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DESIGN OF AN INTEGRATED SOLUTION FOR A PORTABLE HYBRID RENEWABLE ENERGY SYSTEM

Aitor F. Jiménez[1], Rodolfo E. Valdés[1], Ahmed G. Yosry[1,3,*], Eduardo Á. Álvarez[1], Eduardo B. Marigorta[2], Helena M. Ramos[4], Aonghus McNabola[5]

[1]Centro Universitario de Investigacion y Desarrollo del Agua (CUIDA), University of Oviedo, Mieres, Asturias, Spain
[2]Fluid Mechanics Area, Energy Department, campus de Gijón, University of Oviedo, Gijón, Asturias, Spain
[3]Mechanical Power Department, Faculty of Engineering, Port Said University, Port Said, Egypt
[4]Civil Engineering Research and Innovation for Sustainability (CERIS), University of Lisbon, Lisbon, Portugal
[5]School of Engineering, RMIT University, 124 La Trobe St., VIC 3000, Melbourne, Australia

ABSTRACT

Portable hybrid renewable energy systems provide flexible power solutions for remote and temporary applications. However, most existing portable micro-grids exhibit limited hybridization and lack experimental validation. This work presents HY4RES, a fully portable hybrid renewable energy system integrating three renewable systems and a dual energy storage solution based on lithium-ion batteries and a pump-as-turbine (PAT) unit within a standardized 20-ft shipping container. Wind tunnel tests have been conducted to validate the aerodynamic performance of modified Savonius-type rotors under low-speed operating conditions, providing a quantitative basis for system design and integration. In addition, it incorporates a smart energy management architecture based on Internet of Energy concept and Message Queuing Telemetry Transport (MQTT) communication protocols that enable real-time data acquisition, supporting future advanced control strategies.

Keywords: Portable hybrid renewable systems, microgrid energy management, hydrokinetic and wind microgeneration, pump-as-turbine (PAT), Internet of Energy (IoE).

NOMENCLATURE

$MQTT$	Message Queuing Telemetry Transport
$MPPT$	Maximum Power Point Tracking
$VAHT$	Vertical Axis Hydrokinetic Turbine
PMG	Permanent Magnetic Generator
$VAWT$	Vertical Axis Wind Turbine
PP	Number of Pole Pairs
IoE	Internet of Energy
PAT	Pump-as-Turbine
U	Inflow velocity, $[m/s]$
V_{DC}	output voltage, $[V]$
Fe	Electrical frequency, $[Hz]$
C_p	Power coefficient, [-]
P	Turbine power, $[W]$
A	Swept area, $[m^2]$
R	Turbine radius, $[m]$
ρ	Fluid density, $[kg/m^3]$
R	Turbine radius, $[m]$
ω	Rotational speed, $[rad/s]$
λ	Tip speed ratio, [-]

1. INTRODUCTION

The rapid growth of global energy demand, driven by population increase, industrial development and the electrification of new sectors such as transportation, has intensified the need for cleaner and more sustainable electricity generation. According to the International Energy Agency (IEA), global electricity demand is expected to rise by over 25% between 2022 and 2030, largely due to accelerated electrification and digitalization trends [1]. Renewables already supply roughly 33% of global electricity and are projected to surpass 50% of total generation by 2030, driven by declining technology costs. For example, solar photovoltaic (PV) costs have fallen by nearly 90% since 2010, and onshore wind by 70% [2, 3]. Parallel advances in energy storage technologies, digitalization and Smart-Grid strategies are enabling deeper integration of variable renewable energy sources into modern power systems, significantly improving operational flexibility and grid stability [4, 5]. In this context, it is worth highlighting that the primary sources of renewable energy are solar and wind power, accounting for 12% and 10% of global capacity, respectively. In 2022, the global installed capacity of wind energy reached 840 GW, while photovoltaic solar energy totaled 1028 GW [6]. Additionally, hydropower, historically the largest source of renewable energy, maintains an installed capacity of approximately 1330 GW, representing 16% of global

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*Corresponding author: ahmed.gharib@eng.psu.edu.eg capacity. Other emerging low-carbon energy sources, such as ocean currents and tidal power, although still under development, are growing with an estimated global capacity of 1.3 GW, which accounts for less than 1% of worldwide renewable capacity [7]. However, these clean technologies are expected to experience significant growth in the coming years, particularly in regions with abundant hydrographic resources.

Within this global transition, solar and wind energy have become the dominant renewable technologies in terms of newly installed capacity. In 2023, solar energy reached a record of 407 GW, accounting for almost three-quarters of all new renewable installations worldwide [8, 9]. Wind energy also continues to grow, with global installed wind capacity surpassing 1 TW in early 2024 [10]. Conventional hydropower remains the world's largest renewable electricity source, providing approximately 4,300 TWh annually and representing 55% of global renewable generation [11]. In parallel, emerging low-carbon resources (including riverine hydrokinetic turbines, tidal stream generators and marine-current technologies) are gaining attention, particularly in regions with favourable hydrodynamic conditions. These technologies may provide local, predictable renewable power contributions, with small hydrokinetic devices typically producing 50-500 W in small rivers and up to 5-20 kW in large estuarine flows [12, 13]. Beyond large-scale centralized plants, there is increasing interest in distributed and modular renewable energy systems, capable of operating independently of the main grid. Portable hybrid renewable energy systems containerized or skid-mounted, typically ranging from 1 to 20 kW of installed capacity, have emerged as a promising solution for applications such as rural electrification or emergency response, temporary industrial facilities [14, 15]. These systems usually integrate at least two renewable energy sources (for example, PV and micro-wind turbines) together with local storage batteries, all mounted on transportable structures. Their main advantages include rapid deployment (often less than 48 hours), minimal civil works, modular scalability (from 1 to 20 kW) and the ability to adapt the generation mix to the local availability of resources such as irradiance, wind patterns or water flows [16]. Despite their growing adoption, most existing portable hybrid systems remain limited in terms of hybridization depth and functional flexibility. From an engineering standpoint, the design of highly hybridized portable micro-grids poses several challenges, including the coordinated integration of heterogeneous energy sources with distinct temporal characteristics. Additional difficulties arise from the need to select generation technologies capable of operating efficiently under low-speed, turbulent and highly variable flow conditions, which are typical of many deployment environments. Furthermore, ensuring stable and autonomous operation requires the integration of suitable energy storage solutions and the implementation of robust control architectures capable of managing fluctuating resource availability and load demand [17].

The HY4RES system proposed by the University of Oviedo (Spain) directly addresses this gap by combining four small-scale renewable subsystems: solar PV, vertical-axis wind turbines, vertical-axis hydrokinetic turbines and a dual energy storage system based on batteries and pump-as-turbine (PAT) hydraulic storage. All these renewable technologies are installed on a standardized 20 ft shipping container. The system has been deployed at the Port of Avilés (Spain), where it operates under real conditions characterized by turbulent winds, variable irradiance and bidirectional tidal flows, supplying small-scale loads such as lighting, sensing and environmental mitigation equipment.

A distinctive feature of the proposed design is the experimental validation of the selected hydrokinetic turbine technology. Before installation, the turbines have been characterized under controlled laboratory conditions using wind tunnel experiments, allowing the assessment of their aerodynamic performance and supporting the design choices adopted for estuarine operation. This experimental characterization provides a quantitative basis for system integration and performance estimation.

Accordingly, the main contributions of this work are the design of a fully portable hybrid renewable energy system integrating three renewable systems and a dual energy storage solution, the experimental characterization and design validation of the hydrokinetic turbines employed in the system, and the deployment and preliminary performance assessment of the HY4RES demonstrator as a test-bed for advanced control strategies based on $MQTT$ and the Internet of Energy (IoE) and hybrid micro-grid operation.

2. State of the Art of Portable and Hybrid Renewable Energy Systems

2.1 Relevant pilot-scale Systems

Portable and hybrid renewable energy systems have evolved significantly over the past decade, driven by advances in modular low-carbon technologies [18]. These systems are engineered to operate as stand-alone micro-grids, typically integrating two or more renewable subsystems together with electrical storage units, all mounted within transportable platforms [14].

Despite this progress, most commercially available and pilot-scale portable systems exhibit limited levels of hybridization and functional integration. The majority are based on a small number of renewable sources, usually photovoltaic systems coupled with batteries, and adopt relatively simple control strategies. As a result, their ability to exploit resource complementarity and extend operational autonomy remains constrained.

Several projects worldwide illustrate the technological diversity, maturity and operational relevance of portable hybrid renewable systems. For example, the PBX-200 platform developed by Power-Blox (Switzerland) consist of modular "swarm-capable" solar microgeneration blocks delivering up to 1.5 kW per unit, with more than 2,500 units deployed in sub-Saharan Africa and Southeast Asia for decentralized electrification and micro-business development [19]. Its plug-and-play design allows energy units to be interconnected autonomously, enabling aggregation of multiple modules without centralized control. Another example is the BoxPower Solar-Container (United States) that integrates PV modules, lithium-ion batteries and a backup generator into a 10-15 kW containerized platform designed for harsh environments. These systems have played a significant role in wildfire resilience strategies in California, where utility companies have developed portable hybrid containers to maintain critical loads during shut-off events [20]. Also, on a larger scale, the Float-gen (France) offshore wind demonstrator, rated at 2 MW, showcases the feasibility of semi-portable floating platforms for marine energy extraction. The system employs a modular concrete barge foundation that can be towed for deployment and maintenance operations, representing an intermediate concept between permanent offshore installations and portable marine energy units [21]. However, these systems don't incorporate hydrokinetic generation nor hybrid storage devices.

Similarly, Tesla's Portable MegaPack (United States) integrates containerized solar PV arrays with lithium-ion storage systems of up to 3 MWh per unit. These platforms have been used for temporary electrification of construction sites, grid-support applications and emergency power supply during natural disasters, providing rapid deployment renewable capacity with grid-forming inverters and advanced remote monitoring capabilities [22]. Figure 1 shows a picture of the recent developed projects.

More experimental projects include hybrid river-solar microgrid units tested in Canada and Norway, where small hydrokinetic turbines (200-300 W each) are combined with PV arrays to supply riverine communities and scientific outpost [23]. Military research programs in the United States and United Kingdom have also developed hybrid portable micro-grids incorporating foldable PV modules, compact wind turbines and fuel-cell backups to reduce diesel consumption in forward operating bases [24].

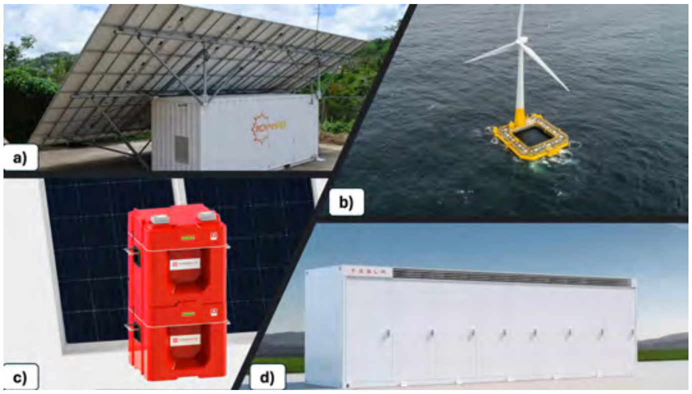


FIGURE 1: Portable, compact and hybrid renewable energy systems: a) BoxPower, b) FloatGen, c) PBX-200 and d) Portable MegaPack.

2.2 Technical Challenges and research gaps

Despite the advances observed, most existing systems remain constrained to micro-generation scales, facing several technical challenges. A primary issue is the efficient coordination of heterogeneous renewable sources operating under variable and unpredictable environmental conditions. Solar, wind and hydrokinetic resources present different temporal profiles and intermittency patterns, requiring advanced forecasting, optimal dispatch algorithms and real-time hybrid control strategies to maximize system reliability [25]. Another challenge involves the storage subsystem, which is often dominated by lithium-ion batteries with limited autonomy in prolonged low-generation periods. Alternative approaches remain under exploded in portable configurations, so the incorporation of novel storage concepts (such as supercapacitors) offers potential improvements in durability and energy flexibility but has yet to be widely adopted [26].

Portability itself introduces engineering constraints related to weight, structural integrity, vibration resistance and environmental exposure. Containerized renewable systems must comply with transport regulations, withstand high humidity, dust ingress, vibration during road or maritime transport and corrosive environments, especially in coastal or industrial locations [27, 28].

Digitalization also represents both an opportunity and a challenge. While modern portable systems increasingly adopt Internet of Things (IoT) devices, edged computing and $MQTT$-based supervisory control architectures, achieving robust, low-latency and cybersecure monitoring remains a significant technical barrier [29]. This is particularly relevant in remote locations with limited connectivity [30].

Economic barriers also persist. Capital costs for portable hybrid systems remain high compared to stationary off-grid installations, due to specialized mounting, ruggedized enclosures, and transport logistics. This limits large-scale deployment in developing regions unless supported by public funding or humanitarian organizations.

From an engineering perspective, several technical gaps remain in the development of portable hybrid renewable energy systems. A key challenge lies in the coordinated integration of heterogeneous renewable sources with distinct temporal behaviours and dynamic responses, such as solar, wind, and hydrokinetic generation [30]. Exploiting the complementarity of these resources requires both appropriate technology selection and advanced energy management strategies.

Energy storage represents an additional limitation, as most portable systems rely exclusively on electrochemical batteries, which may restrict autonomy and accelerate degradation under frequent cycling [26]. The integration of alternative or hybrid storage concepts, such as small-scale hydraulic systems, remains largely unexplored in transportable configurations.

Finally, most existing systems adopt relatively simple supervisory control architectures, often lacking real-time optimization capabilities or advanced monitoring frameworks. As a result, their ability to operate as intelligent, autonomous energy hubs under variable environmental and load conditions is limited. These gaps highlight the need for new portable hybrid concepts that combine multiple complementary renewable sources, diversified storage solutions, and robust control architectures within a compact and portable platform, which is addressed in the present work.

3. Pilot Site Description

3.1 Overall system architecture and layout

The HY4RES pilot plant is implemented as a modular compact-hybrid renewable energy system installed at the Port of Avilés (Spain), on the northern Spanish coast. Its core is a standardized 20 ft shipping container that houses the power electronics, control hardware and part of the storage infrastructure, enabling road-rail-sea transport and rapid deployment demonstrator in different locations within the port area. The facility is conceived as a technological demonstrator to supply small-scale loads such as lighting, environmental mitigation systems and potential recharging points for light electric vehicles, while

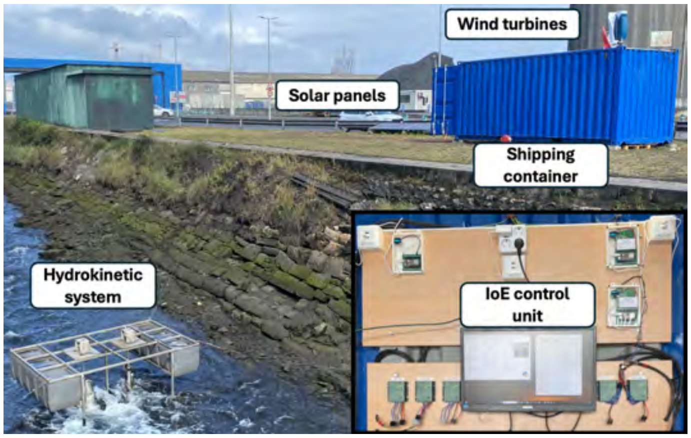


FIGURE 2: General layout of the HY4RES pilot plant.

validating hybrid operation strategies under real port conditions. Figure 2 shows a picture of HY4RES pilot plant.

3.2 Renewable generation subsystems

The hybrid generation system combines four low-carbon technologies: a rooftop wind subsystem consisting of several vertical-axis micro-turbines, a ground-mounted photovoltaic array, a hydrokinetic subsystem installed on a floating or bank-mounted structure in the estuary and a storage system based on both electrochemical batteries and a PAT unit coupled to a water tank. The solar PV system is composed of three monocrystalline modules rated at 0.4 kW each, optimized for variable irradiance conditions and easy maintenance. The array is managed by a dedicated control unit housing the power electronics, maximum power point tracking ($MPPT$) controller and a 2.3 kWh lithium-ion battery, forming the primary electrochemical storage module of the pilot plant. In addition, the PV subsystem includes an integrated data acquisition and communication module that records panel status, solar production and operational parameters, transmitting them in real time to the plant's IoE-based supervisory architecture. Figure 3 shows a picture of the solar PV and the power electronics control device with battery.

The three vertical-axis wind turbines (VAWT) are selected for their ability to operate efficiently in highly turbulent flows and variable wind directions that are typical of port environments, providing a total installed power of 300 W. Two of the turbines employ a modified Savonius drag-based rotor, optimized through geometric refinement of the blades to improve start-up torque and efficiency. The third turbine operates on a lift-based configuration, featuring a three-bladed helical Darrieus rotor designed to ensure smoother rotational dynamics, reduced pulsating torque and improved performance at moderate wind speeds. Figure 4 shows a picture of the three VAWT. The hydrokinetic subsystem is located at the mouth of the river Raíces, nearby the port facilities. It consists of a floating stainless-steel platform that supports two vertical-axis hydrokinetic micro-turbines (VAHT), each rated at 40 W. Both turbines employ a drag-type Savonius rotor configuration, selected for its ability to operate efficiently under low-speed, highly variable and bidirectional flow conditions. This design maximizes the starting torque and maintains stable operation during the approximately 2.5 tidal range that produces alternating flow directions twice daily. Also, each turbine is equipped with a $MPPT$ device, enabling real-time optimization of power extraction under fluctuating hydrodynamic conditions and controlling the 24V battery charging stage. Figure 5 shows a picture of the hydrokinetic floating platform.

FIGURE 3: a) Solar panels on support structure and b) Solar equipment control system and storage battery.

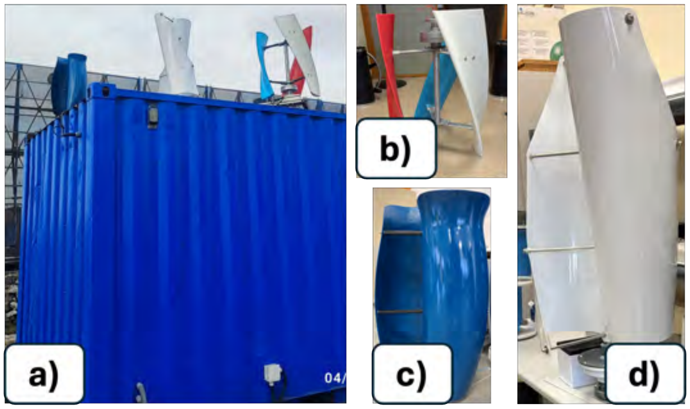


FIGURE 4: a) Wind turbines installed on the shipping container, b) Lift-based helical Darrieus turbine, c & d) Drag-based Savonius VAWT.

3.3 Experimental characterization and design validation of the hydrokinetic turbines

Prior to their installation at the pilot site, the hydrokinetic turbines have been experimentally characterized in a wind tunnel. It should be noted that the results are not directly extrapolable in terms of energy production but are used to corroborate the proper functioning of the rotor under conditions representative of the pilot site. Although turbines are intended to operate in water, experimental characterization has been conducted in air, as aerodynamic testing allows the replication of relevant flow regimes under comparable Reynolds numbers [31]. For the tested rotor geometry and operating range, the Reynolds numbers achieved in

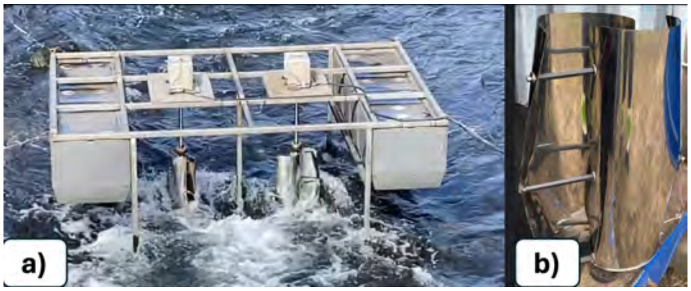


FIGURE 5: a) Hydrokinetic floating platform and b) Drag-based Savonius VAHT.

air are of the same order of magnitude as those expected in water, ensuring dynamic similarity and representative performance coefficients.

Experiments have been carried out in the ETHAN50-ABLWT wind tunnel at the Hydraulic Engineering Laboratory of the University of Oviedo. This facility is equipped with four 180 kW axial fans and allows air velocities of up to 50 m/s, providing controlled flow conditions in test chambers with cross-sectional areas ranging from 2.25 to 5.5 m. In this case, the largest test chamber has been used, making it possible to test a full-scale turbine. Wind speeds of up to 8 m/s are imposed to ensure Reynolds-number similarity with in-field operating conditions (0.8 m/s in water) and to remain consistent with the low-to-moderate flow regimes expected in port and estuarine environments. Figure 6 shows a photograph of the turbine installed in the wind tunnel.

A dedicated instrumentation setup has been implemented to measure both mechanical and electrical variables. The rotational speed (ω) is obtained using a Hall-effect probe mounted on the turbine shaft, while the electrical output voltage (V_{DC}) and the frequency (Fe) of the permanent magnetic generator (PMG) have been monitored using a custom electronic test board. This configuration enables the determination of key dimensionless performance parameters, namely the tip speed ratio ($\lambda = \omega.R/U$) and the power coefficient ($\mathrm{C_p} = P/(0.5.\rho.A.U^3)$), where R is the turbine radius, U is the wind velocity, P is the power extracted from the turbine by the PMG, ρ is the air density and A is the swept area by the blades of the turbine.

The characterization procedure comprised of three main tests. First, the PMG has been characterized to determine the number of pole pairs (pp) and the voltage constant (K_v), yielding a consistent value of 313 $V/krpm$ for 6 pp. The results have confirmed the generator's suitability for low-speed renewable applications and its stable behavior across the operating range. Second, the aerodynamic behavior has been assessed by obtaining the characteristic curve at a constant wind speed of 8 m/s. The results show that the turbine reaches its maximum C_p at 0.16 with a λ of 0.75. This behaviour is characteristic of drag-based Savonius-type rotors and is consistent with values reported in the literature. Figure 7 shows the characteristic curve of the turbine.

Finally, the operation of the commercial $MPPT$ device has been verified under wind tunnel conditions. The PMG is connected to the $MPPT$ and a 24 V battery, and the resulting operating point has been compared with the optimal relationship obtained in the previous test. The measured performance closely matched the predicted values, confirming that the device effectively tracks the maximum power point during the power stage of the turbine.

FIGURE 6: VAWT characterization inside the wind tunnel.

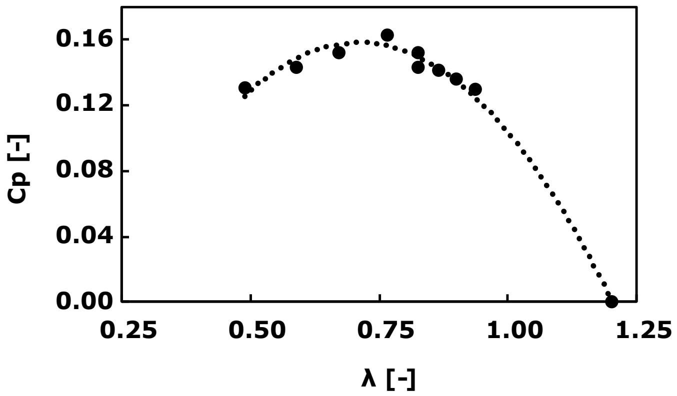


FIGURE 7: The turbine characteristic curve.

3.4 Energy storage subsystem

The energy storage subsystem is implemented through a dual system comprising a conventional battery bank and a hydraulic storage loop based on a PAT unit and a prefabricated water tank of about 0.8 m^3 integrated inside the container. During periods of surplus generation, electrical energy is used to pump water from the channel into the elevated tank; when demand exceeds instantaneous renewable production, the pump operates in turbine mode to recover part of the potential energy stored, emulating the operating principles of a small pumped-storage hydropower plant. It has an installed power of 200 W. This configuration increases the overall flexibility of the micro-grid, enabling peak cutting and

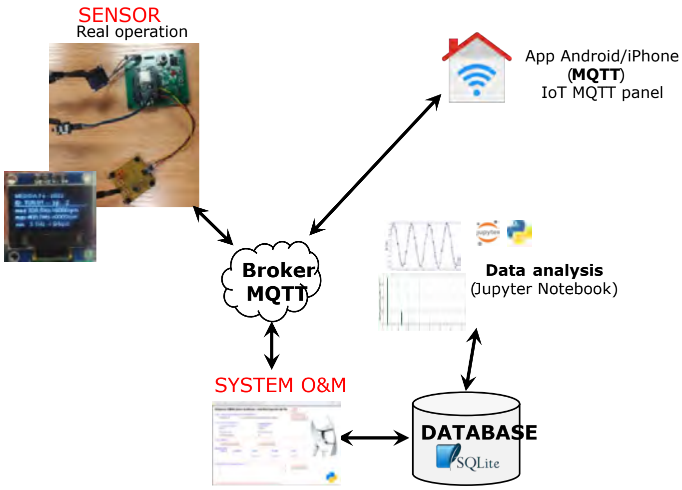


FIGURE 8: Schematic diagram of the control architecture.

improved utilization of intermittent renewable resources.

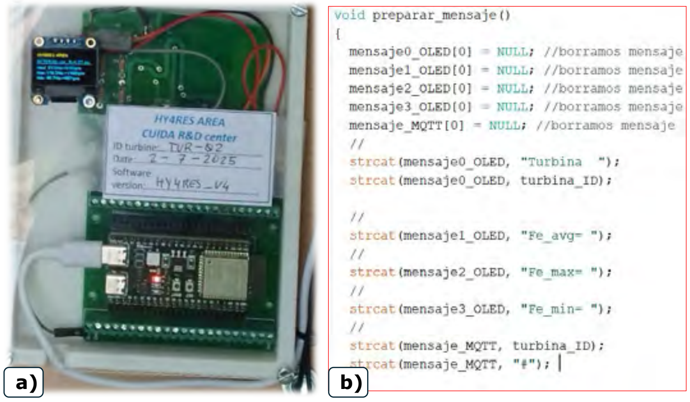
3.5 Energy management and control architecture

All subsystems are coordinated through a Smart Energy Management Architecture (SEMA) based on IoE concept. The architecture integrates distributed sensors, local data acquisition devices, communication hardware and a centralized electronic control board housed inside the sea container. Data acquisition and device supervision are performed using lightweight communication protocols such as $MQTT$, enabling real-time monitoring of generation, storage and load variables while ensuring robust performance under low-bandwidth and intermittent connectivity conditions. Figure 8 shows a descriptive diagram of the control architecture implemented at HY4RES pilot site.

As a first validation step of the proposed digital architecture, a series of pilot tests have been conducted to verify the correct acquisition, transmission and storage of electrical variables. In particular, it has been acquired the Fe from the different $PMGs$. The acquisition system samples the electrical signal at each half-cycle (twelve Fe values on one rotation) which are subsequently averaged to obtain a representative frequency value. This approach allows for the detection of short-term fluctuations while maintaining a compact and manageable dataset for storage and post-processing.

The acquired data are transmitted in real time via the $MQTT$ protocol to a centralized database, where they are stored together with time stamps and system identifiers. Figure 9 illustrates the electronic board and an example snapshot of the pseudocode used to record Fe during a representative operating period. These preliminary tests confirm the correct operation of the sensing devices, the reliability of the communication chain and the availability of a structured data repository suitable for subsequent analysis.

Although no advanced control or optimization algorithms have been implemented at this stage, the successful deployment of the data acquisition and communication infrastructure constitutes a fundamental prerequisite for the development of more sophisticated energy management strategies. The current implementation therefore represents an initial commissioning phase, demonstrating that the HY4RES system is capable of generating, transmitting and storing high-resolution operational data in real time.



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void preparar_mensaje()
{
  mensaje0_OLED[0] = NULL; //borramos mensaje
  mensaje1_OLED[0] = NULL; //borramos mensaje
  mensaje2_OLED[0] = NULL; //borramos mensaje
  mensaje3_OLED[0] = NULL; //borramos mensaje
  mensaje_MQTT[0] = NULL; //borramos mensaje
  //
  strcat(mensaje0_OLED, "Turbina  ");
  strcat(mensaje0_OLED, turbina_ID);

  //
  strcat(mensaje1_OLED, "Fe_avg= ");
  //
  strcat(mensaje2_OLED, "Fe_max= ");
  //
  strcat(mensaje3_OLED, "Fe_min= ");
  //
  strcat(mensaje_MQTT, turbina_ID);
  strcat(mensaje_MQTT, "#");
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FIGURE 9: (a) Electronic board (b) pseudocode of the frequency acquisition system.

Building upon this communication framework, the system supports the implementation of AI-based energy management algorithms and optimization routines, which prioritize renewable energy utilization, minimize battery cycling and coordinate the interactions among the PV, wind, hydrokinetic and PAT subsystems. In this sense, the proposed SEMA provides a scalable and AI-ready framework for advanced control, predictive dispatch and fault detection in portable hybrid renewable micro-grids.

4. Expected Performance and Potential Applications

The expected performance of the HY4RES demonstrator is determined by the combined operation of its four renewable subsystems. On the one hand, under typical coastal irradiance values in northern Spain, the PV subsystem can generate between 1,400 and 1,800 $kWh/year$. On the other hand, the wind subsystem is expected to produce approximately 150-300 $kWh/year$, reflecting the moderate but turbulent wind (4-6 m/s) regimes typical of port environments. Also, the hydrokinetic system provides a continuous low-power contribution estimated at $120-200 kWh/year$, harnessing both bidirectional currents. Finally, the energy storage performance is enhanced by the combination of electrochemical batteries (2.3 kWh of the PV solar array and the four lithium-ion 12V batteries with a total capacity of 600 Wh) and the hydraulic PAT unit. Specifically, it is expected that the PAT subsystem will generate 120-140 $kWh/year$. This hybrid storage strategy reduces battery cycling, improves system resilience and supports stable micro-grid operation during low-generation intervals. Considering the complementarity of solar, wind and hydrokinetic resources, the total expected annual energy yield of the HY4RES system lies between 1,800 and 2,400 $kWh/year$. This makes the demonstrator suitable for powering small-scale loads such as lighting, environmental monitoring and auxiliary equipment, while validating advanced control strategies based on IoE and AI-driven optimization for autonomous hybrid micro-grid management. Figure 10 illustrates the main energy statistics of the proposed portable plant.

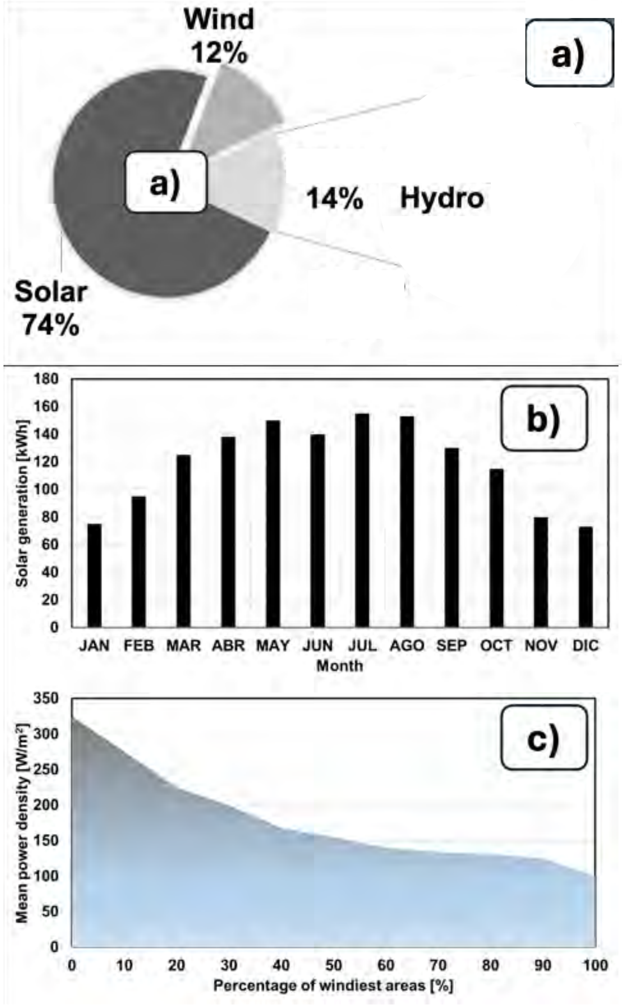

FIGURE 10: Main energy characteristics of the demonstrator: (a) renewable energy distribution, (b) solar potential, and (c) wind potential.

The presented values correspond to annual yields based on resource availability and subsystem characterization. It should be noted that these are estimates, so production will be monitored in the future to establish correlations and verify the predictions made.

5. CONCLUSIONS

This work has reviewed the current state of the art of portable hybrid renewable energy systems and has presented the HY4RES demonstrator as an integrated and experimentally supported solution. While most existing portable micro-grids remain limited in terms of hybridization depth, storage diversity and control sophistication, the proposed system combines three complementary renewable technologies—solar photovoltaic, vertical-axis wind turbines, vertical-axis hydrokinetic turbines and a dual energy storage solution based on lithium-ion batteries and a pump-as-turbine (PAT) unit—within a fully transportable 20-ft container equipped with an IoE-based supervisory architecture. A key contribution of this work is the experimental characterization of the hydrokinetic turbines prior to their deployment. Wind tunnel tests have been conducted to validate the aerodynamic behaviour of the selected Savonius-type rotors under low-speed operating conditions, ensuring Reynolds-number similarity with in-field operation. These experiments provide quantitative performance indicators that supported the design choices adopted for the pilot plant and strengthened the engineering basis of the system integration.

The deployment of HY4RES at the Port of Avilés demonstrates the technical feasibility of operating a multi-source hybrid renewable system under complex environmental conditions, including turbulent winds, variable irradiance and bidirectional tidal flows. The estimated annual energy production ranges between 1,800 and 2,400 kWh, confirming the system's suitability for supplying small-scale loads such as lighting, monitoring devices and environmental mitigation equipment. The integration of electrochemical and hydraulic storage enhances operational flexibility and reduces battery cycling, contributing to improved system resilience. In addition, the implementation of a smart energy management architecture based on IoE and $MQTT$ has enabled real-time acquisition, transmission and storage of high-resolution operational data, validating the digital infrastructure required for advanced energy management. Although the present work focuses on system design, experimental validation and commissioning, the developed architecture provides a scalable and AI-ready framework for future implementation of predictive control and optimization strategies.

Overall, HY4RES constitutes a versatile test-bed for the evaluation of hybrid renewable micro-grids, turbine prototypes and innovative storage concepts in portable configurations.

6. FUTURE WORK

Future work will focus on long-term operational monitoring, in-situ performance validation and the extension of the proposed concept to smart-port and off-grid applications, reinforcing its potential as a resilient and scalable solution for decentralized renewable energy deployment. Additionally, various hydrokinetic turbine designs are planned for testing with the aim of improving the overall efficiency of the plant.

ACKNOWLEDGMENTS

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REFERENCES

[1] IEA. "International Energy Agency, Electricity 2024 – Analysis and Forecasts to 2026." (2024).

[2] IEA. "International Energy Agency, Renewables 2023: Analysis and Forecast to 2028." (2024).

[3] Stec, Małgorzata, Grzebyk, Mariola, Caputa, Wiesława and Hejdukova, Pavlina. "Levels of Renewable Energy Use in Selected European Union Countries–Statistical Assessment of Changes and Prospects for Development." *Comparative Economic Research. Central and Eastern Europe* Vol. 27 No. 3 (2024): pp. 117–140.

[4] Khaleel, Mohamed, Yusupov, Ziyodulla, Alfalh, Bsher, Guneser, Muhammet Tahir, Nassar, Yasser and El-Khozondar, Hala. "Impact of smart grid technologies on sustainable urban development." *Int. J. Electr. Eng. and Sustain.* (2024): pp. 62–82.

[5] Al-Shetwi, Ali Q, Hannan, MA, Al-Masri, Hussein MK and Sujod, Muhamad Zahim. "Latest advancements in smart grid technologies and their transformative role in shaping the power systems of tomorrow: An overview." *Progress in Energy* (2024).

[6] REN21. "Renewable Energy Policy Network, Global Status Report 2024." (2024).

[7] Zhou, Zhibin, Benbouzid, Mohamed, Charpentier, Jean-Frédéric, Scuiller, Franck and Tang, Tianhao. "Developments in large marine current turbine technologies–A review." *Renewable and Sustainable Energy Reviews* Vol. 71 (2017): pp. 852–858.

[8] IEA. "International Energy Agency, PV Global Market Outlook 2024–2028." (2024).

[9] Sousa, Jorge, Lagarto, João, Camus, Cristina, Viveiros, Carla, Barata, Filipe, Silva, Pedro, Alegria, Ricardo and Paraíba, Orlando. "Renewable energy communities optimal design supported by an optimization model for investment in PV/wind capacity and renewable electricity sharing." *Energy* Vol. 283 (2023): p. 128464.

[10] GWEC. "Global Wind Energy Council, Global Wind Report 2024." (2024).

[11] Association, International Hydropower et al. "World Hydropower Outlook 2023." *Opportunities to advance net zero. IHA, London* (2023).

[12] Khan, MJ, Bhuyan, G, Iqbal, MT and Quaicoe, JE. "Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review." *Applied energy* Vol. 86 No. 10 (2009): pp. 1823–1835.

[13] Bahaj, AbuBakr S. "Marine current energy conversion: the dawn of a new era in electricity production." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* Vol. 371 No. 1985 (2013): p. 20120500.

[14] Louie, Henry. *O-Grid Electrical Systems in Developing Countries*. Springer (2018).

[15] Gharib-Yosry, Ahmed, Fernandez-Jimenez, Aitor, Manuel Fernandez Pacheco, Víctor and Rico-Secades, Manuel. "Internet of Energy Applied to Water Hydrokinetic Smart-Grids: A Test Rig Example." *Energy Sustainability*, Vol. 85772: p. V001T01A005. 2022. American Society of Mechanical Engineers.

[16] Syahputra, Ramadoni, Subarkah, Yudha Agung, Purwanto, Kunnu and Soesanti, Indah. "Performance of a portable small hybrid renewable power plant." *2022 2nd International Conference on Electronic and Electrical Engineering and Intelligent System (ICE3IS)*: pp. 109–113. 2022. IEEE.

[17] Olatomiwa, Lanre, Mekhilef, Saad, Ismail, Mahmoud S and Moghavvemi, Mahmoud. "Energy management strategies in hybrid renewable energy systems: A review." *Renewable and Sustainable Energy Reviews* Vol. 62 (2016): pp. 821–835.

[18] Higier, Andrew, Arbide, Adrian, Awaad, Amer, Eiroa, Justo, Miller, Jerry, Munroe, Norman, Ravinet, Alfredo and Redding, Brian. "Design, development and deployment of a hybrid renewable energy powered mobile medical clinic with automated modular control system." *Renewable energy* Vol. 50 (2013): pp. 847–857.

[19] Ramos, Ariana, Meeus, Leonardo, Schittekatte, Tim, Broeckx, Saskia, Fernandez, Luisa and Keyaerts, Nico. *Energy Storage Deployment Handbook*. SSRN (2021).

[20] BoxPower. "BoxPower | Solar Microgrid Solutions." (2024). URL https://boxpower.io/. Accessed: Oct. 22, 2024.

[21] FloatGEN. "FloatGEN, Floating platform | Offshore wind power." (2024). URL https://www.bw-ideol.com/en/floatgen-demonstrator. Accessed: Oct. 22, 2024.

[22] Tesla. "Megapack 2024 | Tesla." (2024). URL https://www.tesla.com/megapack. Accessed: Oct. 22, 2024.

[23] Ileberi, Gbalimene Richard and Li, Pu. "Integrating hydrokinetic energy into hybrid renewable energy system: optimal design and comparative analysis." *Energies* Vol. 16 No. 8 (2023): p. 3403.

[24] Naughton, Brian. "Deployable Wind-Hybrid Power Systems for Defense and Disaster Response Applications." Technical report no. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States). 2021.

[25] Murty, Vallem VVSN and Kumar, Ashwani. "Optimal energy management and techno-economic analysis in microgrid with hybrid renewable energy sources." *Journal of Modern Power Systems and Clean Energy* Vol. 8 No. 5 (2020): pp. 929–940.

[26] Khalid, Muhammad. "A review on the selected applications of battery-supercapacitor hybrid energy storage systems for microgrids." *Energies* Vol. 12 No. 23 (2019): p. 4559.

[27] Li, Linfeng, Zhong, Ming, Ma, Xiaofeng, Zhao, Haowei, Safdar, Muhammad, Chuwang, Dung David and Zhang, Ziran. "Optimal planning of renewable energy infrastructure for ports under multiple design scenarios considering system constraints and growing transport demand." *Journal of Cleaner Production* Vol. 477 (2024): p. 143827.

[28] Moros-Daza, Adriana, Castro, Dariela, Bonifacio, Jose, Amaya-Mier, Rene and Voß, Stefan. "Greening container terminals: An innovative and cost-effective solution for sustainable reefer container storage." *Journal of Cleaner Production* Vol. 466 (2024): p. 142664.

[29] Álvarez, Eduardo Á, Yosry, Ahmed G, Fernández Jiménez, Aitor, Calleja Rodríguez, Antonio and Rico Secades, Manuel. "Diagnostic Strategies for Microturbines Operating Status Applied to Predictive Maintenance: Experimental Test Case." *Turbo Expo: Power for Land, Sea, and Air*,

Vol. 87127: p. V014T37A015. 2023. American Society of Mechanical Engineers.

[30] Ojo, Olụwafemi Tayo, Habeeb, Aliu Opeyemi, Adebiyi, Olubukola Eunice, Olanrewaju, Samuel Ayanwunmi, Olabode, Olawale Johnson and Ezekiel, Smart Ezekiel. “IoT-Enabled Energy Storage Systems For Renewable Energy Grid Integration.” *Path of Science* Vol. 11 No. 3 (2025): pp. 4001–4008.

[31] Gharib-Yosry, Ahmed, Blanco-Marigorta, Eduardo, Fernández-Jiménez, Aitor, Espina-Valdés, Rodolfo and Álvarez-Álvarez, Eduardo. “Wind–water experimental analysis of small sc-darrieus turbine: an approach for energy production in urban systems.” *Sustainability* Vol. 13 No. 9 (2021): p. 5256.

[32] Nassar, Yasser F, Alsadi, Samer Y, El-Khozondar, Hala J, Ismail, Mohamoud S, Al-Maghalseh, Maher, Khatib, Tamer, Sa’ed, Jaser A, Mushtaha, Mohammed H and Djerafi, Tarek. “Design of an isolated renewable hybrid energy system: a case study.” *Materials for Renewable and Sustainable Energy* Vol. 11 No. 3 (2022): pp. 225–240.