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Contributions toward net-zero carbon in the water sector: application to a case study

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ABSTRACT

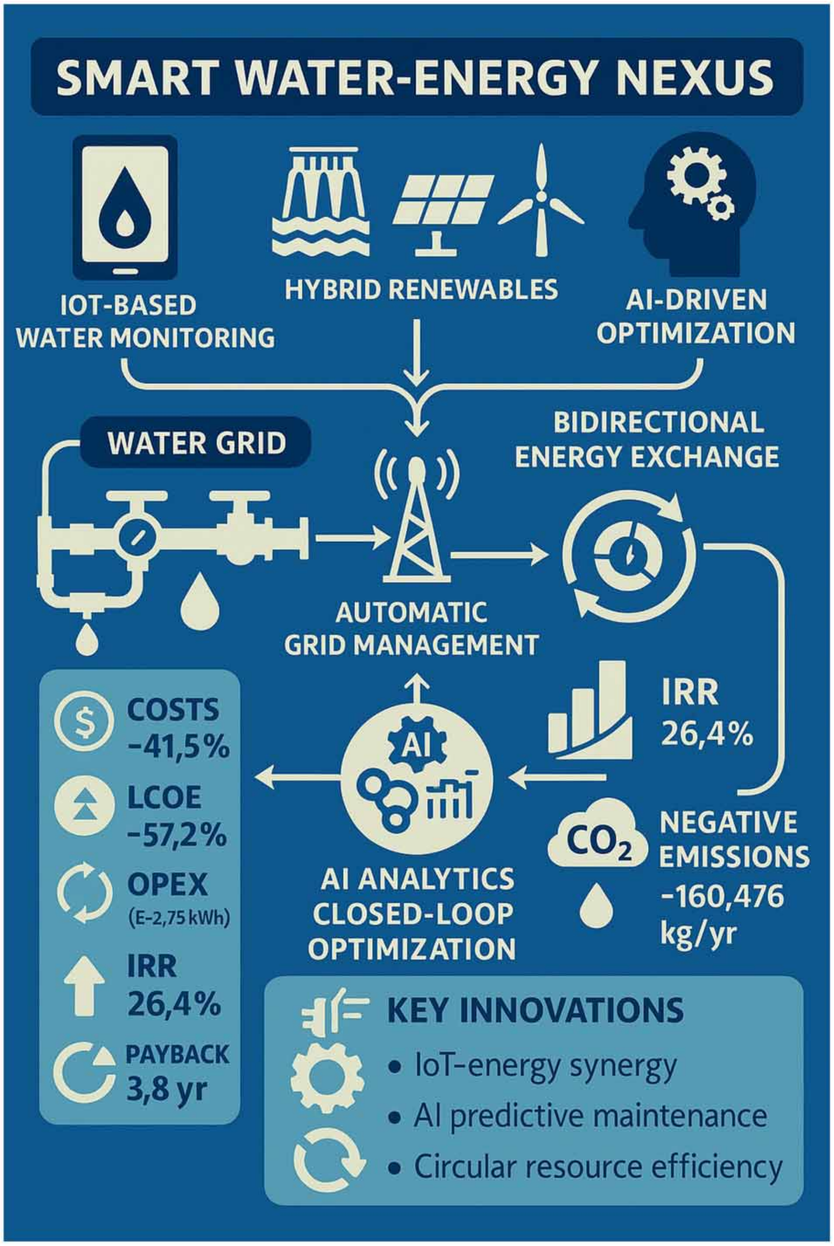
This study presents an integrated smart water-energy nexus framework combining IoT-based water monitoring, hybrid renewables (hydropower/solar/wind), and AI-driven optimization. Real-time sensor data enables automated grid management, while AI analytics optimize operations and predict maintenance needs through a closed-loop system. The solution achieves bidirectional energy exchange, with the full hybrid system (G + H + PV + W) reducing costs by 41.5% (€831K) and LCOE by 57.2% (€0.0475/kWh). Financial analysis confirms viability with 26.4% IRR and 3.8-year payback, while achieving negative CO_2 emissions (−160,476 kg/year). Progressive renewable integration enhances all key performance indicators (KPIs), cutting OPEX by 89.9% (€7,156/year) through optimized operations. Dual water-energy performance metrics (leakage, pressure, % renewable share) ensure balanced and sustainable grid management. Key innovations include IoT-energy synergy, AI-driven predictive maintenance, and circular resource efficiency. The framework demonstrates how smart water grids can achieve both economic and environmental benefits through renewable energy integration and advanced digital solutions.

Key words: carbon neutrality, hydropower, pressure management, renewable energies, smart water grids, sustainability

HIGHLIGHTS

- AI and sensors optimize hybrid grids with real-time predictive maintenance.
- The hybrid system cuts costs by 41.5% and achieves negative CO_2 emissions.
- Strong returns: 26.4% IRR and just 3.8 years to break even.
- OPEX reduced by 89.9% through smart, AI-driven operations.
- Dual water-energy KPIs balance pressure, leakage, and renewables.

GRAPHICAL ABSTRACT



LIST OF VARIABLES

Bei	Represents the energy needed from the batteries for energy needs, in kWh.
Bpi	The feasible battery energy to be used for pump operation, in kWh.
E + i	Energy surplus in kWh.
E_{-}^{i}	Energy deficit in kWh.
E_{c}^{i}	Energy needs.
f_{PV}	Derating factor of solar PV
g	Acceleration due to gravity 9.81 m/s^2.
G_T	Incident solar irradiance in kW/m^2.
$G_{T,\mathrm{STC}}$	Incident solar irradiance at standard test conditions, which is 1 kW/m^2.
H^i	Hydropower generated.

Hp	Hydro turbine power output in kW.
h_{net}	Effective head in m.
$P_{W,STP}$	Output power of wind turbine at standard conditions, in kW.
$\dot{Q}_{turbine}$	Hydro turbine flow rate in m^3/s.
S_W	Output power of wind turbine in kW.
Ss + wi	Total (solar + wind) intermittent renewables.
S^i	Solar energy.
T_c	Cell temperature of solar PV in °C.
$T_{c,STC}$	Cell temperature under standard test conditions, which is 25 °C.
Y_{PV}	Power output during standard test conditions, in kW.
α_P	Temperature co-efficient of power.
η_{hyd}	Efficiency of hydro turbine in %.
ρ_{water}	Water density, which is 1,000 kg/m^3.
ρ	Actual air density, in kg/m^3.
ρ_0	Air density at STP, which is 1.225 kg/m^3.

1. INTRODUCTION

The water sector, encompassing drinking water supply systems (including water treatment plants), wastewater treatment, and rainwater and plantation drainage, incurs significant electricity costs and contributes substantially to carbon emissions due to the energy required for these operations (Hamawand 2023). Given the critical importance of water as a finite and essential resource, its conservation is of the utmost priority (Pokhrel *et al.* 2023). Water utilities responsible for these services are currently facing a range of pressing challenges, including aging and insufficient infrastructure, substantial water losses, and elevated carbon emissions stemming from energy consumption (Ferrari & Savic 2015; Ociepa *et al.* 2019). The ongoing effects of climate change, global population growth, and desertification are exacerbating water scarcity, prompting global concern over both the quality and quantity of available water (Jain *et al.* 2024). As a result, responsible and efficient use of water, with a strong emphasis on minimizing losses, has become imperative (Bouramdane 2023). In this context, the implementation of a smart water grid is being examined to enhance the current performance of water distribution systems, which remain significantly below national benchmarks in terms of efficiency, water loss reduction, and self-sufficient energy production (Ramos *et al.* 2020, 2022, 2023). The municipality of Funchal serves as an appropriate case study for this research, which aims to achieve the following objectives:

- Analyze performance indicators
- Incorporate smart water grid technologies
- Minimize water and energy losses within the network
- Replace pressure-reducing valves with pumps operating as turbines, where feasible
- Increase the integration of renewable energy sources to reduce carbon emissions by developing hybrid energy systems based on intermittent renewables

The pursuit of carbon neutrality is driven by broader sustainability goals, including environmental preservation, ecosystem protection, public health, and alignment with international commitments. Furthermore, reducing Portugal's dependence on imported energy – such as natural gas and fuel oil – is a strategic priority. Achieving full reliance on domestically produced renewable energy would eliminate the need for such imports. Over recent decades, many water utilities in industrialized nations have scaled back investment in infrastructure, resulting in widespread obsolescence and systems that have surpassed their expected service life (Gorelick *et al.* 2023). It is now evident that the water sector must modernize by integrating advanced technologies to improve network performance and efficiency. In addition to safeguarding this vital resource, it is essential to enhance conventional systems through real-time monitoring of water quantity and quality. Moreover, proactive planning is necessary to address challenges posed by extreme weather events, population increases, and other emerging risks.

1.1. Why is net zero a priority for the water sector?

Water is fundamental to life, yet the significant carbon footprint associated with its supply, treatment, and management remains largely underrecognized (Behm *et al.* 2022; Yao *et al.* 2022). The relationship between water and greenhouse gas emissions is often overlooked in the broader discourse on climate change. However, the water sector is a notable contributor to global emissions, and acknowledging this connection is essential – particularly as water demand continues to rise due to population growth, industrialization, and the increasing strain caused by global warming. There are compelling reasons to prioritize sustainability within the water sector. First and foremost, the conservation of water as a natural resource is intrinsically linked to the protection of ecosystems and biodiversity. The sustainable use of water, combined with efforts to reduce the sector's carbon footprint, plays a critical role in preserving natural resources. In the context of intensifying climate phenomena – such as prolonged droughts and flooding due to extreme rainfall – the sector must adopt resilient strategies and technologies that promote efficient water use (Dadmand *et al.* 2020; Makanda *et al.* 2022). The water sector is uniquely positioned to lead by example in the transition toward sustainable practices and decarbonization. Viable and even economically beneficial solutions already exist, offering a clear pathway to lower emissions. Despite the sector's often invisible carbon impact, it is both significant and increasing, particularly in water-stressed regions. Addressing this challenge requires innovative approaches that reconcile the need for safe, reliable water with the urgent necessity of reducing carbon emissions. The adoption of advanced technologies to enhance water efficiency and management is central to achieving greater sustainability (Bazaanah & Mothapo 2024). Water utilities can contribute to this goal by implementing green infrastructure that captures carbon and conserves energy. Furthermore, water reuse practices – such as the use of reclaimed water for toilet flushing, drainage, and irrigation – are fundamental to resource conservation and the pursuit of carbon neutrality. Promoting such strategies across the sector is vital to ensuring long-term environmental sustainability (Rahamathunnisa *et al.* 2024).

1.2. What are the main strategies to optimize utility operations and deliver better sustainability and business outcomes?

To enhance both operational performance and economic outcomes, a comprehensive asset management strategy must first be implemented by the water utility. Although this may appear to be a straightforward undertaking, the reality is that, in many cases, critical information regarding urban water infrastructure – such as pipelines, pumps, valves, reservoirs, and associated facilities – is either incomplete or entirely absent. Details such as the precise location of assets, their technical characteristics, expected service life, current condition, or existing faults are often unknown. This lack of information significantly hinders timely maintenance, necessary repairs, and strategic interventions aimed at improving system efficiency. A clear understanding of the condition and distribution of assets is essential for developing effective strategies for asset rehabilitation and replacement, particularly for infrastructure nearing the end of its useful life (Anastasopoulos 2009). At present, many water utilities have limited insight into the full extent and condition of their infrastructure networks. Addressing this gap is critical to ensuring the effective operation and long-term sustainability of the water distribution system (WDS). Therefore, a structured assessment of urban water resources must be undertaken using a methodology that prioritizes infrastructure rehabilitation. This process should be integrated with the adoption of smart water networks and the implementation of hybrid renewable energy solutions, thereby ensuring a more resilient, efficient, and sustainable water management system.

1.3. Why is important smart water grids and hybrid renewable energy solutions?

Smart water grids (SWG) represent an advanced technological solution designed to enhance the efficiency of water systems through real-time monitoring and management (Garcia *et al.* 2022; Coelho *et al.* 2024a). The implementation of such systems necessitates comprehensive and integrated upstream planning, encompassing several key objectives: evaluating and mapping all existing infrastructure (such as storage tanks, pipelines, and pumping stations) along with their technical specifications; identifying critical areas within the network; recognizing different user profiles; and establishing specific operational goals and performance targets. The real-time data collected by SWG enable informed, timely decision-making by skilled personnel in areas such as network control, water and energy monitoring, and flow regulation (Mutchek & Williams 2014). Additionally, the monitored data can be made accessible to consumers – potentially as a regulatory requirement – empowering them to better understand, manage, and optimize their water usage, ultimately contributing to cost savings and more efficient resource use. Moreover, the analysis of system data and performance outcomes creates opportunities to integrate renewable energy solutions (Carravetta *et al.* 2013; Novara *et al.* 2019; Li *et al.* 2020). These hybrid systems are developed to maximize both efficiency and reliability by combining various renewable sources to ensure a consistent and sustainable electricity supply for the operation of the water network.

2. MATERIALS AND METHODS

2.1. Materials

The monitoring and data collection process within the WDS requires integrated analysis, combining various technological approaches to support system efficiency and informed decision-making. Key concepts introduced in this context include the Internet of Things (IoT), Big Data, artificial intelligence (AI), and machine learning (Gohil *et al.* 2021; Paramesha *et al.* 2024):

- IoT involves the real-time interconnection of physical devices equipped with sensors, electronics, and software, enabling data exchange. In WDS, IoT applications include smart water meters, sensor-equipped SWG, and remote control of operational components such as valves and pumps.
- Big Data refers to vast and complex datasets that exceed the processing capacity of traditional data analysis tools. In the water sector, it enables the evaluation of historical consumption patterns, continuous monitoring, and real-time consumption analysis.
- AI facilitates the development of systems capable of making autonomous decisions, optimizing operations, and predicting failures. Machine Learning, a subset of AI, uses algorithms trained on historical data to improve performance over time, particularly in tasks such as leak detection and loss reduction.
- Digital twins (DT) and SWG enable the real-time replication of system conditions, performance monitoring, and timely intervention, supporting a more responsive and resilient water management infrastructure.

Figure 1 presents the integration of smart technologies into the WDS, detailing the key stages in achieving a digitally enhanced and sustainable management approach:

1. Real-time monitoring of water flow and energy consumption using sensors and meters, facilitated by Internet of Things (IoT) technologies.
2. Centralized data collection and management through a dedicated data center, utilizing Big Data analytics.
3. Error detection and correction through the application of AI.
4. Automated system responses enabled by real-time monitoring, including dynamic pressure regulation based on consumption patterns, leading to energy savings and reduced risk of pipeline overpressure – supported by AI and Machine Learning.
5. Optimized water management through hybrid use of available water resources, incorporating sensors, DT, and SWG.
6. Integration of renewable energy and energy recovery systems, enhanced by AI and Machine Learning for greater sustainability.
7. Promotion of sustainable consumption through integrated resource management and user guidance aimed at reducing waste and excessive use.
8. Improved system resilience and adaptability to challenges such as extreme weather and equipment failures, enabled by real-time alerts, automation, and AI-based decision-making systems.

2.2. Methodology

To ensure the reliability and validity of the results, the chosen methodology incorporates both qualitative and quantitative approaches. This mixed-methods strategy allows for a more comprehensive understanding of the subject matter, balancing data evidence with contextual insights. Data collection procedures are designed to minimize bias and maximize relevance to the research questions, employing tools such as structured surveys and observational techniques where appropriate. Furthermore, each stage of the methodology is aligned with the overarching objectives of the study, ensuring coherence and facilitating replicability in future research, reinforcing the study's commitment to integrity and transparency (Figure 2).

The presented methodology includes seven steps such as: 1. **System Architecture Design** where the methodology begins with establishing an integrated smart water grid infrastructure that combines: (i) IoT Sensor Network: Deployment of flow,

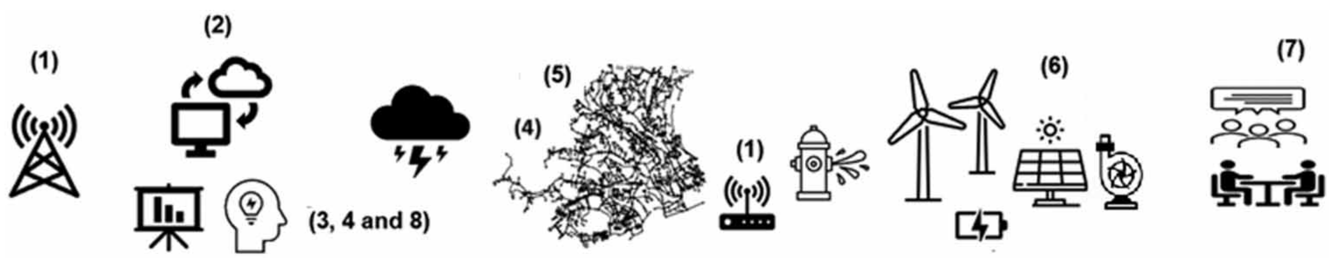


Figure 1 | Scheme of a smart city with smart water-energy management.

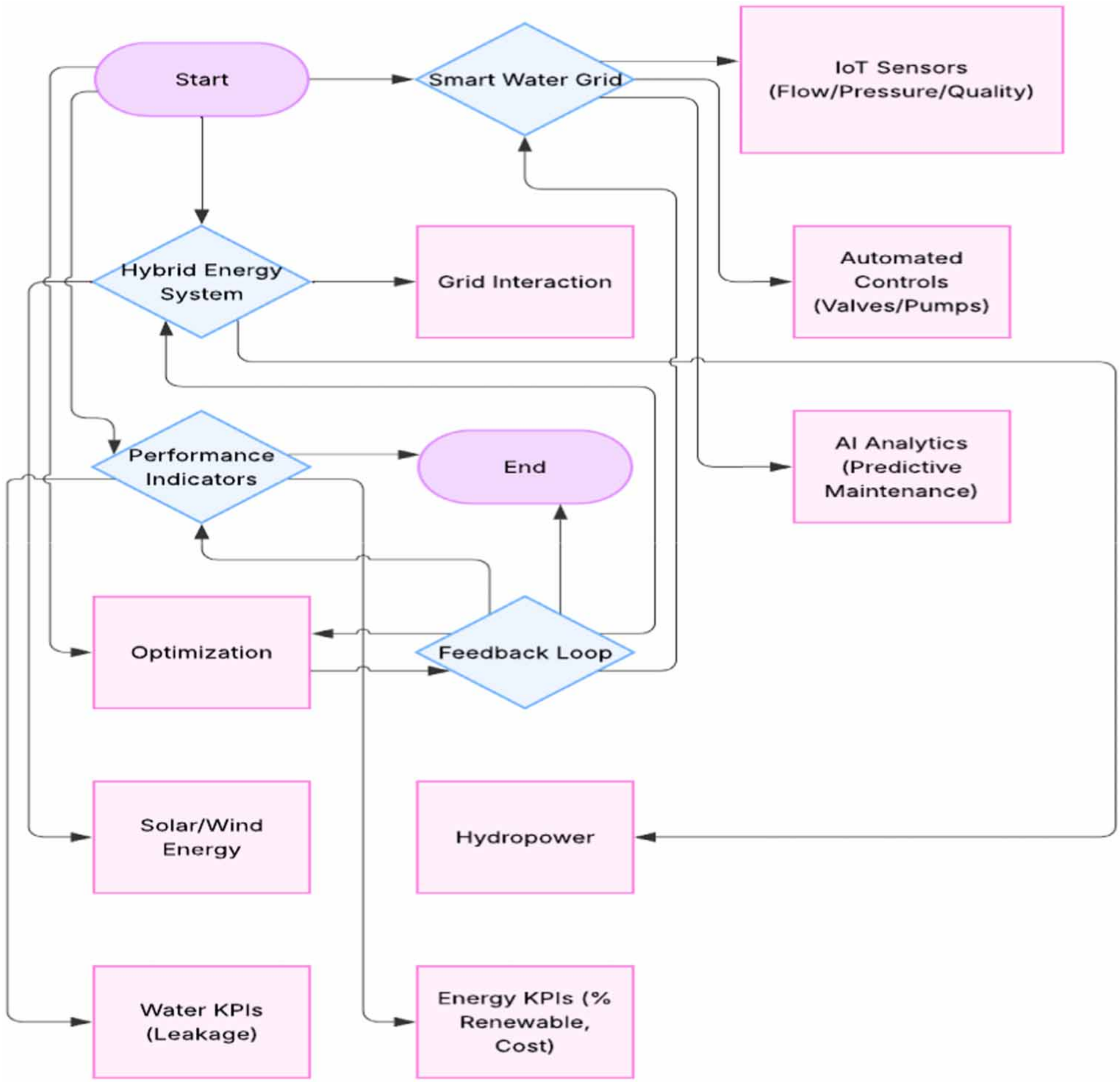


Figure 2 | Summary of the methodology.

pressure, and sensors throughout the distribution system; (ii) Hybrid energy system: Integration of solar, wind, and hydropower generation with traditional grid connections; (iii) Automated control systems: Installation of smart valves and variable-speed pumps with remote control capabilities. 2. **Data Acquisition and Monitoring** assume a continuous real-time data collection from IoT sensors measuring: (i) Water flow rates at key nodal points; (ii) System pressure levels; (iii) Water parameters; (iv) Energy monitoring from renewable energy generation systems and/or grid power consumption and pumping station energy usage. 3. **Performance Indicator Framework** which establishes key performance indicator (KPI) systems: (i) Leakage detection and quantification; (ii) Water delivery efficiency; (iii) Quality compliance metrics; (iv) Percentage of renewable energy utilization; (v) Energy cost per unit water delivered and (vi) Carbon footprint metrics. 4. **AI-Driven Analytics Engine** by implementation of machine learning algorithms for: (i) Predictive Maintenance and demand forecasting; (ii)

Early detection of equipment failures; (iii) Anomaly detection in water network performance; (iv) Pipe degradation modeling; (v) Short-term and long-term water demand predictions; (vi) Seasonal usage pattern analysis. 5. **Optimization and Control System** by development of dynamic pump scheduling: (i) Adjusting pump operations based on real-time demand; (ii) Energy availability (prioritizing renewable sources); (iii) Electricity pricing fluctuations; (iv) Pressure zone optimization by automated valve control to minimize leakage; (v) Maintain optimal pressure levels; (vi) Balance network loads. 6. **Feedback and Continuous Improvement**: (i) Performance indicators and control systems; (ii) Predictive models and actual outcomes; (iii) Energy production and consumption patterns; (iv) Changing demand patterns; (v) Infrastructure aging; (vi) Evolving energy market conditions. 7. **Integration with Energy**: (i) Two-way energy exchange capabilities; (ii) Dynamic energy sourcing based on renewable energy availability; (iii) Optimization algorithms; (iv) System reliability requirements.

The methodology adopted in this research follows a conceptual framework aimed at developing a responsive and self-optimizing WDS. This system is designed to enhance water delivery efficiency while promoting sustainable energy use through the integration of advanced monitoring technologies, data analytics, and automated control mechanisms. The application of this methodology is tailored – though not exclusively – to the specific characteristics of the selected case study. It builds upon prior research and existing developments in the field of SWG, ensuring a context-sensitive implementation that leverages past insights for improved performance and adaptability. Following Steps 1 to 4, the water losses remain a critical issue, with only a slight reduction in unbilled water (non-revenue water) noted in these last five years, in the water municipalities, in Portugal (Vivas 2024). Hence, in 2022, total losses reached 221.6 million m^3/year equivalent to 2.85 times Lisbon's annual water demand (Figure 3(a)). Madeira Island faces even worse inefficiency, with 64.7% unbilled water in 2022. Energy self-sufficiency in Portugal's water sector is low: (i) only 43 out of 251 utilities produce their own energy; (ii) the average self-production rate is 52.48%, but most (32 of 43) generate ≤20% of their needs; (iii) Exceptions like CM Bragança and Águas e Energia do Porto show surplus renewable energy potential. To achieve sustainability, Steps 5 to 7, are focused in the main problem statement, as a motivation for this research, denoting to optimized systems with energy self-production and technological innovations (e.g., hybrid energy systems) which must be prioritized to reduce energy demand, water losses and carbon emissions. Some key points related with high water losses persist, especially in Madeira (64.7%); low energy self-sufficiency – most services rely heavily on external power; renewable energy integration is critical for efficiency and carbon neutrality (Figure 3(b)).

2.3. Basic mathematical formulation

Considering a complete model of a hybrid energy solution based on renewable available sources (Hydro, Solar (PV) and Wind), briefly, the main equations can be used as follows:

$$S^i_{s+w} = S^i + W^i - E^i_c, \, If > 0 \tag{1}$$

$$E^i_c = S^i_{s+w}, \quad \text{If} > 0 \tag{2}$$

$$E^i_+ = S^i_{s+w} \tag{3}$$

$$E^i_- = [E^i_c - S^i - W^i - H^i] \tag{4}$$

$$B^i_e + B^i_p = [E^i_c - S^i - W^i - H^i, \quad \text{If} > 0 \wedge B^i_e \leq B^i] \tag{5}$$

where S^i_{s+w} is the total (solar + wind) intermittent renewables. E^i_+ is the energy surplus in kWh. E^i_- = energy deficit in kWh. S^i =solar energy. H^i = hydropower generated. E^i_c = energy needs. B^i_e represents the energy needed from the batteries for energy needs, in kWh. B^i_p is the feasible battery energy to be used for pump operation, in kWh.

Hydropower would be represented by pump as turbines (PATs). The calculation for the water turbines, is given as follows:

$$Hp = \eta_{hyd} \cdot \rho_{water} \cdot g . h_{net} \cdot \dot{Q}_{turbine} \tag{6}$$

where Hp is the hydro turbine power output in kW. η_{hyd} is the efficiency of hydro turbine in %. ρ_{water} is the water density, which is 1,000 kg/m^3. g is the acceleration due to gravity 9.81 m/s^2. h_{net} is the effective head in m. $\dot{Q}_{turbine}$ is the hydro turbine flow rate in m^3/s. The model uses solar radiation to generate electricity. Solar PV will be one of the most important

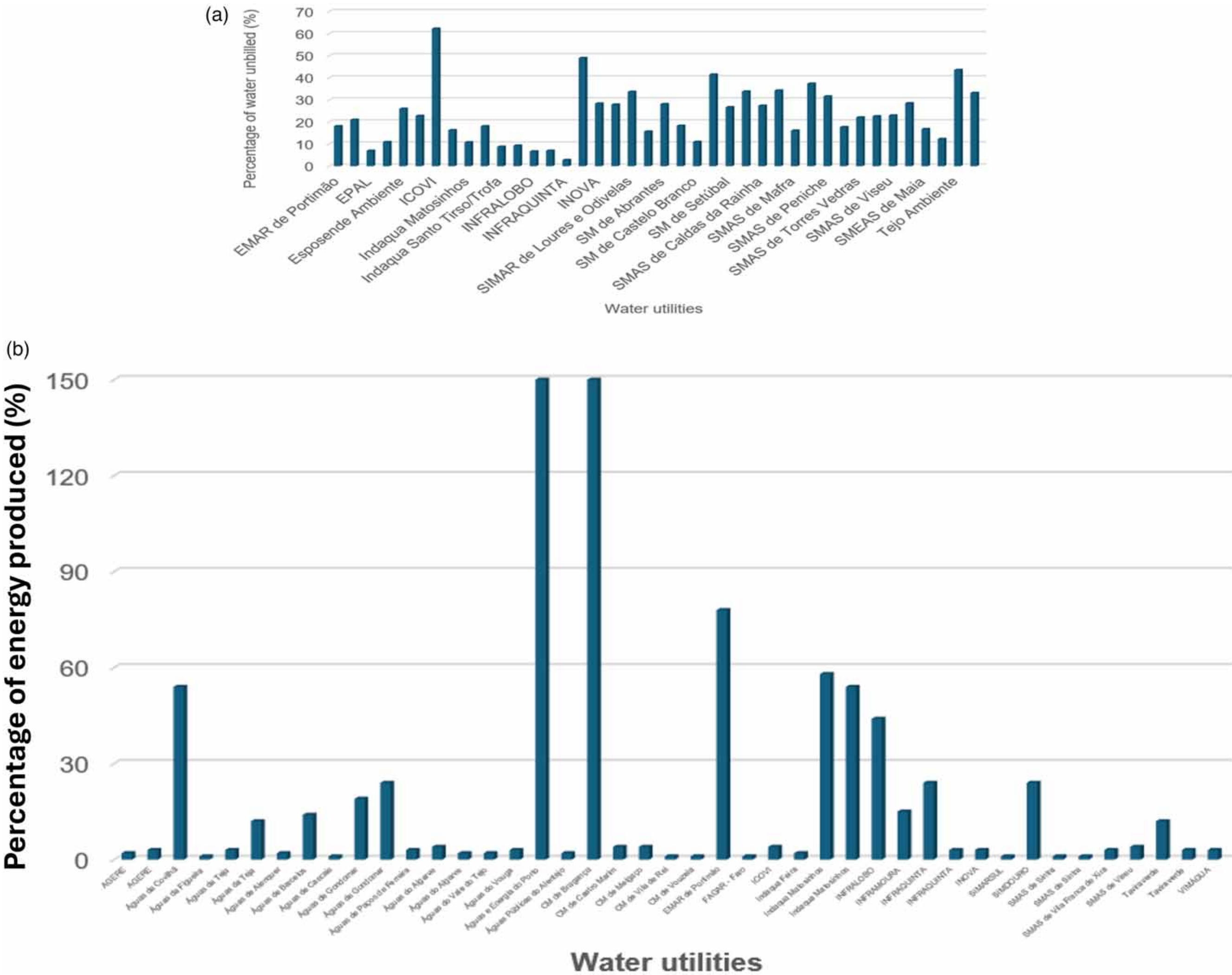


Figure 3 | Percentage of water unbilled in 2022 for the main water municipalities (a) and energy produced in water municipalities (b).

renewables in the next years. The calculation of electricity generated by solar (S) is calculated as follows:

$$S = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,\mathrm{STC}}} \right) [1 + \alpha_P (T_c - T_{c,\mathrm{STC}})] \quad (7)$$

where Y_{PV} is the power output during standard test conditions in kW. f_{PV} is the derating factor of solar PV. G_T is the incident solar irradiance in kW/m^2. $G_{T,STC}$ is the incident solar irradiance at standard test conditions, which is 1 kW/m^2. α_P is the temperature co-efficient of power. T_c is the cell temperature of solar PV in °C. $T_{c,STC}$ is the cell temperature under standard test conditions, which is 25 °C.

The model can also consider the wind turbine's power curve to calculate the power generated by the wind turbine. To obtain the power generated under real conditions, the model uses the following equation:

$$S_W = \left(\frac{\rho}{\rho_0} \right) . S_{W,STP} \quad (8)$$

where S_W is the output power of wind turbine in kW. $P_{W,STP}$ is the output power of wind turbine at standard conditions, in kW. ρ is the actual air density in kg/m^3. ρ_0 is the air density at STP, which is 1.225 kg/m^3.

3. CASE STUDY

3.1. Main system characteristics

The following section presents the water distribution network of the city of Funchal (Figure 4), characterized and calibrated according to four key parameters aligned with the city's specific consumption patterns. These parameters include pipe length, pipe diameter, pipe roughness, and flow rate. Among these, pipe length and diameter are critical design and operational variables that significantly impact the hydraulic performance of the water supply system. The length of the pipes determines the spatial extent of the network and influences pressure losses due to friction, while the diameter directly affects the capacity of the system to transport water efficiently. In combination, these characteristics are essential for ensuring the reliability, efficiency, and pressure stability of the network. Accurate calibration of these parameters is crucial for hydraulic modeling, system optimization, and the effective planning of maintenance and future infrastructure upgrades.

Pipe length refers to the distance between two nodes within the water distribution network. This parameter plays a significant role in determining pressure losses – longer pipes result in greater hydraulic resistance for the same flow rate, leading to increased pressure drops, reduced efficiency, and higher installation and maintenance costs. Pipe diameter, on the other hand, directly influences the hydraulic capacity of the network. Larger diameters are associated with lower head losses and an increased ability to transport higher volumes of water. However, lower flow velocities within larger pipes can promote sediment accumulation, potentially resulting in blockages and deterioration of water quality. Additionally, both larger diameters and longer pipe lengths contribute to higher manufacturing and installation costs. The proper sizing of pipe length and diameter must strike a balance between minimizing head losses and maximizing energy efficiency, while ensuring adequate pressure is maintained at all nodes throughout the network. In summary, pipe length primarily affects the total pressure drop across the system, whereas pipe diameter regulates flow capacity and transport efficiency. Figure 4(c) and 4(d) illustrates the spatial distribution of pipe roughness and the flow parameter across the network. As anticipated, the analysis reveals that lower altitude areas exhibit higher average pressure values (Figure 4(e)). The water supply system must maintain minimum pressure thresholds to ensure consistent service delivery to end users, while also avoiding excessive pressures that may damage infrastructure. Figure 4(e) demonstrates this inverse relationship between elevation and pressure – higher pressures are observed in areas of lower elevation. However, localized pressure reductions are also evident, attributed to the presence of pressure-reducing valves (PRVs) strategically installed within the network to regulate and mitigate excessively high pressure levels.

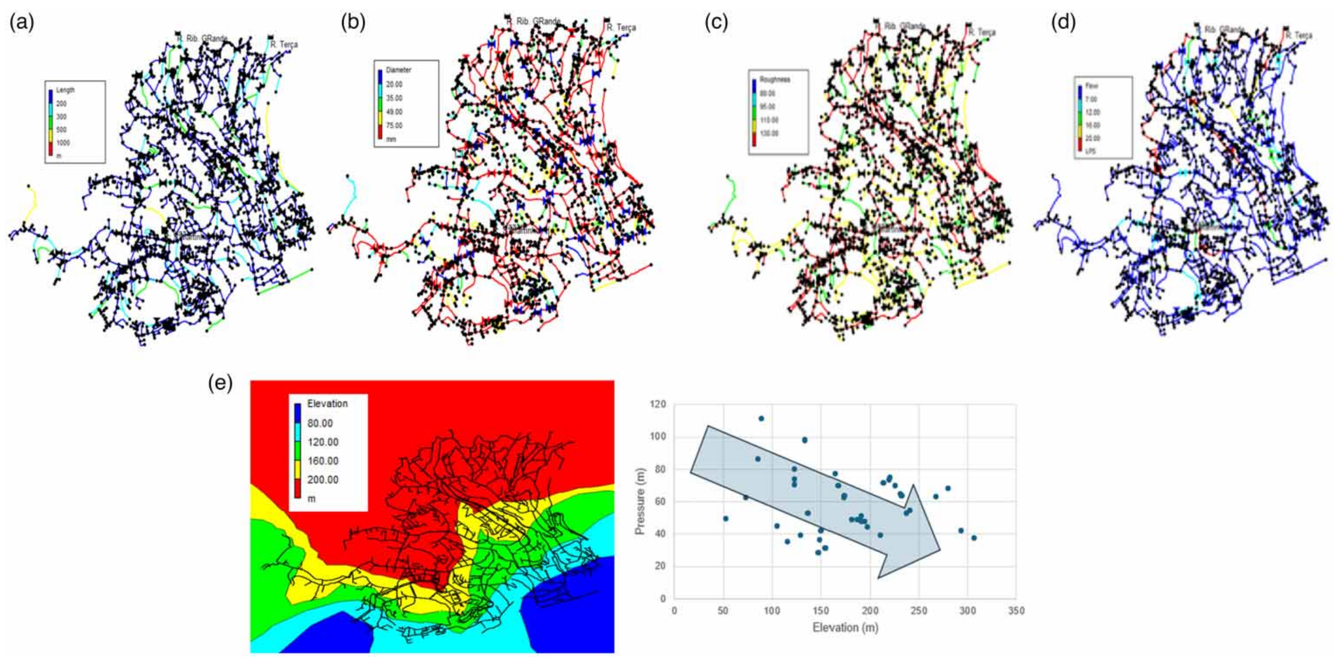


Figure 4 | Water network characteristics: (a) distribution of pipe lengths; (b) distribution of pipe diameters; (c) distribution of pipe roughness; (d) distribution of pipe flow; (e) contour plot of elevation and pressure as function of elevation.

3.2. Pressure and flow management

The various pressure values and their corresponding flow rates across the network are presented in Figure 5, based on the same simulation and parameters as those used in Figure 4.

Figure 5(a) and 5(b) illustrates the pressure and flow rate distribution across the network during peak consumption hours. In contrast, Figure 5(c) and 5(d) presents the same network under minimal demand conditions (super-empty-time), with no active water consumption. The low demand scenario, corresponding to the super load demand period, reflects network pressures at 3 am.

The flow rates exhibit negligible variation between Figure 5(b) (peak demand) and Figure 5(d) (low demand), primarily due to the persistently high level of water losses within the network. These losses remain nearly constant, sustaining elevated flow rates throughout the day. While this condition is advantageous for energy recovery, it underscores the need for operational and efficiency improvements in the network. To enhance pressure management, PRVs have been implemented to mitigate excessive pressure. Additionally, pump-as-turbines (PATs) can be installed in bypass configurations to facilitate energy

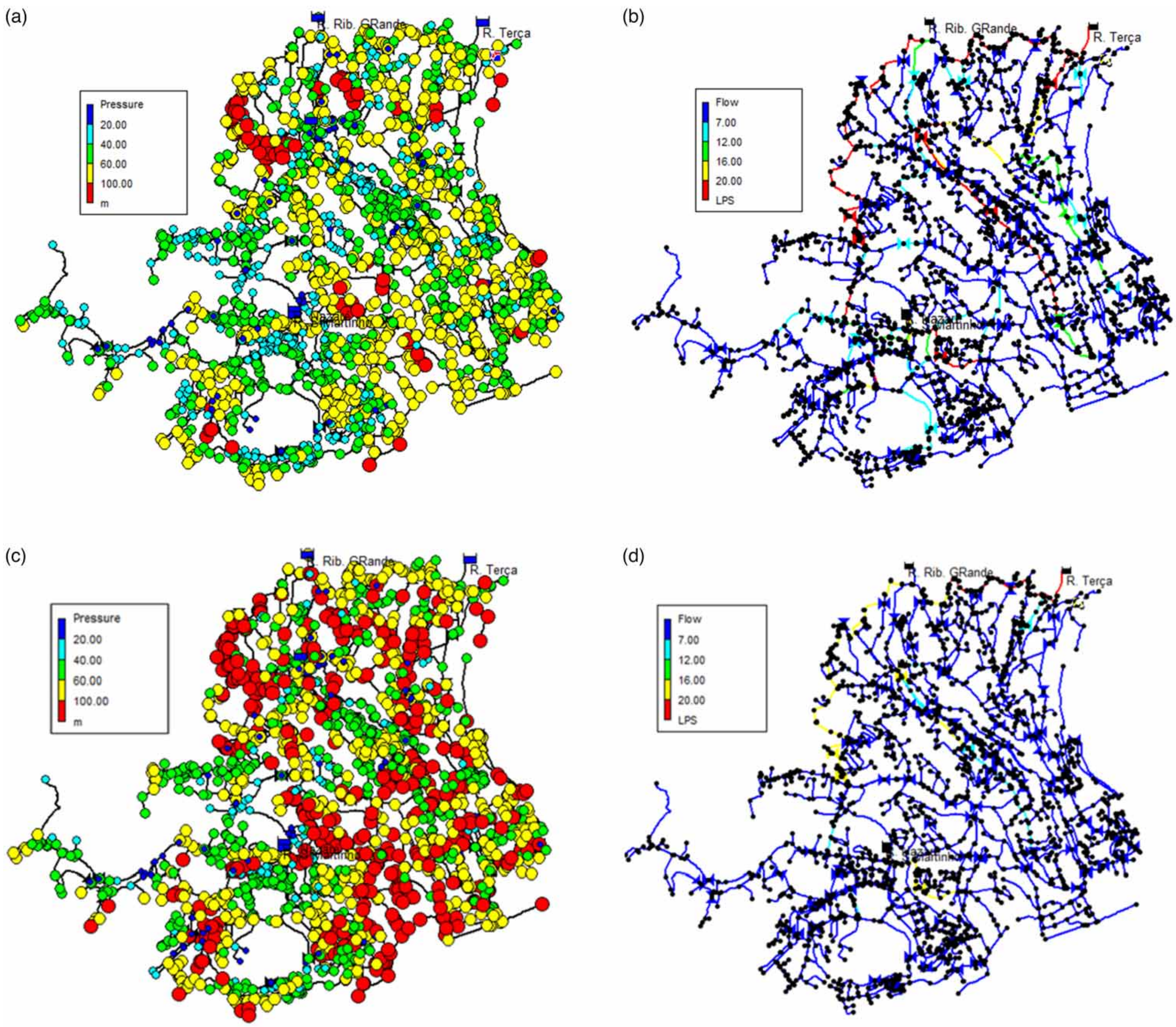


Figure 5 | Distribution in the water network: (a): pressure and (b): flow at rush hours; (c) pressure and (d) flow in load demand period.

generation. Furthermore, the analysis reveals that higher elevation zones typically experience lower pressure values, whereas lower elevation areas – often associated with more deteriorated pipelines – tend to exhibit higher pressures.

3.3. Energy recovery in the water network toward energy transition

One of the main objectives of this study is to utilize excess pressure within the water distribution network to generate electricity for the system's self-consumption. By harnessing this energy, the operational costs can be reduced, as the locally generated power – estimated through simulations – partially displaces the need for grid-supplied electricity, which incurs both variable energy charges and fixed costs. The feasibility of selling surplus electricity back to the grid has also been assessed. However, given the relatively small scale of micro-hydropower generation, the potential revenue from such sales is expected to be minimal compared to the grid's purchasing rates, making this option economically unviable in most cases.

An alternative approach involves integrating additional renewable energy sources with battery storage systems to store excess production. This stored energy could then be deployed during peak demand periods when on-site generation alone may not meet consumption needs. Nevertheless, given the water sector's typically well-integrated and centralized operations, the generated energy is expected to be consumed efficiently at the time of production. To achieve energy recovery, a bypass system incorporating a micro-hydropower plant has been implemented. This system operates either independently or in parallel with PRVs to maintain pressure control while enabling power generation (PORDATA 2024). Figure 6 highlights the PRVs evaluated for energy recovery, with black circles denoting their locations. Among these, PRV52 exhibits the highest head loss, indicating its superior potential for power generation.

Twelve PRVs were evaluated for their potential in energy recovery. Those with average power generation below 1 kW were deemed negligible and excluded from further analysis. Among the assessed PRVs, PRV52 demonstrated the highest energy production capacity, attributable to its significant head loss and elevated flow rates. The total recoverable hydro energy was found to be substantial, amounting to 1.59 MWh per day (averaging 555 MWh annually). This output translates to considerable savings in grid electricity consumption tariffs and a measurable reduction in carbon emissions.

For context, reference (PORDATA 2024) indicates that an average household in the Madeira region consumes approximately 20 kWh per day. Thus, the daily energy recovered from PRV52 could theoretically meet the electricity demands of around 80 homes, underscoring the potential socioeconomic and environmental benefits of this approach.

4. HYBRID ENERGY SOLUTIONS

The initial grid-connected configuration combines grid power with hydropower generation (G + H). Optimization results indicate that the hydropower component requires a nominal capacity of 74.3 kW to meet demand effectively (Table 1). Table 1 further also presents the composition and performance metrics of two enhanced hybrid systems (Coelho *et al*. 2024b):

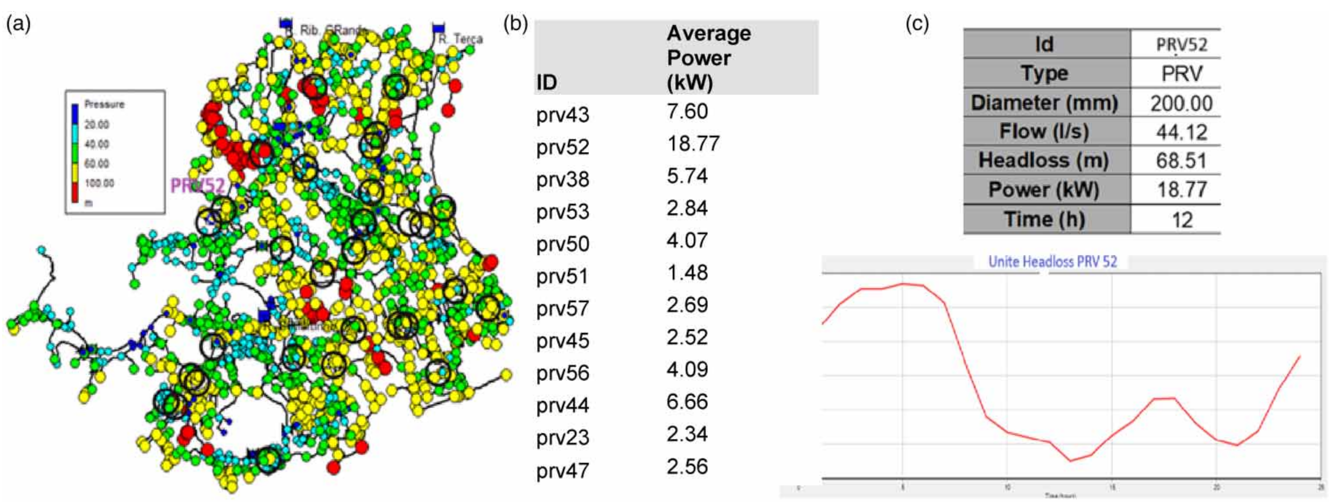


Figure 6 | Distribution of water network pressure, with selected PRVs (black circles): (a) pressure distribution, with PRV52 identified; (b) power available at valves; (c) headloss in PRV52.

Table 1 | Base solution (G + H) and alternative hybrid systems (G + H + PV/ + W)

Component	G + H	G + H + PV	G + H + PV + W	Unit
PV	–	177	177	kW
Wind turbine	–	–	100	kW
System converter	60.7	191	191	kW
Grid	No limit	No limit	No limit	kW
Hydro	74.3	74.3	74.3	kW

Grid-Hydropower-photovoltaic (PV) (G + H + PV) system:

- Integrates solar PV to capitalize on Madeira's high solar irradiance, particularly during peak daylight hours.
- Complements hydropower by providing additional generation during dry seasons or low-flow periods.
- Reduces grid dependence while leveraging hydropower's baseload stability.

Grid-Hydropower-PV-Wind (G + H + PV + W) system:

- Incorporates wind power to exploit the region's consistent ascendent winds along the coast and drainage channel, enhancing system resilience.
- Diversifies the renewable mix, mitigating intermittency risks associated with single-source renewables.
- Maximizes energy autonomy and further minimizes grid electricity purchases.

Table 1 details the installed capacity, annual production, and consumption shares for each system component. The hybrid configurations demonstrate how synergistic integration of renewables can optimize energy reliability, reduce operational costs, and lower carbon emissions compared to standalone solutions.

Figure 7 presents a comprehensive analysis of system characteristics and energy balance across three configurations:

- The base system (Grid + Hydro),
- An enhanced hybrid system (Grid + Hydro + PV), and
- A fully optimized hybrid system (Grid + Hydro + PV + Wind).

The results demonstrate how each progressive integration of renewable energy sources contributes to improved system performance. The base configuration (Grid + Hydro) establishes the reference case for energy production and consumption patterns. The incorporation of PV generation capitalizes on the region's abundant solar resources, particularly during peak daylight hours when electricity demand typically increases.

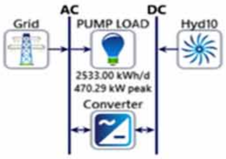
The final configuration (Grid + Hydro + PV + Wind) represents the most robust solution, where wind power complements the other renewable sources by providing consistent generation during evening and night hours, as well as during periods of reduced solar availability. This multi-source approach ensures more stable energy production throughout diurnal and seasonal cycles, while significantly reducing reliance on grid-supplied electricity (Guruprasad *et al.* 2023; Ramos *et al.* 2024). Real-time data collection requires several concerns as presented in Amitaba *et al.* (2024), Sudiarti *et al.* (2024) and Titi *et al.* (2025).

The energy balance analysis in Figure 7 quantifies these improvements, showing the proportional contributions from each energy source and their collective impact on overall system efficiency and reliability. Notably, the hybrid configurations demonstrate how a strategic combination of complementary renewable technologies can optimize energy autonomy while minimizing operational costs and environmental impact.

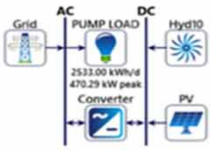
Table 2 presents a comparative performance analysis of three system configurations:

- The base system (Grid + Hydro, G + H),
- The PV-hybrid system (Grid + Hydro + PV, G + H + PV), and
- The full hybrid system (Grid + Hydro + PV + Wind, G + H + PV + W).

G+H	Production (kWh/yr)	%
Hydro	553,405	54.5
Grid Purchases	461,712	45.5
Total	1,015,117	100
	Consumption (kWh/yr)	%
AC Primary Load	924,545	93.6
Grid Sales	62,902	6.37
Total	987,447	100



G+H+PV	Production (kWh/yr)	%
PV	289,766	25.4
Hydro	553,405	48.4
Grid Purchases	299,069	26.2
Total	1,142,240	100
	Consumption (kWh/yr)	%
AC Primary Load	924,545	84.3
Grid Sales	172,061	15.7
Total	1,096,606	100



G+H+PV+W	Production (kWh/yr)	%
PV	289,766	20.7
Wind100	380,926	27.2
Hydro	553,405	39.6
Grid Purchases	174,643	12.5
Grid Sales	428,561	31.7
Total	1,398,740	100
	Consumption (kWh/yr)	%
AC Primary Load	924,545	68.3
Grid Sales	428,561	31.7
Total	1,353,106	100

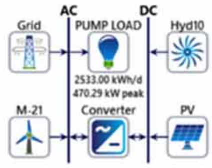


Figure 7 | Characteristics of the base system (Grid + Hydro) and energy balance and of hybrid solutions: Grid + Hydro + PV and Grid + Hydro + PV + Wind.

Table 2 | Economic and environmental KPIs

	Base system G + H	Proposed solution G + H + PV	Proposed solution G + H + PV + W
Net present cost	€1.42M	€1.19M	€831,070
CAPEX	€493,504	€621,165	€738,556
OPEX	€71,659	€43,793	€7,156
LCOE (per kWh)	€0.111	€0.0838	€0.0475
CO2 emitted (kg/year)	252,048	80,269	−160,476
IRR (%) and PB (year)		IRR (%): 21.9 PB (year): 4.5	IRR (%): 26.4 PB (year): 3.8

The evaluation is conducted using three key performance indicators (KPIs):

- Power output capacity (kW)
- Levelized cost of energy (LCOE, €/kWh)
- Annual CO_2 emissions (tons/year)

The base system (G + H) establishes the reference case, demonstrating the standalone contribution of hydropower generation. The PV-hybrid system (G + H + PV) shows significant improvements in all KPIs, with solar PV generation reducing both LCOE and carbon footprint while increasing total power output.

The full hybrid system (G + H + PV + W) achieves optimal performance, where wind power integration provides additional benefits:

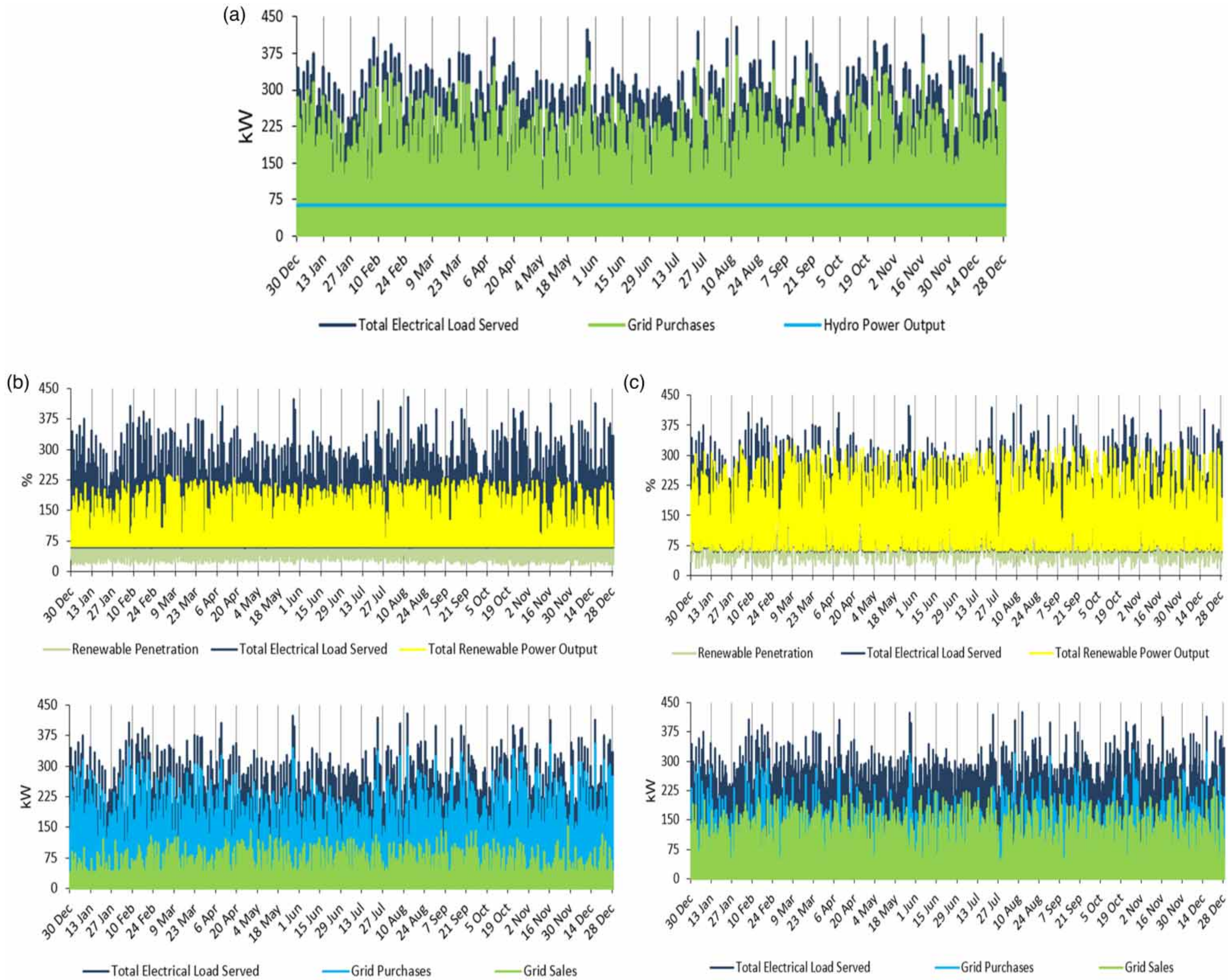


Figure 8 | Energy balance for different solutions: (a) G + H – base system; hybrid solutions: (b) G + H + PV and (c) G + PV + W.

- Enhanced system reliability through generation diversification
- Further reduction in LCOE through complementary generation profiles
- Maximized CO_2 emissions reduction

For a comprehensive understanding, Figure 8 complements this analysis by presenting the detailed energy balance across all configurations. It visually demonstrates:

- The proportional contribution of each energy source;
- Seasonal variations in generation patterns;
- The resulting reduction in grid dependence.

Together, Table 2 and Figure 8 provide a complete techno-economic and environmental assessment of the system evolution from basic to fully hybridized configuration.

5. CONCLUSIONS

A newly developed methodology was presented for an integrated Smart Water-Energy Nexus framework, combining IoT-enabled water management with hybrid renewable energy systems through AI-driven optimization. The approach follows a cyclic workflow of (i) Data acquisition and monitoring; (ii) Deploys IoT sensors to collect real-time data on water flow, pressure, across the grid; (iii) Hybrid energy integration combining hydropower (from excess water pressure), solar, and wind energy to power operations or sell to the grid; (iv) Interfaces with the main grid for bidirectional energy exchange; (v) enhance automated control and AI analytics; (vi) Uses sensors and automated valves/pumps to dynamically adjust to water distribution; (vii) suggests AI analytics for predictive maintenance, detecting leaks or equipment failures and performance optimization; (viii) Evaluates dual KPIs by water metrics for leakage rates, pressure stability; (ix) and energy metrics for renewable energy share and cost efficiency; finally (x) it implements a feedback loop to refine system parameters (e.g., valve settings, energy dispatch), sustainability outcomes and closes the loop by feeding optimization insights back to the start, ensuring continuous improvement in resource efficiency and carbon reduction.

Some key innovations are defined: (i) Couples water and energy management via real-time IoT data and renewable synergy; (ii) Leverages AI to balance operational demands with sustainability goals; (iii) Quantifies success through integrated water-energy KPIs. This methodology enables resilient, cost-effective, and low-carbon smart water grid operations.

On the other hand, the comparative analysis of the three system configurations reveals significant improvements in both economic and environmental performance through the progressive integration of renewable energy sources. The key findings can be summarized as follows:

Economic Performance:

- The full hybrid system (G + H + PV + W) demonstrates superior economic viability, with a substantial 41.5% reduction in net present cost (€831,070) compared to the base system (€1.42M).
- While CAPEX increases by 49.7% from the base system to the full hybrid system, this is offset by an 89.9% reduction in OPEX (from €71,659 to €7,156 annually).
- The LCOE shows a progressive decrease from €0.111/kWh (base system) to €0.0475/kWh (full hybrid system), representing a 57.2% improvement in cost efficiency.

Financial metrics:

- The proposed solutions show attractive financial returns, with the full hybrid system achieving an internal rate of return (IRR) of 26.4% and a payback period (PB) of 3.8 years, outperforming the PV-hybrid system (IRR: 21.9%, PB: 4.5 years).
- These strong financial indicators confirm the investment viability of renewable energy integration.

Environmental impact:

- CO_2 emissions show a remarkable transition from 252,048 kg/year (base system) to negative emissions (−160,476 kg/year) in the full hybrid system, representing not just emission reduction but actual environmental remediation.
- The PV-hybrid system achieves a 68.2% reduction in emissions compared to the base system.

System evolution:

- The results demonstrate that each additional renewable component (PV then wind) contributes to progressive improvements across all performance indicators.
- The full hybrid system's negative emissions suggest it generates sufficient clean energy to offset other carbon-intensive processes, representing a net environmental benefit.

The analysis strongly supports the implementation of the full hybrid system (G + H + PV + W) as it offers: (i) the lowest lifetime costs (NPC); (ii) the most competitive energy costs (LCOE); (iii) the strongest financial returns (IRR and PB); (iv) the most favorable environmental profile and (v) the greatest potential for sustainable energy generation.

These findings highlight the technical and economic feasibility of transitioning to fully hybridized renewable energy systems, with significant benefits for both operators and the environment. The results suggest that the higher initial capital investment is justified by the substantial operational savings and environmental benefits achieved over the system's lifetime.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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