Development of Rainwater Hydroelectric and Solar Technologies for Renewable Energy towards Sustainability Campus.

Mohd Khairul Amri Kamarudin
Faculty of Applied and Social Sciences, Gong Badak Campus, University Sultan Zainal Abidin

Siti Nor Fazillah Abdullah
Faculty of Applied and Social Sciences, Gong Badak Campus, University Sultan Zainal Abidin

Ahmad Shakir Mohd Saudi
Centre of Water Engineering Technology, Malaysia France Institute (MFI), Universiti Kuala Lumpur (UniKL)

Ismafatin Nabilah Ismail
East Coast Environmental Research Institute, Gong Badak Campus, University Sultan Zainal Abidin

他

https://hdl.handle.net/2324/7395492

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 11, pp.16-24, 2025-10-30. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

Development of Rainwater Hydroelectric and Solar Technologies for Renewable Energy towards Sustainability Campus

Mohd Khairul Amri Kamarudin[1,2], Siti Nor Fazillah Abdullah[3], Ahmad Shakir Mohd Saudi[4], Ismafatin Nabilah Ismail[5], Firdaus Mahamad Ali[6], Lokman Abd Rahman[7], Firdaus Muhammad-Sukki[8]

[1,3]Faculty of Applied and Social Sciences, Gong Badak Campus, University Sultan Zainal Abidin, 21300 Kuala Nerus, Terengganu, Malaysia, [4]Centre of Water Engineering Technology, Malaysia France Institute (MFI), Universiti Kuala Lumpur (UniKL), Bandar Baru Bangi 43650, Selangor, Malaysia, [2,5] East Coast Environmental Research Institute, Gong Badak Campus, University Sultan Zainal Abidin, 21300 Kuala Nerus, Terengganu, Malaysia, [6]Global and Entrepreneurship Research and Innovation Centre, Universiti Malaysia Kelantan, Campus Kota, Locked Bag 36, Pengkalan Chepa, 16100 Kota Bharu, Kelantan, Malaysia, [7]Sekolah Menengah Kebangsaan Belara, 21200, Kuala Terengganu, Terengganu, Malaysia, [8]School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Edinburgh EH11 4BN, United Kingdom.

corresponding author: mkhairulamri@unisza.edu.my

Abstract: *This research assesses the development of rainwater hydroelectric and solar technologies for renewable energy towards sustainability campus at Universiti Sultan Zainal Abidin (UniSZA) Malaysia to support sustainability campus in Green Campus agenda. The system includes a 300 W monocrystalline PV panel alongside a rainwater cross-flow microturbine. The hydroelectric generation yielded 0.208 W, equating to 137.28 J (0.038 Wh) with a storage tank volume of 1.76 m³ and a flow rate of 0.00267 m³/s. The PV subsystem contributed 38 W under moderate irradiance, which is 12.7 % of its rated capacity, thus augmenting power generation during low rainfall periods. Outcomes validate the reliability of the system with the PV component functioning throughout dry periods. This configuration enhances energy availability despite varying weather conditions in tropical areas. The study underlines the importance of hybrid systems and calls for future changes to increase efficiency through enhanced storage capabilities, turbine design, and control systems.*

Keywords: hybrid renewable energy system; hydroelectric; rainwater; renewable energy; solar energy

1. INTRODUCTION

The global shift to renewable energy systems is now a requisite owing to growing issues concerning climate change, the depletion of resources, and energy security. In this regard, Malaysia and Southeast Asia as a whole are searching for sustainable energy assets to mitigate the use of fossil fuels while meeting international commitments like the Paris Agreement [1, 2]. With respect to the Malaysian equatorial climate, the region has high rainfall as well as a great deal of solar irradiation which provides opportunities for harnessing further diversification of renewable energy resources, especially capitalising on natural hydrological and atmospheric cycles [3].

As of 2022, the energy sector within Malaysia continues to rely on conventional fossil fuels as its primary source of power, with coal and natural gas contributing 92% of the electricity in Malaysia [4, 5]. However, the government is working towards this goal via the Twelfth Malaysia Plan as well as the Malaysia Renewable Energy Roadmap (MyRER) which plans to boost the renewable energy share to 31 % by 2025 and 40 % by 2035 [6]. These targets will only be achievable by increasing the share of traditional technologies like solar PV and hydropower alongside developing responsive integrative solutions to Malaysia's unique seasonal climates

The development of solar energy in Malaysia has received reasonable attention due to the country's average irradiance of solar energy within the range of 4.21 to 5.56 at kWh/m² /day, with maximum potential during the dry inter-monsoonal months which range from March to November [7]. On the other hand, rainwater harvesting has primarily been put into practice for non-energy related purposes, such as domestic water supply and urban drainage systems. When applied in micro-hydroelectric generation, these urban infrastructures can also be utilized for low-head, small-scale hydropower systems [8]. While the integration of standalone solar and hydropower machines has been researched comprehensively, the harnessing of rainwater harvesting systems alongside a solar PV plant to improve energy production capacity is still an untapped area. In Malaysia, most studies revolving around hybrid renewable energy focus on solar–biomass or solar–wind hybrids and tend to ignore the synergistic possibilities that exist between water harvesting and solar technologies [9, 10]. This gap in research can boost innovation, especially in the context of a climate responsive energy system that seeks to mitigate fluctuations and uncertainties associated with renewable resources.

In response to an identified research gap, this research concentrates on the innovation of integrated rainwater and PV energy for clean energy in support of a sustainable campus. This project was carried out at the Universiti Sultan Zainal Abidin (UniSZA) Gong Badak Campus, Terengganu, Malaysia. It aims to leverage the country's high solar energy potential during the dry season and optimize on the large availability of hydrometeorological resources during the Northeast Monsoon (November-March) months. Unlike conventional solar systems which serve as independent energy sources, this configuration harnesses solar energy to facilitate the management of water storage and flow control, thereby sustaining the functional reliability of the hydroelectric subsystem during droughts.

This study seeks to improve the localised renewable energy options in tropical areas by integrating solar PV inputs with rainwater hydroelectric systems, emphasising their reliability, efficiency, and sustainability. This particular approach contributes directly to the discourse surrounding the water energy connection, as well as sustainable urban infrastructures which advocate for multifunction systems that increase resource interplay [11]. This also aligns with Malaysia's wider policy efforts towards developing a resilient, low-carbon energy future and adds valuable empirical evidence to the world's knowledge on integrated renewable energy systems.

The search for environmentally friendly and self-sustaining energy systems in the tropical parts of the world has received significant attention due to the development of hybrid systems which combine different forms of renewable energy. This is crucial in Southeast Asia because the climate variability, high level of humidity, and monsoonal changes pose additional challenges to the operation of single-conventional renewable energy technologies. Despite the implementation of stand-alone solar PV or micro-hydro systems, single-source renewable energy technologies tend to have more challenging shortcomings in areas with extreme seasonal variations [12].

For instance, in Sarawak, Malaysia, solar PV systems are often defeated by the Northeast Monsoon season (November-March) due to heavy cloud cover and heavy rain, which leads to lowered solar irradiance and electricity generation [13]. On the other hand, rainwater harvesting systems, while increasingly adopted into the designs of sustainable buildings, really do come into their own when it comes to the inter-monsoonal dry seasons characterized by low precipitation from March to September [14]. Such outliers highlight the constraints mono-resource systems face while functioning in tropical climates and steer the search towards integrative, adaptable frameworks.

The development of hybrid renewable energy systems (HRES) has emerged as a more effective alternative considering dual systems, as they provide more benefits working in conjunction which increases overall energy availability and system reliability throughout the year. As noted by [15], dual-source, particularly solar-hydro or solar-wind hybrids, show superior load matching and operational stability under changeable weather conditions. In their analysis of microgrids design models in Southeast Asia, the hybrid models were more consistent in the energy produced and, in the lifecycle, cost compared to the single-source installations. There still seems to be a gap within literature that deals with high-head hydropower or large-scale riverine systems, as micro-hydropower generated from rainwater has received little focus, particularly in constructed environments like campuses or residential buildings.

Recent studies have started to pay attention to this particular gap. In one such instance, [16], showed that the micro-hydropower potential of rooftop rainwater harvesting systems in urban Indonesia could be utilised for harvesting energy even from negligible rainfall provided adequate water storage and height differences exist. Likewise, [17] studied the urban drainage systems of Kuala Lumpur and their feasibility as micro-hydro energy generation systems and proposed the idea of 'secondary purpose' infrastructure for energy cogeneration. However, the cooperation of these systems with solar PV in a coordinated tactical approach has not yet been investigated.

As discuss by [18], climate responsive infrastructure and emphasise the consideration of hydrological and meteorological factors in the planning of renewable energy systems. This research takes that approach by shifting the system's operational logic to the specific dry and wet months of Malaysia's hydro-solar seasonal Water-Energy interface applying solar PV in the dry months and switching on the rainwater fed hydroelectric parts in the wet months. To summarize, the use of integrated systems of renewable energy in tropical regions is widely recognised, but the specific synergy of rainwater harvesting for hydroelectric generation and solar PV is still underexplored, especially in Malaysia. This research attempts to address this gap by designing and testing a hybrid RWH–PV system at UniSZA located at Gong Badak, Terengganu. The aim of the study is to develop a rainwater hydroelectric and solar technologies for renewable energy towards sustainability campus in supporting sustainability campus in Green Campus agenda.

2. METHODOLOGY

2.1 Study Area

The hydrological cycle was harnessed to both generate power and preserve water resources in a hybrid renewable energy system that has been developed and mounted at Faculty of Applied Social Sciences buildings, Universiti Sultan Zainal Abidin (UniSZA), Gong Badak Campus, Terengganu (Fig. 1). The system captures rain and incorporates PV solar cells, allowing it to assess its performance in the tropics during the high-solar insolation period which is differentiated by rainfall and drought.

Fig. 1. RawHydro System installment

2.2 Subsection System Description and Hybrid Integration Design

The building features a total roof area of 684.48 m², equipped with eight downspouts for capturing rainwater, however, for the purpose of this study, only two 4-inch (approx. 0.1016 m) downspouts were customised to funnel rainwater into a purpose-built water harvesting system. These downspouts empty into a 400-gallon (approx. 1.7619 m^3) storage tank made of high-density polyethylene (HDPE) which is mounted on the third floor of the building. The tank is placed at this height in the building because of its high elevation in relation to the slope of the roof which is beneficial for storing gravitational potential energy for downstream hydroelectric conversion.

A water pipe of 2 inches (0.0508 m) in diameter directs water to a cross-flow microturbine situated before the ground. The system utilises a vertical drop height (gross head) of 4.267 m from the water tank outlet to the turbine nozzle. This gravitational head is sufficient enough to create hydraulic pressure strong enough to drive the turbine and thus, converting potential energy from the stored rainwater into mechanical and subsequently electrical energy. Subsequently, the harvested energy is stored in a battery after the AC output is converted to DC output through energy harvesting circuits (Fig. 2).

Fig. 2. Hybrid renewable energy system distribution board

To calculate the flow rate of water through the turbine, the volumetric method was employed, relying upon the primary hydrological formula:

$$Q = \frac{V}{t} \qquad \text{Equation (1)}$$

Where, Q is the flow rate, V total volume of water discharged (m³), and t is time taken for full discharge (s) [19]. A solar PV subsystem was included into the system to assist the rainwater-fed turbine to preserve operationality during low precipitation months particularly during the March to November inter-monsoonal dry phase in Malaysia. The PV system has a single monocrystalline solar panel with mechanical specifications of 1640 mm × 990 mm × 35 mm and is rated at 30 V / 300 W. [20] said that this particular panel type was chosen due to its high efficiency and strong performance under the extreme temperatures and solar irradiance typical for Malaysian regions. The power output and size of the solar panel are sufficient to satisfy the auxiliary load demand of the system. In terms of inverters, a SUOER FPC 1000AL (12 V) was installed to accommodate the need to convert DC electricity from the PV panel into AC power. The 1000W wave inverter has an integrated digital display which provides monitoring in real time of voltage, frequency, and load, thus ensuring stable operation of the other components which are connected.

To control the flow of power between the PV module and the energy storage system, a FELICITY MPPT Solar Charge Controller (SCCM4524-II) has been implemented. Supporting configurations of both 12 V and 24 V, this second-generation controller can accept a maximum current of 45 A. Furthermore, the use of MPPT technology or maximum power point tracking allows the system to control operating points dynamically to increase the energy harvest to improve system efficiency [21]. For energy storage, the system employs a LEOCH VRLA battery (model L0002) rated at 12 V / 105 Ah. It was the first choice due to operational dependability, a sealed construction, and compatibility with cycles of sporadic solar power availability. The battery stores power generated during sunny periods and provides electricity during cloudy weather or at night to support uninterrupted system operations.

Also, a tap for non-potable uses like irrigation was added to the water storage tank in order to conserve water [22]. In order to maintain functionality during prolonged dry periods, a solar PV system was incorporated into the design. The PV panels produce power that is used to control a water pump which fills the turbine when there's not enough natural head pressure. This form of hybridization solves the issues associated with Malaysia's rainfall and solar radiation pattern [23].

Fig. 3 flow diagram shows how the solar PV subsystems interact with the rainfall hydropower one. Rainwater gathered on the rooftop is stored on the third level and fed through a cross-flow turbine to produce power. Hydro controller controls the turbine output. At the same time, solar energy is collected by a PV panel and controlled by an MPPT controller. Both types of renewable energy are used to charge a joint battery storage system. The DC power from the battery is processed into AC power through the inverter and then supplied to loads. This figure focusses on the hybrid power system control philosophy adopted to maintain continuous power supply for diverse environmental conditions.

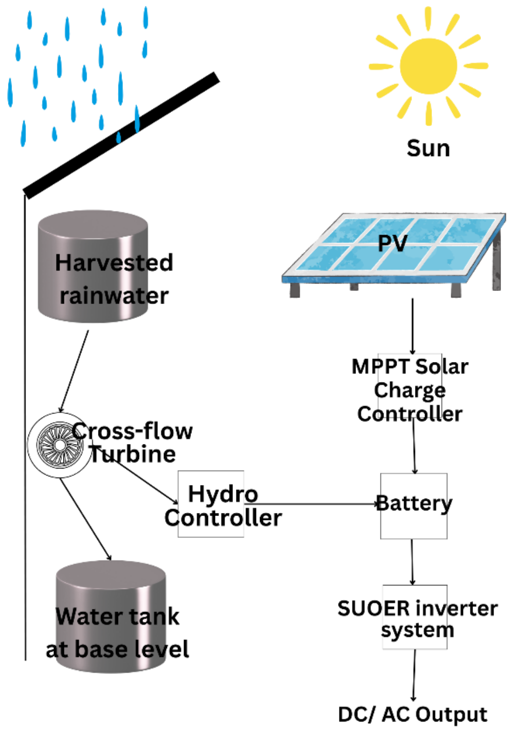

Fig. 3. Energy Flow Architecture of the Hybrid Rainwater–Solar PV Power System

3. RESULT AND DISCUSSION

3.1 Hydroelectric Output Performance

The micro-hydroelectric subsystem underwent isolative assessment testing with the solar PV module disassembled to evaluate its energy generation capabilities. The water storage tank utilised collected rainwater to fill up completely. The stored water was let go under pressure, descending through a pipe to stimulate the cross-flow microturbine stationed at the base level. To totally empty the tank through the turbine, the system needed 11 minutes (660 seconds). This corresponds to a calculated average flow rate of:

$$Q = \frac{V}{t} = (1.76 \text{ m}^3)/660 \text{ s} = 0.00267 \text{ m}^3/\text{s}$$

Where, Q is flow rate, V is volume of water and t is elapse time. In the course of this flow event, the turbine successfully produced an average electrical energy of 16 V and 0.013 A which corresponds to power output of:

$P_{hydro} = V \times I = 16 \text{ V} \times 0.013 \text{ A} = 0.208 \text{ W}$
$E_{hydro} = P \times t = 0.208 \text{ W} \times 660 \text{ s} = 137.28 \text{ J}$ (≈0.038 Wh)

Where P is power, V represents voltage and I is current. As stated previously, the modest power output is in alignment with the head height (4.267 m), cubic flow per second, and the expected range of efficiency (30 % - 50 %) of micro-hydropower small cross-flow turbines. Furthermore, it demonstrates the losses due to friction included in the pipe, nozzle and turbine conversion loss inefficiencies [24].

In this study, Darcy–Weisbach equation was used to estimate the frictional head loss in the vertical 2-inch (0.0508 m) pipe, length of 6 m (assumed) and friction factor f ≈ 0.03f ≈ 0.03f ≈ 0.03 for PVC [25, 26]. This resulted in an estimated head loss of 0.52 m, reducing the effective hydraulic head to 3.75 m from 4.267 m. We further estimated theoretical output based on the power equation $P = \eta \rho g Q H$ using estimated turbine efficiency of 40%, Q=0.00267m^3/s and H = 3.75 m = 3.75, yielding ~ 39.3 W. The actual measured output (0.208 W) reflects cumulative real-world losses stemming from poor turbine geometry, inefficiencies related to nozzle construction, mechanical transmission losses, and electrical conversion inefficiencies. This indicates a nominal system efficiency of less than 1%, which is in line with the prototype scale and non-optimized experimental configuration. The summary of estimated losses system as shown in Table 1.

Table 1: Summary of estimated head losses, theoretical output, and actual performance of the rainwater hydroelectric subsystem. Losses reflect pipe friction, limited head height, and turbine inefficiencies inherent in early-stage prototype configurations.

Loss Component	Parameter / Assumption	Estimated Loss	Remarks
Friction Loss (pipe)	2" PVC pipe, 6 m length, f = 0.03, v ≈ 2.62 m/s	~0.52 m head loss (~12%)	Calculated using Darcy–Weisbach equation
Effective Head	Initial head = 4.267 m	Reduced to ~3.75 m	After accounting for pipe friction

Theoretical Output Power	η = 0.40, Q = 0.00267 m³/s, H = 3.75 m	~39.3 W	Based on standard hydro power formula
Measured Output Power	16 V × 0.013 A	0.208 W	Output measured at turbine terminals
Overall System Efficiency	Actual vs. theoretical output	~0.53%	Reflects combined hydraulic, mechanical, and electrical inefficiencies
Likely Additional Losses	Nozzle turbulence, turbine design, power conversion	Unquantified	To be addressed in future design optimizations

3.2 Photovoltaic Output Performance

The PV subsystem includes a 300W (30 V) monocrystalline solar panel connected via a FELICITY MPPT controller and SUOER inverter system. Observations during peak daytime operation producing 38 watts of power, with 13.4 V and 2.9 A. This value aligns with the output from a solar panel operating under moderate solar irradiance, not at peak noon levels. If the system is rated at 300 W this means the panel is producing about 12.7% of its peak-rated power at the time. The change in the output value can be due to factors like partial shading, the angle at which the solar panel is mounted, or surrounding temperature influences including the ambient temperature [27]. The hybrid system showed promising results, with solar energy effectively supporting the hydroelectric system during low rainfall months. Table 1 indicate the summary of estimated losses in Rainwater Hydroelectric Subsystem**.**

3.3 Hybrid Renewable Energy Output Performance

The system, which consists of PV and hydropower subsystems, provides a steady supply of electricity. In order to ensure continuous energy generation during rainfall, the hydro subsystem will serve as the main energy source while maintaining PV panel operation. The PV subsystem takes over as the main energy source during dry seasons or times with little rainfall, enabling system operation. The system is set up in a hybrid configuration to compensate for the limits of the subsystems and guarantee operational efficiency all year long. In comparison, the hybrid configuration has increased performance in terms of energy availability and energy reliability because the solar subsystem increases energy production during dry periods and conversely the hydro subsystem becomes dominant in the wet season. The average energy production of the whole system with both subsystems is greater than that of a stand-alone hydroelectric or PV system. This clearly demonstrates the advantages of these fundamentally different systems working together to utilize the natural resources in a tropical region**.**

The current research has explained how effective a hybrid renewable energy system is which consists of micro-hydroelectric and photovoltaic technologies, using collected rain water and solar energy as aids. Testing the hydroelectric subsystem in isolation revealed that a tank with 1.76m³ volume that discharges in excess of 11minutes provides an average power output of 0.208 W, thus, in total energy the system yields close to 137.28 J (0.038 Wh). However, given the gross head of the system was bound to a limited (4.267 m), flow rate of 0.00267 m³/s and cross-flow turbine's efficiency of 30-50 % – this outcome is in somewhat-expected results. It also coupled output losses due to internal pipe friction and mechanical inefficiencies of the turbine. At the same time, the PV subsystem's energy output remained stable, providing 38 W of output under moderate irradiance levels with a voltage of 13.4 V and current of 2.9 A. Due to changing weather conditions, less than optimal tilt angles, and overheating, the solar panel with 300 W rating could only deliver around 12.7 % of its maximum output. Still, the solar subsystem performed better than the hydro subsystem during the dry seasons.

Across diverse geographical contexts, comparative studies reveal the immense prospects of hybrid renewable systems in energy security, economic viability, and environmental sustainability. In Nigeria, the study looked at the performances of a hybrid system, comprising PV, hydro, diesel, and battery storage. Here, performance-wise, the hybrid system achieved a commendable renewable fraction of about 77.2 %, thereby reducing carbon dioxide (CO_2) emissions by about 77.1 %, compared to the conventional PV/diesel systems-a clear whitewash in the environmental standing of the hybrid designs, as the lesser dependence on fossil fuel practically translates to a drastic reduction in greenhouse emissions. The hydro-PV configurations provide a balanced energy supply mix, also taking advantage of solar energy during the day and hydropower when it is raining to guarantee continuous energy supply [28].

In Uganda Kisiizi Hydro Power Mini-Grid was developed by using a hybrid approach of solar PV, hydro, and diesel generators to deliver reliable electrification to the rural areas. With this strategic mix, renewable (solar and hydro) and non-renewable (diesel) energy backup is supplied to maintain energy stability, especially where energy supply is subject to seasonal variation. In this hybrid set-up, the operational costs are reduced; energy remains more resilient through an assured supply during bad weather conditions. Hence the model can really serve to electrify rural areas in developing regions where energy access is still an issue [29].

A hybrid micro-hydro as well as solar PV system is optimized using HOMER Pro software for provision of efficient as well as appropriate energy to off-grid communities within Assam, India. For the optimisation process, energy load, cost, and system efficiency have been assigned high priority such that the resultant end system design not only shows technical feasibility but also financial acceptability. The hybrid system leverages locally available renewable resources as a renewable solution for rural electrification instead of installing a large grid infrastructure [30].

A study by [31] investigated the design and modelling of a hybrid mini-hydro and solar PV microgrid system for rural electricity in Ethiopia's Gilgel Abay river valley. The system consisted of a 174.2 kW hydropower plant, a 48 kW solar PV array, and a 226.3 kWh battery storage system. The hybrid system used 100% renewable energy, providing continuous electricity to around 292 homes and community centres. The cost of energy was estimated at $0.08/kWh, indicating economic sustainability and environmental friendliness.

Likewise, in Malaysia, a study was conducted in Selangor that identified the optimum configuration of hybrid systems for rural electrification with PV-hydro-grid. This design presented lower net present costs and higher penetration of renewable energy compared to the conventional grid-connected systems. The hybrid system thus has the ability to adapt itself to local demand for energy while also maximizing the application of clean energy resources. In this way, it drastically cuts down the operation costs as well as the levels of pollution [32].

The findings of these comparative studies lead to the conclusion of better performance of hybrid renewable energy systems across various conditions. They demonstrate how locally adapted solutions, integrating local renewable resources (solar, hydro) and optimised control systems, are able to provide guaranteed energy supply, improve energy efficiency, and reduce environmental footprint. Not only do such systems ensure contribution to global sustainability goals, but they also offer viable solutions to energy access, particularly in remote or rural areas.

The potential of this hybrid system for wider use in institutional buildings or in off-grid rural communities is encouraging though challenging aspects exist. To capture more rainwater, more roof area should be provided in larger buildings, but larger storage tanks and mounting that could withstand the loads, in addition to increasing the size or number of turbines to handle greater hydraulic flows, would be required [18]. In the case of rural electrification, logistical issues like the absence of adequate maintenance support, initial capital requirement, and the necessity of training the communities for operating and maintaining the system, may limit implementation [33]. Besides, the PV component scaling up would also require multiple module integration, higher inverter capacity, and stronger charge controller to handle increasing power [34]. Hence, although the system is intrinsically modular and expandable, on-site feasibility studies should be conducted in future to adapt the design to individual site conditions and to maximize the energy-yield potential in different environmental and socio-economic context.

While the study did not conduct a comprehensive cost-benefit analysis (CBA), initial economic insights show the hybrid systems are likely to provide much better long-term payback compared to stand-alone PV or micro-hydro alone. The use of two sources of input means that energy output is far stabler, season by season, reducing reliance on grid power or diesel generators (primarily for off-grid applications). This hybrid system is also cost competitive with traditional gas or diesel-based energy systems and helps avoid fuel costs and reduce carbon emissions compared to traditional fossil fuel-based energy systems [35]. Although stand-alone solar PV systems might have lower capital costs, the resource is intermittent and underperforms during the monsoon season, as do stand- alone micro-hydro systems which are heavily reliant on available rainfall.

According to literature, hybrid PV-hydro systems may reduce the LCOE and increase the renewable fraction. New studies confirm the economic feasibility of hybrid solar PV–micro-hydro plants, particularly for off-grid or decentralized contexts. In their 2024 work, an off-grid solar PV–hydro was optimized using HOMER Pro simulation and genetic algorithms and LCOE was reported to be USD 0.0453/kWh which was an indication towards boosting the contribution of hydropower to improve the economic feasibility of the components, and meanwhile to lower down dependency on energy storage systems [36]. Another work investigating an empirical PV/hydro/battery hybrid for rural electrification presents an LCOE of USD 0.0953/kWh, 36 than that of a standalone PV–battery (USD 0.29/kWh) which benefits from mutual load profile such as a hybrid system (62.5% PV, 37.5% hydro) [37].

In addition, a review article published recently highlights that dispatchable hydropower can substantially enhance grid stability and lower LCOE in a PV-integrated system by counteracting the intermittency of solar radiation and affording the flexible following of load, two functions well within reach for hydropower [38]. These results validate our rationale for the hybrid design, and have great potential for long term financial sustainability especially in the monsoon-tropical setting such as Malaysia. But then it would need higher cap investments to scale this up, intensive system adaptations, and project specific engineering for an optimal cost effectiveness.

The conceptual design of the hybrid renewable energy system is highly feasible for wide application in different tropical and monsoon affected regions capturing solar and rainwater resources based on seasonal adjustability. This is similar to the hydrometeorological regime in many countries in Southeast Asia (e.g., Indonesia, Philippines)[39], sub-Saharan Africa (e.g., Uganda, Ghana) [40] , and tropical Latin America (e.g., Colombia, Brazil), where solar insolation is at maximum during dry seasons, while rainwater is abundant in wet periods . The modularity of the system, with adjustable catchment sizes and rainwater tank volumes, as well as different PV capacities, provides an opportunity for local optimization based on a range of building sizes, level of rainfall intensity and energy requirements [41]. Moreover, the integration with standalone community mini-grids and distributed rural electrification programmes increases its relevance at policy level, in particular for areas where the cost of national grid expansion is deemed high [42]. An attempt to implement such adaptation would involve the development of guidelines for determining the adequacy of water storage, analysis of building rooftop geometry, and consideration of available local maintenance and cost-benefit criteria. However, the model adds to the international dialogue about distributed clean energy and it is aligned with UN Sustainable Development Goals (SDGs), notably SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

4. CONCLUSION

In a tropical climate, this study effectively illustrates the development of rainwater hydroelectric and solar technologies for renewable energy towards sustainability campus in supporting sustainability campus in Green Campus agenda. By using solar energy during dry seasons and collected rainwater during monsoon seasons, the system, which was installed at Universiti Sultan Zainal Abidin (UniSZA), takes advantage of Malaysia's seasonal changes. The micro-hydroelectric subsystem produced a modest energy output of 0.208 W, influenced by limited head height and flow rate, while the PV system generated 38 W under moderate irradiance, showcasing better reliability in dry seasons. When combined, the hybrid system achieved greater energy availability and operational stability than either subsystem alone, highlighting the synergistic benefits of integrated renewable technologies. This approach not only supports Malaysia's clean energy transition goals but also offers scalable solutions for sustainable energy generation in other tropical and off-grid environments. In the next phase of this study, a long-term, continuous surveying of the hybrid system will be made over several Northeast and Southwest monsoon cycles to assess the reliability, robustness, and effectiveness of the hybrid system over various seasonal hydrometeorological conditions. This longitudinal evaluation is critical to establish the stability of the system and its potential for a broader dissemination in the tropical context. Further research is needed on the systematic optimisation of the system by increasing storages, upgrading turbine design, on-line data acquisition and the adaptive parameterisation to changing climatic and hydraulic conditions.

ACKNOWLEDGEMENT

This research has been carried out under Geran Dalaman Penyelidikan Universiti RG010 (UniSZA/2023/KELESTARIAN/10) provided by Universiti Sultan Zainal Abidin (UniSZA).

5. REFERENCES

[1] Bai, Wuliyasu, Long Zhang, Shengfang Lu, Jingzheng Ren, and Zhiqiao Zhou. "Sustainable energy transition in Southeast Asia: Energy status analysis, comprehensive evaluation and influential factor identification." Energy 284 (2023): 128670.

[2] Otieno, Okendo Edwin, and Farzaneh Hooman. "Optimal Allocation of Renewable Energy Resources to Improve Voltage Profile and Minimize Power Losses on the Most Critical Buses Prone to Voltage Instability." International Exchange and Innovation Conference on Engineering & Sciences, 2024.

[3] S. N. F. Abdullah, A. Ismail, H. Juahir, R. B. Ahmad, F. Lananan, N. M. Hashim, N. Ariffin, M.A. Zali, T. A. T. Mohd, M. H. K. Hussin, R. I. S. R. Mahmood, J. F. A. Jamil, S. M. Desa. Chemical Composition of Rainwater Harvested in East Malaysia. Environmental Engineering Research, 27(2) (2022) 200508–0. https://doi.org/10.4491/eer.2020.508.

[4] F. S. M. Chachuli, N. A. Ludin, M. A. M. Jedi, N. H. Hamid. Transition of Renewable Energy Policies in Malaysia: Benchmarking with Data Envelopment Analysis. Renewable and Sustainable Energy Reviews, 150 (2021) 111456. https://doi.org/10.1016/j.rser.2021.111456.

[5] Ohtaki, Michitaka. "Frontiers of Oxide Thermoelectric Materials for Power Generation Applications." In International Exchange and Innovation Conference on Engineering and Sciences, vol. 10, pp. XXVIII-XXIX. Kyushu University, 2024.

[6] MALAYSIA RENEWABLE ENERGY ROADMAP (MYRER) – Renewable Energy Malaysia. (2021). Retrieved from: https://www.seda.gov.my/reportal/myrer/

[7] S. S. A. Wahid, M. S. Ramli, Z. A. Noorden, K. K. Hassan, S. A. Azli. 2017. "A Review on Highlights and Feasibility Studies on Solar Energy Utilization in Malaysia." AIP Conference Proceedings 1875, (September 2012). https://doi.org/10.1063/1.4998385.

[8] S. N. F. Abdullah, A. Ismail, H. Juahir, L. Badlishah, R.A. Faturrahman, R. Umar, M.K.A Kamarudin, and N.H. Muzlinda. Rainwater Harvesting Opportunities: Water Resource Sustainability. Journal of Sustainability Science and Management, 17 (1) (2022) 84-98. http://doi.org/10.46754/jssm.2022.01.006.

[9] N. A. Osman, C. W. Qin. Pre-Feasibility Study on the Suitability of the Installation of Wind Solar Hybrid Energy System in Peninsular Malaysia. Journal of Materials Science and Applied Energy, 6 (3) (2017) 200–204. http://eprints.intimal.edu.my/1071/.

[10] A. A. K. Alhijazi, R. A. Almasri, A. F. Alloush. A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review. Sustainability (Switzerland), 15 (24) (2023) 1–24. https://doi.org/10.3390/su152416803.

[11] W. Wu, H. R. Maier, G. C. Dandy, M. Arora, A. Castelletti. The Changing Nature of the Water–Energy Nexus in Urban Water Supply Systems: A Critical Review of Changes and Responses. Journal of Water and Climate Change, 11 (4) (2020) 1095–1122. https://doi.org/10.2166/wcc.2020.276.

[12] M. Kaur, S. Garg, R. Sharda, K. G. Singh. Effect of Seasonal Variation on the Performance of Solar Photovoltaic Pumping System under Field Conditions. Indian Journal of Agricultural Sciences, 89 (5) (2019) 867–72. https://doi.org/10.56093/ijas.v89i5.89673.

[13] A. W. Azhari, K. Sopian, A. Zaharim, M. Al Ghoul. 2008. A New Approach for Predicting Solar Radiation in Tropical Environment Using Satellite Images - Case Study of Malaysia. WSEAS Transactions on Environment and Development, 4 (4) (2008) 373–78.

[14] S. Rahman, M. T.R. Khan, S. Akib, N. Che Din, S. K. Biswas, S. M. Shirazi. Sustainability of Rainwater Harvesting System in Terms of Water Quality. The Scientific World Journal, (2014). https://doi.org/10.1155/2014/721357.

[15] U. O. Ikitde, A. A. Adebiyi, I. E. Davidson, and A. S. Akinyemi. Enhanced Electric Power Adaptability Using Hybrid Pumped-Hydro Technology with Wind and Photovoltaic Integration. Energy Engineering: Journal of the Association of Energy Engineering, 120 (9) (2023)1939–1961. https://doi.org/10.32604/ee.2023.027574.

[16] R. H. Virgianto, Q. A. Kartika. Simulation of Rainwater Harvesting Potential to Satisfy Domestic Water Demand Based on Observed Precipitation Data in Jakarta. Journal of Engineering and Technological Sciences 53 (6) (2021) 210604. https://doi.org/10.5614/j.eng.technol.sci.2021.53.6.4.

[17] A. F. A. Jalil, J. Pasupuleti, M. R. B. Khan. 2019. Feasibility Evaluation of Micro-Hydropower System Generation for Different Types of Sewage Treatment Plants. International Journal of Recent Technology and Engineering (IJRTE), 8 (4) (2019) 6338–41. https://doi.org/10.35940/ijrte.d5117.118419.

[18] M. Z. M. Salleh, M. N. M. Nasir, Z. H. Bohari, M. F. Sulaima, E. Z. Ahmad, M. F. Baharom, P. J. Soh. Integrating Micro-Hydro and Solar PV in Rainwater Harvesting: A Hybrid Generation Approach. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 121 (2) (2024) 106–31. https://doi.org/10.37934/arfmts.121.2.106131

[19] T. Uchiyama, S. Miyamoto, K. Horie, K. Takamure. Simultaneous Measurement of Volumetric Flowrates of Gas–Liquid Bubbly Flow Using a Turbine Flowmeter. Sensors 23 (4270) (2023) https://doi.org/10.3390/s23094270.

[20] P. Karunakaran, A. K. S. Lau, A. N. R. Reddy. Photovoltaic versus Micro-Hydropower for Rural Non-Grid Connected Areas of Equatorial Sarawak. Journal of Telecommunication, Electronic and Computer Engineering, 8 (12) (2016) 129–33.

[21] D. Mazumdar, C. Sain, P. K. Biswas, P. Sanjeevikumar, B. Khan. Overview of Solar Photovoltaic MPPT Methods: A State of the Art on Conventional and Artificial Intelligence Control Techniques. International Transactions on Electrical Energy Systems, (2024) https://doi.org/10.1155/2024/8363342.

[22] S. N. F. Abdullah, A. Ismail, H. Juahir, F. Lananan, N. M. M. Hashim, N.Ariffin, T. A. T. Mohd. Estimation of Rainwater Harvesting by the Reflectance of the Purity Index of Rainfall. Environmental Science and Pollution Research, 28 (27) 35613-35627. https://doi.org/10.1007/s11356-021-12772-6.

[23] K. V. Teong, K. Sukarno, J. H. W. Chang, F. P. Chee, C. M. Ho, J. Dayou. The Monsoon Effect on Rainfall and Solar Radiation in Kota Kinabalu. Transactions on Science and Technology, 4 (4) 2017 460–465. http://transectscience.org/.

[24] Mafruddin, S. D. Handono, D. Irawan, K. Ridhuan. Improving Turbine Performance by Optimizing Nozzle Design. International Journal of Engineering Trends and Technology, 72 (12) (2024) 55–63.

[25] F. Ntengwe, M. Chikwa, L. Witika. Evaluation Of Friction Losses In Pipes And Fittings Of Process Engineering Plants. International Journal of Scientific & Technology Research, 4(10) (2015) 330-336. https://doi.org/10.14445/22315381/IJETT-V72I12P105

[26] N. Musa, .J. Y. Jiya, T. K. Aderoju, Development of a Test Rig for the Determination of Headloss and Friction Factor of Polyvinyl Chloride (PVC) Pipes. Journal of Energy Technologies and Policy, 6 (5) (2016) 17–24.

[27] C. Saiprakash, A. Mohapatra, B. Nayak, and S. R. Ghatak. Analysis of Partial Shading Effect on Energy Output of Different Solar PV Array Configurations. Materials Today: Proceedings, (2021). https://doi.org/10.1016/j.matpr.2020.08.307.

[28] J. O. Oladigbolu, M. A. M. Ramli, Y. A. Al-Turki. Optimal Design of a Hybrid PV Solar / Micro-Hydro / Diesel / Battery Energy System for a Remote Rural Village under Tropical. Electronics, 9 (2020) 1491. doi:10.3390/electronics9091491.

[29] R. Cartland, A-M. Sendegeya, J. de D. K. Hakizimana. Performance Analysis of a Hybrid of Solar Photovoltaic, Genset, and Hydro of a Rural-Based Power Mini-Grid: Case Study of Kisiizi Hydro Power Mini-Grid, Uganda. Processes, 11 (1) (2023) https://doi.org/10.3390/pr11010175.

[30] R. R. Kanna, R. R. Singh. A Feasibility Study on Balarbhita for Advancing Rural Electrification with a Solar—Micro-Hydro Hybrid System. Frontiers in Energy Research, 10 (2022) 960045. https://doi.org/10.3389/fenrg.2022.960045.

[31] G. N. Checklie, T. Tadiowose, N. A. Ejigu. Design and Modeling of Hybrid Solar PV/Mini Hydro Micro-Grid Systems for Rural Electrification: A Case of Gilgel Abay River, Ethiopia. Journal of Electrical Power & Energy Systems, 7 (1) (2023) 26–46. https://doi.org/10.26855/jepes.2023.06.005.

[32] H. Borhanazad, S. Mekhilef, R. Saidur, G. Boroumandjazi. 2013. Potential Application of Renewable Energy for Rural Electrification in Malaysia. Renewable Energy, 59 (2013) 210–19. https://doi.org/10.1016/j.renene.2013.03.039.

[33] S. A. Vincent, A. Tahiru, R. O. Lawal, C. E. Aralu, Hybrid renewable energy systems for rural electrification in developing countries : Assessing feasibility , efficiency , and socioeconomic impact. World Journal of Advanced Research and Reviews, 24(2) (2024) 2190–2204.

[34] Al Hasibi, R. A., Haris, A. An analysis of the implementation of a hybrid renewable-energy system in a building by considering the reduction in electricity price subsidies and the reliability of the grid. Clean Energy, *7*(5) (2023)1125–1135. https://doi.org/10.1093/ce/zkad053

[35] K. R. Ajao, O. A. Oladosu, Popoola, O. T. Cost-Benefit Analysis of Hybrid Wind-Solar Power Generation by Homer Power Optimization Software. Journal of Applied Science and Technology (JAST)*, 53*(9) (2011) 167–169.

[36] C. D. Iweh, G. C. Semassou, R. H. Ahouansou, Optimization of a Hybrid Off-Grid Solar PV—Hydro Power Systems for Rural Electrification in Cameroon. Journal of Electrical and Computer Engineering, (2024) https://doi.org/10.1155/2024/4199455

[37] R. R. Kanna, R. R. Singh,. A feasibility study on Balarbhita for advancing rural electrification with a solar—Micro-hydro hybrid system. Frontiers in Energy Research, 10 (2022) 960045. https://doi.org/10.3389/fenrg.2022.960045

[38] C. D. Iweh, E. R. Akupan,. Control and optimization of a hybrid solar PV – Hydro power system for off-grid applications using particle swarm optimization (PSO) and differential evolution (DE). Energy Reports, *10* (2023) 4253–4270. https://doi.org/10.1016/j.egyr.2023.10.080

[39] T. Phan-Van, P.,Nguyen-Ngoc-Bich, T. Ngo-Duc, T. Vu-Minh, P. V. V. Le, L. Trinh-Tuan, T. Nguyen-

Thi, H. Pham-Thanh, D. Tran-Quang. Drought over Southeast Asia and Its Association with Large-Scale Drivers. Journal of Climate, 35(15) (2022) 4959–4978. https://doi.org/10.1175/JCLI-D-21-0770.1

[40] M. L. Griffiths, , K. R. Johnson, F. S. R. Pausata, J. C.White, G. M. Henderson, C. T. Wood, H. Yang, V. Ersek, C. Conrad, N. Sekhon, End of Green Sahara amplified mid- to late Holocene megadroughts in mainland Southeast Asia. Nature Communications, 11(1) (2020) 1–12. https://doi.org/10.1038/s41467-020-17927-6

[41] D. Palit, A. Chaurey Off-grid rural electrification experiences from South Asia: Status and best practices. Energy for Sustainable Development, 15(3) (2011) 266–276. https://doi.org/10.1016/j.esd.2011.07.004

[42] M. Semaan, S. D. Day, M. Garvin, N. Ramakrishnan, A. Pearce. Optimal sizing of rainwater harvesting systems for domestic water usages: A systematic literature review. Resources, Conservation and Recycling: X, 6(February), (2020) 100033. https://doi.org/10.1016/j.rcrx.2020.100033