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Exploring the Performance and Challenges of AC and DC Coupled Solar Hybrid Systems in Malaysian Rural Schools

By Azlan Arifin[1], Ramizi Mohamed[2], Abdul Muhaimin Mahmud[3]

ABSTRACT:
Reliable energy access in rural schools is necessary for educational and community development. Solar hybrid systems, particularly Direct Current (DC) Coupled designs, offer a sustainable solution. However, they face significant scalability, maintenance complexity, and charge controller dependency challenges. This paper addresses these issues and presents an adaptive model to optimize DC Coupled solar hybrid systems. Applying Basic Qualitative Inquiry, semi-structured interviews were conducted during this study with five experts, including site officers, maintenance contractors, and a senior electrical engineer. The results reveal that rigid system design, high upgrading costs, and charge controller inefficiencies limit scalability and long-term performance. System reliability will suffer from a lack of maintenance, especially battery management and overheating prevention. The Adaptive DC Coupled System Solution Model (ADCSM) was proposed to overcome these challenges, including adaptive system restructuring, AC-DC hybrid integration, advanced charge controller optimization technologies, and intelligent monitoring technologies. This paradigm improves the system's flexibility, efficiency, and sustainability and provides a cost-effective and scalable strategy for policymakers, engineers, and researchers to manage rural energy.

Keywords: *Solar Hybrid Systems, DC Coupled, Scalability Challenges, Charge Controller Optimization, Renewable Energy in Rural Schools.*

1. Introduction

In many socio-economic structures, mainly rural and remote regions, access to quality, affordable energy solutions is critical to development (Rangel et al. 2023; Yakub et al. 2024). In Malaysia, where some schools in remote areas have difficulty obtaining reliable electricity, education and community activities may be disrupted significantly due to electricity supply loss (Ahamad et al. 2022). Notably, there are 140 schools located off-grid that rely on solar hybrid energy systems. The systems integrate renewable generation by solar Photovoltaics (PVs) with auxiliary diesel generator power systems to provide stable electricity during the insufficiency of solar power generation (Fawy et al. 2023). Depending on the desired solar hybrid energy implementation, two configurations are primarily utilized in hybrid applications: Alternating Current (AC) Coupled and DC Coupled systems (Figure 1 & 2). All these configurations have various operating characteristics and

| [1]PhD candidate in Department of Electric, Electronics and System Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia.
[2]Senior Lecturer of the Department of Electrical, Electronic and Systems Engineering at Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia
[3]Electrical Engineer at the Public Works Department of Malaysia (PWD)

performance parameters (D. Kumar et al. 2017). Nevertheless, notable challenges persist, especially within DC Coupled systems, which encounter restrictions regarding scalability, flexibility, and maintenance demands (Pires et al. 2023). Therefore, we must further explore these challenges to enhance their performance and guarantee sustainability.

DC Coupled systems are widely employed in rural areas due to their relatively lower initial installation costs, which result from a decrease in the prices of solar panels and batteries (Khan et al. 2023). However, their dependence on charge controllers to manage power, combined with a lack of modularity, limits their ability to scale with changing energy needs (Abdelwanis & Elmezain 2024). This lack of flexibility severely limits the ability of these systems to expand capacity over time, thus leading to limited scalability (Piao et al. 2021). For instance, in rural school scenarios, the number of students and their energy demands also grow alongside them (Michael-Ahile et al. 2024). Unfortunately, DC Coupled systems are often unable to adapt to such changes, leaving these schools with insufficient electricity power supply and, in some cases, forcing reliance on the costly operation of diesel generators (Aemro et al. 2020).

In addition to the issues on scalability, DC Coupled systems face significant challenges associated with maintenance and operational complexity. The reliance on charge controllers, essential for managing power flow from PV arrays to battery storage systems, introduces additional technical and operational complexity (Hasan & Serra, 2023). Furthermore, these Malaysian rural schools are often in remote or rural areas, and technicians who can perform preventive maintenance or troubleshoot problems are not nearby. As a result, system failures occur with greater frequency, interrupting energy delivery and minimizing system reliability (Pereira et al. 2022).

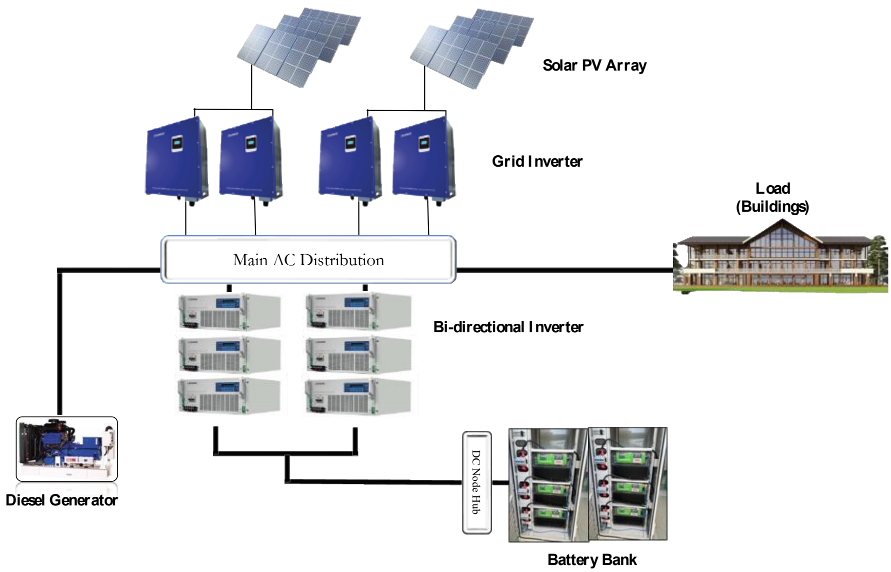

Figure 1. AC Coupled System Diagram for Rural School Malaysia

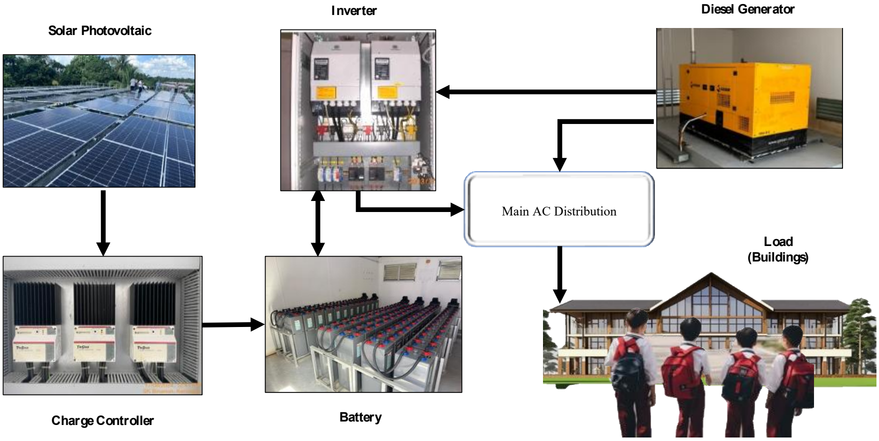

Figure 2. DC Coupled Diagram for Rural Schools Malaysia

Considering these pressing challenges, this study seeks to comprehensively analyze the performance and limitations of AC and DC Coupled solar hybrid systems implemented in Malaysian rural schools. This study aims to achieve two goals. First, it investigates the reasons for the limited scalability and flexibility of DC Coupled solar hybrid systems in such settings. Second, to study the implications of dependency on charge controller for DC Coupled systems' maintenance and operational complexity.

This study addresses the present limitations by conducting a comparative analysis of AC Coupled and DC Coupled solar hybrid systems implemented in Malaysian rural schools to provide a more accurate assessment of the two solar hybrid systems. Accordingly, the study provides valuable insights into these two system configurations' relative advantages and limitations by analyzing their performance characteristics, scaling properties, and operational challenges. DC coupled systems are more common in rural areas due to their lower cost. Thus, they are a primary focus here despite their difficulty (Pratheeba et al. 2023).

The contribution and significance of this study extend across various levels. That is, the findings can develop policies and guidelines for enhancing rural energy access at the government level. Moreover, focusing on the specific challenges of DC Coupled systems, the study contributes to designing more cost-effective and scalable renewable energy solutions for other government educational institutions (Gbadamosi et al. 2022).

At an industry level, the study findings can inform energy solution providers and system integrators in designing and executing resilient solar hybrid systems. By identifying the key challenges related to scalability and maintenance, the study inspires the development of innovative components, such as modular system designs and advanced charge controllers, that can improve system performance and usability (Hasan & Serra Altinoluk, 2023a).

The article is organized as follows: A literature survey of AC and DC Coupled solar hybrid systems, which discusses their features, effectiveness, and challenges of DC Coupled systems design at rural schools, is provided in the following section. The third section explains the methodology used in this qualitative research, including how data are collected and analyzed. In this fourth section, the findings are shared along with their implications, attempting to identify possible solutions by considering the challenges. Finally, the fifth section discusses the key findings and concludes with recommendations and a path forward for future research.

2. Challenges and Effectiveness of DC Coupled Solar Hybrid Systems in Rural Schools

In many rural regions, access to reliable electricity is one of the most significant barriers to improving the quality of education and the lives of the community (Acuna et al. 2021; Leduchowicz-Municio et al. 2022). Building on this, solar hybrid energy systems are a vital solution for providing electricity for rural areas, especially schools (Benti et al. 2022; Mbumba et al. 2024; Nera & Nyikadzino 2023). The most common approach is the coupling of renewable energy sources, such as PV arrays, with diesel generators. In particular, there are two configurations for this coupling: AC Coupled and DC Coupled systems (Valencia-Díaz et al. 2025). Both topologies have supported energy bonuses in off-grid environments. However, there are differences between operational performance and scalability (Aljafari et al. 2022). Accordingly, this paper reviews the literature reporting on the strengths and weaknesses and the gaps in research regarding hybrid solar systems, specifically in the case of Malaysian rural schools.

There are two system types: AC Coupled and DC Coupled systems. Most AC Coupled systems are converted from DC to AC energy produced by PV arrays using grid inverters, with this alternating current distributed to loads or batteries through bidirectional inverters (Dziri et al. 2022; Pratheeba et al. 2023). This design provides very high flexibility, making it easy to integrate other renewable energy sources, such as solar or wind turbines (Ma et al. 2022). Three-phase AC Coupled systems can also independently provide power to loads if the batteries fail (H. F. Ahmed et al. 2024). Nevertheless, the higher upfront installation costs of AC Coupled systems (approximately 8 to 10% compared to DC Coupled systems) are a key obstacle to deployment, especially in resource-limited rural environments (Sheta et al. 2023).

In contrast, DC Coupled systems have PV arrays that connect to a DC bus through charge controllers to control the amount of electricity flowing to battery banks (Elmorshedy et al. 2023). Although DC Coupled systems are more cost-effective during initial installation, they face limitations in scalability and operational complexity (Pires et al. 2023). Jiang et al. (2021) emphasized that DC Coupled systems necessitate battery capacities that at least equal or exceed the energy output from PV arrays while limiting the ability to expand capacity as time passes. This limitation is especially problematic in rural schools where energy demand increases due to growing enrollment or infrastructure expansion. Furthermore, the rigid structure of DC Coupled systems makes including more renewable energy sources challenging, which decreases their flexibility in rapidly changing environments (Bharatee et al. 2022).

Another major problem is that DC Coupled systems depend on charge controllers (Y. A. Kumar et al. 2024). Charge controllers also help manage the energy transferred from PV arrays to batteries, ensuring that the batteries are charged efficiently and safely (Mirzaei et al. 2017). These components, however, are subject to technical failures and require frequent maintenance, which can be particularly complex in rural areas where access to trained technicians is limited (Uchenna Izuka et al. 2023). In addition, studies demonstrate that if charge controllers fail, that can cause system-wide downtime, as DC Coupled systems cannot "run" without functioning batteries (Pires et al., 2023). Consequently, this dependency voids the reliability of DC Coupled systems and, thus, makes them less suitable for high energy outputs in off-grid locations (Arunan et al. 2024).

In the case of rural school electrification in Malaysia, maintenance strategies involving solar charge controllers are mostly managed under the responsibility of the Public Works Department (JKR), as it is the implementing authority for these systems. Two main categories of maintenance are enforced: preventative maintenance, which is performed every four months, and corrective maintenance, which is triggered by system failure reports that require immediate action by the contractor. Despite systematized maintenance schedules, corrective maintenance is hindered by school inaccessibility. A number of those schools are situated in deep interior regions, with poor road access and long distances hindering the contractors' ability to respond quickly. As a result, system breakdowns, particularly on the charge controller side, can lead to more extended downtime since the failure may not be detected immediately (JKR Malaysia 2018). According to West et al. (2024), adopting preventive maintenance strategies can improve productivity and reduce downtime costs; however, managers should also consider the broader effects of downtime. Although the adoption of preventive maintenance would improve reliability or redesign the system, such system-improving solutions are not yet operational due to logistical constraints for rural schools and the heavy reliance on scheduled maintenance contracts. This situation highlights the implications of technical and structural administration deficiencies, underscoring the pressing need for context-specific maintenance models for rural energy infrastructures.

From a performance perspective, AC Coupled systems exhibit higher operational scalability and efficiency (Belik & Rubanenko 2024). The modularity of batteries allows for increased capacity expansion and the combination of different renewable energy sources like wind and hydro to be better utilized in various situations (Helling et al. 2019). On the other hand, DC Coupled systems have the advantage of charging a battery more efficiently and are better suited for energy storage applications (Challouf et al. 2024). These characteristics, however, pose significant constraints to their performance, particularly their inability for off-battery operation and much more significant energy losses due to oversized DC components and cable losses (He et al. 2020).

Even with the extensive study conducted in solar hybrid systems, several gaps must be resolved. First, most have focused on technical specifications and cost comparisons but have not explored stakeholder lived experience, such as those of engineers and maintenance contractors managing such systems (H. F. Ahmed et al. 2024; García-Muñoz et al. 2022; He et al. 2020; Helling et al. 2019; Pires et al. 2023). Second, the scalability struggles of DC Coupled systems in rural settings such as Malaysia have received minimal scholarly attention thus far (Mahmud & Blanchard 2016; Mohamed et al. 2014; See et al. 2022). Finally, no unified frameworks explore the interdependence between scalability, operational constraints, and performance of systems, suggesting a need for more research in this area (Pratheeba et al. 2023).

The insights from this review suggest that AC Coupled systems have flexibility and reliability advantages but may present a significant cost barrier that limits their appeal in rural schools. On the other hand, while DC Coupled systems initially compete on lower-cost entry points, they are extremely limited in their scale and operational complexity. In addition, innovative solutions are required to address these challenges and improve the flexibility and maintainability of DC Coupled systems without overly inflating costs. Nonetheless, this research efficaciously meets the demand for searching for new solar hybrid energy that shall be more sustainable for rural schools in Malaysia.

3. Research Methods

The underlying goal of this study was to utilize a qualitative research approach to analyze the performance and limitations of AC and DC Coupled solar hybrid systems at rural schools in Malaysia. This study is a Basic Qualitative Inquiry, a research design model particularly applicable to research on the experiences and perspectives of stakeholders directly participating in the management and maintenance of solar hybrid systems (Patton, 2023). Semi-structured interviews and field observations were the primary data collection methods, and a purposive sampling approach was taken to select participants (S. K. Ahmed 2024). Consequently, data were analyzed with manual coding and thematic analysis to explore patterns in the data and develop insights (Virginia & Victoria, 2022). Nevertheless, ethical issues were well dealt with to maintain the trustworthiness of the research process (Badr & Lhoussaine, 2024).

The main techniques used for data collection were semi-structured interviews and observations in the field (Heting Chu 2024). Five participants from Public Works Department (PWD) officers and maintenance contractors participated in interviews for this study. Remarkably, they are credible as they have more than ten years of experience, as referred to by Bradfield et al. (2023), and are directly involved in managing, maintaining, and supervising solar hybrid systems in Malaysian rural schools (Bradfield et al. 2023). Although the qualitative nature and small number of respondents in the study may raise concerns about the research's generalizability, it is also noteworthy that the research was intentionally conducted to secure higher-level perspectives from individuals directly responsible for the management and implementation of solar hybrid system maintenance in Malaysian rural schools. The five participants were not only knowledgeable about system functioning but also in a position to provide strategic and operational inputs with a strong basis in field knowledge and experience. Both PWD officers and maintenance contractors were interviewed on a semi-structured basis. A semi-structured interview guide was developed to ensure consistency across the interviews yet allow all participants to elaborate and provide their perspectives in their own words (Gary Barkhuizen et al. 2024). At the same time, some key discussion points were the scalability limitations of DC Coupled systems, the issues of dependency on the charge controller, and input from participants on how to overcome these issues to improve system performance. Such interviews enabled the researcher to gather first-hand concerns about stakeholders' practical and operational issues. The diverse expertise of participants also ensures an inclusive and credible perspective of the issues affecting DC Coupled solar hybrid systems in rural schools, making them highly eligible to provide relevant and reliable insights for this research (Bates et al. 2023).

Field observation was performed alongside interviews to triangulate the data collected (Uwe Flick 2022). The observations were centered on recording the physical arrangements of the solar hybrid systems, the maintenance methods conducted, and the systems' operational conditions. Including these observations with the interview data complemented, the findings provide a more robust picture grounded in personal experience and external verification (Shin & Miller 2022). These methods were preferred because they comprehensively address the complexities and contextual factors of solar hybrid systems in rural schooling, aligning with the study's aim and research questions.

Subsequently, purposive sampling was applied to select participants who have first-hand knowledge of the operation and maintenance of solar hybrid systems (S. K. Ahmed 2024). The target population was people from the PWD and maintenance contractors since they were directly involved in enabling the systems to operate and be sustainable. Qualitative research is more about depth of insight than sample size (Michael Quinn Patton 2023). Therefore, five participants were selected. A smaller number of samples enabled a deeper investigation into the broader issues and elements determining the system's performance (Catherine Dawson 2024). Moreover, training the participants with the relevant information formed the basis of the sampling technique, ensuring both the specifically relevant and relatively broader scope for the context within which the data was used for meeting the objectives of this study (Briony Sharp et al. 2024).

Data was analyzed through manual coding and thematic analysis using Microsoft Word (Naeem et al. 2023). Referring to Naeem et al. (2023), this study's analytic process started with reviewing and coding interview transcripts to elucidate common concepts and themes. Correspondingly, the codes were combined into higher-order themes, e.g., social acceptability of room-based systems, operational challenges, and performance comparisons between AC and DC Coupled (Naeem et al. 2023). A selection was made for thematic analysis since it offers a rigorous method for identifying, analyzing, and interpreting patterns within qualitative data (Virginia & Victoria, 2022). This approach ensured that the findings were grounded in the data and directly relevant to the research aims by concentrating on the apparent themes in participants' responses (Majumdar 2022). Through manual coding, the codebook served as an instrument to facilitate the researcher's careful immersion in the data and develop a more nuanced understanding of participants' insights (Philipp Mayring 2022).

Ethical considerations were essential to the research process (Dan Kaczynski et al. 2024). Participants were also informed about the study and their rights as participants, including the right to withdraw at any time (Nii Laryeafio & Ogbewe 2023). Informed consent was obtained prior to collecting data, and participants were assured of the confidentiality and anonymity of their responses (Aurini & Iafolla 2023). Additionally, referring to Aurini and Iafolla (2023), this study also adhered to national and international ethical guidelines approved by the relevant ethics review board (Aurini & Iafolla 2023).

Other than that, some strategies were utilized to enhance the validity and reliability of the research findings (Dr. Khatib Ahmad Khan et al. 2024). Triangulation was performed by combining interview data with field observations, providing a broad understanding of the research problem (Uwe Flick 2022). Simultaneously, member checking was performed, in which participants reviewed the interview transcriptions to verify the veracity of the data (de Loyola González-Salgado et al. 2024). According to de Loyola González-Salgado et al. (2024), this process steered to valid findings representative of participants' perspectives (de Loyola González-Salgado et al. 2024). Additionally, an audit trail was maintained to clarify the data collection and analysis process, improving the transparency and replicability of the study (Bingham 2023).

The approach outlined in this study creates a valuable framework for further exploration of the performance and challenges faced by solar hybrid systems installed in Malaysian rural schools. Employing Basic Qualitative Inquiry through semi-structured interviews and observations resulted in a rich, in-depth understanding of the research problem. Furthermore, a purposive sampling method was employed to ensure the participants could shed better light on insights. At the same time, the data were entered and analyzed manually using inductive coding and thematic analysis. Such a systematic method fulfills the research objectives. Correspondingly, it provides key findings that can help improve the design, scaling up, and successful implementation of hybrid solar systems to meet rural needs.

4. Findings

The findings of this study provide a better insight into the challenges, maintenance issues, and upgrade strategies of DC Coupled solar hybrid systems in Malaysian rural schools. Qualitative analysis of interviews with PWD officers and maintenance contractors highlighted that system scalability, operational efficiency, and charge controller performance were key themes from the data collected. The interviews help identify some of the key differences and potential areas for improvement to increase the sustainability and execution efficiency of such systems.

Figure 3 graphically displays the relationship between coding categories and themes, highlighting the key findings of this study. First, one of the crucial findings is that upgrading DC Coupled systems is very hard due to scalability limits. The system's design means charge controllers are placed right next to the battery banks, limiting expansion, especially in schools where space is at a premium. Furthermore, upgrading the systems is sometimes not feasible, mainly due to the high cost of adding new components, like batteries and solar panels. A few highlighted that DC Coupled systems cannot operated without battery-side storage. Therefore, battery degradation is the main problem in long-term operations. Over time, this dependence makes it more challenging for rural schools to maintain and operate these systems without substantial financial capital.

A significant finding with DC Coupled systems is the complexity of maintaining these systems due to charge controller considerations. At the other end of the spectrum, from those who argued that the maintenance process was relatively simple and only required periodic cleaning, some pointed out that overheating, charge controller failure and improper battery configurations can negatively impact a system's functionality. In addition, the operational burden is further increased as the system must be constantly tuned or equalized and frequently recalibrated to maintain functionality. The charge controller is the heart of the battery system and, if not maintained, can cause it to overcharge or undercharge, which negatively affects battery health and causes premature, expensive replacements.

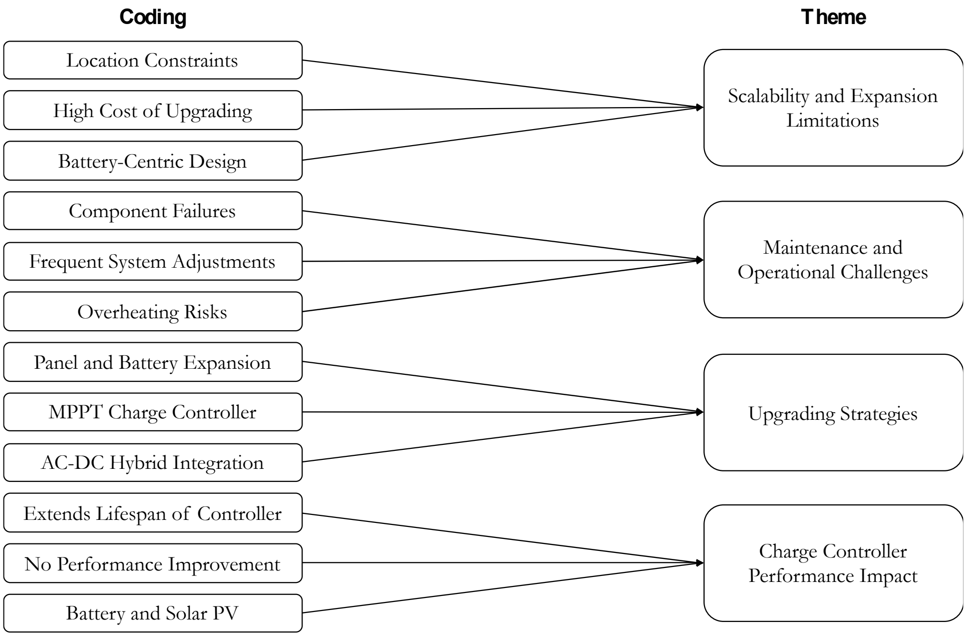

Figure 3. Coding Categories and Themes from the Interview Transcripts

Other than that, optimization and upgrade strategies have been applied to improve DC Coupled system performance. Several participants mentioned better system performance as they increased the number of solar panels, upgraded charge controllers to Maximum Power Point Tracking (MPPT) technology, and increased battery capacity. However, such enhancements usually demand increased financial investment and more physical space, rendering them ineffective in all rural schools. Several participants added that most solutions combine AC Coupled and DC Coupled systems, which offer flexibility in the storage systems and optimize power. This point is further supported by the insights obtained during an interview with the project manager of the Public Works Department, who pointed out that, with current technological developments, upgrading DC-coupled hybrid solar systems is not as high as it was believed to be in the past. Multiple setups can now effectively work together in a single solar hybrid system, allowing greater flexibility and scalability. These moves undermine traditional attacks on the inflexible design of DC-coupled systems and suggest a growing recognition that modular flexibility is an integral aspect of system design.

Moreover, different perspectives emerged among participants while assessing the impact on system performance when performing maintenance on charge controllers. Regular maintenance improves the system's performance by preventing overheating and ensuring consistent energy flow, thus maintaining efficiency. Others argued that while maintenance ensures a system is functional, it does not improve performance, as components naturally degrade over time. Depending on how stakeholders view maintenance, this difference could be attributed to some stakeholders perceiving maintenance purely as routine servicing. In contrast, others leverage maintenance as a proactive action to ensure the optimal operation of components.

While there were familiar results, there were also unexpected results, some of which call into question our understanding of system limitations for DC Coupled systems. With technological growth, as reported by some stakeholders, it is no longer a big deal to upgrade DC Coupled systems, mostly since modern modular design and configurations allow systems to be expanded as needed. This contradicts the position of others who said space limits, cost restraints, and technical difficulties are still significant roadblocks to scaling. Furthermore, while many participants view AC-DC hybrid integration as a business opportunity, others question whether integration of AC and DC components leads to cost savings or makes management of the entire system more complex.

In summary, the research validates the current scalability challenges in DC Coupled architectures with the expansion level of the threshold, which is limited by cost, space, and design. Additional concerns, such as operational challenges concerning charge controller reliability and risks of overheating, were also described as critical issues. Nevertheless, various upgrading methods were practical solutions, including panel expansion, MPPT charge controllers, and hybrid connection with AC systems. Nevertheless, the relevance of maintaining a charge controller to the performance of a system is disputed since some claim that charge controller maintenance increases charging efficiency. In contrast, others consider regular maintenance to be important only to stability. Several surprising results indicated that further upgrades via DC Coupled systems are getting increasingly easier with advanced technology, contradicting traditional views that these systems are inherently rigid and challenging to expand. Such learning will be crucial for promoting efficient and scalable DC Coupled solar hybrid systems in rural schools. Therefore, future research should focus on cost-effective modular designs, advanced charge controller technologies, and hybrid system integration models to optimize energy solutions for off-grid communities.

5. Discussion

The findings of this study provide a comprehensive understanding of the challenges and performance of AC and DC Coupled solar hybrid systems in Malaysian rural schools. In particular, the study highlighted scalability concerns, maintenance complexity, and charge controller performance limitations, which proved critical in DC Coupled systems and their inflexible infrastructure, battery storage-dependent functionality, and high upgrade costs. The results also identified maintenance-related challenges, particularly with the charge controllers, as the significant factors impacting system performance and long-term sustainability. Although various upgrading strategies were identified, such as increasing solar panels, optimizing charge controllers, and integrating AC and DC Coupled systems, financial constraints and space limitations continue to pose significant barriers. This was emphasized by several participants who noted the limited placement of new components and the high cost of additional charge controllers as major challenges. Moreover, whether charge controller maintenance directly enhances system performance remains unresolved, with some participants viewing it as essential for preventing failures. In contrast, others argue that it does not significantly contribute to improved efficiency.

The study revealed that DC Coupled systems have the most significant limitation on scale due to a lack of flexibility. The results confirm that these systems must have charge controllers and battery banks nearby, limiting scalability within schools where space is already limited (Hasan & Serra Altinoluk 2023). Participants highlighted this, and it aligns with technical literature, such as Jiang et al. (2021) and Bharatee et al. (2022), which report on the issues of flexibility in DC coupled systems. Additionally, the cost of adding new components, including batteries and solar panels, further exacerbates this issue, making large-scale upgrades impractical in many cases (Pires et al. 2023). This challenge meets one of the study's primary objectives: finding the reasons behind the low scalability and flexibility reported in DC Coupled solar hybrid systems. In line with this, adding new components will also contribute to energy cost and space as DC Coupled systems do not have an intermediary. When the energy supply increases, the only available solution is to install more batteries (Pratheeba et al. 2023). Thus, the rigid structure of DC Coupled systems makes this a fundamental challenge to their long-term role in rural school settings.

Another significant finding is the complexity of maintaining DC Coupled systems, particularly regarding charge controllers. Results suggest that while some maintenance tasks, such as cleaning heatsinks and ventilation fans, are relatively straightforward, other aspects, such as preventing overheating and ensuring proper battery configuration, require more technical expertise. Charge controllers are essential for system reliability; their failure can cause downtime, increase operating and maintenance costs, and accelerate battery life degradation (Papageorgiou et al. 2024). These findings directly support the second research question for the study, which aimed to analyze how charge controller dependency affects operational complexity and maintenance demands as reported by Uchenna Izuka et al. (2023) and Pires et al. (2023). Although some participants maintained that maintenance is fundamental for the charge controllers' longevity and to avoid inefficiency, others replied that maintenance does not improve anything about how the system works. It just helps keep it running. This difference of opinion implies that although charge controller maintenance is critical in reducing failures within the system, its contribution to efficiency improvements is still under considerable debate.

In order to improve the performance of DC Coupled solar hybrid systems, the study revealed different upgrading strategies that have been adopted. All seemed very exciting as participants shared thoughts on addressing the internal constraints of the systems under consideration, such as MPPT charge controllers, battery storage expansion, and AC and DC Coupled systems. While promising, such strategies tend to be expensive and space-consuming, severely limiting their potential in rural schools. Many pointed out that significant challenges persist in enhancing energy efficiency in large-scale implementations, including limited space and high costs. However, some participants were confident that technology makes DC Coupled upgrades more practical. Thus, this advancement of technology suggests a crucial area for future research efforts on how emerging designs for modular systems will help DC Coupled systems address more flexible or scalable solutions that advance their viability for off-grid applications.

6. Adaptive DC Coupled System Solution Model (ADCSM)

Based on the discussion of the challenges and constraints faced in DC Coupled solar hybrid systems, this study proposed an Adaptive DC Coupled system Solution Model (ADCSM) for rural schools to address scalability issues, dependency on charge controllers, maintenance challenges, and long-term system effectiveness (Figure 4).

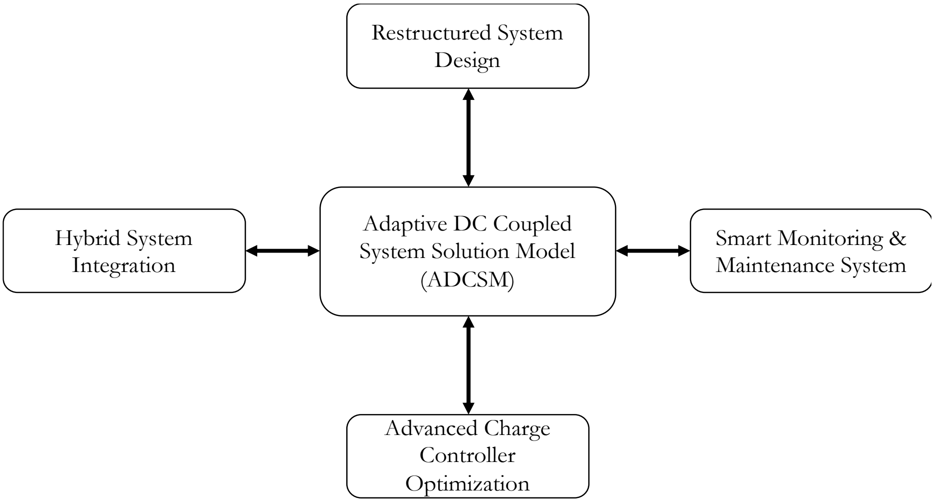

Figure 4. The Adaptive DC Coupled System Solution Model (ADCSM)

The first element in ADCSM, Restructured System Design, focuses on optimizing the placement of solar panels, batteries, and charge controllers to minimize energy losses and improve scalability. Concurrently, schools can expand their solar capacity more easily by relocating system components without excessive infrastructure adjustments. The second element, Hybrid System Integration, enables a combination of AC and DC Coupled technologies to enhance energy distribution. This integration reduces dependency on battery storage by allowing direct energy usage from solar PV during daylight hours and improving overall system reliability. The third element, Advanced Charge Controller Optimization, involves upgrading to MPPT charge controllers, applying automated energy regulation, and introducing redundant charge controllers to prevent system failures. These improvements enhance power management and battery lifespan. Finally, the Smart Monitoring and Maintenance System utilizes Internet of Things (IoT)-based real-time monitoring and predictive maintenance to optimize system efficiency. This component minimizes unexpected failures and improves maintenance planning through automated diagnostics. Therefore, by integrating these components, ADCSM provides a comprehensive, scalable, and cost-effective solution to improve the performance and sustainability of DC Coupled solar hybrid systems in rural schools.

7. Conclusion

This study significantly contributes to industry and academia's management and optimization of solar hybrid energy systems, particularly in rural schools. From a practical perspective, the findings provide valuable solutions for policymakers, engineers, and system designers seeking to improve solar hybrid systems' scalability, efficiency, and operational reliability. Hence, by identifying the constraints and challenges encountered, this study highlights the need for cost-effective modular system designs that facilitate future expansion while minimizing technical and financial barriers.

From an academic perspective, this study contributes qualitative evidence on the real-world applications of solar hybrid systems, moving beyond technical performance metrics to focus on the lived experiences of system operators and maintenance personnel. It is worth mentioning that solar hybrid systems in Malaysian rural schools are applied in a variety of geographical and logistical environments with case-specific operational issues. Some of the schools are less than 70 km from the nearest town, and some are over 100 km away (Mohd Zeki et al., 2020). Each typology represents greater degrees of separation and inaccessibility. Additionally, the modes of transportation to these sites vary significantly, involving combinations of land, air, and water travel, depending on the school's location. The differences in remoteness and transport logistics directly impact the feasibility, cost, and reliability of any hybrid system design, including AC-DC integration. As a result, the current application of solar hybrid systems in these diverse rural contexts already offers a valuable site for evaluating the technical and operational feasibility of these systems, including the AC-DC hybrid concept demonstrated in this research. As such, this study provides a human-centered perspective that outlines practical limitations and potential solutions to improve system performance. Moreover, these findings establish a foundation for future research on hybrid AC-DC integration, new charge controller technologies, and cost-effective maintenance solutions.

DC Coupled solar hybrid systems, while offering advantages in scale and reliability, still require further innovation to address budget constraints, space limitations, and maintenance challenges. While various upgrade options exist, rural schools often struggle to implement them due to financial and space constraints. Additionally, while charge controller maintenance can help prevent system failures, its direct impact on efficiency is still debatable. Thus, future research should focus on cost-effective modular designs, Artificial Intelligence (AI)-driven predictive maintenance, and AC-DC hybrid configurations to enhance the sustainability and efficiency of hybrid solar systems in rural applications.

Considering these challenges, solar hybrid energy systems can increase sustainable energy accessibility for off-grid communities. However, the study's limitations, including the small participant sample and qualitative nature, require further quantitative evaluation to confirm the system performance improvements. Considering this perspective, future research should focus on scalable and cost-effective solutions that ensure long-term reliability, flexibility, and efficiency in renewable energy deployment for rural areas.

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