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Optimized Configuration and Operation of Isolated Microgrid Systems for Rural Electrification: Baron Technopark

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***Abstract*—** Microgrid systems represent a significant advancement in energy supply technologies, particularly for rural communities lacking access to electricity; however, these systems are predominantly reliant on diesel generators (DG). The formulation and selection of suitable configurations, alongside operational patterns, must be meticulously evaluated in the pursuit of economically viable and dependable microgrid systems.

Consequently, this research sought to devise an optimal configuration and operational for microgrid systems situated in isolation, utilizing the Baron Techno Park (BTP) in Indonesia as a case study. The optimization process was executed utilizing HOMER software, integrated with an operating cost comparison, with particular emphasis placed on daily load fluctuations, the selection of control algorithms, the reconfiguration of the power supply system, and the regulation of diesel generator operational hours. The proposed microgrid system yielded a surplus energy production of 16.7%, a renewable fraction (RF) of 100%, a levelized cost of electricity (LCOE) of $5.6 per kWh, a net present cost (NPC) of $3,97M. In summary, the study shows that by slightly increasing the capital cost of PV system procurement, it can reduce the operating cost of $629 from the base system in the long term.

***Keywords*—** Isolated, Rural Electrification, Excess energy, Microgrid optimization, Operating cost reduction.

I. INTRODUCTION

The depleting reserves of fossil fuels have prompted the exploration and incorporation of renewable energy sources as a viable alternative solution. The overarching aim of these initiatives is to mitigate the ecological damage inflicted by the combustion of fossil fuels. Consequently, this has spurred the advancement of microgrid systems that utilize renewable energy sources in proximity to consumers, thereby minimizing the necessity for extensive transmission lines and the consequential energy losses. Nevertheless, systems that primarily rely on renewable energy sources are confronted with certain limitations, including variability in power output. The identified challenges underscored the necessity for the application of diverse optimization methodologies. This has culminated in the adoption of demand-side energy management strategies tailored for residential and commercial load profiles to enhance the efficacy of renewable energy utilization (Bhamidi & Sivasubramani, 2020; Martirano et al., 2019).

Given the escalating integration of renewable energy resources within microgrid control systems, this architectural framework necessitates multifunctional converters that can significantly improve the interaction among power generation sources, electrical loads, and energy storage systems(Liu & Liu, 2019). In addition, a microgrid energy management strategy aimed at conserving fossil fuels and mitigating CO2 emissions is primarily focused on leveraging renewable energy along with battery storage capacity, while utilizing a diesel generator solely as a supplementary backup(Anglani et al., 2017). The amalgamation of these diverse generation sources to stabilize load profiles within a hybrid power generation framework can be effectively facilitated by the incorporation of a battery system for energy storage (Sulistyo & Far, 2020). Consequently, during periods of surplus renewable energy generation, the energy storage batteries may be charged independently, thereby obviating the necessity for diesel generator activation (Azahra et al., 2020).

The Baron Techno Park (BTP) area located in Gunung Kidul Regency, Special Region of Yogyakarta, was chosen for this study with the aim of optimizing the design system to update the current existing conditions with the potential of existing renewable energy resources. A 36 kWp solar energy (PV) system is used to drive all activities carried out in the BTP area. There are also other alternative energy sources in the area, such as wind energy (WG) and diesel generators (DG). The focus of this study is to optimize the existing microgrid system during the operational phase. This is achieved by operating PV and DG without involving WG because not working properly. This research process leads to the development of system components as a basic configuration. Furthermore, load patterns are included to improve energy efficiency and expand system capabilities. This shows that the purpose of the proposed system is to maximize the use of efficient renewable energy sources with operational cost criteria limitations due to the isolated location.

II. METHODS

A. *Location and Data*

BTP encompasses a spatial extent of 9.25 hectares within the jurisdiction of Gunung Kidul Regency in Yogyakarta. This area is strategically located in proximity to the coastline, precisely at the geographical coordinates of latitude -8.132 and longitude 110.544. The premises feature a variety of infrastructures, which include a central facility, an administrative hub, a security checkpoint, and accommodations for employees. These edifices are outfitted with illumination, climate control systems, and various electrical devices, thereby generating a daily energy requirement characterized by a specific load profile, as demonstrated in the accompanying schematic. Photovoltaic (PV) system installations, alongside battery storage solutions, have been integrated to furnish electrical power to these structures via the AC/DC coupling converters as delineated in the diagram of **Error! Reference source not found.** Concurrently, there exists a significant energy demand on the BTP, which is met by a diesel generator (DG) that supports the water pumping mechanisms utilized for both the Sea Water Reverse Osmosis (SWRO) and Brackish Water Reverse Osmosis (BWR) systems, catering to non-potable water requirements, **Error! Reference source not found.**.

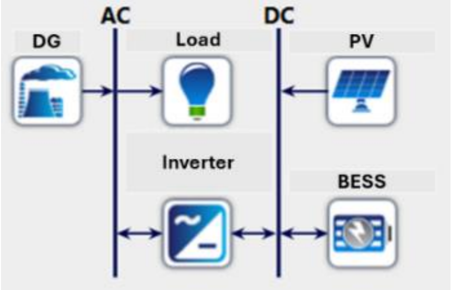

Figure 1. Schematic of BTP Proposed System.

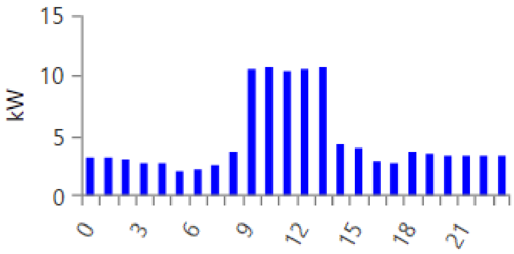

Figure 2. Daily Profile

In (Prawitasari et al., 2024), the proposed system was selected with a configuration as in Table 1, where DG operates from 6.00 p.m. until 06.00 a.m. The hybrid system was modeled using a simulation environment that incorporated real-world data for solar irradiance, **Error! Reference source not found.**. The system's performance was evaluated under various load conditions to assess energy balance, storage efficiency, and overall system reliability. The optimization was conducted using a heuristic algorithm, which iteratively adjusted system components and control strategies to minimize energy losses and maximize operational efficiency.

Table 1. Configuration of the Power Generation System.

Parameter	Proposed System Configuration
Photovoltaic (PV)	36 kWp
Wind Generator (WG)	5 kW
Diesel Generator (DG)	20 kW
Battery Energy Storage System (BESS)	288 kWh288 kWh

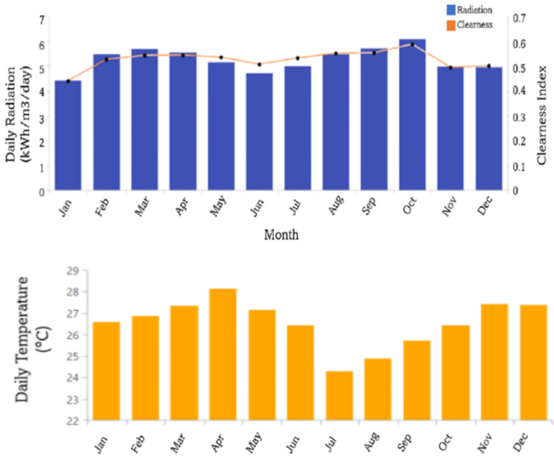

Figure 3. Baron Technopark Daily Radiation and Daily Temperature

B. *Optimization Scheme*

Currently, WG is not functioning properly, so system optimization is carried out by considering the proposed system (Prawitasari et al., 2024) and improving the existing system using the Homer optimizer. In Table 2, the configuration of the proposed system was selected and analyzed based on some optimization objectives and limitations with optimization criteria in savings.

Table 2. Optimizing Parameters

Optimization Criteria	Constraints
Criteria 1 (Minimum)	Operating cost < of all
Criteria 2 (Minimum)	NPC < of all

C. *Economic Calculations*

The principal computation executed by HOMER was the Total Net Present Cost (NPC), commonly referred to as the life-cycle cost. NPC encompassed the aggregate expenses incurred by the system throughout its operational lifespan, which included costs associated with installation, equipment replacement, operational and maintenance expenses, as well as fuel expenditures.

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Moreover, it functioned as a benchmark optimization metric within HOMER to evaluate the economic viability of the system. The computation was conducted utilizing (1) to minimize the NPC, thereby demonstrating an enhanced performance of the scenario (HOMER ENERGY, 2016).

$$\mathbf{NPC}\ (\$) = \sum_{t=0}^{T} \mathbf{C_{capital,t}} + \mathbf{C_{o\&m,t}} + \mathbf{C_{replacement,t}} + \mathbf{C_{fuel,t}} - \mathbf{R_{salvage,t}} \quad (1)$$

In the equation, T represented the lifetime of the project, $C_{capital,t}$ denoted the capital cost for the system in year t, $C_{o\&m,t}$ showed the operational and maintenance cost in year t, $C_{replacement,t}$ showed the replacement cost in year t, $C_{fuel,t}$ denoted the fuel cost in year t, and $R_{salvage,t}$ represented the salvage price at the same time t. Furthermore, HOMER generated an output concerning energy pricing and computed the levelized cost of energy (LCOE) expressed in \$/kWh through the application of (2). The LCOE represents the quotient of the annualized expenses associated with electricity generation relative to the aggregate useful electric energy produced, functioning as a critical metric for evaluating financial viability (HOMER ENERGY, 2016).

$$\mathrm{LCOE} = \frac{C_{tot}}{E_{AC,prim} + E_{DC,prim} + E_{def} + E_{grid,sales}} \quad (2)$$

The operational expenditure represents the annualized aggregate of all expenditures and income, excluding the initial capital expenditures. In the equation, $C_{ann,tot}$ denoted the total annualized cost (\$/yr), $C_{ann,cap}$ showed the total annualized capital cost (\$/yr). The operating cost represents, (3), functioning as a critical metric for evaluating financial viability (HOMER ENERGY, 2016).

$$C_{operating} = C_{ann,tot} - C_{ann,cap} \quad (3)$$

III. RESULTS AND DISCUSSION

At the beginning of the optimization using the Homer Optimizer with Search Space. This stage will set the maximum relative precision of the decision variables allowed for convergence. In Table 3, the results of the optimization are closer to the best system. The dispatch control strategy to monitor the operation of renewable energy generators, diesel generators (DG), and storage devices is the cycle charging (CC) and load-following (LF) methods (Fatin Ishraque et al., 2021; Habib et al., 2022). The simulation results for a 36 kWp photovoltaic (PV) generator, with particular emphasis on the Battery Energy Storage System (BESS), Wind Generator (WG), and Diesel Generator (DG) across various scenarios, are delineated in (Prawitasari et al., 2024). Within the scope of that investigation, the parameters employed to ascertain a favorable economic perspective included the minimization of production costs coupled with the maximization of the benefit-to-cost ratio. The findings indicated that the load-following (LF) dispatch strategy exhibited the most advantageous economic characteristics. Consequently, in the forthcoming simulation, the load-following (LF) design optimization will be implemented as the dispatch control mechanism.

Table 3. Configuration of the Power Generation System.

Schematic design	Configuration
A	DG + PV BESS, with DG operating time 6.00 p.m. until 06.00 a.m and PV 41.3 kWp
B	DG + PV BESS, with DG operating time 6.00 p.m. until 06.00 a.m. and PV 37.5 kWp
C	PV BESS, with PV 37.5 kWp, DG idle
D	DG, with DG operating time 24hours

Solar photovoltaic systems produce electrical energy throughout daylight hours. Their efficiency in electricity generation is enhanced when solar radiation is incident directly upon the photovoltaic surfaces. Simulation using the optimizer was carried out on the base system without using WG, the design results A were obtained. In addition, an optimizer simulation was carried out with search space, obtaining a minimum system that only uses photovoltaics of 37.5 kWp, namely design C. Design B itself was simulated if the system uses photovoltaics of 37.5 kWp and is added with a DG system according to operating hours. DGs are designed to function as auxiliary power sources during instances of electricity disruption or to provide electrical support in isolated regions that lack connectivity to the national power grid. In **Error! Reference source not found.**, the monthly electricity production for designs A and B is shown where DG fills the PV output production gap. In the illustrated graph, it is evident that for a duration of 365 days, distributed generation (DG) is operational to fulfill the requisite load demands due to the inadequacy of photovoltaic (PV) output. DG can be utilized to reduce costs associated with reactive power, reduce distribution losses, and improve voltage stability (John Nirmala et al., 2022).

In the configuration designated as Scheme A, as depicted in Figure 4 (a), the annual photovoltaic (PV) energy generation is quantified at 64,102 kWh, while the diesel generator (DG) output is recorded at 306 kWh, accompanied by a cumulative fuel consumption of 62.2 \$/yr to adequately satisfy the load requirements during the months of June and July. Conversely, in Scheme B, illustrated in Figure 4 (b), the annual PV energy generation is reported at 58,275 kWh, with the DG output escalating to 1,554 kWh, resulting in a total fuel consumption of 316 \$/yr to fulfill the load demands over the months of June, July, August, and September.

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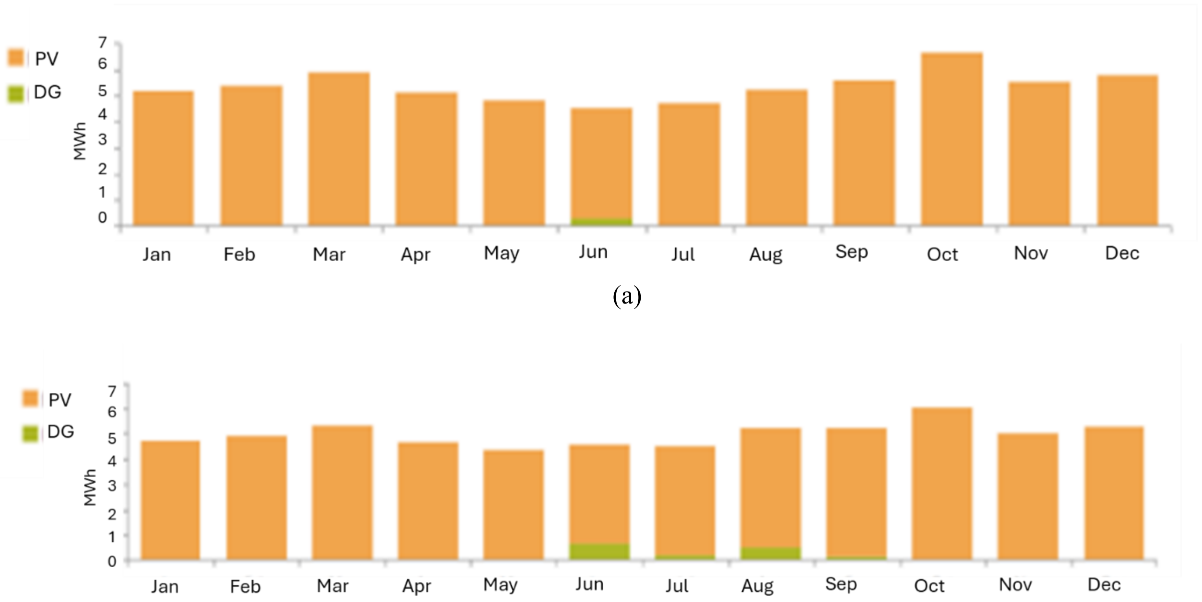
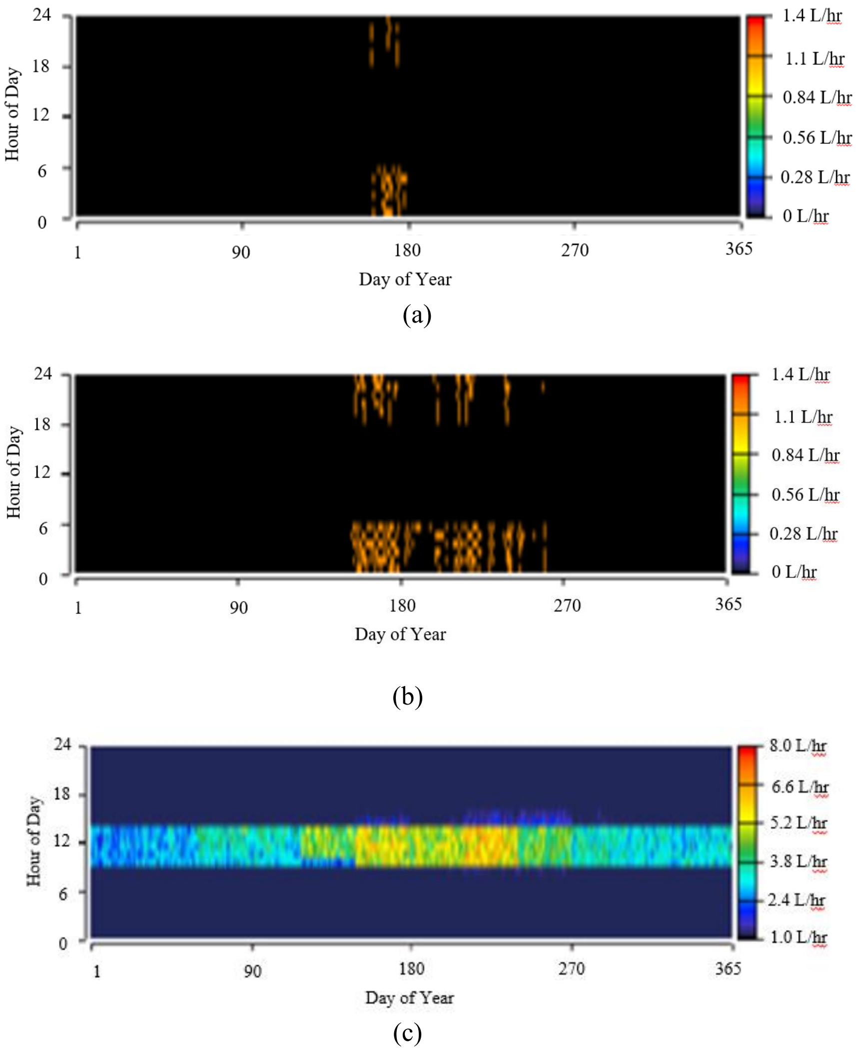


(a)

(b)

Figure 4. Monthly Electric Production (a) Schematic A (b) Schematic B.

DG fuel consumption is shown in **Error! Reference source not found.**, where DG operates based on predetermined operational times. In **Error! Reference source not found.** (a) total fuel consumed 58,6 L and operational life 294 year (b) total fuel consumed 311 L and operational life 57,9 year (c) fuel is mostly used during the day when the water pump machine is functioning, total fuel consumed 15.842 L and operational life 1,71 year. The energy produced by DG is also followed by the operational costs of the fuel used and reduces the number of operating life of the machine. Hybrid renewable energy systems such as solar and wind have very little operating costs once installed, as they do not require fuel or ongoing resource inputs. (Hassan et al., 2023). The findings derived from the optimization analysis reveal that operational expenses are depicted in Figure 6. The operational expenditure associated with the system utilizing DG amounts to $23,815, representing the highest cost in comparison to the alternative configurations. Within the framework of the proposed optimization schemes, the operational costs of the other configurations are significantly lower than the base system's operational costs, which are below $8,379, specifically comprising scheme A at $7,868, scheme B at $8,171, and scheme C at $7,750. When categorized in descending order, the operational costs rank as follows: scheme B, scheme A, and scheme C. The diminished operational cost of scheme C can be attributed to the fact that DG functions solely as a backup resource, thus incurring no fuel expenses. In contrast, scheme B, which incorporates the configuration of scheme C supplemented by DG, experiences a marginal increase in operational costs of approximately $421. An analysis of the energy distribution to the loads in schemes B and C as illustrated in Figure 5 (b) indicates that scheme B enables DG to fulfill the load requirements, whereas in scheme C, DG is not operational during that period. For both scheme A and scheme B, the configuration of the generator remains identical, with the sole distinction being the substantial photovoltaic capacity employed; consequently, the variation in operational expenditures amounts to $303. Figure 5 (a) illustrates Scheme A, which necessitates fewer distributed generation operations to fulfill load demands. Based on the graphical representation, the strategy that satisfies the load demands while adhering to the minimal operational cost criterion is designated as scheme A.



(a)

(b)

(c)

Figure 5. Consumption (a) Schematic A (b) Schematic B (c) Schematic D

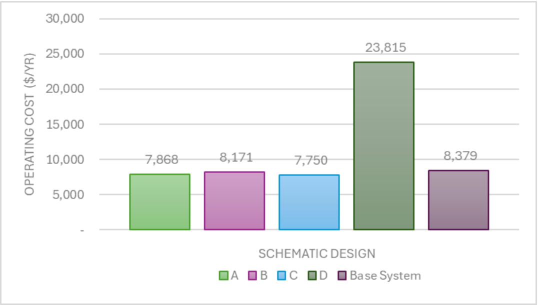


Figure 6. Operating cost comparison of the system

Studies in isolated Indonesia have shown that hybrid systems, including solar and hydro, can significantly reduce NPC and COE, making renewable energy more accessible and affordable in remote areas (Astianta Ferry Rahmat et al., 2020). The optimization process was assessed in terms of the LCOE, NPC, and renewable fraction (RF) (Dahiru & Tan, 2020). In Figure 7, the analysis illustrates the (NPC) associated with the optimized design framework, revealing that design D, which exclusively employs Distributed Generation (DG) as its power source, achieves the minimum NPC value. In contrast, schemes A, B, and C exhibit nearly identical NPC values, with the configuration devoid of DG presenting the lowest NPC. Furthermore, the implementation of DG within the hybrid system for scheme A is comparatively less than that observed in scheme B. The data depicted in the graph indicates that the design scheme fulfilling load requirements while adhering to the criteria of minimal NPC value is scheme A.

The Levelized Cost of Energy (LCOE) serves as a metric to assess the cost competitiveness among diverse energy technologies, which encompass both renewable energy sources and fossil fuels (Comello et al., 2017). The mean economic outlay associated with energy generated from a solar photovoltaic-diesel hybrid system, rated at 295.0 kW, approximates 0.349 US$/kWh (Rehman, 2021). As illustrated in Figure 8, the LCOE values reveal that the minimal LCOE occurs in design D, quantified at 0.5 cent$/kWh, whereas the LCOE for designs that incorporate renewable energy alongside battery storage, specifically schemes A, B, and C, yield significantly higher LCOE values of 5.47 cent$/kWh, 5.49 cent$/kWh, and 5.65 cent$/kWh respectively. Among these three schemes, scheme A is identified as producing the lowest LCOE value at 5.47 cent$/kWh. The declining expenses associated with lithium-ion batteries are anticipated to render them the most economically advantageous alternative in any hybrid configuration (Carroquino et al., 2021), thereby facilitating a reduction in LCOE within these systems contingent upon the utilization of Li-Ion batteries.

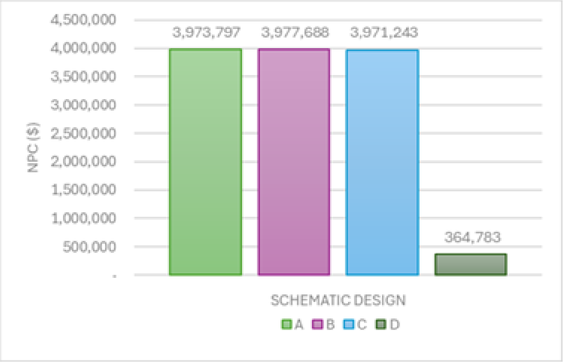


Figure 7. Net Present Cost comparison of the system.

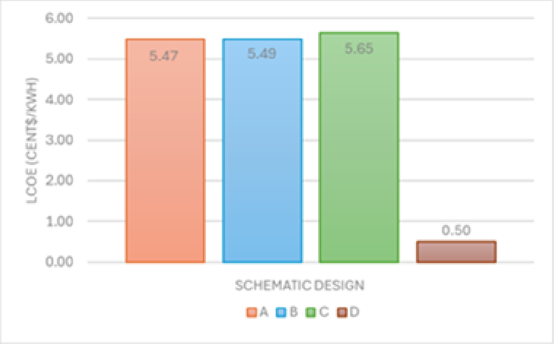


Figure 8. LCOE comparison of the system

In the context of operational expenditures, photovoltaic (PV) systems must be incorporated into the foundational framework. Figure 9 illustrates the quantity of PV that is necessary for integration into the system. Designs A and B/C incorporate 5.3 kWp and 1.5 kWp of PV, respectively. The incorporation of PV into design C facilitates a reduction in operating costs amounting to $629; however, the unmet load necessitates provision to ensure the functionality of the distributed generation (DG) system. The integration of PV along with extended DG operating hours in scheme A results in a more substantial reduction in operating expenses, totaling $511, in comparison to scheme B, which achieves a mere savings of $208. The estimated battery lifetime for each design is different, the battery lifetime of design A is 16.5 years with an annual throughput of 17,697 kWh/yr, design B is 17 years with an annual throughput of 17,242 kWh/yr and design C is 17.7 years with an annual throughput of 16,537 kWh/yr. The anticipated lifespan of design B is inferior to that of design C, notwithstanding the equivalence in their respective PV capacities, attributable to the elevated battery throughput, which additionally incorporates input energy derived from DG. In **Error! Reference source not found.**, it shows the excess energy from design. The excess energy of each design in can be used for trading or system development (Boumaiza, 2023; Jihyun Lee et al., 2017; Park et al., 2016; Triadi et al., 2023). The pie chart illustrates the distribution of five sections labeled A, B, C, D, and the Base System. Section D has the highest share at 26.89%, suggesting it plays a dominant role in the system. In contrast, the Base System holds the smallest portion, with only 14.00%, indicating a minimal contribution relative to the other sections. Sections B and C are closely aligned at 16.28% and 16.69%, respectively, showing similar levels of involvement, while Section A stands slightly higher at 22.06%. The surplus electricity generated by design C surpasses that of design B, as evidenced by the capacity-based metric which indicates that the quantity of renewable energy produced is divided by the total generation utilized, thereby resulting in a higher renewable energy capacity that can be harnessed, consequently yielding a more substantial surplus.

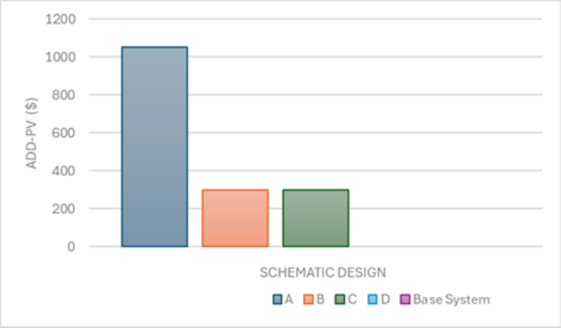


Figure 9. Cost of adding PV to the system

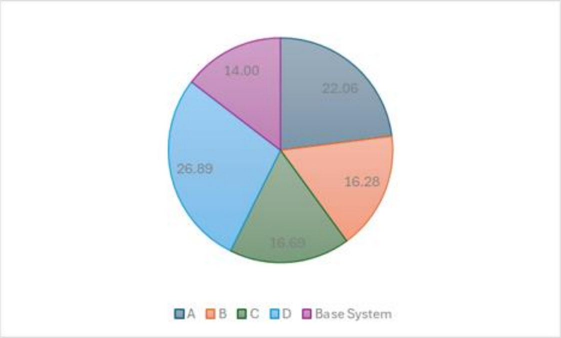


Figure 10. Excess Energy (%)

IV. CONCLUSION

Factors such as solar irradiance, wind velocity, and fuel consumption exert a substantial influence on the economic evaluation of energy systems. Within the Indonesian framework, elevated diesel costs lead to augmented operational expenditures, thereby highlighting the pivotal importance of regional energy potential in the formulation of energy systems for isolated areas distant from the primary electricity grid. As a result, in these remote regions, hybrid energy systems can be tailored to harness locally accessible energy resources, thereby facilitating the incorporation of intermittent energy sources.

In this investigation, the integration of photovoltaic (PV) technology into a system with a capacity of 5.3 kWp, referred to as scheme A, was conducted to enhance system reliability in accordance with established criteria, specifically aimed at reducing diesel fuel operational expenses $511 and diminishing net present cost (NPC) values. The excess energy generated by scheme A, quantified at 22.06%, can be allocated for supplementary loads within Baron Technopark, and further PV installations may be conceptualized for additional agrivoltaics zones situated beneath the PV arrays.

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