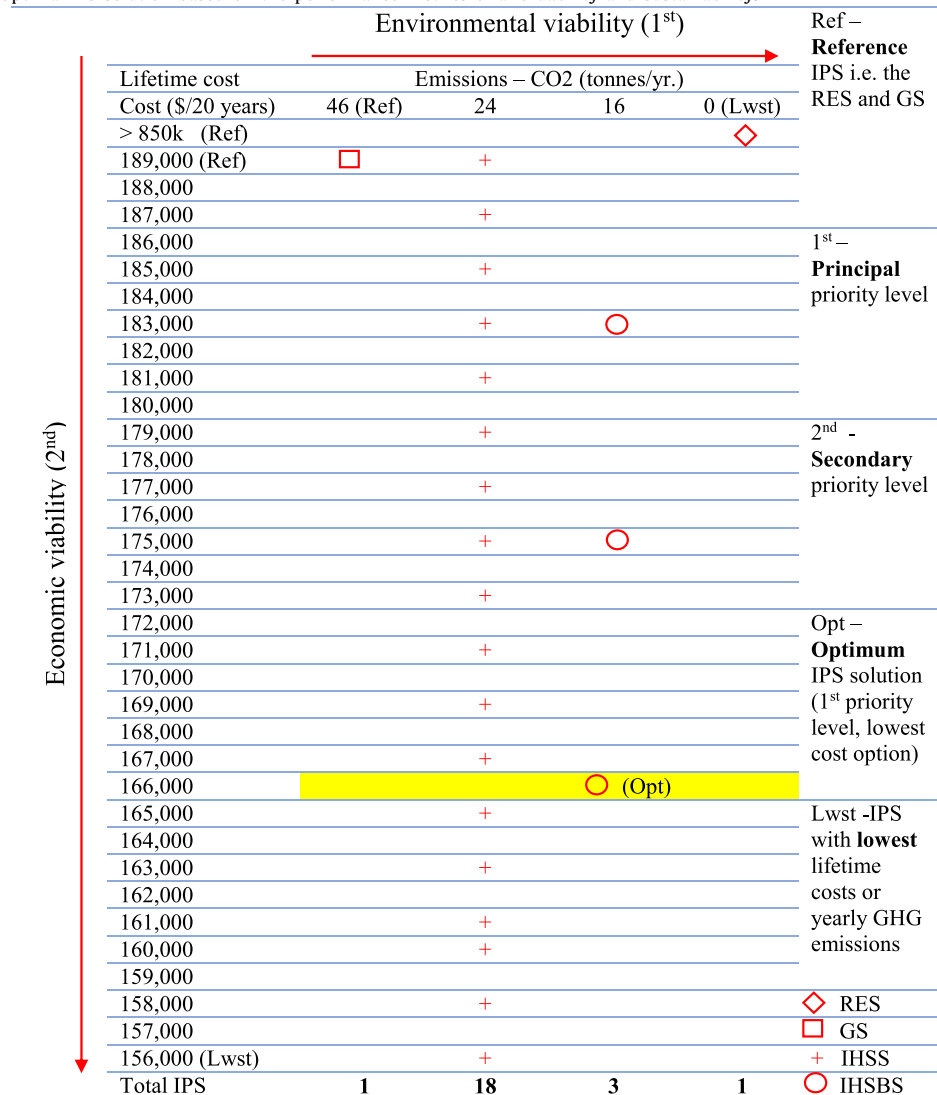
**Table 2**

A breakdown of the Practical IPS solutions and reference systems' capacities against their technical compositions, environmental and economic implications.

Power system	Capacity			Implication	
	Solar-PV (kW <sub>p</sub> )	Battery (kWh)	Diesel Generator (kW)	(Environmental CO <sub>2</sub> tonnes/year)	Economic (\$/20 years)
RES100	100	82	–	0	867,000
GS15.5	–	–	15.5	46	189,000
IHSS44	44	–	11	24	189,000
IHSS43	43	–	11	24	187,000
IHSS42	42	–	11	24	185,000
IHSBS13	13	9	11	16	183,000
IHSS41	41	–	11	24	183,000
IHSS40	40	–	11	24	181,000
IHSS39	39	–	11	24	179,000
IHSS38	38	–	11	24	177,000
IHSS37	37	–	11	24	175,000
IHSBS12	12	9	11	16	175,000
IHSS36	36	–	11	24	173,000
IHSS35	35	–	11	24	171,000
IHSS34	34	–	11	24	169,000
IHSS33	33	–	11	24	167,000
IHSBS11	11	9	11	16	166,000
IHSS32	32	–	11	24	165,000
IHSS31	31	–	11	24	163,000
IHSS30	30	–	11	24	161,000
IHSS29	29	–	11	24	160,000
IHSS28	28	–	11	24	158,000
IHSS27	27	–	11	24	156,000

**Table 3**

Optimal IPS solution based on the performance metrics of affordability and sustainability.



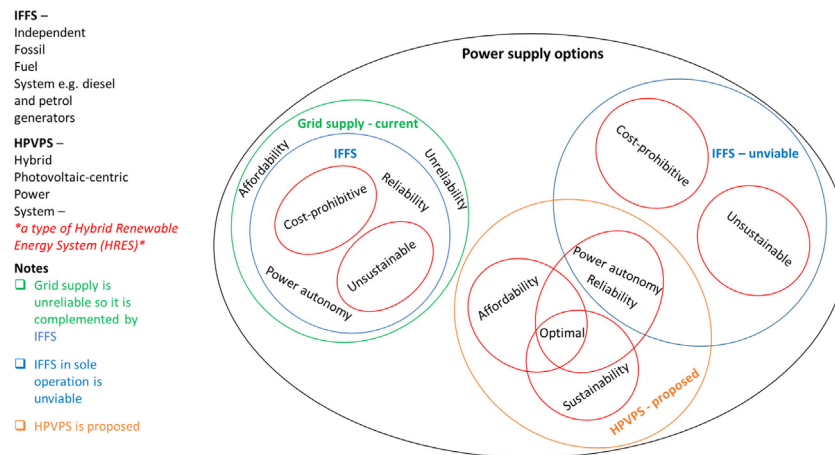


Fig. 3. Euler diagram highlighting the benefits of a hybrid photovoltaic-centric power system (HPVPS) option.

## 5. Discussion

The IHSBS was 4% costlier than the IHSS over their lifetimes (when the metrics of affordability and sustainability were unified). However, the 33% reduction in yearly GHG emissions of the former power system solution over the latter, favours the implementation of the IHSBS for commercial centres in Nigeria. The IHSBS (90% LF) was also a better self-consuming system than the IHSS (66% LF). This is as a result of the integration of an ESS in the IHSBS. The exclusion of an ESS from the IHSS meant that the system generated excess energy, 24% more than the IHSBS. This translated to wasted energy, owing to the underdevelopment of a transactive electricity market (TEM) in Nigeria. As such, the IHSBS was a better performing system in matching daily energy production with the commercial centre's energy demand.

The results from this study have shown the superior performance of PV-Battery-Diesel hybrid power systems over IFSSs against the impact metrics of affordability and sustainability. It also shows the added benefits of reliability and power supply autonomy for these hybrid power systems over conventional power grid systems (Arowolo et al., 2019; Peffley and Pearce, 2020). The optimal system in this study, the IHSBS, better sized the capacity of its ESS (reduced capacity size by 3 kWh) and DG (reduced capacity size by 4.5 kW) components in comparison to the "IHSBS 2" in Olówósejé et al. (2020)'s study. Furthermore, the system had a lifetime cost reduction of 30% over same. Highlighting findings in the literature on how optimising the ESS component of the power system solution, based on capacity sizing and operation strategies, could realise environmentally cleaner IPS with economic viability. Overall, these results support efforts towards ensuring access to affordable, reliable, sustainable and modern energy for all. These results bring third generation hybrid power systems to the fore in driving sustainable electrification and creating a sustainable environment for emerging economies. An enabling environment is a requisite in fostering the proliferation of these technologies. For example, the imposition of a 10% tax duty on solar modules in Heinrich-Böll-Stiftung (2019) (an import-dependent economy) could inhibit this.

Optimising these hybrid power systems for a favourable environmental impact still realises economically viable systems. The 4% difference in costs that makes the environmentally optimised power system (IHSBS) costlier than the economically optimised system (IHSS) over their lifetime is considered insignificant. This is especially so, as some of these systems lose substantial sums when they are deployed sub-optimally in operation. The 4% added cost is also considered an investment (environmental responsibility) in supporting the global drive on deeply decarbonising the

environment. As some technologies (carbon capture, storage and sequestration) may still take years to upscale in the fight against climate change, highlighting the importance of social responsibilities i.e. relatively higher power systems development costs (with increased environmental and social benefits) could offer long-term economic gains and be pivotal in realising environmental targets and meeting nationally determined contributions (NDC). This would be considered as such until energy and particularly climate policies (such as carbon taxation) are designed to adequately tackle the possible long-term economic implications of implementing non-environmentally focused HRESs.

Therefore, the conscious decision to implement environmentally clean HRESs lies with the power project owners/developers. In emerging economies, individuals/sectors implementing energy autonomous solutions have a role to play in being environmentally responsible.

## 6. Conclusions

This study has validated the performance of scalable hybrid PV-centric power systems over IFSS solutions for the C&I sectors. The results found distributed sustainable energy solutions offered the same benefits of power autonomy and reliability as IFSSs but with the added benefits of affordability and sustainability. The IHSBS was the optimum power system solution when assessed against the three impact metrics (affordability, reliability and sustainability). The IHSBS was also the better self-consuming system with a 90% LF compared to the IHSS with a 66% LF. The implementation of power system solutions with significant consideration for environmentally clean solutions could boil down to environmental responsibility borne by the project developer. Social action could yet be an area of consideration in combatting climate change whilst technology is emerging. These technologies could take years to upscale to a significant level of impact in the battle against climate change.

The results were able to demonstrate that a more impactful approach towards realising holistic power system solutions for emerging economies was in evaluating the equal importance of socio-environmental factors with economic factors. Creating an enabling environment (through policies and regulations i.e. the development of TEM) that facilitates the proliferation of third generation hybrid power systems (with increased RE penetration) in emerging economies presents a viable approach in mitigating the impact of climate change on our environment. These could be more effective than carbon taxation (based on the current pricing structure) and outright bans on IFSS in access-deficient regions.

Findings from this study established a relationship between lifetime cost implications and the percentage share of RE contribution in HPVPSs. It further elicited the relationship between lifetime cost implications and yearly GHG emissions reduction. A limitation of this study was the fact that a sensitivity analysis was not carried out to explore these findings in detail. Further research on our part, will focus on the shift from third generation hybrid power systems to fourth generation hybrid power systems that eliminate diesel generators using electric vehicles (EVs) for enhanced energy storage.

### CRedit authorship contribution statement

**Samuel Olówósejé:** Conceptualisation, Writing - original draft, Technical analysis. **Paul Leahy:** Review, Editing, Supervision, Direction. **Alan P. Morrison:** Review, Editing, Supervision, Direction.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.jegy.2021.03.039>.

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