

Techno-Economic Optimization of Clean Energy Hybrid Systems in the Context of Assorted Battery Storage Technologies

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Abstract

This paper presents a techno-economic analysis of hybrid energy systems based on different battery energy storage technologies (BESS) of lithium-ion battery (LIB), Nickel metal-hydride (NiMH), Nickel-cadmium (Ni-Cd) and Lead Acid Battery (LAB). Three different hybrid power system configurations of solar photovoltaic (PV) and battery (PV/BESS), wind turbine (WT) integrated with battery (WT/BESS) and PV/WT/BESS were studied. The techno-economic optimizations were performed based on applying modern intelligent computational techniques of Flower Pollination Algorithm (FPA) and Particle Swarm Optimization (PSO). Simulations conducted for the hybrid systems show that the most cost-effective energy system configuration has a Cost of Energy (COE) of 0.125 \$/kWh, Net Present Cost (NPC) of \$76,402.00 and Deficit Power Supply Probability (DPSP) of 0.012 as obtained by the FPA optimization technique in the PV/WT/BESS. Besides, it was also found that among the four battery technologies selected for this study, LIB exhibited the best techno-economic benefits regarding the number of batteries required, COE and the NPC of a small-scale hybrid power system for the case study location. The viability and application prospects of other selected BESS have also been established in the framework based on the results obtained.

Keywords: Battery Storage Systems; Cost of Energy; Net Present Cost; Optimization Algorithms; Renewable Energy; Electricity.

Introduction

The electricity demand has continued to increase with the growth in the socioeconomic revolution. The quest for sustainable development has increased the demand for clean and sustainable energy across the world. Electrical energy from Renewable Energy (RE) is fast becoming the overriding form of energy among others (Qian et al., 2017). The demand for electrical energy is subject to continuous changes in line with the techno-economic development of different geographical locations around the world. The present situation of the global energy supply is such that about 80% of energy is supplied through the combustion of fossil fuels (Abdin & Mérida, 2019). The incremental annual global demand for electricity has been estimated to be about 2.3% (Abdin & Mérida, 2019; Ramesh & Saini, 2020). The challenge of increasing demand for electricity and the anticipated

environmental pollution coupled with their consequential adversities has forced actions on the exploitation of RE (Yousri et al., 2019). The unpredictability of renewable energy sources (RES) due to the stochastic variation in weather conditions has hampered the complete reliance on the technologies for power generation. The situation is worse when using a single source of RE compared to the integration of two or more RE technologies. The randomization effect of weather on the output power stability, reliability, and security can be compensated through the use of energy storage systems (ESS) such as batteries (Ramesh & Saini, 2020). Implementation of small-scale RE through the application of solar PV and wind turbine (WT) can be integrated with batteries to provide a stable power supply to residential or commercial buildings. A hybrid electricity supply scheme of integrated RE generators with ESS has created opportunities for the deferral of grid power extension. Extension of large electric power grid to rural communities is usually not an economically viable option for rural electrification (Mohammed et al., 2017). Therefore, this study dwells on the investigation of the techno-economic feasibility of clean and renewable energy systems based on different battery storage technologies.

Objectives of the Study

This study focuses on the following objectives:

- optimal sizing of small-scale hybrid integrated RE systems based on different BESS technologies for rural power generation.
- techno-economic assessment of three different hybrid configurations for the determination of the most cost-effective optimal power system.
- optimization through multi-objective intelligent computational algorithms of Flower Pollination Algorithms (FPA) and Particle Swarm Optimization (PSO).

Problem Statement

The application of Battery Energy Storage System (BESS) in RE particularly for small-scale rural electrification has taken a conspicuous lead in the deployment of sustainable energy across the world. The foremost constraint in the deployment of RE is the stochastic variation of weather conditions. The quest for reasonable economic development requires that energy is made available whenever it is needed. In the absence of ESS, the output power produced by the generators in RE systems cannot be predicted or controlled. This presents the fact that ESS such as BESS is classically needed to support the installation of weather-dependent RE systems such as solar PV and WT generators in small-scale electricity and the storage system must be carefully selected. BESS are mostly selected based on their core technical characteristics and potential advantages.

Limitation of the Study

Conventionally, a power system can be deployed through the techniques of on-grid or off-grid connections to supply electricity to the targeted consumers. On-grid power systems

are tie or connected to the national electric power networks especially for large scale power supply. Contrarily, an off-grid power system can be described as a standalone power system supplying independent electricity to a household or small rural community. Therefore, the limitation of this study is that it takes into consideration an off-grid energy system providing electricity to isolated rural community located away from the national electric power supply infrastructure.

Literature Review

In recent times, many literature studies have dealt with the challenges of sizing hybrid energy systems with integrated BESS. An assessment of independent grid-connected photovoltaic PV/wind/biogas with integrated battery hybrid power systems in northern Nigeria was conducted (Jumare et al., 2020). The results obtained showed a substantial decrease in the NPC and COE with a reduction in component sizing of the proposed system. A study on off-grid hybrid energy systems for the electrification of rural healthcare facilities in Nigeria was performed through a comparative study and sensitivity analysis (Oladigbolu et al., 2021). In addition to the reduction of the NPC and COE, the outcome also revealed a substantial annual reduction in carbon dioxide emission of 1304 kg/year. Optimal sizing and techno-economic analysis of an off-grid hybrid energy system for rural electrification were developed for a rural community in Bangladesh (Islam et al., 2022). The study demonstrated the effectiveness of the suggested optimization method from the outcomes of the two approaches compared. The optimization of a PV/Wind/Battery/Diesel hybrid system for electrification of a rural community was carried out by Baseer et al. (2019). The proposed system was analyzed based on BESS for the satisfaction of electrical load demand and carbon dioxide emissions reduction with no evidence of sensitivity analysis.

A hybrid power configuration comprising fuel cell/wind/solar PV/battery for power generation in an off-grid mode was presented for a small household (Babatunde et al., 2022). It was established that the best approach to dealing with the optimal sizing of a small-scale hybrid RE is by considering multiple metrics of economic, technical and environmental issues. Based on the sustainability principle, the analyses of different hybrid energy systems were carried out comparatively between single and multiple hybrid energy systems with BESS optimization criteria (Babatunde et al., 2022). The simulations performed with HOMER are in eight different feasible configurations showing different techno-economic performances. The outcome of the study is expected to help energy stakeholders within the targeted university community to make informed decisions in planning for off-grid electrification of energy facilities in tertiary institution campuses. In addition, the case study of a rural community in India was presented through a Firefly algorithm optimization for the sizing of a hybrid energy system based on solar PV, wind turbine and battery storage for electrification of far-flung communities at the lowest achievable cost (Sanajaoba, 2019). In the studies presented so far, BESS is utilized as the

main ESS but the economics of the diversity of different battery storage technologies needs to be investigated.

Utilization of BESS in RE depends more on the appropriate sizing of the battery concerning their different performance indicators. In some cases, the combination of financial constraints and technical issues can be used for the determination of the size of integrated BESS in hybrid systems. Whichever indicator is to be used, optimization is completely necessary to minimize the investment and operating costs of the energy system. In the context of reliability, optimal sizing of ESS can be performed by the minimization of costs of investment in the operations of hybrid power systems (Bahramirad et al., 2012). In the operation of Microgrids (MGs), the system can be operated either in a standalone or grid-connected mode as shown in Figure 1. Sizing of BESS is usually achieved concurrently with the design and sizing of the energy production generators. This is necessary from the overall techno-economic point of view of a small-scale hybrid energy system. Subsequently, a fair trade-off between the optimal sizing of BESS and the energy-generating system components was investigated in the context of their techno-economic sustainability in this study.

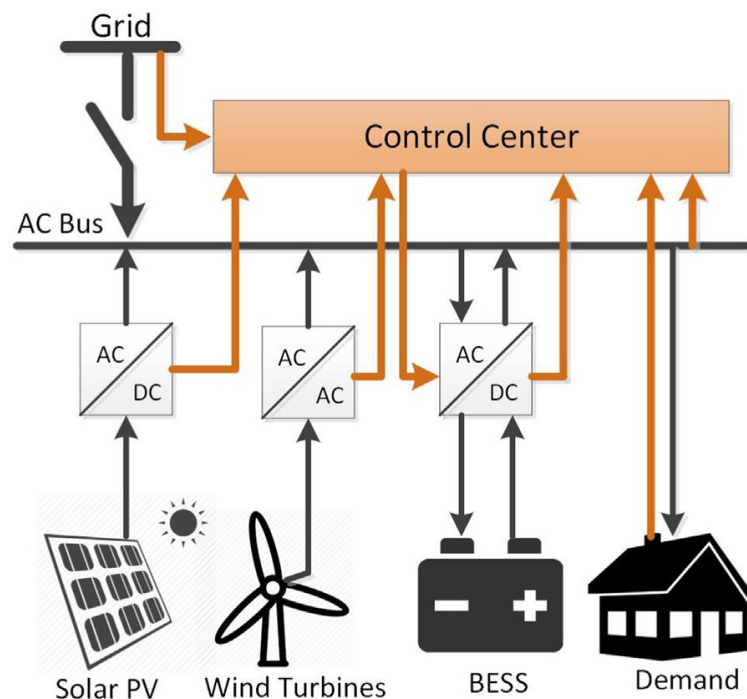


Figure 1: The structure of a microgrid in both island and grid-connected operations (Yang et al., 2018)

Methodology

Load Specifications of the Study Site and System Configurations

A case location of a remote community of Ogume in Nasarawa State, Nigeria was selected for this study. A total of 52 households are situated in the community which is presently

isolated from the national electric power supply grid. The profile of the electric power demand of the locality is presented in Figure 2. Being a typical rural community in a developing country, the basic demand for electricity is for domestic lighting, processing of agricultural produce for domestic consumption, pumping of water and operation of domestic electrical appliances. The proposed hybrid integrated configuration of the power system components is shown in Figure 3.

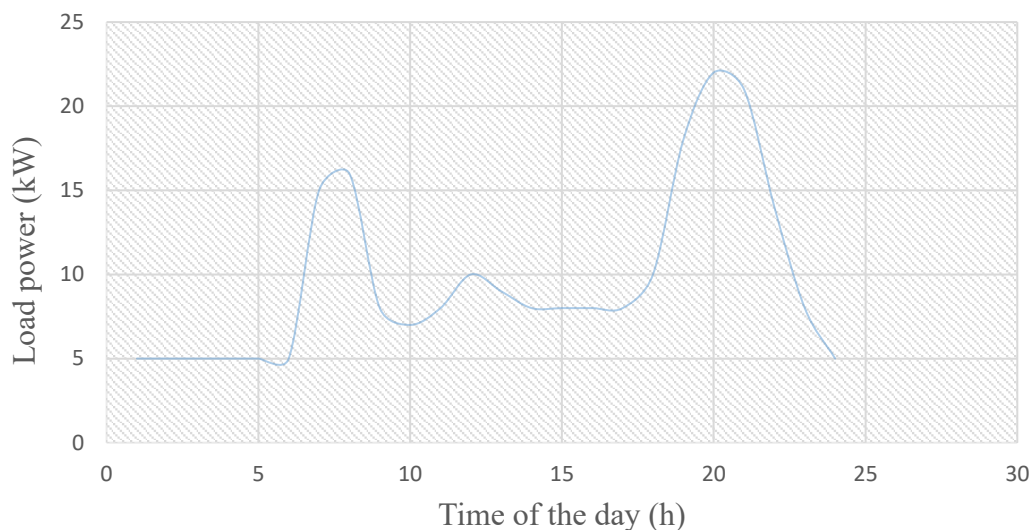


Figure 2: Daily load profile of the study area

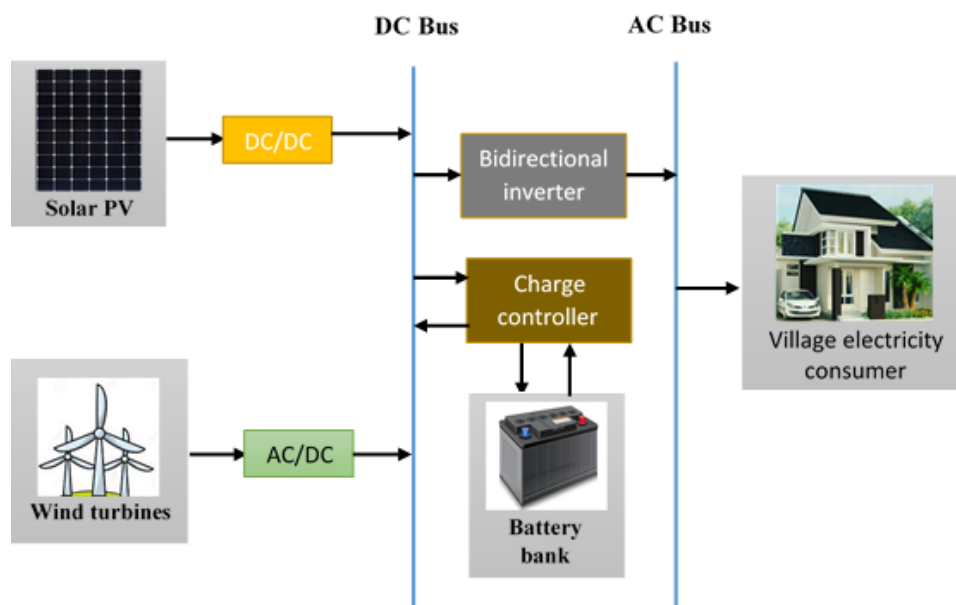


Figure 3: Configuration of hybrid energy components for PV/WT/BESS

Optimization Algorithms: Currently, there are various optimization algorithms for solving a variety of engineering problems. In an attempt to find solutions to optimization problems, a careful selection approach must be embraced for the adoption of the most suitable optimization algorithm. Therefore, this study adopted a Flower Pollination Algorithm (FPA) and Particle Swarm Optimization (PSO) for their ability to escape the local minima and perform global optimization in the optimal sizing solution spaces.

Flower Pollination Algorithm (FPA): The FPA optimization technique is derived from the computational intelligent behaviors of pollinator activities on flowering plants. The algorithm has dual optimization capability of local and global searching mechanisms in a solution space. Yang et al. (2013) discovered the optimization capability of FPA and it was subsequently utilized for solving numerous optimization problems. The procedural flowchart of the FPA optimization algorithm adopted in this study is presented in Figure 4. The algorithm was considered suitable for the set of optimization problems defined in this paper based on its capability for efficient computational time and ability to handle large input data. With the application of the pollination characteristics of flowering plants, FPA can execute cross-pollination via the principle of levy flight to achieve effective optimization solutions.

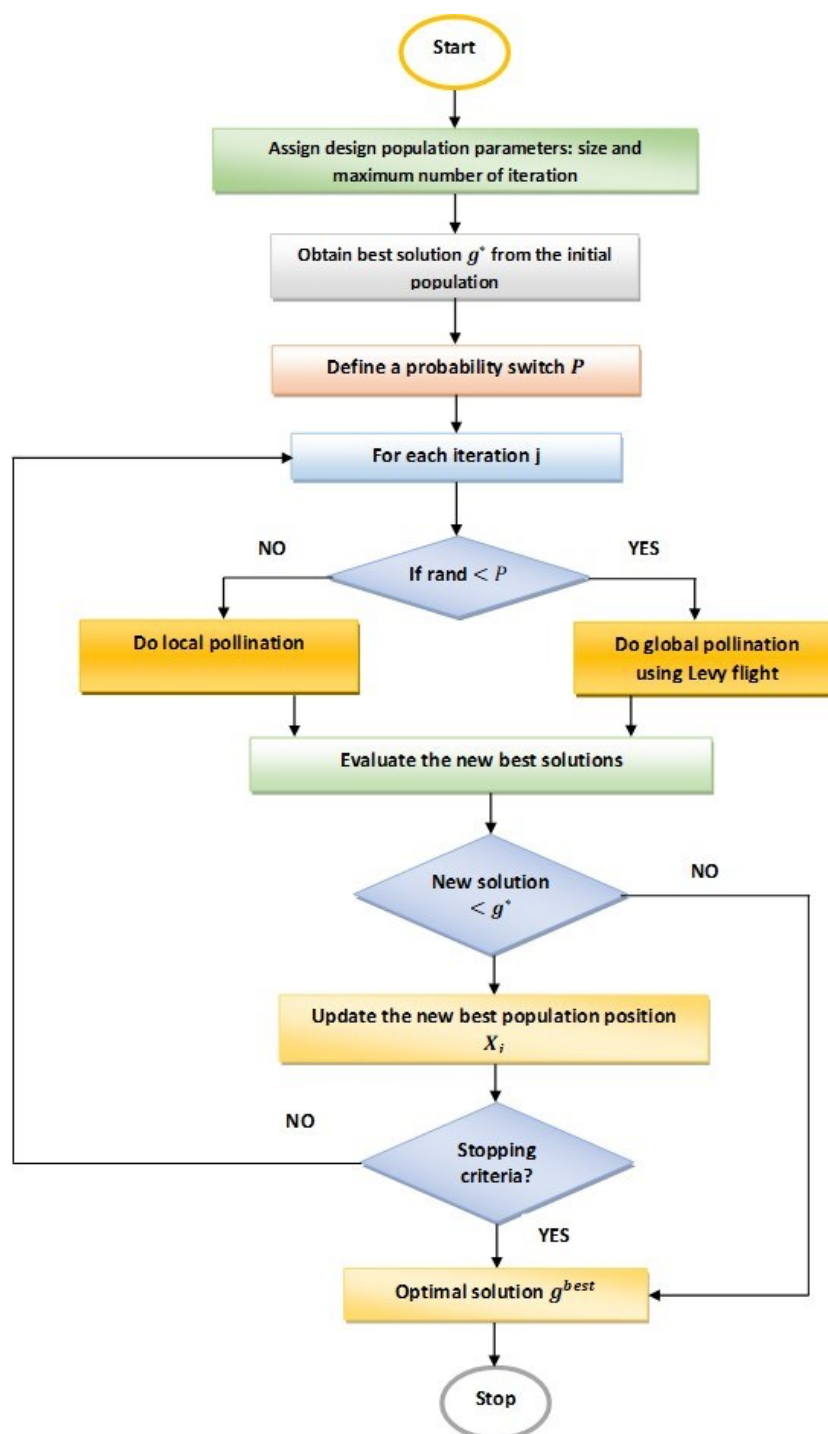


Figure 4: Flowchart of the FPA optimization

Particle Swarm Optimization (PSO): The PSO technique is a biologically inspired random search algorithm for solving different kinds of optimization problems (Wang et al., 2018; Muhammad et al., 2022). Characteristically, the PSO algorithm is based on the swarm intelligent behaviors of some animals such as birds and fish. The main advantage of this algorithm is the ease of its implementation by the strategic movement of animals with

swarming behaviors. The computational intelligent capabilities of PSO have been applied in many fields to provide solutions to problems based on iterative changing of velocity and position equations. The steps of the optimal techno-economic model potential of the PSO algorithm used in this study are presented in Figure 5.

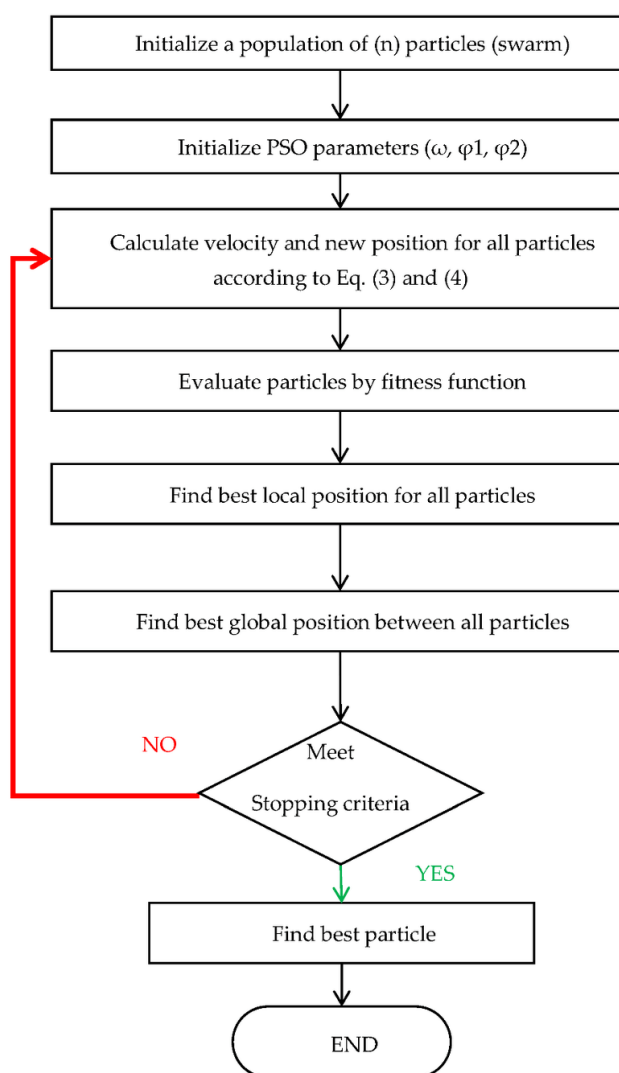


Figure 5: Flowchart of the PSO algorithm (Salman et al., 2018)

Modeling of the Hardware Energy Components

Solar Photovoltaic (PV) System Modeling: There are varieties of mathematical modeling for solar PV systems based on the existence of the associated input parameters. However, the model adopted in this study is presented by the National Renewable Energy Laboratory (Elhadidy, 2002) and given as follows:

$$P_{PV} = \frac{G_r}{G_R} P_M [1 + \tau(T_c - T_o)] \quad (1)$$

For small-scale rural electrification project, there is usually a need for several number (N_{PV}) of solar PV panels to be connected in series or parallel configurations. The average monthly solar radiations and the clearness index of the case study area is presented in Figure 6. A PV system with rated power capacity of 0.5 kW is used in this study. The expression for the total amount of power generated from the cascaded number of solar PV can be expressed as:

$$\begin{aligned} P_{PV}^T \\ = P_{PV} \times N_{PV} \end{aligned} \quad (2)$$

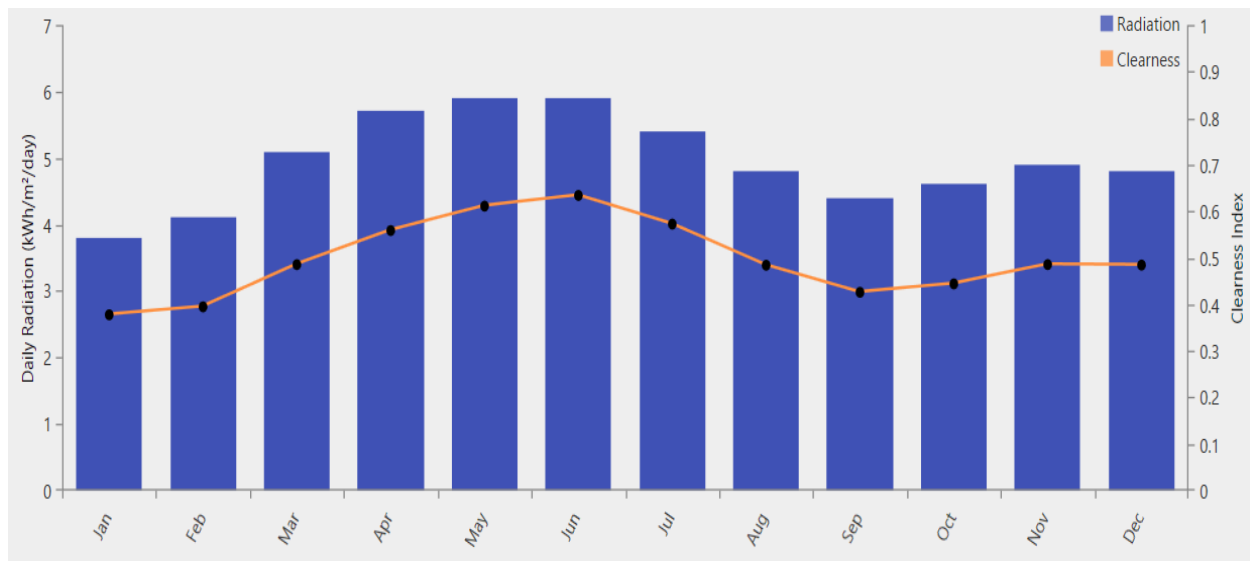


Figure 6: Average monthly solar radiation (Hussaini & Matazu, 2023)

Wind Turbine (WT) Energy System Modelling: A wind turbine system is a mechanically rotating device position at a height above the ground level to capture and convert wind energy into electrical energy. An effective wind turbine modeling is required in the optimization of wind power generation due to the distinctive fluctuating nature of wind speed. Figure 7 shows the average monthly wind speed of the study area. The expected electrical power from a wind turbine system (P_{WT}) can be calculated based on the rated power $P_{WT(rated)}$ as follows (Kaabeche & Ibtouen, 2014; Ramli et al., 2018):

$$\begin{aligned} P_{WT} \\ = \begin{cases} 0 & \text{if } v \leq v_{in} \text{ or } v \geq v_{co} \\ P_{WT(rated)} \times \left(\frac{v - v_{in}}{v_r - v_{in}} \right)^3 & \text{if } v_{in} \leq v(t) < v_r \\ P_{WT(rated)} & \text{if } v_r \leq v \leq v_{co} \end{cases} \end{aligned} \quad (3)$$

The value of v can be found by using the Eq. (4) (Al-Ghussain et al., 2021) and λ = coefficient of friction of the landscape is usually in the range of 0.1 and 0.25 (Mohseni & Brent, 2020):

$$v = v_{ref} \times \left(\frac{h_{hub}}{h_{ref}} \right)^\lambda \quad (4)$$

For a given number of wind turbines, N_{WT} , the total electric power P_{WT}^T that can be generated by the wind turbine is given by the equation (5):

$$P_{WT}^T = P_{WT} \times N_{WT} \quad (5)$$

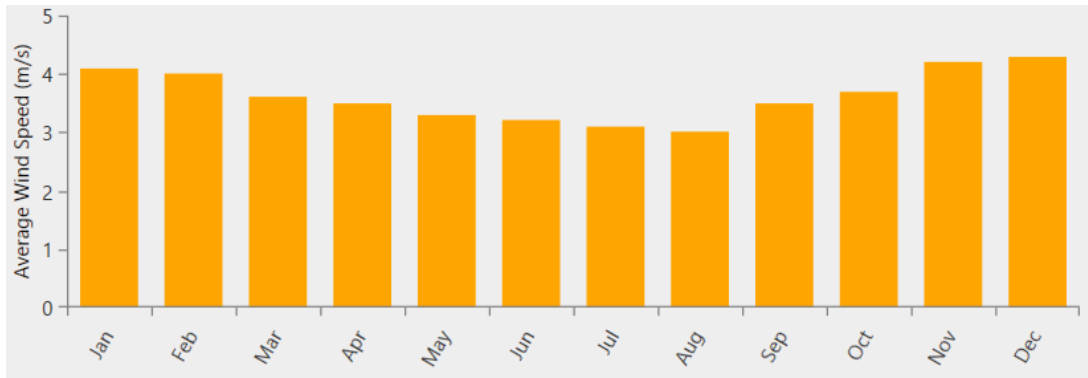


Figure 7: Average monthly wind speed of the study area (Hussaini & Matazu, 2023)

Modelling of the Battery Storage System: To deal effectively with the challenge of fluctuating weather variability affecting the output power from renewable energy, BESS with fast response times (milliseconds) are used for real-time energy compensation (Saez-de-Ibarra et al., 2016). Application of BESS in RE gives controllable and predictable support with less intermittent constriction (Rasmussen, 2011), increase flexibility and penetration level (Zantye et al., 2022). The operation of BESS integrated in a hybrid energy system involves some dynamic conditions concerning time. Modeling of BESS occurs in two different folds of charging and discharging conditions with respect to present time (t) and the previous time ($t - 1$). The equations for the mathematical modeling of the two possible dynamic scenarios with respect to load demand situations are presented in Eq. (6) and (7) (Maleki & Pourfayaz, 2015). When the energy produced by the hybrid system is greater than load demand, the available battery capacity can be presented as shown in Eq. (6). In Eq. (7), the mathematical representation gives the scenario where the load demand is less than the energy generated by the hybrid system.

$$E_{BESS}(t) = E_{BESS}(t - 1) * (\sigma - 1) + \left[P_{PV}^T(t) + P_{WT}^T(t) - \frac{P_L(t)}{\eta_{INV}} \right] * \eta_{BESS} \quad (6)$$

$$E_{BESS}(t) = E_{BESS}(t - 1) * (\sigma - 1) + \left[\frac{P_L(t)}{\eta_{INV}} - (P_{PV}^T(t) + P_{WT}^T(t)) \right] \quad (7)$$

Modelling of the Converter: Conventionally, the reality of combined solar PV energy system and wind turbine generator in a hybrid system require the use of power inverters.

Inverters are efficient power electronic interfacing devices for the conversion of DC voltage to AC voltage. Most household electrical appliances use AC voltage and it is thus required that where DC power is generated especially from the solar PV, inverters are required to conversion to AC power. While selecting an inverter for use in RE, the rating can be determined based on the peak load demand (P_L) and efficiency η_{INV} . Hence, the expression for inverter power is given in Eq. (8) (Hemeida et al., 2020):

$$P_{INV} = P_L * 1/\eta_{INV} \quad (8)$$

The required number of inverters can be determined by the Eq. (9):

$$N_{INV} = \frac{P_L}{P_{INV}} \quad (9)$$

Economic Cost Modelling: The main objective function in this study is the minimization of the NPC, COE and DPSP of the proposed hybrid energy system based different BESS technologies.

Net Present Cost: The objective cost function of the NPC can be expressed by Eq. (10).

$$\text{Min NPC} = [C_{IP} + C_{OMC} + C_{RC}] \quad (10)$$

The NPC of the proposed energy system has three cost components of Initial Project Cost (C_{IP}), Operation and Maintenance Cost (C_{OMC}) and Component Replacement Cost (C_{RC}). The mathematical expression for the C_{IP} is given in Eq. (11) based on reformulation for inclusive installation cost.

$$C_{IP} = 1.3C_{PV}N_{PV} + 1.25C_{WT}N_{WT} + 1.05C_{BESS}N_{BESS} + 1.025C_{INV}N_{INV} \quad (11)$$

Moretti et al. (2019) and Barakat et al. (2020) presented C_{OMC} using Eqs. (12).

$$C_{OMC} = (C_{PV/OM}N_{PV} + C_{WT/OM}N_{WT} + C_{BESS/OM}N_{BESS} + C_{INV/OM}N_{INV}) \quad (12)$$

For the replacement cost, the PV and WT are expected to last for the entire life span of the hybrid power system which is for $n = 20$ years. They are accordingly expected not to be replaced. The replacement cost of the BESS after a period of five years and inverter after ten years can be calculated based on Eqs. (13) and (14) (Maleki et al., 2020) correspondingly.

$$C_{RC/BESS} = P_{BESS} * \left[1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}} \right] \quad (13)$$

$$C_{RC/INV} = P_{INV} * \left[1 + \frac{1}{(1+i)^{10}} \right] \quad (14)$$

Cost of Energy

In a MG, minimization of the economic cost is a fundamental challenge which must be resolved. Therefore, the minimization of the COE which is the cost at which the energy produced is sold to break even the operational life time of the energy system in \$/kWh. The expression for the minimization of the objective function based on the COE is given by the expression in Eq. (15):

$$\begin{aligned} \text{Min} & \text{COE} \\ [N_{PV}, N_{WT}, N_{BESS}, N_{inv}] & \end{aligned} \quad (15)$$

Subject to the following constraints:

$$\begin{aligned} N_{PV}^{Min} & \leq N_{PV} \\ & \leq N_{PV}^{Max} \end{aligned} \quad (16)$$

$$\begin{aligned} N_{WT}^{Min} & \leq N_{WT} \\ & \leq N_{WT}^{Max} \end{aligned} \quad (17)$$

$$\begin{aligned} N_{Inv}^{Min} & \leq N_{Inv} \\ & \leq N_{Inv}^{Max} \end{aligned} \quad (18)$$

$$\begin{aligned} N_{BESS}^{Min} & \leq N_{BESS} \\ & \leq N_{BESS}^{Max} \end{aligned} \quad (19)$$

However, the mathematical expression for COE is given as shown in Eq. (20) (Darling et al., 2011):

$$COE = \frac{NPC}{\sum_{t=1}^{8760} P_L} \times CFR \quad (20)$$

$$\begin{aligned} CFR & \\ & = \frac{i(1+i)^n}{(1+i)^n - 1} \end{aligned} \quad (21)$$

Energy System Reliability

In the design of a hybrid MG based on RE, consideration for acceptable reliability index must be taken into cognizance. Therefore, the concept of Deficient Power Supply Probability (DPSP) must be addressed. Typical values of DPSP are in the range of number between 0 and 1. A value of 0 indicates that the total energy demand is completely met without any constriction. Contrarily, a value of 1 indicates that energy demand is never supply in its wholeness. Therefore, the expression for the determination of DPSP at any given period of time (t) is given as:

$$\begin{aligned} DPSP(t) & \\ & = \sum_{t=1}^{8760} \frac{[P_L(t) - P_T]}{P_L(t)} \end{aligned} \quad (22)$$

Results and Discussions

Results Analysis: This section presents the results based on the simulations conducted on the proposed hybrid systems in terms of minimization of costs and drastic reduction in the size of the components. The optimization algorithms of FPA and PSO techniques were used to obtain the techno-economic analysis of the proposed hybrid system in different configurations of PV/BESS, WT/BESS and PV/WT/BESS. The techno-economic specifications of energy components of the hybrid system used for the simulations are shown in Table 1. The result distinction of the two different optimization algorithms used in solving the set of optimization problems defined by the objective function are presented in Table 2 - 5. The techno-economic optimization was conducted in four different scenarios through different BESS technologies.

Table 1: Energy component specifications for the hybrid systems

Component	Investment cost (\$/Unit)	Replacement cost (\$/Unit)	Maintenance and repair cost(\$/year)	Rated capacity	Efficiency (%)	Lifetime (Year)
Solar PV	1200	1100	50	1 kW	15	20
Wind turbine	1400	1400	100	1 kW	-	20
Inverter	800	800	5	5 kW	90	10
Battery						
Lead acid	250	250	5	200 Ah	85	5
Lithium-ion	380	380	5	200 Ah	95	5
Nickel cadmium	310	310	5	200 Ah	90	5
Nickel Metal Hydride	320	320	5	200 Ah	90	5

In Table 2, three different hybrid energy configurations were studied based on the techno-economic optimizations of the defined objectives. Techno-economic and weather input data were used for conducting the simulations for optimal analysis of solar PV, WT and BESS of LIB technology. The configurations are PV/BESS, WT/BESS and PV/WT/BESS through the optimal computational algorithms of FPA and PSO. From the results obtained, the most economically viable configuration presented in terms of NPC was PV/BESS showing \$70,720.52. However, the component configuration with the least COE of 0.125 \$/kWh was presented by PV/WT/BESS having the lowest DPSP of 0.012 and NPC of \$76,402.00 generated by the FPA optimization technique as shown in Table 2. In Table 3, the results of the simulation for the optimal hybrid configurations with Ni-MH BESS are shown. Similar to the configuration in Table 2, the hybrid systems have PV/BESS, WT/BESS and PV/WT/BESS but the results of COE, NPC and DPSP obtained for the techno-economic configuration are generally higher than the LIB technology. It was generally observed that

the results presented by the simulations using LIB provided the best techno-economically viable outcomes with the fewest number of BESS required for energy storage compared to Ni-MH, Ni-Cd and LAB. The elements of the techno-economic scenario provided by the Ni-MH are next to LIB in terms of the set of performance indices investigated in this study. The NPC and the COE provided by the hybrid systems in all the simulations highly depend on the number of BESS technologies used. The FPA algorithm presented better techno-economic results than the PSO in all the simulations. It was observed that in the FPA optimization algorithm for the PV/BESS hybrid configuration, Ni-MH, Ni-Cd, and LAB required 2, 4 and 6 more numbers of BESS respectively more than LIB. Similarly, for WT/BESS and PV/WT/BESS, Ni-MH, Ni-Cd, and LAB require a higher number of BESS than the LIB. The additional number of BESS required and other components are responsible for increasing the COE and NPC of the hybrid power systems using Ni-MH, Ni-Cd and LAB.

Table 2: Simulation results of the optimal hybrid configurations with LIB BESS

Hybrid component	Algorithm	N_{PV}	N_{WT}	N_{BESS}	N_{Inv} (kW)	NPC (\$)	COE (\$/kWh)	DPSP (%)
PV/BESS	FPA	28	-	20	5	70,720.52	0.132	0.031
	PSO	30	-	21	6	71,234.24	0.134	0.033
WT/BESS	FPA	-	31	27	-	73,205.10	0.129	0.030
	PSO	-	32	27	-	74,792.00	0.131	0.031
PV/WT/BESS	FPA	20	14	16	4	76,402.00	0.125	0.012
	PSO	22	14	18	4	77,687.82	0.127	0.014

Table 3: Simulation results of the optimal hybrid configurations with Ni-MH BESS

Hybrid component	Algorithm	N_{PV}	N_{WT}	N_{BESS}	N_{Inv} (kW)	NPC (\$)	COE (\$/kWh)	DPSP (%)
PV/BESS	FPA	29	-	22	5	70,100.61	0.133	0.033
	PSO	30	-	22	5	71,932.86	0.136	0.035
WT/BESS	FPA	-	31	28	-	74,105.10	0.131	0.033
	PSO	-	31	29	-	77,290.30	0.132	0.033
PV/WT/BESS	FPA	22	14	18	4	77,222.50	0.127	0.014
	PSO	22	15	19	4	78,217.32	0.129	0.016

Table 4: Simulation results of the optimal hybrid configurations with Ni-Cd BESS

Hybrid component	Algorithm	N_{PV}	N_{WT}	N_{BESS}	N_{Inv} (kW)	NPC (\$)	COE (\$/kWh)	DPSP (%)
PV/BESS	FPA	30	-	24	5	70,825.20	0.133	0.035
	PSO	31	-	24	5	72,013.48	0.135	0.036
WT/BESS	FPA	-	31	29	-	75,340.35	0.132	0.035
	PSO	-	32	30	-	76,201.90	0.132	0.036
PV/WT/BESS	FPA	23	15	19	4	77,670.61	0.128	0.015
	PSO	23	16	19	4	78,289.68	0.129	0.017

Table 5: Simulation results of the optimal hybrid configurations with LAB BESS

Hybrid component	Algorithm	N_{PV}	N_{WT}	N_{BESS}	N_{Inv} (kW)	NPC (\$)	COE (\$/kWh)	DPSP (%)
PV/BESS	FPA	34	-	26	5	71,407.41	0.136	0.037
	PSO	35	-	28	5	72,051.22	0.139	0.038
WT/BESS	FPA	-	36	29	-	75,862.23	0.134	0.037
	PSO	-	38	29	-	76,322.45	0.137	0.038
PV/WT/BESS	FPA	23	18	22	4	77,745.34	0.131	0.015
	PSO	25	18	24	4	79,442.31	0.134	0.018

Discussions of Results: The present scenario in the traditional electricity market is such that energy consumers pay their electricity bills following their consumption. In such a situation, consumers are given the liberty to control their energy consumption to minimize their expenses on electricity. This is necessary because, throughout the world, the price of energy is to some extent unpredictable due to unstable markets. The instability can be resolved through the use of BESS to help energy consumers shape the pattern of their electricity consumption. BESS gives opportunities to rural communities to utilize small-scale RE systems to generate electricity based on cost-saving mechanisms. Negative environmental impacts orchestrated from the combustion of fossil fuels in diesel generators can be minimized through the necessary integration of BESS and RE portfolio standards. The investment cost of a small-scale hybrid RE and its subsequent COE are both dependent on the cost of BESS. The technological potential capability of a BESS is an important factor in hybrid power investment based on its different characteristics. From a techno-economic perspective, different BESS technologies have been studied and the results of the simulations conducted placed LIB above other batteries. It was observed that the initial capital cost of the storage systems is a major contributory factor. The overall technical performance of LIB in terms of cycling efficiency and energy density played a significant role in the targeted cost minimization in the proposed MGs. Figure 8 shows the variation in the number of batteries with the different BESS technologies in the proposed hybrid energy systems.

Going by the evaluation of the results presented so far, it can be deduced that the utilization of BESS is an integral component of RE for power generation. The techno-economic performances shown by the different battery technologies investigated exhibited some variations. Though they are all technically feasible but economically vary with LIB showing the least COE and NPC. The variation in the number of BESS required for energy storage in the proposed hybrid systems can be attributed to the variation in their specific power and volumetric energy densities. From the viewpoint of the purchasing cost of the selected BESS, LAB has the lowest but in the overall cost estimation for the NPC and COE, the LIB, Ni-MH and Ni-Cd offer the best solutions. The performances of Ni-MH and Ni-Cd are marginally below that of LIB indicating that they can serve as close substitutes to LIB from the perception of investment cost and the cost of electricity. The performance lead shown

by the LIB and Ni-MH are based on their capability to support high power levels with low self-discharge rates.

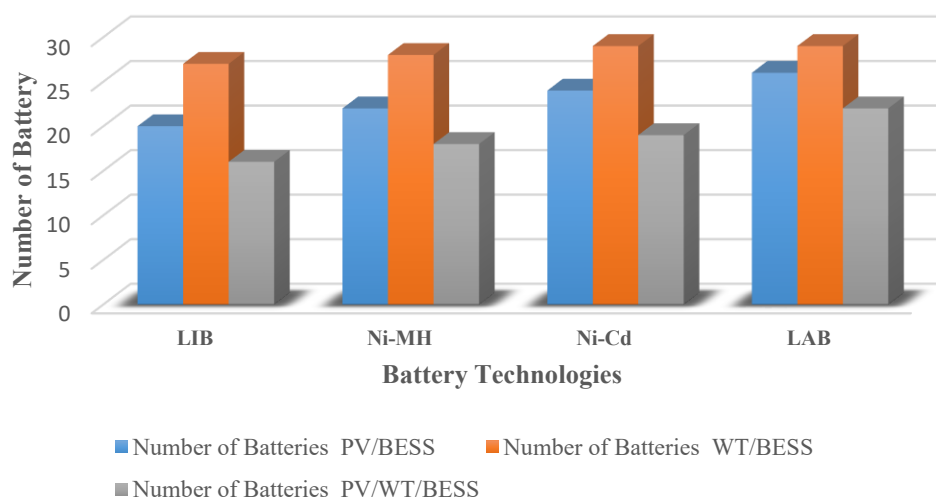


Figure 8: Variation in the number of batteries with the different BESS technologies in the proposed hybrid energy systems

Simulations based on the optimization of the objectives were conducted using FPA and PSO. The results of the power output generated on a typical day through the FPA optimization algorithm are shown in Figure 9. The smallest unit cost of electricity obtained in the three hybrid power configurations is US\$0.125/kWh was presented by PV/WT/BESS through the FPA. The overall results indicated that the selected algorithms effectively explore the techno-economic and environmental data for optimization of the COE and NPC of the proposed hybrid systems. The initial SOC of the batteries imposed on the simulations was taken as 80%. Variations in weather conditions are responsible for the power supply insufficiency thus causing the slight deviation from meeting the energy demand completely and hence the small values of DPSP recorded in all the scenarios. The two algorithms were selected based on their efficient performance in finding solutions to optimization problems in the solution-searching space (Qian et al., 2017). The comparative analysis conducted revealed the superiority of FPA over the PSO notwithstanding that they both have the potential for global searching mechanisms in optimization. The convergence performance of the algorithms is shown in Figure 10. The description is such that the FPA converges faster than the PSO in a shorter time but both algorithms are suitable for the optimization of the sizing problems. However, considering the fact that battery storage systems generally play a very significant for energy supply stability. Batteries can store energy produced during peak production times for use during times when output is low or demand is high. This is because intermittent renewable energy sources, like solar and wind, do not produce power consistently due to their dependence on weather and time of day. By

distributing the electrical supply more evenly, this improves the stability and dependability of renewable power systems. Thus, batteries utilized in RE can provide for stabilization of electricity, reliability based on frequency regulation, improved efficiency and self-reliance.

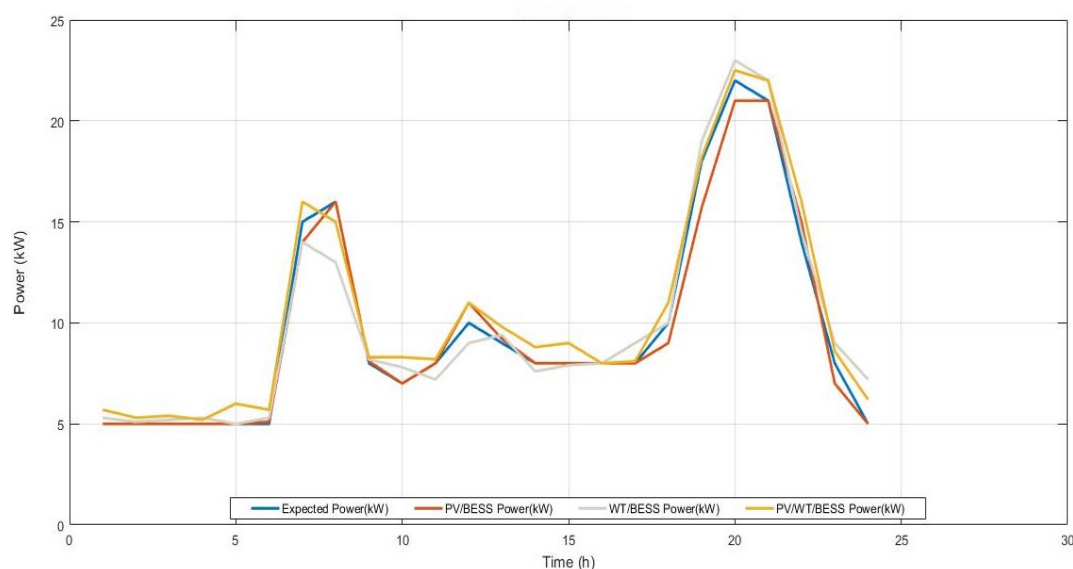


Figure 9: Power output generated on a typical day through the FPA optimization technique

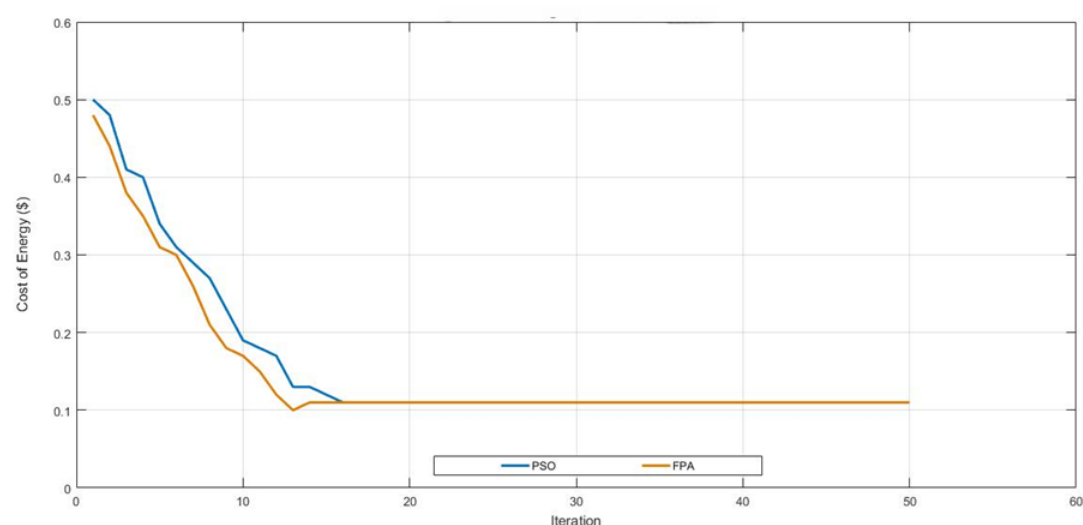


Figure 10: Convergence performance of the optimization algorithms

Concluding Remarks and Recommendations

The use of ESS for the integration of RE is classically an important endeavor in the small-scale electrification of rural communities. They are however presently not as cost-effective as expected especially in the deployment of small-scale RE. In this paper, the techno-economic optimization of some hybrid RE energy configurations based on different battery technologies was presented. The analysis of the results presented was based on the technical index of the number of optimal hybrid energy components and the ideal economic

cost consideration. The battery energy storage technologies of LIB, Ni-MH, Ni-Cd and LAB were used in the simulations performed for the techno-economic optimizations using the algorithms of FPA and PSO. Conclusively, it has been established that LIB has the best techno-economic cost with a better option for energy storage application in small-scale RE. Despite the poorest performance shown by the LAB, the maturity and affordability due to low initial cost are still responsible for the leading application of LAB in small-scale RE hybrid power systems. The following recommendations can be made about the outcomes of this study:

- there is need for increasing global economic investment and technological solutions towards lowering the cost of BESS for economical usage and efficient deployment in small-scale RE.
- more techno-economic optimization may be required to be conducted to ensure further energy cost savings for the proposed hybrid MGs.
- Technological priority and policy portfolio must be sustained to drive down the cost of BESS for small-scale RE applications.

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