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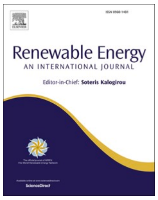

Conceptual hybrid energy model for different power potential scales: Technical and economic approaches

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ABSTRACT

This research attempts to address the gap between the theoretical fundamentals of hybrid renewable energy systems and their practical implementation at different scales through a new Conceptual Hybrid Energy Model (COHYBEM). The main objective was to develop a multi-variable model to allow a new complete and comprehensive techno-economic analysis of the performance of possible hybrid renewable power systems at different scales. The purpose is to evaluate the influence of critical parameters by changing key parameters in the developed model and identifying their impacts. It covers big data analyses, simulation and optimization of hybrid energy solutions, combining wind, solar and hydropower energy sources with the energy storage technology of pump hydropower storage. The research also denoted the Pareto front with the increasing power installed, for the maximum efficiency and total satisfied demand by Wind + PVSolar and by Hydro converges to a higher percentage, while a minimum waste by Wind + PVSolar is also progressing towards the increasing scales. In terms of investment costs for the 243 analyzed case studies, it varies between 45 k€ to 2.1 M€, resulting in a net present value (NPV) between 18 and 600 k€ and a payback period around 6–17 years depending on the power scale analyzed.

1. Introduction

Currently, the global population is confronted with the necessity to mitigate climate change and alter the trajectory of energy systems in this transition era. Renewable Energy Sources (RES), specifically wind and PV solar power, have emerged as viable solutions to towards sustainable low-carbon energy systems across the water sector. They possess a significant potential to reduce energy prices and dependence on fossil fuels in the short and long term [1,2].

Despite increasing market uncertainties, the focus on energy security and cleaner energy systems, especially in the European Union, has triggered an unprecedented policy momentum towards accelerating energy efficiency and renewable energy integration.

The European Union has established ambitious goals to achieve a carbon-neutral economy by 2050. As a component of this commitment, the European Union aims to augment the proportion of renewable energy in its final energy consumption to a minimum of 32 % by 2030 [3,4]. The International Energy Agency (IEA) reported that the increase in renewable energy production capacity reached an all-time high in 2020, demonstrating the resilience of the renewable energy sector despite the disruption caused by the pandemic worldwide. According to the International Renewable Energy Agency (IRENA), renewable energy generation accounted for around 26 % of the world's electricity generation in 2020, with wind and solar contributing approximately 9 % of the total. In 2023, the world added 50 % more renewable capacity compared to the previous year. The COP28 climate talks called for a tripling of renewable energy capacity and doubling energy efficiency improvements by 2030. Additional renewable electricity capacity reached 507 GW in 2023, with solar PV making up three-quarters of global additions, according to the International Energy Agency's (IEA) Renewables 2023

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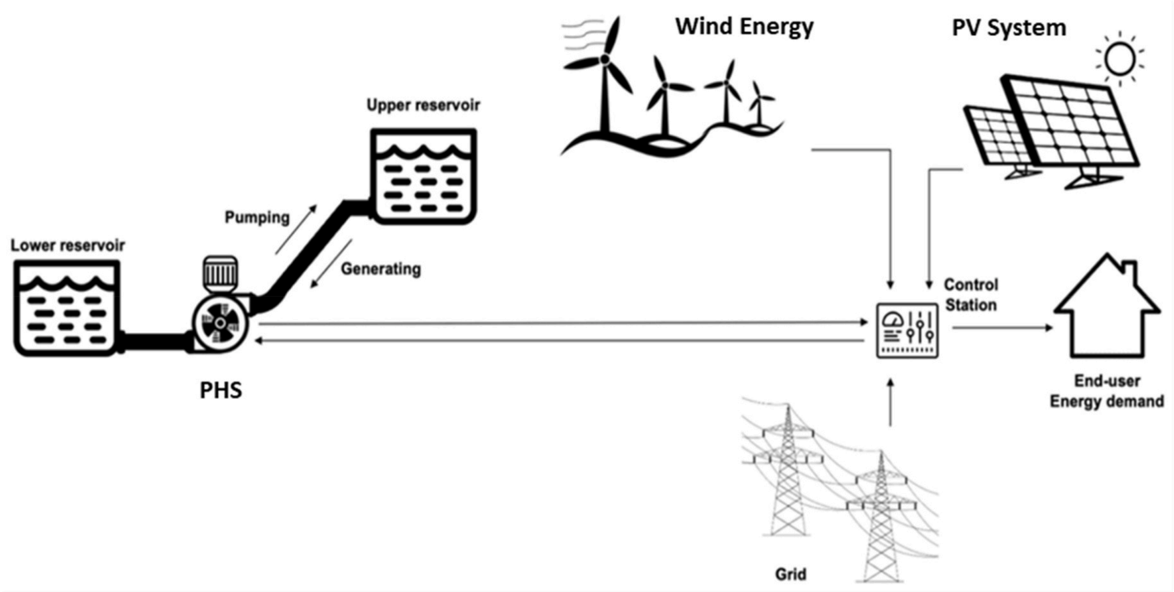

Fig. 1. Proposed COHYBEM techno-practical scheme.

report. This unprecedented growth is being driven by increasing policy support, growing energy security concerns, and improved competitiveness against fossil fuel alternatives. Furthermore, IRENA predicts, the global renewable capacity additions could surpass 550 GW in 2024, a significant increase of almost 20 % [3–6]. This is primarily attributable to the more rapid deployment of residential and commercial PV installations, and the faster implementation of recent policies and incentives.

Since the power of the sun is an insurance in the search for clean and affordable energy, solar power, harnessed through photovoltaic (PV) panels and solar thermal systems, is encouraging decentralized electricity production and energy autonomy on a local scale. Recent technological advances have accelerated the adoption of solar power, leading to rapid cost reductions and efficiency improvements.

The abundant nature of sunlight allows solar PV to be used in a variety of locations, from urban rooftops to rural communities without a grid connection. However, the intermittent nature of solar irradiation requires innovations in energy storage systems in order to guarantee an uninterrupted supply of electricity. Furthermore, urban planning strategies that take solar production potential into account can maximize the integration of solar technologies. Many countries, especially in Europe, have actively pursued alternatives to imported fossil fuels in response to higher electricity prices caused by the global energy crisis.

This shift has created a favorable environment for solar PV, especially for residential and commercial systems that can be installed quickly to meet growing demand for renewable energy. Today, Solar PV is the primary driver of global renewable capacity expansion, accounting for 65 % of growth with distributed applications, including residential and commercial systems, accounting for almost half of global PV expansion [7–12].

Wind power has transcended its historical association with windmills to emerge as a formidable competitor in the global energy landscape. Advancements in turbine design and production, aerodynamics, and materials have resulted in higher capacity factors and greater energy efficiency. The versatility of wind power is exemplified by its utilization in both onshore and offshore installations, each of which is tailored to distinct geographical and resource conditions.

Efforts by governments, industries, and research institutions have resulted in the advancement of wind power as a cost-effective source capable of meeting significant portions of global electricity demand. The challenges associated with wind power energy generation are being solved through sophisticated energy storage solutions and smart grid integration technologies [13–16]. Until the conclusion of 2023, it is anticipated that the annual global onshore wind capacity additions will increase by 70 %, surpassing the record set in 2020. This growth is driven by the commissioning of projects in China. It is anticipated that the annual off-shore additions will increase by nearly 50 % by the conclusion of 2024 [17–20].

Hydropower plants harness the potential energy of water to generate electricity, providing a dependable source of energy that contributes to both energy security and environmental sustainability. A significant advancement has been made in the field of hydropower, as conventional hydropower has experienced a growth of more than 75 %, resulting in an installed capacity of over 1230 GW. Pump Hydropower Storage capacity, on the contrary, grew by over 50 %, reaching 130 GW in 2021. Together, they account for over half of global renewable installed capacity. Hydropower generated approximately 65 % of all renewable generation or over 16 % of all electricity generation, making it extremely very important not only as a renewable generation source, but for power systems worldwide and intermittent renewables integration [12–18].

Hydropower costs vary depending on the project's size and specification, with the largest cost component being the civil works, which account for roughly 45 % of the costs. This includes the construction of the dam/reservoirs, tunnels, canal, and powerhouse, as well as any other complementary infrastructure. This is followed by the expenses associated with the procurement of electro-mechanical equipment, which constitute approximately 33 % of the total expenses [21–25].

The global weighted average, levelized cost of electricity, of utility-scale hydropower projects was €0.045/kWh in 2010–2021 – lower than any fossil-fuel-based project [26–30]. LCOE values can vary substantially because of the investment costs, but also depending on how the plant is designed to operate (to provide base or peak load or ancillary services) and the capacity factors achieved. The attraction of hydropower lies on its applicability at various scales, from micro and small installations that empower local communities to medium or large hydropower plants that contribute significantly to national energy portfolios.

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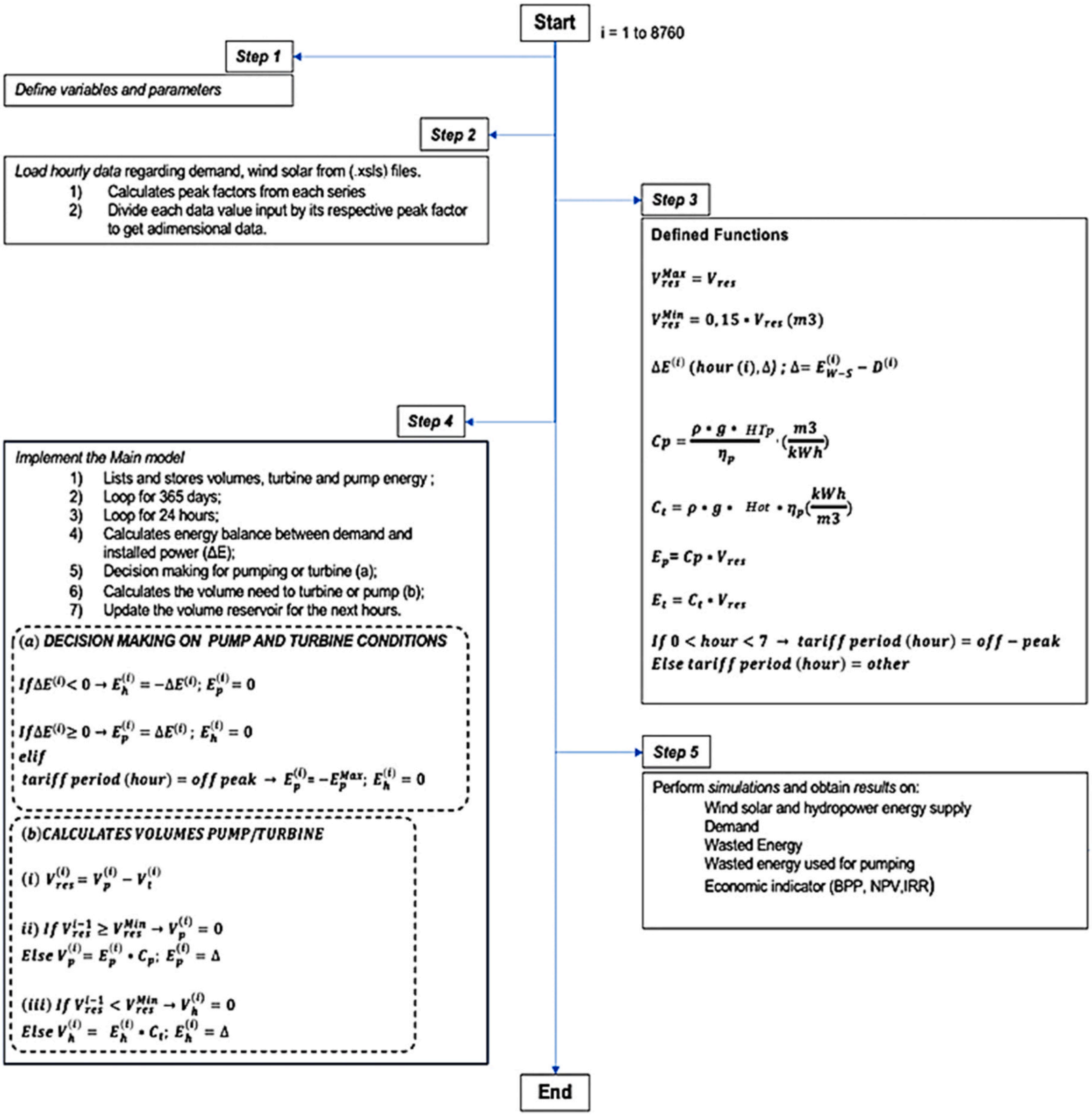


Fig. 2. COHYBEM flowchart for optimized hybrid energy solutions.

130 GW in 2021. Together, they account for over half of global renewable installed capacity. Hydropower generated approximately 65 % of all renewable generation or over 16 % of all electricity generation, making it very important not only as a renewable generation source, but for power systems worldwide and intermittent renewables integration [26,28].

Considering various power scales, micro-hydropower plants, which are distinguished by their small scale (typically having capacities below 100 kW) and localized impact, have garnered attention for their capability to provide clean energy to remote areas and off-grid communities [18]. These installations often rely on small streams or rivers with limited net head and flow rates in order to act turbines and produce electricity. Recent technological advances have made micro-hydro systems more economically viable and environmentally friendly. Furthermore, the integration of micro-hydropower plants with energy storage solutions and intelligent grid management enhances their reliability and capacity to be integrated into the water sector and create microgrids [31–36].

Small hydropower plants make the connection between micro hydropower and medium or large hydropower installations, offering more substantial capacity than micro (up to 10 MW) and keeping the emphasis on decentralized energy production at community level, but also can provide a consistent and reliable power supply to the grid [37–41]. These plants often use moderate net head and flow rates, which makes them adaptable to various geographic contexts. Technological advancements, such as fish-friendly turbines and optimized sediment management systems, have significantly reduced the environmental impact of small hydropower plants [42–45]. The integration of small hydropower plants with other renewable sources and energy storage technologies improves their contribution to the grid stability and energy resilience. Large hydropower plants represent the pinnacle of hydropower engineering, not only because of their substantial capacity (exceeding 10 MW), but also because of the possibility of making a significant contribution to national energy grids. These projects often involve the construction of large dams and reservoirs, which can have a significant impact on river ecosystems and local communities [27].

The growth of renewable energy presents a transformative idea that extends beyond individual energy sources to an integrated and harmonious energy ecosystem. Hybrid systems that incorporate solar, wind, hydropower, and energy storage technologies present a comprehensive

Table 1
Technical input and output parameters.

Input		Output	
- g	gravity acceleration (m/s^2)	- $D^{(i)}$	demand at hour “i” (MW)
- ρ	water density (kg/m^3)	- $E_{W-S}^{(i)}$	wind-solar energy at hour “i” (MW)
- H_{0t}	net head (m)	- $\Delta_E^{(i)}$	difference between wind-solar energy and demand at hour “i” (MW)
- H_{Tp}	total pump head (m)	- $E_h^{(i)}$	hydro energy at hour “i” (MW)
- η_t	turbine efficiency (%)	- $E_p^{(i)}$	pump energy at hour “i” (MW)
- η_P	pump efficiency (%)	- E_h^{Max}	maximum hydro energy (MW)
- $\frac{Q_t^{Min}}{Q_t^{Max}}$	minimum turbined flow fraction allowed (−)	- E_p^{Max}	maximum pump energy (MW)
- $\frac{Q_p^{Min}}{Q_p^{Max}}$	minimum pumped flow fraction allowed (−)	- $V_{res}^{(i)}$	reservoir’s volume at hour “i” (m^3)
- $D_{non-dim}^{(i)}$	non-dimensional demand at hour “i” (−)	- $V_p^{(i)}$	pumped volume at hour “i” (m^3)
- D_p	peak demand (MW)	- $V_t^{(i)}$	turbined volume at hour “i” (m^3)
- $P_{W-S\ non-dim}^{(i)}$	non-dimensional wind-solar energy at hour “i” (−)	- V_p^{Max}	maximum pumped volume (m^3)
- P_{W-S}^{Inst}	wind-solar power installed (MW)	- V_t^{Max}	maximum turbined volume (m^3)
- P_{W-S}^{Efest}	wind-solar effective power (MW)	- Q_p^{Max}	maximum pumped flow (m^3/s)
- $Rest_{grid}$	grid restriction (%)	- Q_t^{Max}	maximum turbined flow $\left(\frac{m^3}{s}\right)$
- V_{Res}^{Max}	maximum reservoir’s volume $\left(m^3\right)$		
- V_{Res}^{Min}	minimum reservoir’s volume $\left(m^3\right)$		

Table 2
Parameters assumed for wind/solar, turbine installed capacities, and maximum volume of the upper reservoir, in different HES scales.

Cases		Solar installed power (MW)			Hydropower installed (MW)	Maximum upper reservoir volume (m^3)
Micro Scale (Cases j, 1 to 81)		0.01	0.05	0.1		
Wind installed power (MW)	0.01	j = 1	j+1	… …	0.01; 0.05; 0.1	1500; 7500; 15,000
	0.05	j+1	… .	… …		
	0.10	j+2	… …	81		
Small Scale (82 to 162)		0.2	0.5	0.8		
…. .	0.2	j = 82	….	….	0.2; 0.5; 0.8	20,000; 50,000; 80,000
	0.5	….	….	….		
	0.8	….	….	162		
Medium Scale (163 to 243)		1	2	3		
….	1	j = 163	….	….	1; 2; 3	100,000; 200,000; 300,000
	2	….	….	….		
	3	….	….	243		

solution to the issue of energy intermittency [31,46]. The dynamic interaction between diverse renewable energies enhances the resilience of energy systems, thereby enhancing energy security and stability [32]. Furthermore, intelligent grid management, demand response strategies, and predictive analysis are crucial for managing energy transitions that optimize production, consumption, and storage. Moreover, the emergence of energy cooperatives and community micro-grids exemplifies the democratization of energy, enabling local communities to be both consumers and producers [34]. Nonetheless, advancements in turbine technology and dam design have resulted in the establishment of more productive and environmentally-friendly large hydropower plants [28]. These plants play an important role in balancing energy demand and supply, especially in regions with high electricity consumption. It is anticipated that solar PV additions will continue to increase in 2024/2025, despite the challenges posed by wind expansion. The declining module prices, increasing efficiencies and interest in distributed solar PV systems, and a policy imperative for large-scale arrangement drive higher annual solar additions in all major markets [35–38]. New set indices should be indexed in the water systems to evaluate the accuracy of the models [47]. Likewise, the indices should not only focus on technical aspects, but should also address the evaluation of indicators that allow the monitoring of the different goals of the sustainable development objectives [48].

The use of pumps operating as turbines (PATs) in distribution systems offers a cost-effective and sustainable alternative to traditional energy generation and regulation methods. PATs are primarily employed to recover energy from excess pressure in water distribution networks, converting hydraulic energy into electricity. This process not only increases energy efficiency but also contributes to reducing energy waste [49]. One of the major advantages of PATs is their simplicity and low cost compared to conventional turbines, making them highly attractive for small and medium-scale applications [50].

Regulation of PATs can be challenging since pumps are not originally designed for reverse operation. However, modern control strategies and variable operation strategy (VOS) have significantly improved their performance and adaptability [51]. From an environmental perspective, PATs provide multiple benefits. They facilitate the generation of renewable energy without requiring large infrastructure investments or disrupting ecosystems, as is often the case with traditional hydropower plants. By integrating PATs into existing water distribution networks, energy recovery can be achieved without altering natural watercourses or landscapes, contributing to reduced greenhouse gas emissions and fostering sustainable energy practices [52].

Table 3
Fixed parameters for different HES scales.

	Scales		
	Micro	Small	Medium
Type of turbine:	PAT	Francis	Francis
Peak Consumption (MW):	0.05	1	4
Net Head (m):	20	80	150
Turbine efficiency (%):	0.5	0.8	0.8
Pumping efficiency (%):	0.7	0.7	0.7
Minimum turbined flow fraction allowed:	0.7	0.4	0.4
Minimum pumped flow fraction allowed:	0.5	0.5	0.5
Turbine generation coefficient (kWh/m3):	0.03	0.18	0.33
Water pumping coefficient (m3/kWh):	0.08	0.32	0.6

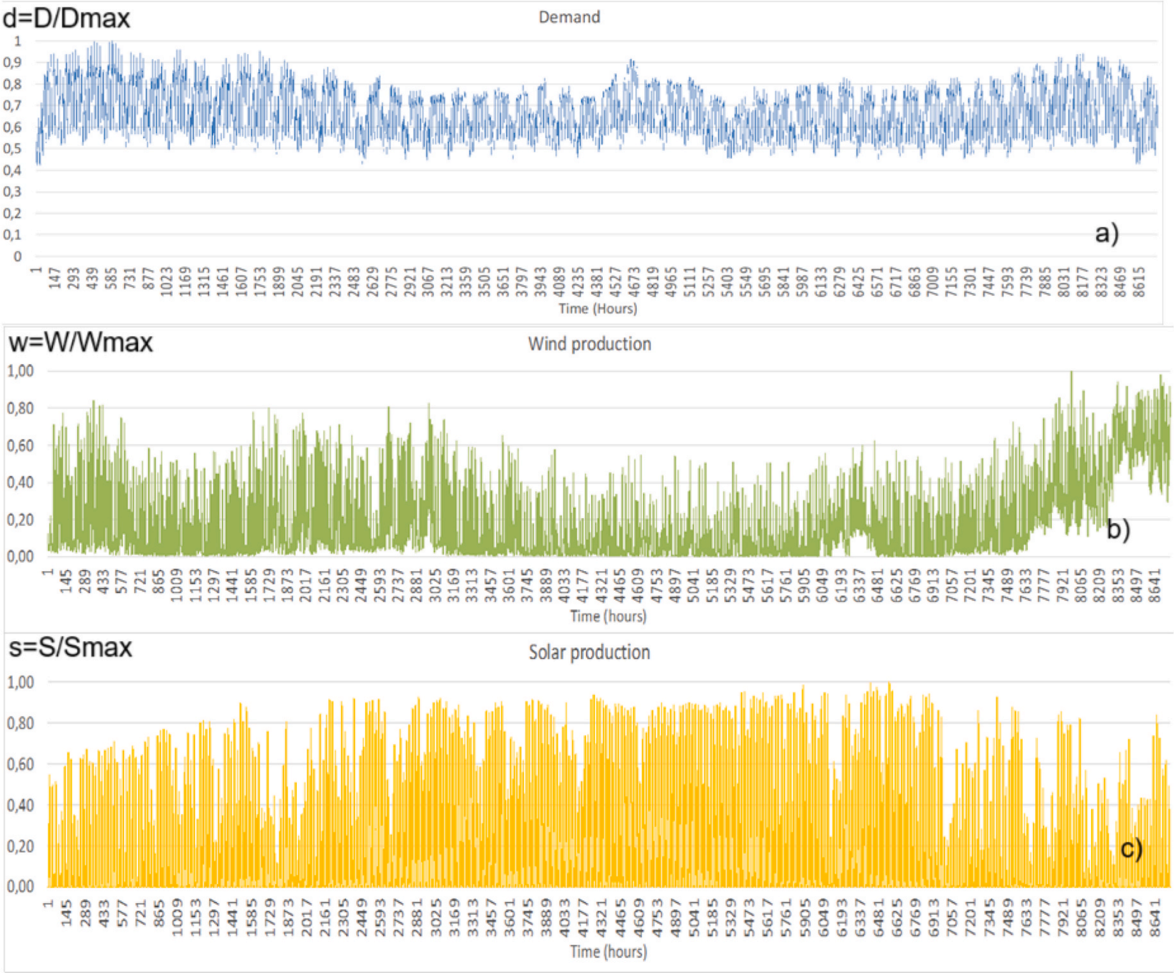


Fig. 3. Example of dimensionless (divided by the maximum value) average annual series for demand (a), wind (b), and solar (c) energy generation.

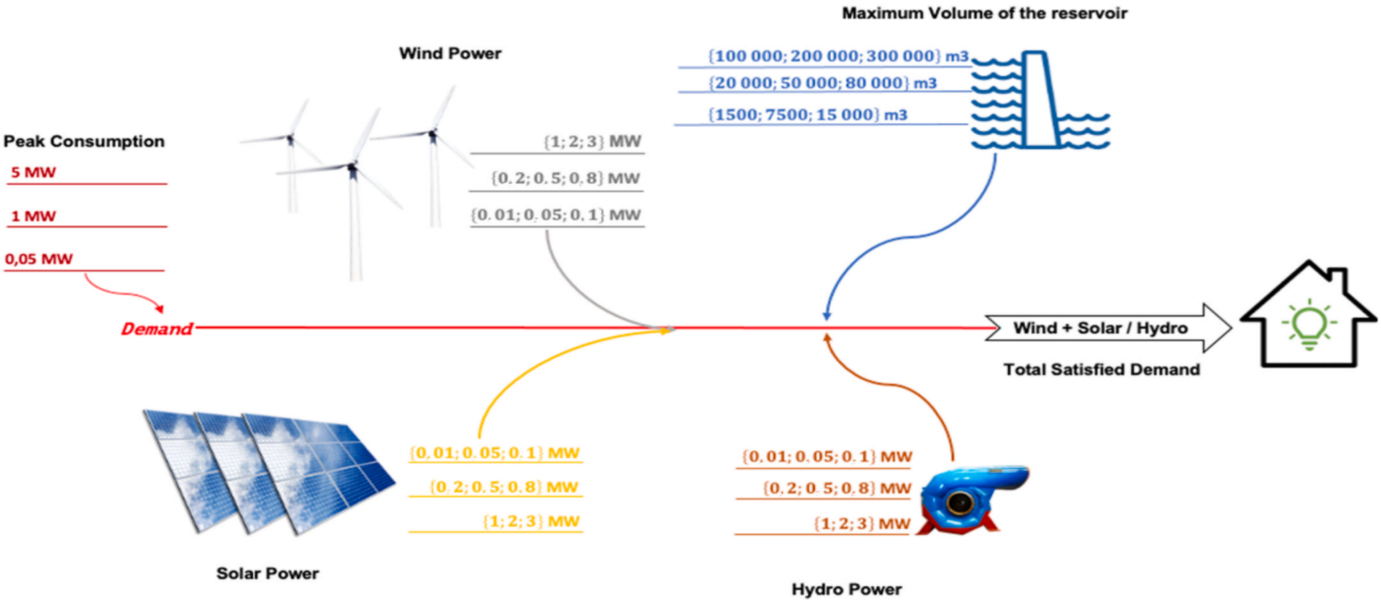


Fig. 4. HES: schematic diagram for different analyzed combinations.

PATs also improve the overall energy efficiency of distribution systems by utilizing excess hydraulic energy that would otherwise be wasted. In water distribution networks, pressure management is crucial to preventing pipe bursts and leaks, which can lead to significant water loss [53]. PATs not only recover energy but also help to regulate pressure, thereby extending the lifespan of infrastructure and reducing

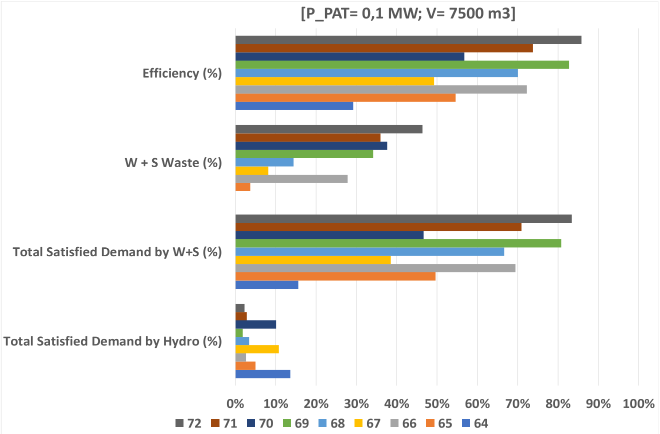


Fig. 5. Micro HES behavior for a PAT power of 0.1 MW and a storage reservoir size of 7500 m^3.

Table 4
Energy tariffs used (€/kWh).

Peak	Half-Peak	Off-Peak	Super Off-Peak
0.0927	0.0406	0.0115	0.0115

maintenance costs [54]. The recovered energy can be fed back into the grid or used to power other parts of the system, further enhancing its economic and operational efficiency [55].

This research work is structured as follows: **Section 1**, as former presented includes a detailed and recent literature review on the subject of HES. **Section 2** presents the materials used in this investigation and the proposed methodology of the Conceptual Hybrid Energy Model (COHYBEM), to identify the best HES, where the type is characterized, as well as the basic modelling equations and assumptions are presented. **Section 3** presents results and discussion relatively to 243 developed simulations covering more than 50,000 parameters for the three well-identified power scales, in terms of technologic design and economic analyses. COHYBEM is developed in Python, which allows a new complete and comprehensive techno-economic analysis with the purpose to evaluate the influence of critical parameters, such as installed wind and solar, turbine and pump powers, energy storage by pumped-storage, and reservoir volume, on the performance of the whole system's efficiency, flexibility and reliability. Ultimately this investigation covers data analyses, simulation and optimization of hybrid energy solutions, combining wind, solar and hydropower energy sources with a crucial energy storage technology, of Pump Hydropower Storage (PHS), in different power scales. A detailed comparison is made considering the most influential parameters in the system efficiency, flexibility and reliability. **Section 4** presents the main conclusions of this work taking into consideration the literature review, different power scales analyzed, addressing the gap between the theoretical fundamentals and the practical implementation through a multi-variable model.

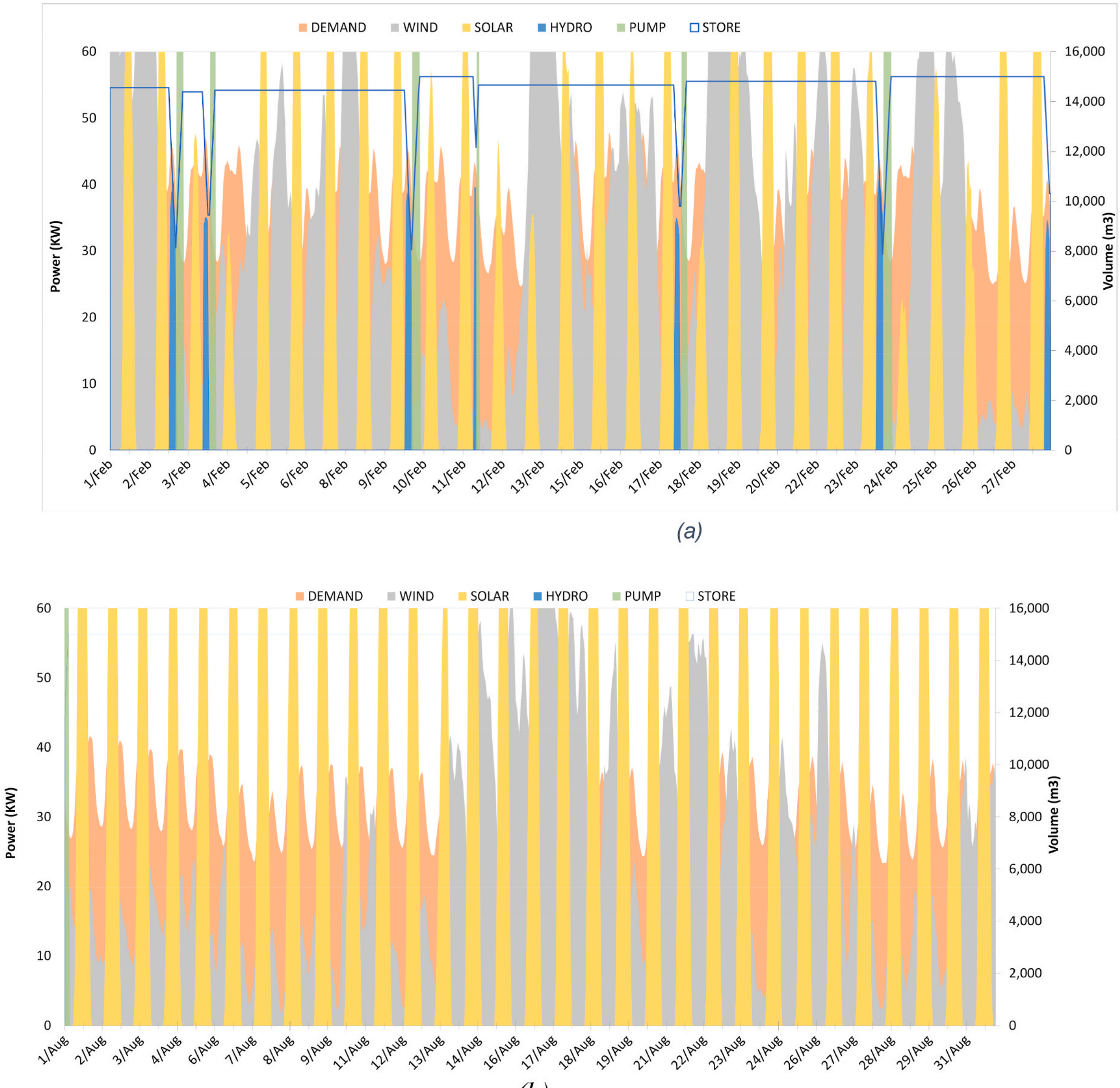
2. Methodology and materials

The proposed research methodology [1] is divided into four parts in order to create a conceptual hybrid energy model: (i) an integrated concept of hybrid energy solutions (HES) is conceived; (ii) a software code is developed in Python, depicting a HES with PHS, as a tool to develop various power combinations to address the optimization concern associated with the integration of intermittent renewable energies, as a technical sustainable and economic energy solution, through the analyzes of viability on diverse configuration power scales; (iii) the model allows to perform a series of simulations, which reveal the optimized arrangement; (iv) the ultimate objective is to analyze the behavior and adaptability of each potential hybrid energy system, including the ability to store excess wind/solar energy production during periods when energy demand is lower than production, the impact of tariffs, and the ability to produce hydropower during periods when the demand exceeds the production.

The system behavior will enhance both the technical and economic aspects of energy production, leading to a highly efficient utilization of available resources in a certain region.

Table 5
Economic analysis for the configurations 1–27 of the HES.

Case	Hydro cost (€)	Wind cost (€)	Solar cost (€)	Maintenance costs (€)	Total investment cost (€)	Energy sell (€)	B/C (−)	NPV (€)	PBP (years)	IRR (%)
1	3584	2000	1500	283	7367	1219	1.20	1407	6	12.5 %
2		10,000	1500	460	15,544	3510	1.75	11,298	4	19.0 %
3		20,000	1500	860	25,944	4982	1.44	11,027	5	15.4 %
4		2000	7500	380	13,464	3141	1.82	10,675	4	19.8 %
5		10,000	7500	700	21,784	4962	1.77	16,297	4	19.3 %
6		20,000	7500	1100	32,184	5919	1.37	11,356	5	14.5 %
7		2000	15,000	680	21,264	3949	1.38	7785	5	14.7 %
8		10,000	15,000	1000	29,584	5386	1.35	9923	5	14.3 %
9		20,000	15,000	1400	39,984	6167	1.09	3381	6	11.1 %
10		2000	1500	140	7224	1361	1.38	2694	5	14.7 %
11		10,000	1500	460	15,544	3602	1.80	12,132	4	19.7 %
12		20,000	1500	860	25,944	5184	1.51	12,860	5	16.3 %
13		2000	7500	380	13,464	3287	1.92	12,003	4	20.9 %
14		10,000	7500	700	21,784	5070	1.82	17,277	4	19.8 %
15		20,000	7500	1100	32,184	6182	1.44	13,745	5	15.5 %
16		2000	15,000	680	21,264	4227	1.50	10,313	5	16.1 %
17		10,000	15,000	1000	29,584	5560	1.40	11,503	5	15.0 %
18		20,000	15,000	1400	39,984	6412	1.15	5608	6	11.9 %
19		2000	1500	140	7224	1381	1.41	2879	5	15.0 %
20		10,000	1500	460	15,544	3648	1.83	12,556	4	20.0 %
21		20,000	1500	860	25,944	5260	1.54	13,558	5	16.6 %
22		2000	7500	380	13,464	3304	1.93	12,155	4	21.1 %
23		10,000	7500	700	21,784	5088	1.83	17,443	4	19.9 %
24		20,000	7500	1100	32,184	6192	1.45	13,837	5	15.5 %
25		2000	15,000	680	21,264	4252	1.51	10,536	5	16.3 %
26		10,000	15,000	1000	29,584	5594	1.78	11,817	5	15.1 %
27		20,000	15,000	1400	39,984	6482	1.16	6245	6	12.1 %



(a)

(b)

Fig. 6. Energy mix for February (a) and August (b): Demand 0.05 MW, Wind 0.05 MW, Solar 0.05 MW, Volume 15,000 m^3.

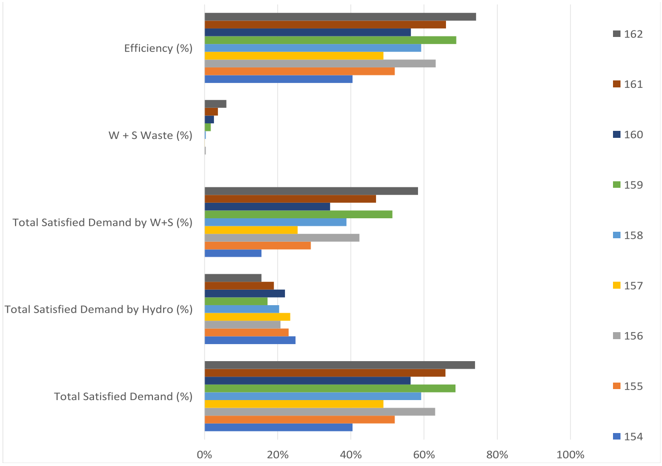


Fig. 7. Francis installed power 0.8 MW with a reservoir volume of 80,000 m^3.

2.1. HES characterization

A conceptual hybrid energy model (COHYBEM), combining wind, solar, with a pumped hydro storage system is represented in Fig. 1. The components of a system are: photovoltaic or Solar Power (PV), wind energy, energy storage system (pumped-hydro storage (PHS)), grid energy purchase, a control station and end-user (energy demand).

The developed model incorporates a representative HES composed of wind and photovoltaic energy sources combined with PHS, to provide results on the technical, economic, and environmental aspects and can be used to bridge theory and tangible and sustainable hybrid energy solutions, with insights on the behavior, operating principles, constraints, inputs, and outputs of the system. The methodology flow chart is described in Fig. 2.

There are distinct steps in the model structure, ensuring flexibility, sustainability, and adaptability. Data collection of defined variables, function definitions, main optimized code, simulations and outcomes are all included in COHYBEM. Adding more functions or type of analyses and incorporating real data is possible with the modular design.

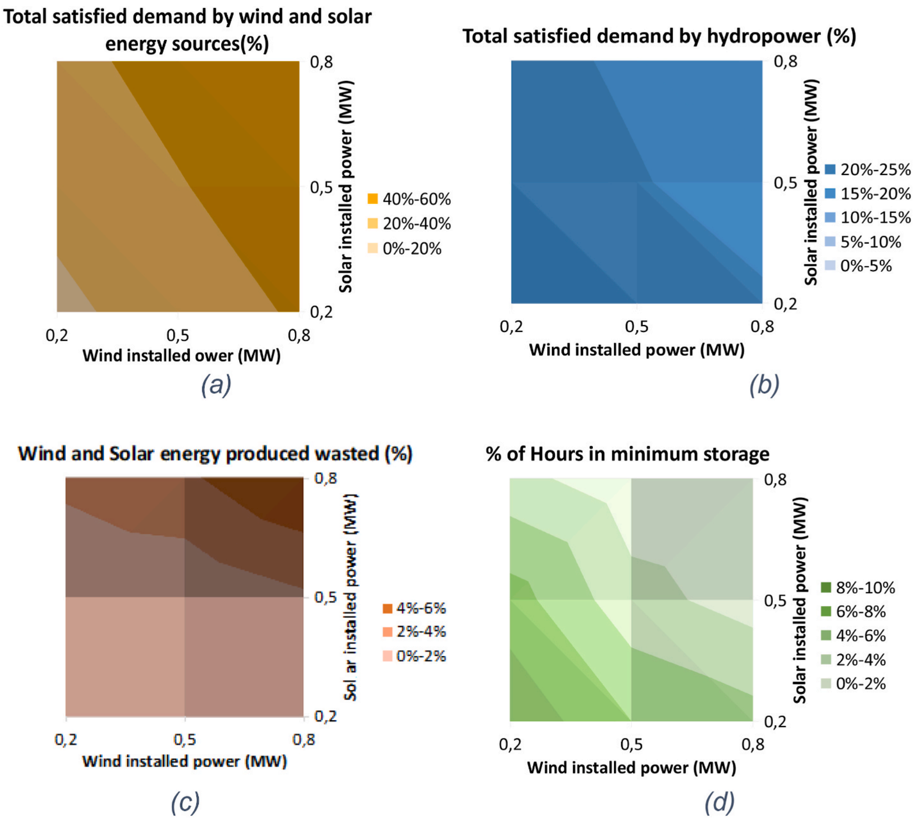


Fig. 8. Results for case 160: Francis turbine with 0.8 MW and reservoir volume 80,000 m^3: (a) Total satisfied demand by wind and solar energy sources; (b) Total satisfied demand by hydro; (c) Wasted wind and solar energy produced; (d) Percentage of hours where the upper reservoir is in minimal storage capacity.

Step 1. Define necessary variables and parameters: this step defines various physical and techno-economic variables and parameters related to the energy system, such as peak consumption, installed power, energy prices, and reservoir volume. These parameters are crucial as they define the upper limits for energy generation and consumption. Peak consumption represents the maximum energy demand that needs to be met by the hybrid system, and the installed capacities, define the maximum energy generation potential of wind, solar, and hydropower sources. Physical proprieties, net head of turbines and pumps head (i.e., $H0_t$ and HT_p), turbine efficiency (η_t), and pump efficiency (η_p), affect the energy conversion efficiency and are essential for pump-hydropower potential. These values should be meticulously determined, engineering specifications, and the location's resource availability.

Step 2. Load hourly data: Hourly data for wind production, solar production, and energy demand is loaded from Excel files. Through a selection of peak factors, non-dimensional values are obtained and organized as database. These data are used in subsequent steps for simulations.

Step 3. Define functions for the system to operate: Calculates the lower reservoir volume as 15 % of the maximum upper reservoir volume. Defines functions such as: calculate_energy_changes(hour, ΔE)" that calculates the energy changes at a specific hour; "calculate_turbine_generation_coefficient" that calculate the turbine generation coefficient; and calculate_water_pumping_coefficient" that calculates the pumping coefficient. As well as calculate the maximum hydro and pump energy available according to the volume of water available in the system, and that define the hourly rate tariff period (e.g., 0–7h off peak).

Step 4. Main calculations: Implements the hybrid energy system running: The run_hybrid_system_model function is the main part of the simulation. It calculates energy changes, turbine, and pump coefficients, and tracks the volume of the reservoir and other hourly variables. It evaluates whether to pump water into the reservoir or generate electricity through the turbine. The model logic captures the complex interplay between energy supply, energy demand, and the reservoir role as an energy storage technology.

Annual hourly cycle (8760 iterations).

- Retrieves hourly data from the non-dimensional database;
- Multiplies the non-dimensional values by peak demand, wind, and solar installed power;
- Calculates the energy balance between demand and installed power (ΔEi);
- Decides on: turbine operation to meet demand or sell energy to the grid. For pumping it is done during lower demand hours (0–7h), and if there is a surplus of energy in the system;
- Calculates the pump and hydro generated energy according to the defined conditions (flow and head);
- Calculates the pumped and turbined volume according to the defined conditions;
- Updates the reservoir volume for the next hour.

Step 5. Simulations and results: the "simulate_hybrid_system" function calculates, energy supply from renewable sources and demand, wasted energy, energy used for pumping, revenue, costs, and economic indicators such as payback period, net present value, and internal rate of return. It also calculates the self-sufficiency of the system efficiency ((total energy supplied/demand) *100). The model calculates key parameters that enable a comprehensive understanding of the system's performance. From this step, results about the wind, solar and hydro energy supplied, energy sold and self-consumed, revenue, cost, profit, basic payback period, net present value, internal rate of return, and the efficiency of the system can be assessed. The modeling assumptions, mathematical equations, and variable inputs are combined to obtain results about the complexities of energy generation, consumption, and economic metrics.

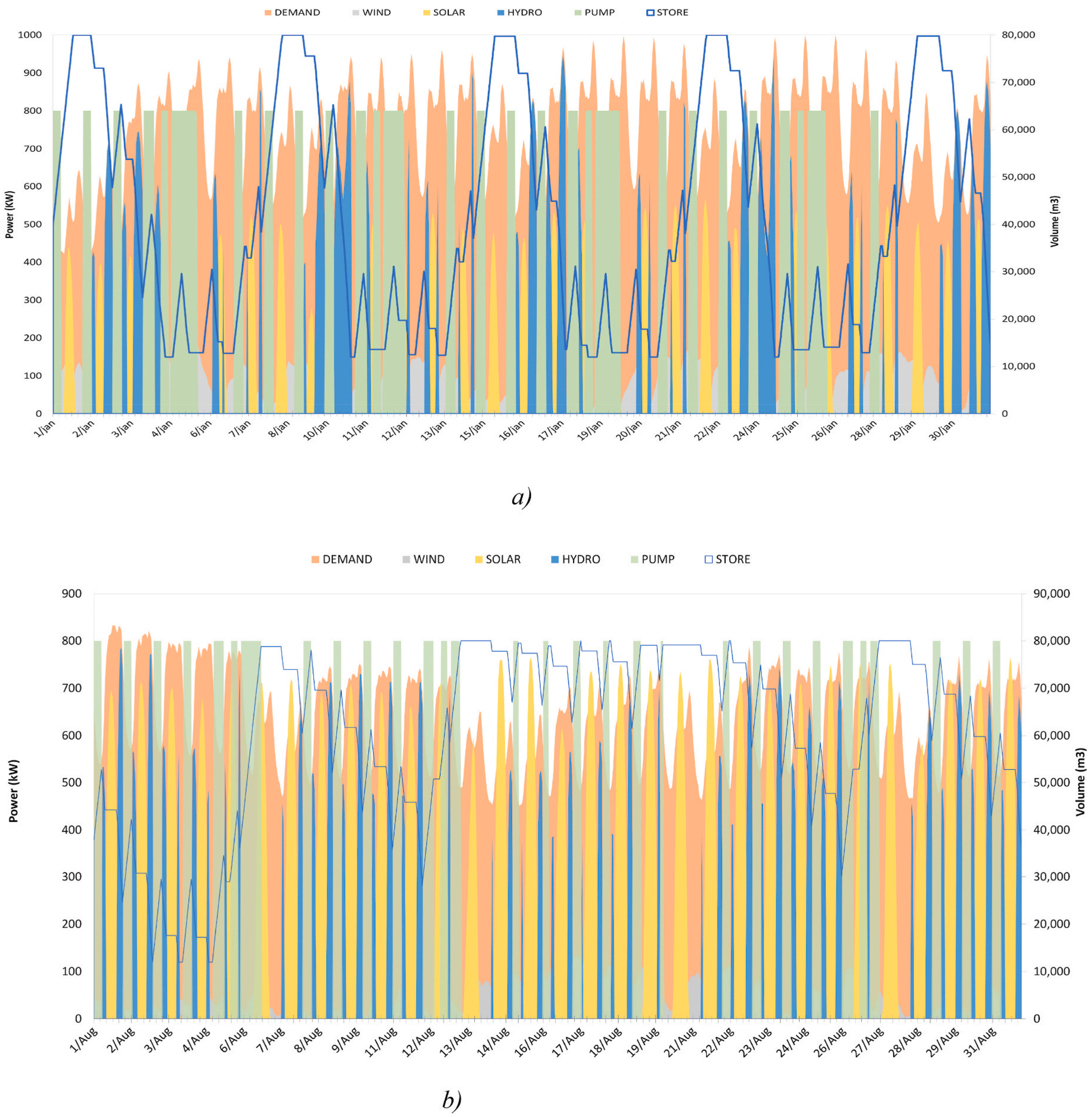


Fig. 9. Energy mix winter (a) and summer (b) months: Demand 1 MW, Wind 0.2 MW, Solar 0.8 MW, Volume 80,000 m3.

As a result, COHYBEM was developed in Python and presents the following main procedures, as illustrated in Appendix I.

COHYBEM presents some limitations associated with assumptions made to keep computational feasibility. These include the assumption of constant efficiency values (for Pumps and Turbines) and normal operating conditions. It also relies on user-defined parameter values, not incorporating geographic-specific weather or topographical data, which can influence renewable energy generation.

Important input and output parameters, described in Table 1, regarding the physical and technical aspects of the components that constitute the HES, need to be considered prudently and assumed.

Other parameters, regarding economic aspects are also considered and implemented. Parameters such as electricity price (€/kWh), feed-in tariffs prices (€/kWh) and discount rate values, are assumed in order to provide accurate economic results. The total stored energy *Eh* (kWh) in the active volume of a reservoir is calculated by Equation (1):

$$E_h = \eta_t{}^*\rho^*g^*H_{0t}{}^*V = c_t{}^*V \ \ (\text{kWh}) \tag{1}$$

where, ct is the turbine generation coefficient (kWh/m^3) and V stand for volume (m^3).

The energy used to pump the water volume to a specific total pump head, with a specific pumping efficiency, is described by Equation (2):

$$E_p = \frac{\rho^*g^*H_{Tp}{}^*V}{\eta_p} = c_p{}^*V \ \ (\text{kWh}) \tag{2}$$

where, c_p is the water pumping coefficient of the pump/motor unit (m^3/kWh).

The turbine generation coefficient, c_t (kWh/m^3) in Equation (1) and the water pumping coefficient c_p (m3/kWh) in Equation (2) are two fundamental parameters of the PHS components. Regarding the operation of the different components in the hybrid system, Equations (3) and (4) present the operating conditions and constraints assumed for each system combination.Operation conditions:

Operation conditions:

$$
\begin{gathered}
\textit{Regarding, installed power and energy} \\
P_{W-S}^{Efet} = P_{W-S}^{Inst} * Rest_{red} \\
E_{W-S}^{(i)} = E_{W-S\ non-dim}^{(i)} * P_{W-S}^{Efet} \\
D^{(i)} = D_{non-dim}^{(i)} * D_p \\
\Delta_{\boldsymbol{E}}^{(\boldsymbol{i})} = E_{W-S}^{(i)} - D^{(i)} \\
\textit{Regarding, operation} \\
\textit{If } \Delta_E^{(i)} < 0 \rightarrow E_h^{(i)} = -\Delta_E^{(i)}, \\
\textit{else } \; E_p^{(i)} = 0 \\
\textit{If } \Delta_E^{(i)} > 0 \rightarrow E_h^{(i)} = 0, \\
\textit{else } \; E_p^{(i)} = \Delta_E^{(i)} \\
\textit{Regarding storage volume} \\
V_{Res}^{Min} > 0.15 V_{Res}^{Max} \\
V_{res}^{(i)} = V_{res}^{i-1} + V_p^{(i)} - V_t^{(i)} \\
V_p^{(i)} \geq \frac{Q_p^{Min}}{Q_p^{Max}} V_p^{Max} \; ; \; V_t^{(i)} \geq \frac{Q_t^{Min}}{Q_t^{Max}} V_t^{Max}
\end{gathered}
\tag{3}
$$

Restrictions:

$$
\begin{gathered}
\textit{Regarding volume:} \\
\textit{If } V_{res}^{(i)} \geq V_{Res}^{Max} \rightarrow V_p^{(i)} = 0 \\
\textit{Else } V_p^{(i)} = \frac{E_p^{(i)} \eta_p}{\rho g H_{Tp}} * 3600 \\
\textit{If } V_{res}^{(i)} \leq V_{Res}^{Min} \rightarrow V_t^{(i)} = 0 \\
\textit{Else } V_h^{(i)} = \frac{E_h^{(i)}}{\rho g H_{0t} \eta_t} * 3600 \\
\textit{Regarding tri} - \textit{time tariff period :} \\
\textit{If } time_{tarif\ period}^{(i)} = \textit{off peak period} \rightarrow E_p^{(i)} = \textit{Pump power installed}, E_h^{(i)} = 0 \\
\textit{Else } E_p^{(i)} = 0, E_h^{(i)} = -\Delta
\end{gathered}
\tag{4}
$$

Hence, the computational model that addresses the optimization approach as a hybrid hydro-solar-wind system serves as an essential tool in assessing the viability and performance of a multi-source energy generation infrastructure comprising wind, PVsolar, hydropower resources and pumped-storage solution.

A structured and modular approach has been adopted, facilitating the clear demarcation of distinct stages of the modeling process, from the initialization of system parameters to the economic assessment of the hybrid system's financial feasibility. Notably, the code integrates the notion of minimum and maximum flow fractions, stipulating the operational boundaries for the turbine and pump. These constraints are contingent on the operational range and capacity of the turbine and pump systems, providing the essential governance mechanisms to maintain operational integrity. These conditions materialize as essential elements within the model, governing the calculation of pumped and turbined volumes of water, which ultimately impact the reservoir's energy capacity. The reservoir, a crucial component in the system, is dynamically monitored as the code progresses through a comprehensive simulation process, dissecting each hour over an annual time frame (i.e., 8760 iterations).

2.2. Modelling assumptions

Considering that one of the objectives of this research is to evaluate the influence of critical parameters in the hybrid system and to identify optimal hybrid solutions across different scales, we varied the installed capacities of wind and solar power, the maximum upper reservoir volume, and turbine/pump capacities, as outlined in Table 2. Meanwhile, other parameters—such as peak consumption, net head, pumping and turbine efficiency, turbine generation coefficient (c_t) and water pumping coefficient (c_p)—were held constant. These fixed parameters were applied across all selected scales, with their values specified in Table 3.

The data series of dimensionless average year of hourly consumption, wind, and photovoltaic productions, are used as input data in the model (Fig. 3).

The schematic diagram with all different combinations of simulated values for the three analyzed scales is represented in Fig. 4.

For analyzes of costs and profits, the unit costs of purchasing equipment for different renewable sources and maintenance costs are considered (see Fig. 5). The unitary capital costs assumed for wind and solar are 200,000 €/MW and 150,000 €/MW, respectively.

The unitary costs for turbine and hydraulic pump equipment vary according to the type of equipment (i.e., installed power) for Pump as Turbine (PAT) and Francis, by Equations (5) and (6), respectively.

$$
Cost_{PAT} = 150 + 2084 * P^{-1} \left(\frac{€}{kW} \right) \tag{5}
$$

$$
Cost_{Francis} = 25.698 * P^{-0.560135} * H^{-0.127243} \left(\frac{€}{kW} \right) \tag{6}
$$

A discount rate according to Equation (7) is considered, also a lifespan of the project of 25 years (n) is assumed for Equation (8). Subsequently, in order to obtain results for economic indicators, such as net annual saving (AS), payback period (PBP), net present value (NPV), and internal rate of return (IRR), Equation (8), is applied. Other indicators such as benefit/cost ratio and total investment costs are considered.

$$
\begin{gathered}
TA = [(1 + T1) x \, (1 + T2) x \, (1 + T3)] - 1 \\
\textit{where:} \\
T1 \; (\textit{Interest}); \\
T2 \; (\textit{Risk rate}); \\
T3 \; (\textit{Inflation Rate}); \\
TA \; (\textit{Discount rate}).
\end{gathered}
\tag{7}
$$

$$
\begin{gathered}
AS = \textit{Benefit} - \textit{Cost} \; (€) \\
PBP = \frac{C}{AS} \quad (\textit{years}) \\
NPV = \sum \frac{B - C}{(1 + TA)^n} \; (€) \\
IRR = \sum \frac{B}{(1 + TA)^n} = \sum \frac{C}{(1 + TA)^n} \, (\%)
\end{gathered}
\tag{8}
$$

The rates assumed for all the different cases are interest (2.41 %), risk (6.9 %) and inflation (1 %), accordingly to recent hydropower systems estimations [46]. Following Equation (7), regarding the discount rate, a value of 10 % was assumed for all cases. The tariff rates applied to calculate the profit from selling and buying electricity to the national grid were accounted through the relative data of the three hourly rate electricity prices (e.g., applied in Portugal mainland), as shown in Table 4.

One of the parameters to assess if the hybrid energy system is functioning well, is the COHYBEM efficiency. This parameter is calculated by Equation (9) and concerns, total energy produced by the hybrid energy system minus by the total wasted energy by wind and solar sources (not used) and divided by total demand. The total energy generated (GWh) is the sum of both wind, solar and hydro sources production.

$$COHYBEM\ efficiency = \frac{Total\ energy\ genareted - Total\ wasted\ wind\ and\ solar\ energy}{Total\ demand} * 100\ (\%) \tag{9}$$

In the next section is presented the results based on all simulations proceeded on three power scales: micro, small and medium/large.

3. Results and discussion

COHYBEM is used to provide simulations based on 81 cases studies identified for each scale of power ranges and storage volumes, where the methodology is repeated, changing wind, solar, turbine/pump installed powers and upper reservoir volume values associated to each series, totalizing 243 HES combined solutions (see Appendix II).

This research includes also an economic analysis to compare the various solutions investigated. The analysis focuses on initial costs, operating and maintenance costs, the benefit of selling energy and the return on investment. In the following, remarks on the most significant cases will be given, while the economic analysis results will be shown for selected cases 1–27, 82–108, and 217–243. Only the acquisition of the turbomachine was considered a cost on the hydro side, proposing the scenario that the main set-up of PHS facilities already exists and only needs maintenance. Also, the cost associated with maintenance of the infrastructures and equipment represents 4 % of the total costs.

Only some results will be presented to avoid similar trends associated with small changes in the global system characterization.

3.1. Micro scale

3.1.1. Technical behavior

At the micro-scale, in a total of 81 scenarios (Table 5 only shows 27 with significant results), varying wind, solar, and hydro installed power, as well as the volume of the upper reservoir, were performed. The key parameters for these simulations were as follows.

- Installed power of renewables: (0.01; 0.05; 0.1) MW
- Volume of the upper reservoir: (1500; 7500; 15,000) m^3
- Peak consumption: 0.05 MW
- Net head: 20 m
- Turbine type: Pump as turbine (PAT)
- Turbine (in reverse mode of a pump) efficiency: 0.5
- Pumping efficiency: 0.7

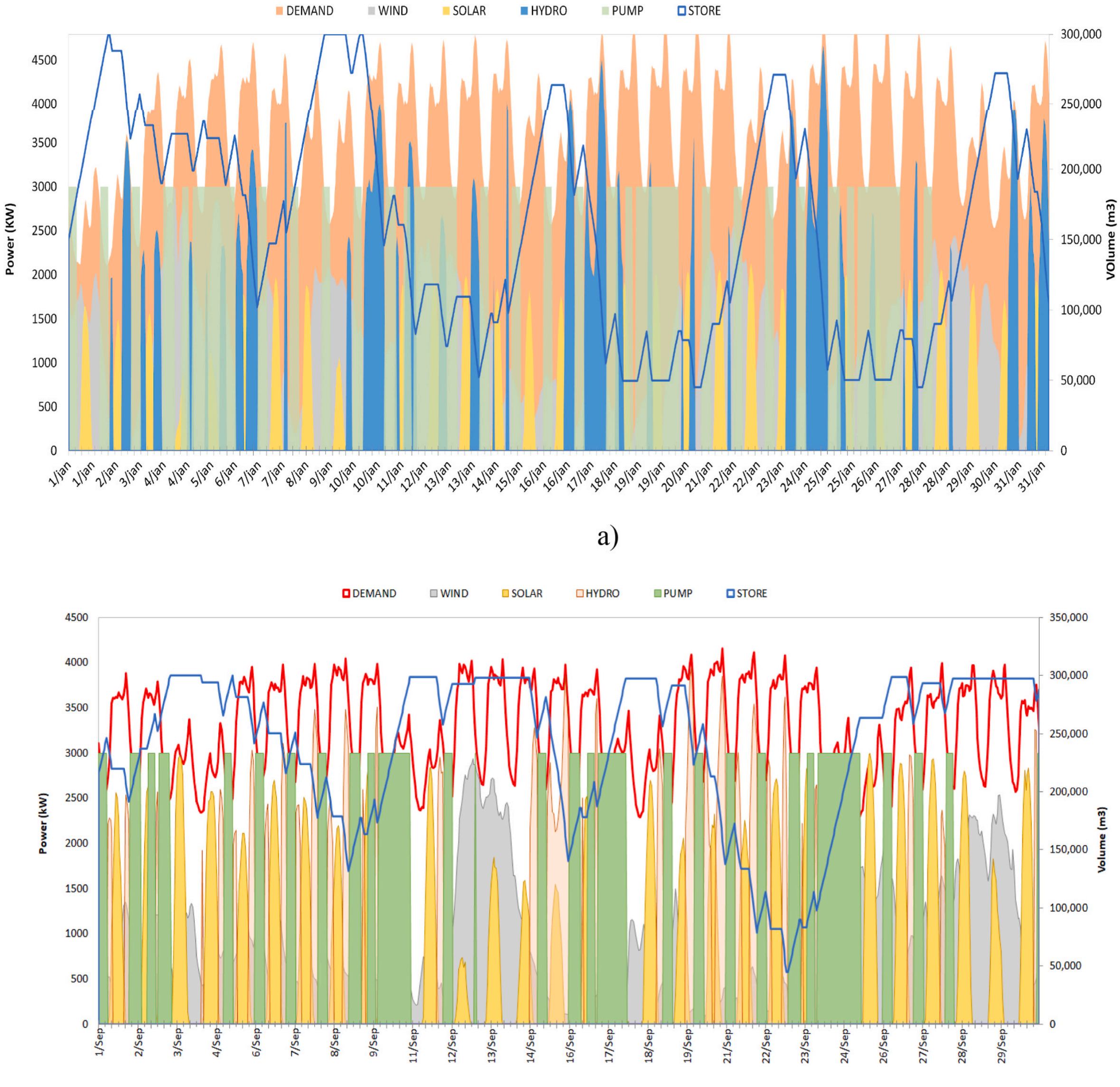
For cases 64–72, the system satisfied more energy when values of PAT installed power were higher. Higher PAT installed power is reflected in superior hydropower production, higher demand supply and better overall the system efficiency. The system satisfies a total of 29 % of the demand, being the contribution of wind plus solar powers and hydropower more than 70 % of share.

Hydropower satisfies for 5–14 % of the demand, when solar PV and wind energy generated satisfies 30–830 %. The hydro production is 13 MW for a total volume of around 450,000 m^3. The total energy pumped in the period is 36 MW, for a volume of 455,000 m^3, assuming continuing water supply to further hydro production. Also, is noticeable that there is a continuous energy and water supply, trough low minimal storage hours (2 %), meaning that the upper reservoir is supplied by the pump to maintain minimum the volume reservoir conditions, thus being able to generate more energy trough the turbines. Increasing the volume of the reservoir to 15,000 m^3, and PAT installed power 0.1 MW (cases 73–81), leads to more hydropower generation. Hence, the system experiences substantial gains in terms of total satisfied demand and hydropower production, thereby indicating the importance of the availability of a certain volume of water.

The power grid and energy storage is suggested in Fig. 6: (a) for a winter month and (b) for a summer month, representing the power and energy available for the timeline modelled. In this Fig. 6: (i) curves of

Table 6
Economic analysis for scenarios 82–108 of HES.

Case	Hydro cost (€)	Wind cost (€)	Solar cost (€)	Maintenance costs (€)	Total investment cost (€)	Energy sell (€)	B/C (–)	NPV (€)	PBP (years)	IRR (%)
82	228,940	40,000	30,000	11,958	310,898	31,616	0.67	−117,691	11	5.4 %
83		100,000	30,000	14,358	373,298	49,260	0.94	−25,703	8	9.2 %
84		160,000	30,000	16,758	435,698	66,939	1.14	66,596	7	11.8 %
85		40,000	75,000	13,758	357,698	47,141	0.93	−27,895	9	9.1 %
86		100,000	75,000	16,158	420,098	64,541	1.13	61,871	7	11.7 %
87		160,000	75,000	18,558	482,498	80,512	1.27	138,677	6	13.3 %
88		40,000	120,000	15,558	404,498	61,899	1.12	54,931	7	11.6 %
89		100,000	120,000	17,958	466,898	78,494	1.27	137,399	6	13.4 %
90		160,000	120,000	20,358	529,298	92,850	1.35	199,541	6	14.4 %
91		40,000	30,000	11,958	310,898	32,469	0.40	−328,022	17	0.8 %
92		100,000	30,000	14,358	373,298	50,294	0.96	−16,323	8	9.5 %
93		160,000	30,000	16,758	435,698	68,251	1.16	78,504	7	12.1 %
94		40,000	75,000	13,758	357,698	48,103	0.95	−19,164	8	9.4 %
95		100,000	75,000	16,158	420,098	65,921	1.16	74,402	7	12.0 %
96		160,000	75,000	18,558	482,498	82,242	1.30	154,382	6	13.7 %
97		40,000	120,000	15,558	404,498	63,266	1.15	67,342	7	11.9 %
98		100,000	120,000	17,958	466,898	80,038	1.30	151,411	6	13.7 %
99		160,000	120,000	20,358	529,298	94,886	1.39	218,024	6	14.8 %
100		40,000	30,000	11,958	310,898	32,738	0.70	−107,508	11	5.8 %
101		100,000	30,000	14,358	373,298	50,517	0.97	−14,293	8	9.6 %
102		160,000	30,000	16,758	435,698	68,788	1.18	83,379	7	12.2 %
103		40,000	75,000	13,758	357,698	48,242	0.96	−17,900	8	9.4 %
104		100,000	75,000	16,158	420,098	66,226	1.17	77,167	7	12.1 %
105		160,000	75,000	18,558	482,498	82,852	1.31	159,918	6	13.8 %
106		40,000	120,000	15,558	404,498	63,514	1.16	69,594	7	12.0 %
107		100,000	120,000	17,958	466,898	80,400	1.44	154,698	6	13.8 %
108		160,000	120,000	20,358	529,298	95,335	1.39	222,098	6	14.9 %



a)

b)

Fig. 10. Energy mix for summer (a) and winter months (b): Demand 5 MW, Wind 1 MW, Solar 3 MW, Volume 300,000 m^3.

power demand, wind, solar, hydro and pump (left y-axis); (ii) curve for the storage volume by water pumped into the reservoir (right y-axis).

3.1.2. *Economic analysis*

Smaller installed PAT capacity values are analyzed, since for higher capital costs increase, a viability analyses can help on the implementation decision, for 25 years lifespan (Table 5).

It is observed in Table 5, high wind and solar installed capacity leads to higher investment costs, but also more profit from energy sale. For all the cases, the project is viable, and the payback period rounds 5 years. For case 23, where 70 % of the demand is satisfied, the net present value is the highest value, being 17,443€, for a payback period of 4 years. This evidence the potential of micro systems, since besides being technically viable is also profitable, with a short return on investment. The results indicate that micro-scale systems are well-suited for regions with limited budgets and modest energy demands. The initial capital investment for a micro-scale system is relatively low, making it an attractive option for rural or remote areas.

3.2. *Small scale*

3.2.1. *Technical behavior*

The key parameters for these simulation scanarios were as follows.

- Installed power: (0.2; 0.5; 0.8) MW
- Volume of the upper reservoir: (20,000; 50,000; 80,000) m^3
- Peak consumption: 1 MW
- Net head: 80 m
- Turbine type: Francis
- Turbine efficiency: 0.8
- Pumping efficiency: 0.7

For cases, 154–162 (Fig. 7), it is features the larger configuration for this scale. With higher wind and solar installed power, more capable is the system to satisfying the demand. Larger configurations lead to more profit reaching a maximum of 107,008 €. Also wasted energy is 0 % for the smaller configuration and increases, following the increase in installed power, reaching a maximum of 6 %. As installed power increases, hydropower production decreases around 10 % for this range of

Table 7
Economic analysis for scenarios 217–243 of HES.

Case	Hydro cost (€)	Wind cost (€)	Solar cost (€)	Maintenance costs (€)	Total investment cost (€)	Energy sell (€)	B/C (–)	NPV (€)	PBP (years)	IRR (%)
217	1,204,105	200,000	150,000	62,164	1,616,269	246,404	1.30	470,916	6	13.8 %
218		400,000	150,000	31,158	1,754,105	300,836	1.42	737,767	6	15.2 %
219		600,000	150,000	39,158	1,954,105	348,229	1.48	940,720	6	15.9 %
220		200,000	300,000	29,158	1,704,105	295,038	1.44	741,945	6	15.4 %
221		400,000	300,000	37,158	1,904,105	345,507	1.51	972,821	6	16.3 %
222		600,000	300,000	45,158	2,104,105	389,685	1.54	1,146,598	5	16.7 %
223		200,000	450,000	35,158	1,854,105	341,105	1.53	989,675	5	16.5 %
224		400,000	450,000	43,158	2,054,105	387,134	1.57	1,180,245	5	17.0 %
225		600,000	450,000	51,158	2,254,105	434,654	1.61	1,384,357	5	17.5 %
226		200,000	150,000	23,158	1,554,105	279,323	1.50	769,722	6	16.1 %
227		400,000	150,000	31,158	1,754,105	329,506	1.57	998,006	5	16.9 %
228		600,000	150,000	39,158	1,954,105	373,233	1.60	1,167,682	5	17.3 %
229		200,000	300,000	29,158	1,704,105	324,996	1.59	1,013,871	5	17.2 %
230		400,000	300,000	37,158	1,904,105	372,062	1.64	1,213,865	5	17.7 %
231		600,000	300,000	45,158	2,104,105	414,560	1.65	1,372,384	5	17.9 %
232		200,000	450,000	35,158	1,854,105	367,333	1.66	1,227,743	5	18.0 %
233		400,000	450,000	43,158	2,054,105	412,779	1.69	1,413,032	5	18.3 %
234		600,000	450,000	51,158	2,254,105	457,538	1.71	1,592,074	5	18.5 %
235		200,000	150,000	23,158	1,554,105	285,477	1.53	825,579	5	16.5 %
236		400,000	150,000	31,158	1,754,105	336,388	1.60	1,060,476	5	17.4 %
237		600,000	150,000	39,158	1,954,105	385,241	1.65	1,276,683	5	17.9 %
238		200,000	300,000	29,158	1,704,105	332,442	1.63	1,081,464	5	17.7 %
239		400,000	300,000	37,158	1,904,105	380,814	1.68	1,293,307	5	18.2 %
240		600,000	300,000	45,158	2,104,105	427,004	1.71	1,485,344	5	18.5 %
241		200,000	450,000	35,158	1,854,105	376,800	1.71	1,313,673	5	18.6 %
242		400,000	450,000	43,158	2,054,105	421,241	1.73	1,489,839	5	18.7 %
243		600,000	450,000	51,158	2,254,105	464,604	1.73	1,656,211	5	18.9 %

Table 8
Peak consumption, turbine/pump installed power, volume of the reservoir, for micro, small and medium/large options/scenarios.

Scale	Peak Consumption, Cp (MW)	Francis installed power (MW)	PAT installed power (MW)	Volume of the reservoir (m3)	Options
Micro	0.05	–	0.01	7500	Option 1
		–	0.1	15,000	Option 2
Small	1	0.5	–	50,000	Option 3
		0.8	–	80,000	Option 4
Medium/ Large	4	1	–	200,000	Option 5
		3	–	300,000	Option 6

cases. For case 154, the smallest configuration of this serie, hydro production plays a crucial role, producing 25 % of the total satisfied demand, using 2,731,382 m^3 to produce around 488 MWh. The pump consumes 870 MWh from intermittent sources, pumping 2,729,761 m^3. The system has an efficiency of 40 % and 0 % of the energy is wasted.

Case 160 represents a configuration where solar power has the highest share of installed power in the mix of boths renewable sources, with a Francis turbine type with the capacity of 0.8 MW. Solar and wind installed power is set at 0.8 MW, 0.2 MW, respectively. This configuration makes the hydro component an important component to the system energy producing trio. The hybrid energy system produces 1.12 GWh, where 22 % comes from hydro energy and 24 % through wind and solar sources. The hydro energy (430 MWh) was obtained using 2,410,573 m^3 of water, the pumped back again into the upper reservoir 2,440,707 m^3, spending 778 MWh. The PHS had 2 % of the time with minimal storage. The system efficiency is 59 %, satisfying 56 % of the demand. Also Fig. 8, shows the percentage of total satisfied demand by renewable sources, of wind and solar energy produced that is wasted, and hours that the upper reservoir is in minimum capacity conditions.

The energy mix for this scenario can be seen in Fig. 9: (a) for a winter month and (b) in a summer month.

On August, solar installed capacity exploits its full potential, by producing almost two times more, since more effective hours of production are available. During daytime (6h–18h), solar PV supply most of the demand, during the first and last hours hydro helps the system to continually supply energy to the grid. Hydro acts as an assistant in the energy mix trio, when solar PV is not able to supply the demand, hydro produces energy during the off-peak times depending on the reservoir capacity.

3.2.2. *Economic analysis*

For small-scale solutions, cases 82–108, results are stated in Table 6.

It is observed that for higher configurations of the system the payback period decreases. The total costs increase with installed wind and solar capacity. For case 108, the system satisfies 74 % of the demand, with 6 % wasted energy, and also has a payback period of 6 years and a net present value of 222,098€ (the maximum value). This table evidences the cost effectiveness for small scale solutions. For small configurations the net present value is negative, since initial investment cost are substantial, and the system is not able to produce enough profit from selling energy to the grid. This makes those scenarios non-viable economically.

3.3. *Medium/large scale*

3.3.1. *Technical behavior*

For this Medium/Large scale the key parameters used in the COHYBEM were as follows.

- Installed power: (1; 2; 3) MW
- Volume of the upper reservoir: (100,000; 200,000; 300,000) m^3
- Peak consumption: 5 MW
- Net head: 150 m
- Turbine type: Francis
- Turbine efficiency: 0.8

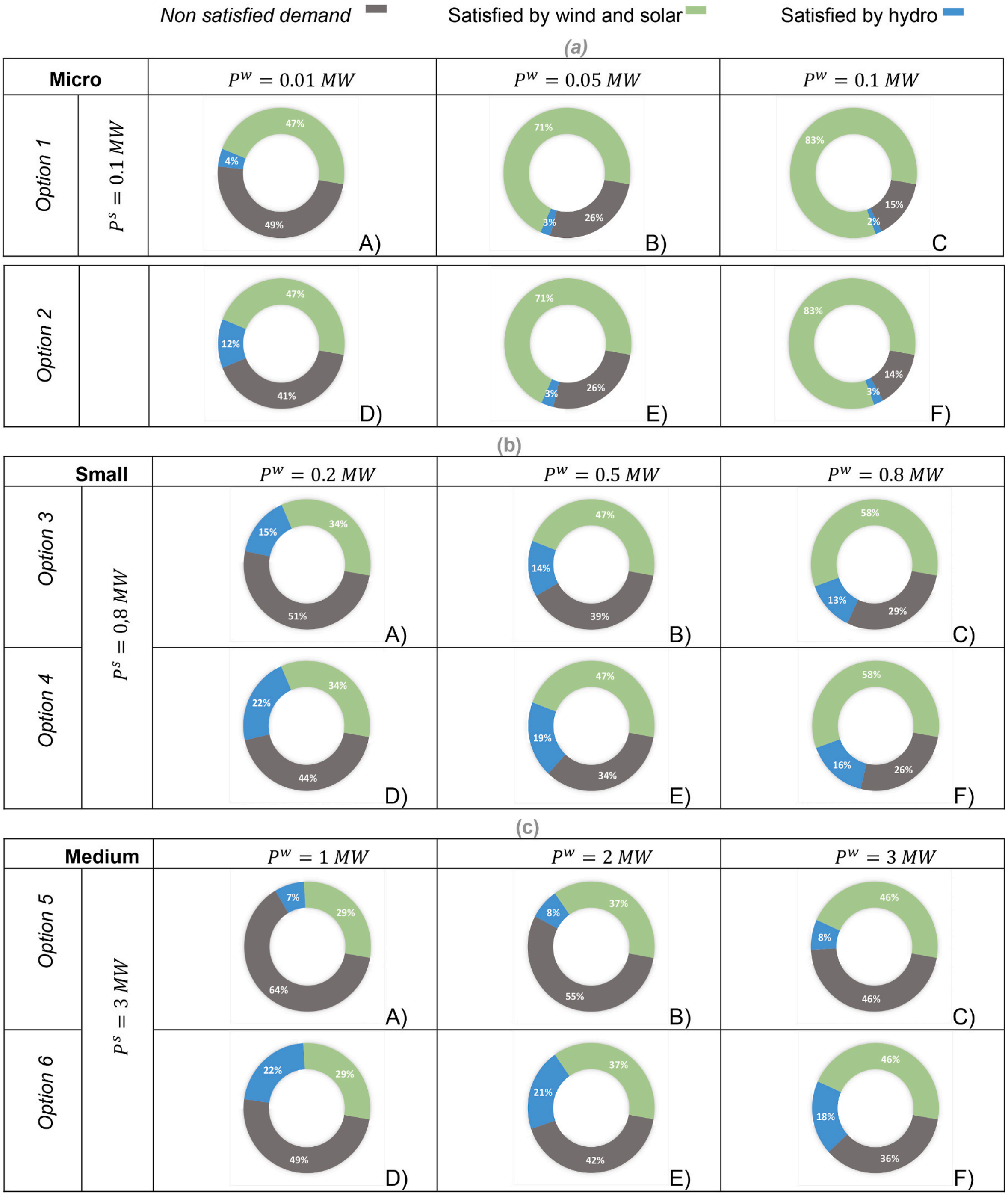


Fig. 11. One average year results for different scale options: (a) micro; (b) small; (c) medium configurations, for different solar (Ps) and wind (Pw) powers (A to F).

- Pumping efficiency: 0.7

In the same line as for small-scale analysis with higher hydropower availability, the energy mix for these scenarios can be seen in Fig. 10, for January and September representing the power and energy available for the modelled timeline. It is quite explicit hydropower contribution to mitigate fluctuation patterns from other intermittent energy sources. In the winter when solar effective hours of production are reduced (e.g., for the region used in this analysis), hydropower compensates in the energy production balance, by supplying energy when solar is not available. In the summer, wind sources are affected by fluctuations, so when wind energy is not existing, hydropower, again, complement. It interacts with solar generating patterns, supplying energy when necessary.

3.3.2. *Economic analysis*

For the large power series scale, the values for the cases 217–243, are stated in Table 7. The increasing both wind and solar installed powers, leads to more profit, although initial capital costs are higher. It is important to balance those two metrics so that the system be profitable.

The payback period is relatively low for all cases, being around 5 years. Case 243 presents the highest net present value, 1,656,211€. In this case the system satisfies 85 % of the demand with 1 % wasted energy, making with both a technical and economical viable solution.

3.4. *Comparison analysis*

Following the results obtained for each series, a comparison of

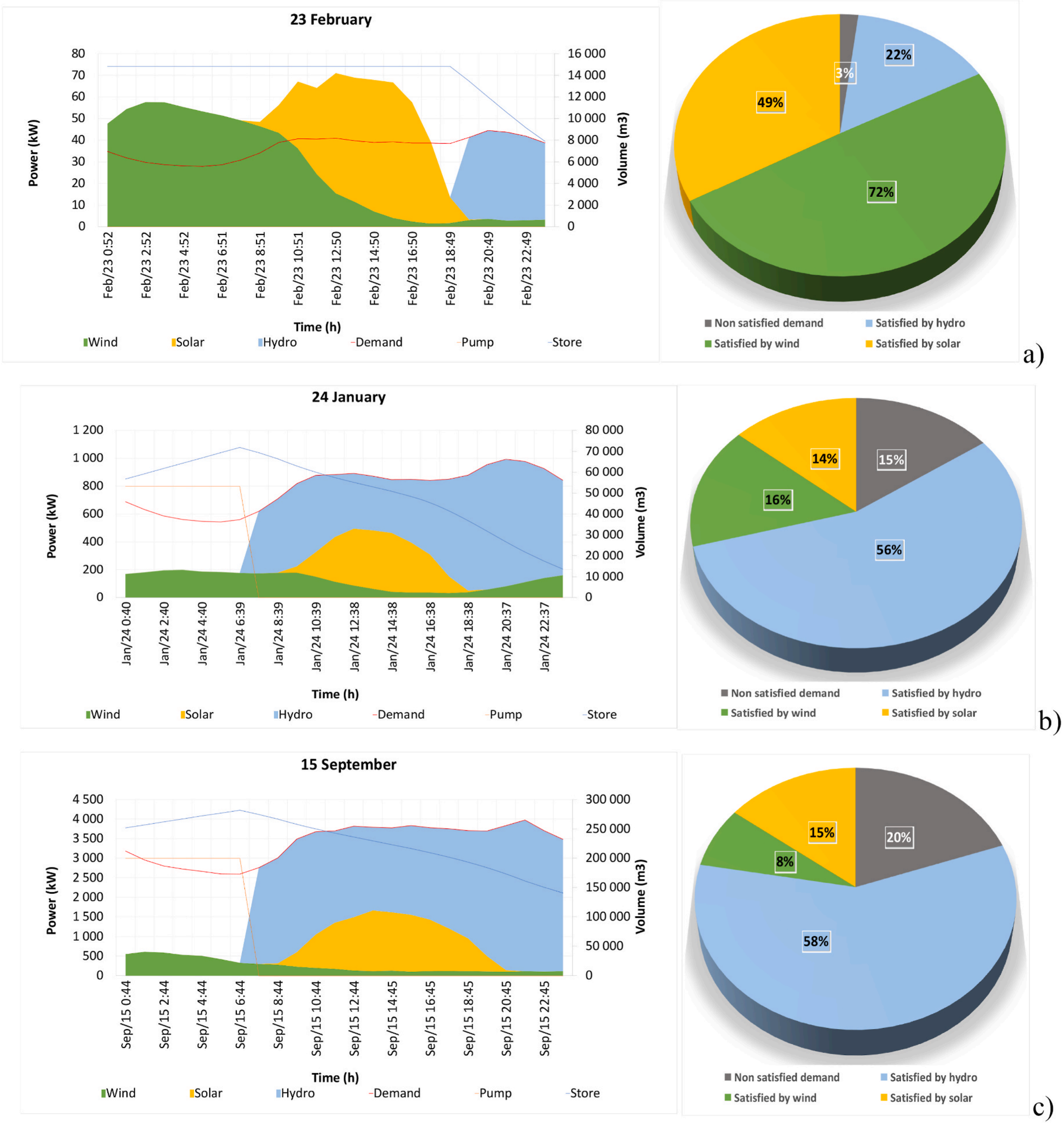


Fig. 12. Energy mix of 24h for different days and scales: a) micro, b) small and c) medium.

systems behavior, from micro, small and medium scales, is important to define each metrics, since the systems are multivariable and scalable. The metrics compared are total satisfied demand (by wind, solar, hydro), and the system efficiency. Inherent to those metrics are parameters that also should be taken into, such as volume of the reservoir, installed capacity of renewable sources, and type of turbine/pump. Regarding this, more results are presented, as well as options chosen to be analyzed (Table 8).

In Fig. 11, are represented the system scenario Options (1–6) chosen for an average year selected. Options 1 to 6 are assumed as having the solar installed capacity at its highest value, since is known from the obtained results that between wind and solar sources, wind contributes with a more continuous energy supply, not depending on solar diurnal patterns. Also increasing wind installed power instead of solar, allows the system to produce and supply more energy, therefore satisfying more demand.

In Fig. 12 is represented examples of information about the energy mix for options 2, 4 and 6 from, during a 24-h period of time, in different scales.

Fig. 13 represents all scenarios simulated depending on the peak consumptions chosen for each scenario scale series, power installed for HES and storage volume capacity, showing a higher trend of hydro contribution when volume increases, with PHS better integrating and balancing the energy mix, with lesser percentage for wind and solar waste.

After it was found pareto fronts for the best average solutions (Fig. 14): 1- Total Satisfied Demand by Hydro (%) >5 % for all scales; 2- Total Satisfied Demand by W + S (%) > 67 % for all scales; 3- W + S Waste (%) <30 % for all cases; 4- system Efficiency (%) > 50 % for micro scale, >70 %, for small and medium/large scale, it is possible to better identify the more recommendable HES, depending on the power scales installed. It is denoted the envelopes, in terms of maximum efficiency and total satisfied demand by W + S and by hydro converges towards a higher percentage, while it is also progressing to the minimum waste by W + S.

In Fig. 15 is represented the net present value, profit from selling

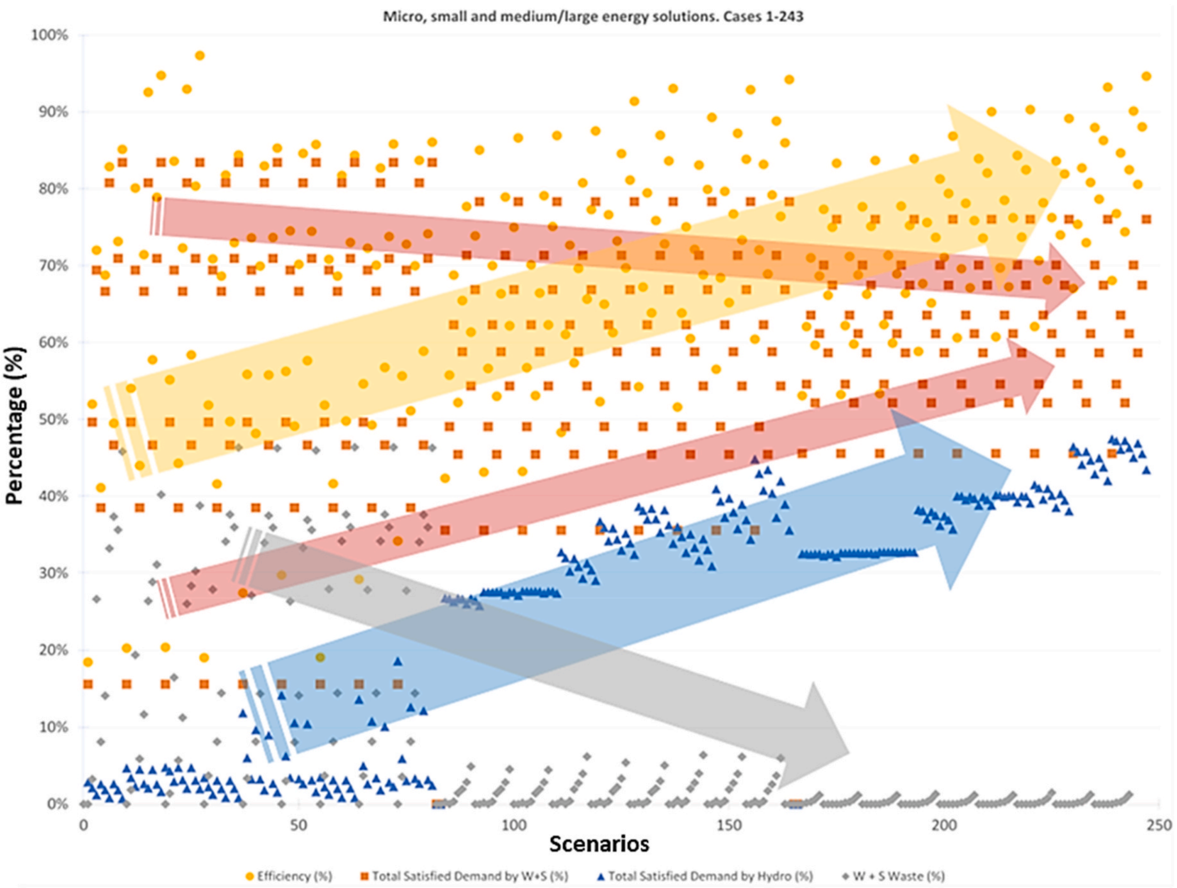


Fig. 13. All (1–243) case scenarios simulated and the system behavior (arrows show the trends).

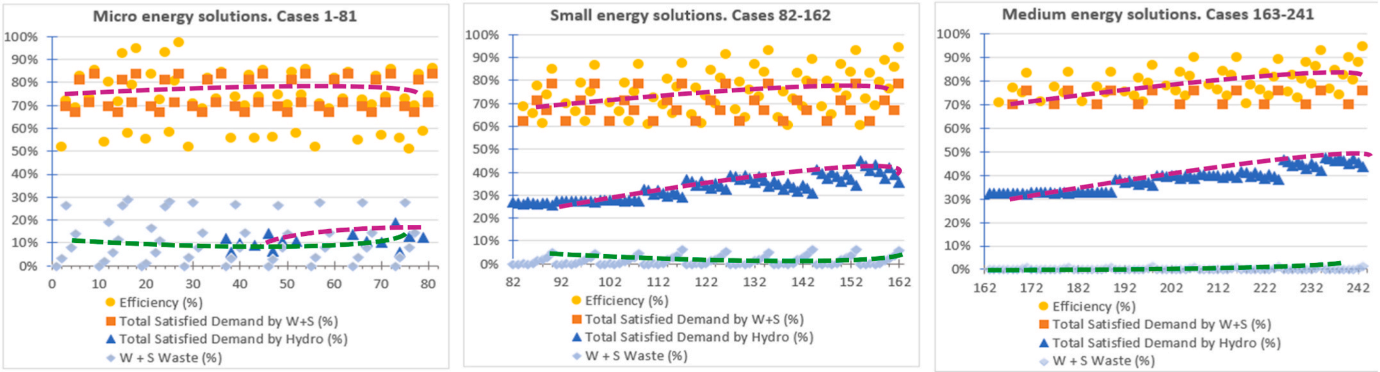


Fig. 14. Pareto fronts towards the best HER solutions based on 243 simulations: rose dot line - maximum average envelops (efficiency and total satisfied demand by W + S and by Hydro) and green dot line - minimum envelop (W + S waste).

energy to the grid and total investment cost, for some selected cases: 1–27 (micro), 82–108 (small) and 217–243 (medium/large) scale scenarios.

Regarding the comparative analyses, and results, there are some noticeable trends between scale scenarios in terms of technical behavior: the multiple role of hydro, since it can produce energy and create water reserves according to what is needed for a better system efficiency; also wind and solar have a major weight in the system regarding the energy supplying; the system relies on this sources to satisfy most of the demand (being wind the source that was a major weight in the duo, in terms of production, due to less source volatility). Overall, it is noticeable that, regarding the different scenarios in each scale, the choice between micro-scale, small-scale, and medium/large-scale systems depends on the specific energy requirements, available resources, and the investment costs associated to each scale. In terms of economic analysis viability studies are recommended since the power installed strongly influence the final results.

Micro scale systems suit remote and minimal demand locations, small systems offer versatility, and medium/large scale are ideal for meeting significant energy requirements in grid-connected solution.

4. Conclusions

The literature review conducted in this study confirms that pumped hydropower storage (PHS) is the most established and widely used energy storage technology. PHS allows surplus energy to be stored when

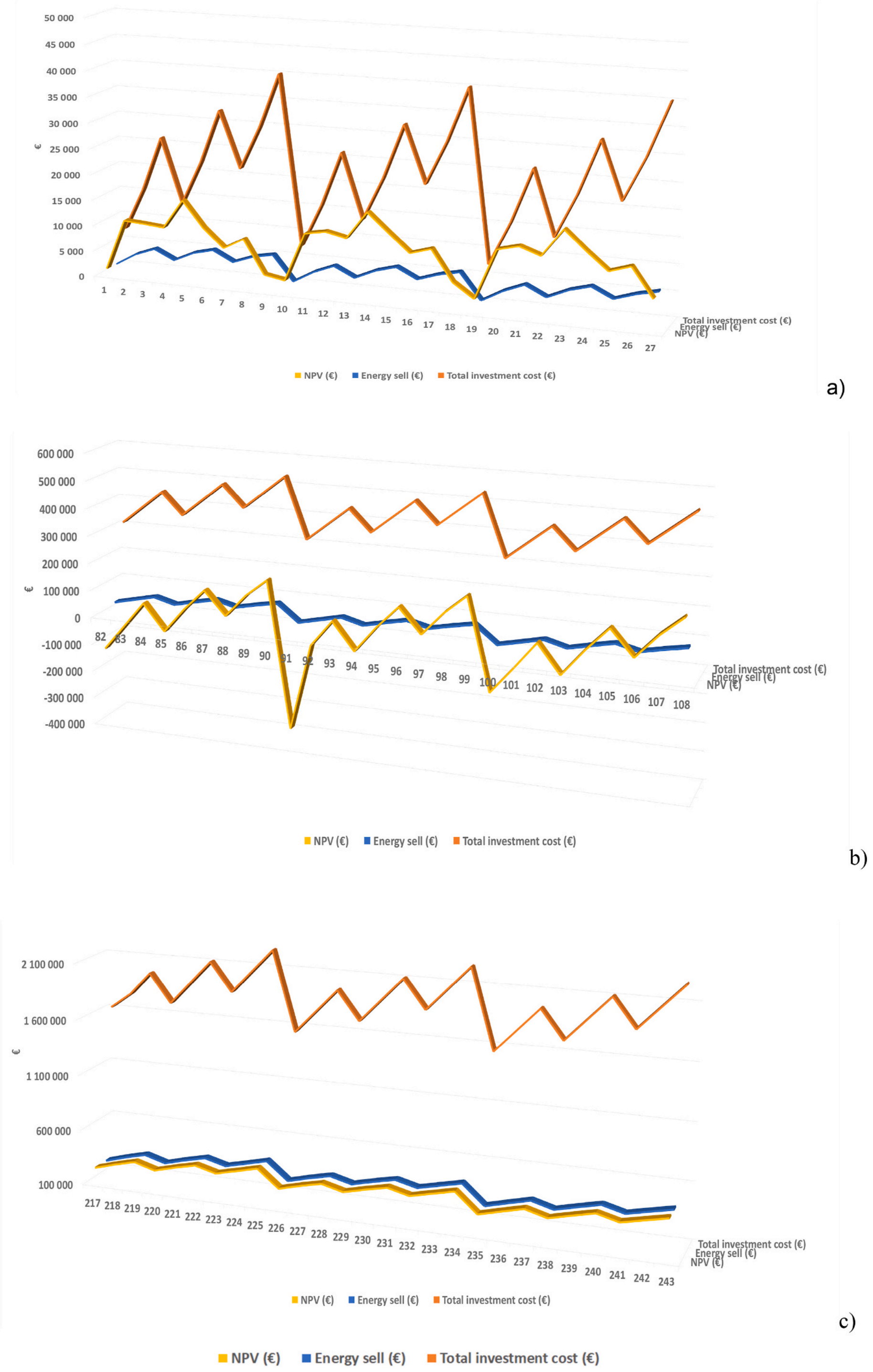


Fig. 15. Net present value, profit from selling energy to the grid, total investments cost for cases 1–27 (micro), 82–108 (small) and 217–243 (medium/large) scales.

generation exceeds demand and released when direct generation is insufficient, providing a reliable and flexible backup for intermittent renewable energy sources (RES). This enhances system flexibility and reliability by mitigating the variability of renewables, leveraging the complementary nature of different sources. Integrating energy storage systems in hydropower plants with other renewables, such as wind and solar, presents a promising solution for the transition from fossil fuels to clean energy. This balanced combination addresses intermittency and volatility challenges, enabling low-cost electricity generation and storage while reducing carbon emissions and supporting climate change mitigation efforts. In this context, a multi-criteria framework was employed to optimize the availability and storage of renewable energy. Various system configurations were tested, totaling 243 different cases. The micro-scale system is characterized by relatively small storage volumes and limited wind and solar energy capacities, making it suitable for local energy supply or off-grid generation. Simulations on a micro-scale demonstrated the scalability, flexibility, and profitability of these solutions. As installed capacities of wind, solar, and hydropower increased, overall energy production and the ability to manage system storage also improved. This scalability is a key factor for adapting the system to different energy demands. The volume of the upper reservoir was a decisive factor for energy storage capacity, with increased storage volumes significantly improving the system's ability to efficiently store surplus energy. This is critical for aligning energy supply with demand and minimizing wasted energy.

The choice of energy converters and pump/turbine efficiency also influenced overall system performance. Higher turbine efficiency led to greater power generation and energy storage capacity. However, the benefits must be weighed against costs, as higher-efficiency wind and photovoltaic (PV) solar systems may require a higher initial investment. Additionally, larger-scale power scenarios (wind, solar, and hydropower) consistently outperformed smaller configurations in terms of energy generation, waste reduction, and economic benefits. These findings suggest that larger-scale hybrid systems may be a favorable option for regions with suitable resources and existing water infrastructure. However, system optimization is critical, especially for larger configurations. Optimizing the system reduces energy waste, improves efficiency, and maximizes economic benefits. Achieving the right balance between wind, solar, and hydropower capacities is crucial for optimal system performance.

From an economic perspective, the analysis indicates that the micro-scale system is feasible. Benefit-cost (B/C) values suggest favorable economic returns and the positive net present value (NPV) demonstrates the project's viability. The payback period (PBP) and internal rate of return (IRR) also provide attractive indicators for such hybrid energy systems. The percentage of unsatisfied demand ranged from 49 % to 14 %, depending on the variation of installed wind power (from 10 kW to 100 kW), resulting in 93 % satisfaction when both wind and PV solar were considered. Investment costs for the analyzed case studies ranged between 10 and 45 k€, with less than 10 k€ in sold energy, leading to an NPV of less than 18 k€ and a payback period of six years or less.

On the other hand, small-scale results underscore the importance of optimizing hybrid energy systems to maximize energy production, minimize waste, and ensure economic viability. The results highlight the role of each component—wind, solar, and hydropower—and how they interact in different configurations. The flexibility and storage capacity provided by hydropower are key to maintaining energy supply and ensuring overall system efficiency. With increased hydropower capacity (500 kW < P < 1 MW), hydropower plays a more significant role in satisfying demand, with minimal wasted wind and PV solar energy. Total investment in this hybrid solution was estimated at around 500 k€, with an NPV of less than 300 k€ and a payback period between six and 17 years. Finally, the trends observed in small-scale simulations are also reflected in medium and large-scale systems. Higher wind and solar capacities, combined with larger turbine capacities, lead to greater efficiency and demand satisfaction. Hydropower is critical for balancing fluctuations in energy production from wind and solar plants. For medium/large systems, total investments ranged from 1.6 to 2.1 M€, with an NPV of 300–600 k€, and a payback period of approximately six years.

A detailed analysis identified the most recommended hybrid energy system (HES) solutions based on specific metrics: total satisfied demand by hydropower (>5 % across all scales), total satisfied demand by wind and solar (>67 % across all scales), wind and solar waste (<30 % in all cases), and system efficiency (>50 % for micro-scale, >70 % for small and medium/large-scale systems). As installed power increases, system efficiency and total satisfied demand by wind, solar, and hydropower converge towards higher percentages, while waste from wind and solar decreases.

In summary, the findings from this study offer valuable insights into the design and optimization of hybrid energy systems across different power scale scenarios. The conclusions provide critical perspectives for stakeholders interested in renewable energy while ensuring economic viability, system flexibility, net-zero carbon goals, sustainability, and reliable solutions based on eco-friendly and well-proven technologies. By carefully considering technical, economic, and regional factors, and tailoring configurations to specific project requirements, highly efficient and profitable hybrid energy systems can be developed, contributing to a sustainable energy future in this new era of energy transition.

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CRediT authorship contribution statement

Helena M. Ramos: Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **João Pina:** Software, Formal analysis, Data curation. **Oscar E. Coronado-Hernández:** Validation, Supervision. **Modesto Pérez-Sánchez:** Writing – review & editing, Writing – original draft, Methodology. **Aonghus McNabola:** Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acronyms

HES	Hybrid energy system
LCOE	levelized cost of electricity
PAT	Pump as Turbine
PHS	pump hydro storage
PV	Photovoltaic
REN	Redes Energéticas Nacionais
RES	Renewable energy sources

Variables

AS	Annual Savings (€)
B/C	Benefit/Cost ratio (−)
c_p	Water pumping coefficient of the pump/motor unit (m^3/kW)
c_t	Turbine generation coefficient (kW/m^3)
$Cost_{Francis}$	Francis turbine equipment cost (€)
$Cost_{PAT}$	Pump as turbine equipment cost (€)
D –	Demand (W)
$D^{(i)}_{non-dim}$ –	Non-dimensional demand at hour “I” (−)
D_p	Peak demand (W)
E	Energy (J)
$E^{(i)}_{W-S}$	Wind-solar energy at hour "I" (W)
$E^{(i)}_{h}$	Hydropower energy at hour "I" (W)
E^{Max}_{h}	Maximum hydro energy (W)
$E^{(i)}_{p}$	Pump energy at hour "I" (W)
E^{Max}_{p}	Maximum pump energy (W)
G	Gravity acceleration (m/ s^2)
H_0	Net head (m)
H_T	Total elevation (m)
IRR	Internal rate of return (%)
NPV	Net present value (€)
P_c	Peak consumption (W)
P	Power (W)
$P^{(i)}_{W-S\ non-dim}$	Non-dimensional wind-solar energy at hour "I" (−)
P^{Efest}_{W-S}	Wind-solar effective power (W)
P^{Inst}_{W-S}	Wind-solar power installed (W)
PBP	Payback period (years)
Q^{Max}_{p}	Maximum pumped flow ($\frac{m^3}{s}$)
Q^{Max}_{t}	Maximum turbined flow ($\frac{m^3}{s}$)
Q^{Min}_{p}	Minimum turbined flow ($\frac{m^3}{s}$)
Q^{Min}_{t}	Minimum turbined flow ($\frac{m^3}{s}$)
$Rest_{grid}$	Grid restriction (%)
S	Solar power(W)
$Time_{tarif\ period}$	Tariff period (hours)
TA	Discount rate (%)
V	Volume of water (m^3)
$V^{(i)}_{p}$	Pumped volume at hour "I" (m^3)
V^{Max}_{p}	Maximum pumped volume (m^3)
$V^{(i)}_{res}$	Reservoir’s volume at hour "I" (m^3)
V^{Max}_{Res}	Maximum reservoir’s volume (m^3)
V^{Min}_{Res}	Minimum reservoir’s volume (m^3)
$V^{(i)}_{t}$	Turbined volume at hour "I" (m^3)
V^{Max}_{t}	Maximum turbined volume (m^3)
W	Wind power (W)

Greek Letters

$\Delta^{(i)}_{E}$	Difference between wind-solar energy and demand at hour "I" (W)
η_P	Pump efficiency (%)
η_t	Turbine efficiency (%)
ρ	Water density ($\frac{Kg}{m^3}$)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.121486.

References

[1] J. Pina, Power Potential Based on Python Model and Data Analysis for Hybrid Pumped Hydropower Storage at Different Scales: Technical and Economic Analysis for Micro, Small and Large Systems, IST, 2023. MSc Thesis.

[2] International Energy Agency, Renewable Energy Market Update: Outlook for 2022 and 2023, IEA Publications International Energy Agency, April 2022. www.iea.orgContactinformation:www.iea.org/about/contact. Typeset in France by IEA - May 2022.

[3] ENERGY TRANSITION, The World Added 50% More Renewable Capacity Last Year than in 2022, World Economic Forum, Feb 8, 2024. https://www.weforum.org/agenda/2024/02/renewables-energy-capacity-demand-growth/. March 2024.

[4] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EMPTY, Strategy for Financing the Transition to a Sustainable Economy, Strasbourg, 2021, 6.7.2021, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0390. July 2023.

[5] International Energy Agency, Renewable Energy Market Update - 2021, 2021. https://www.iea.org/reports/renewable-energy-market-update-2021/renewable-electricity. June 2023.

[6] C. Perpiña Castillo, C. Hormigos Feliu, C. Dorati, G. Kakoulaki, L. Peeters, E. Quaranta, N. Taylor, A. Uihlein, D. Auteri, L. Dijkstra, Renewable Energy Production and Potential in EU Rural Areas, Publications Office of the European Union, Luxembourg, 2024, https://doi.org/10.2760/458970,JRC135612.

[7] E. Quaranta, A. Georgakaki, S. Letout, A. Kuokkanen, A. Mountraki, M. Grabowska, J. Gea Bermudez, J. Tattini, Clean Energy Technology Observatory: Hydropower and Pumped Hydropower Storage in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, https://doi.org/10.2760/841176, JRC134918.

[8] M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (version 55), Prog. Photovoltaics Res. Appl. 27 (1) (2019) 3–12.

[9] The Future of Hydropower: Sustainable Practices, Innovative technologies and new scientific insights, in: E. Quaranta (Ed.), SUSTAINABILITY, ISSN 2071-1050 (Online), (Special Issue Sustainable Water Management), 2021 JRC118910.

[10] X. Zou, J. Wu, B. Huang, Y. Ni, A review on energy storage technologies for sustainable energy applications, Appl. Energy 282 (2021) 116061.

[11] P. Shandilya, E. Quaranta, O. Coronado-Hernández, H.M. Ramos, Hydropower advantages over batteries in energy storage of off-grid systems: a case study, ISSN 1996-1073, Energies 16 (17) (2023) 6309. JRC134709.

[12] Quaranta, Hydropower in the European Union: State-Of-The Art, Future Opportunities and Main Issues within the Current Social, Energy, Geopolitical and Climate Situation. Book Chapter in Sustainable Development of Renewable Energy Technologies, Elsevier, 2023 in press.

[13] H.M. Ramos, B. Vargas, J.R. Saldanha, New integrated energy solution idealization: hybrid for renewable energy network (Hy4REN), Energies 15 (11) (2022) 3921.

[14] IRENA, Renewable Energy Benefits: Leveraging Local Capacity for Small-Scale Hydropower, International Renewable Energy Agency, Abu Dhabi, 2023, 978-92-9260-546-9.

[15] F. Di Maria, E. Ghiani, S. Mocci, A review on the optimization techniques for wind power integration into power systems, Renew. Sustain. Energy Rev. 96 (2018) 440–459.

[16] J.K. Kaldellis, K.A. Kavadias, The wind energy (r) evolution: a short review of a long history, Renew. Energy 53 (2013) 1–11.

[17] IRENA, The Changing Role of Hydropower: Challenges and Opportunities, International Renewable Energy Agency, Abu Dhabi, 2023, 978-92-9260-522-3.

[18] IRENA, Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi, 2022.

[19] Y.D. Mulugeta, Y.S. Mohammed, Analysis of small hydropower viability for rural electrification: a case study of Tendaho micro hydropower project in Ethiopia, J. Clean. Prod. 294 (2021) 126274.

[20] E. Quaranta, H.M. Ramos, U. Stein, Digitalisation of the European water sector to foster the green and digital transitions, Water 15 (2023) 2785, https://doi.org/10.3390/w15152785.

[21] D. Flückiger, U. Deichmann, S. Karytsas, S. Xenarios, Power density improvement of a micro-hydropower turbine by reducing the rotor tip leakage vortex, Renew. Energy 133 (2019) 334–345.

[22] L. Zhang, Y. Liu, J. Zhang, Y. Yuan, Z. Du, A review on sizing optimization and energy management of renewable microgrid with energy storage systems, Energy Convers. Manag. 246 (2021) 114977.

[23] D.J. Ashwell, C. Vogel, P. Gauché, A review of small-scale hydro power in South Africa: past, present and future, Renew. Sustain. Energy Rev. 117 (2020) 109506.

[24] W. Weijermars, L. Pel, W.H. Hager, W.J. de Lange, Factors influencing small hydropower development in the European Union: insights from the past and projections for the future, Renew. Sustain. Energy Rev. 104 (2019) 235–244.

[25] E. Deenadayalan, E. Natarajan, R. Uppaluri, Sustainable solutions for small hydropower plants—a review, Renew. Sustain. Energy Rev. 49 (2015) 1080–1098.

[26] J.J. Fry, A. Misech, M. Morris, A.J. Schleiss, Research themes and strategic actions to promote hydropower as a catalyst for the energy transition in Europe, Journal on Hydropower & Dams 29 (3) (2022) 37–47.

[27] A. Pagoropoulos, V.K. Tsoukala, I. Koutiva, C.S. Psomopoulos, Optimal operation of an isolated micro-hydro small-scale hybrid system with energy storage for rural electrification, J. Energy Storage 28 (2020) 101279.

[28] E. Quaranta, in: Mejdi Jeguirim (Ed.), 8 - Hydropower in the European Union: State-Of-The Art, Future Opportunities and Main Issues within the Current Social, Energy, Geopolitical, and Climate Situation, 1, Advances Renewable Energy Technologies, Sustainable Development of Renewable Energy, 2024, pp. 281–302, https://doi.org/10.1016/B978-0-443-13613-9.00009-X, 9780443136139.

[29] A.J. Sabadell, G. Câmara, The future of large hydropower plants: a critical analysis, Renew. Sustain. Energy Rev. 119 (2020) 109616.

[30] M.M. Sarkar, A. Alam, T.R. Das, P. Saha, Environmental impact assessment of a large hydro power plant: a case study, Sci. Total Environ. 649 (2019) 1258–1265.

[31] IRENA, Renewable Power Generation Costs in 2022, International Renewable Energy Agency, Abu Dhabi, UAE, 2023, 2023.

[32] European Commission, Energy Costs, Taxes and the Impact of Government Interventions on Investments, Final Report Cost of Energy (LCOE), 2020.

[33] D. Moser, P. Bebi, P. Brang, H.R. Heinimann, Hydroelectric potential of the Swiss waterways: method, limitations, and impact of the energy strategy 2050, Renew. Energy 99 (2016) 1125–1136.

[34] R. Elia, S. Arapostathis, A.S. Gonçalves, A. Kusiak, A. Markou, S. Papadopoulou, M. Zeyringer, Integrating renewable energy sources in future energy systems: opportunities, challenges, and regulatory perspectives, Appl. Energy 294 (2021) 116991.

[35] J. Salazar, J.R. Paredes, E. Rosales-Asensio, J. Sierra-Pérez, Design and optimization of a hybrid renewable energy system for off-grid electrification in a rural area in Peru, Renew. Energy 174 (2021) 1303–1314.

[36] M. Simão, H.M. Ramos, Hybrid pumped hydro storage energy solutions towards wind and PV integration: improvement on flexibility, reliability and energy costs, Water 12 (2020) 2457, https://doi.org/10.3390/w12092457.

[37] E.N. Nyeche, E.O. Diemuodeke, Modelling and optimisation of a hybrid PV-wind turbine-pumped hydro storage energy system for mini-grid application in coastline communities, J. Clean. Prod. 250 (2020) 119578, https://doi.org/10.1016/j.jclepro.2019.119578. ISSN 0959-6526.

[38] Muhammad Shahzad Javed, Tao Ma, Jakub Jurasz, Muhammad Yasir Amin, Solar and wind power generation systems with pumped hydro storage: review and future perspectives, Renew. Energy 148 (2020) 176–192, https://doi.org/10.1016/j.renene.2019.11.157. ISSN 0960-1481.

[39] X. Wang, L. Chen, Q. Chen, Y. Mei, H. Wang, Model and analysis of integrating wind and PV power in remote and core areas with small hydropower and pumped hydropower storage, Energies 11 (2018) 3459, https://doi.org/10.3390/en11123459.

[40] G.E. Arnaoutakis, G. Kefala, E. Dakanali, D.A. Katsaprakakis, Combined operation of wind-pumped hydro storage plant with a concentrating solar power plant for insular systems: a case study for the island of rhodes, Energies 15 (2022) 6822, https://doi.org/10.3390/en15186822.

[41] D.A. Katsaprakakis, A. Proka, D. Zafirakis, M. Damasiotis, P. Kotsampopoulos, N. Hatziargyriou, E. Dakanali, G. Arnaoutakis, D. Xevgenos, Greek islands' energy transition: from lighthouse projects to the emergence of energy communities, Energies 15 (2022) 5996.

[42] R.Z. Falama, W. Skarka, S.Y. Doka, Optimal design and comparative analysis of a PV/Mini-Hydropower and a PV/battery used for electricity and water supply, Energies 16 (2023) 307, https://doi.org/10.3390/en16010307.

[43] A. Zisos, G.-K. Sakki, A. Efstratiadis, Mixing renewable energy with pumped hydropower storage: design optimization under uncertainty and other challenges, Sustainability 15 (2023) 13313, https://doi.org/10.3390/su151813313.

[44] M. Rossi, M. Renzi, D. Štefan, S. Muntean, Small-scale hydropower and energy recovery interventions: management, optimization processes and hydraulic machines applications, Sustainability 14 (2022) 11645, https://doi.org/10.3390/su141811645.

[45] Z. Wang, G. Fang, X. Wen, Q. Tan, P. Zhang, Z. Liu, Coordinated operation of conventional hydropower plants as hybrid pumped storage hydropower with wind and photovoltaic plants, Energy Convers. Manag. 277 (2023) 116654.

[46] H.M. Ramos, J.E. Sintong, A. Kuriqi, Optimal integration of hybrid pumped storage hydropower toward energy transition, Renew. Energy 221 (2024) 119732, https://doi.org/10.1016/j.renene.2023.119732. ISSN 0960-1481.

[47] M.C. Morani, A. Carravetta, O. Fecarotta, R. Montillo, Detailed audit of the energy efficiency in water systems: new performance indices, Water Resour. Manag. 38 (4) (2024) 1241–1260.

[48] Camila Andrea Garcia-Rodriguez, López Jiménez, Petra Amparo, Modesto Pérez-Sánchez, R. Sanchis, Methodology for assessing progress in sustainable development goals indicators in urban water systems. How far are we from the 2030 targets? Sustain. Cities Soc. 112 (2024) https://doi.org/10.1016/j.scs.2024.105616.

[49] A.A. Bazmi, G. Zahedi, Sustainable energy systems: role of optimization modeling techniques in power generation and supply—a review, Renew. Sustain. Energy Rev. 15 (8) (2011) 3480–3500.

[50] H.M. Ramos, A. Borga, M. Simão, New design solutions for low-power energy production in water pipe systems, Water Sci. Eng. 2 (4) (2009) 69–84.

[51] A. Carravetta, G. Del Giudice, O. Fecarotta, et al., Energy production in water distribution networks: a PAT design strategy, Water Resour. Manag. 26 (2012) 3947–3959, https://doi.org/10.1007/s11269-012-0114-1.

[52] C. Giudicianni, D. Mitrovic, W. Wu, G. Ferrarese, F. Pugliese, I. Fernández-García, E. Creaco, Energy recovery strategies in water distribution networks: literature review and future directions in the net-zero transition, Urban Water J. (2023) 1–16.

[53] Stefanizzi, M., Filannino, D., Fiorese, G. D., Torresi, M., & Balacco, G. Techno-economic comparison between commercial energy recovery devices in a complex urban water distribution network: pumps as turbines, cross-flow turbines and energy harvesting control valves. Cross-Flow Turbines and Energy Harvesting Control Valves.

[54] H.M. Ramos, M. Pérez-Sánchez, P.S. Guruprasad, A. Carravetta, A. Kuriqi, O. E. Coronado-Hernández, P.A. López-Jiménez, Energy transition in urban water infrastructures towards sustainable cities, Water 16 (3) (2024) 504.

[55] A. Telikani, M. Rossi, N. Khajehali, M. Renzi, Pumps-as-Turbines'(PaTs) performance prediction improvement using evolutionary artificial neural networks, Appl. Energy 330 (2023) 120316.