Water Resources Management (2024) 38:1011–1025
https://doi.org/10.1007/s11269-023-03706-7

Water Microturbines for Sustainable Applications: Optimization Analysis and Experimental Validation

A. M. Rodríguez-Pérez[1,2] · **C. A. Rodríguez-Gonzalez**[1] · **R. López**[3,4] ·
J. A. Hernández-Torres[1] · **J. J. Caparrós-Mancera**[1]

Received: 3 May 2023 / Accepted: 13 December 2023 / Published online: 19 December 2023

Abstract

The use of microturbines in irrigation applications represents a great opportunity for increasing sustainable energy generation. Irrigation systems have water flow that can be used to generate electricity based on microturbines that are acceptably configure such, that efficiency in crop irrigation is not affected. This research validates this use of microturbines through a system designed specifically for the characterization of microturbine generation technology. This system includes a closed water pumping circuit capable of working under, different water flow settings, as well as flow, pressure, and electricity generation sensors. For this system, the production range of the microturbines and the pressure loss associated with the various proposed configurations are characterized and specifically quantified for the best performance. After design and characterization of a scalable microturbine system, the feasibility and benefits of this application to supporting most relevant crops supplied by localized irrigation are analysed. The experiments demonstrate the greatest benefit with the implementation of 15 series microturbines each at 80 V, alongside non-Citrus fruit, where a favourable balance is achieved for the amortization period in vineyards and citrus fruit. The results validate a profitable and sustainable design for electricity generation, with return on investment rates of up to 53%. Therefore, this research offers real and extensive applications, while being scalable to rural, residential, urban and industrial settings.

Key Points

- Development of an experimental system for the characterization of water microturbines and validation in irrigation systems.
- Design of a system to obtain clean energy from the pressure head excess of irrigation systems based on experimental characterization.
- Analysis of the feasibility and investment of the application of the sustainable energy generation system to different crops.

Keywords Sustainability · Irrigation, energy · Hydrology

Extended author information available on the last page of the article

1 Introduction

The use of excess energy in pressurized water systems is one possible alternative to the pico and microgeneration based hydroelectricity. This generation strategy is included in action plans and policies that favour the development of a sustainable economy. Additionally, it is compatible with the requirements of social and environmental wellness (Rodríguez-Pérez et al. 2021a; Fetting 2020; Fry et al. 2022; Morar et al. 2021; Sinagra, 2023; Rigo et al. 2022; Simionescu et al. 2020). The development of microturbine technology should be considered to achieve a reduction in primary energy consumption. Moreover, such a system can help to improve the security of the energy system (Pirard et al., 2022; Rodríguez-Pérez and Pulido-Calvo 2019; Romero-Marrero et al. 2018; e Souza et al. 2023).

The price of electric energy is a key factor for the planning and management of water distribution systems. The potential for energy savings and the impact of different alternatives to achieve energy efficiency in water supply systems are highly variable depending on geographical constraints and hydraulic characteristics (Lima et al. 2019; Van der Voet et al. 2019).

Water or hydraulic turbines are being installed to save energy and to lessen the environmental impact of agriculture. Currently, the European Union (hereafter EU) has implemented ecolabels that allow consumers to identify products and services that have a reduced environmental impact during its life cycle (Kijek 2015; Pajula et al. 2017; Cordella et al. 2020). This labelling system can be implemented in water distribution networks, which would contribute to improving the environmental information received by the final water consumer.

There is currently great scientific and technical interest in analysing and evaluating the possibilities of recovering unused energy in pressurized and gravity water distribution systems. Such research investigates the optimal location and operating scheme of the hydraulic machine to be installed, as well as its influence on the control and management of the pipeline network.

This body of specialized literature has evaluated the use of pico and microturbines in hydraulic networks as an alternative to generate electricity from unused hydraulic energy. There are regulating valves in most plantations that are used to dissipate the excess energy by controlling or reducing pressure head of the flow. The objective of these works is to take advantage of this excess of energy. Table 1 presents relevant studies. The literature is limited regarding the use of pico and microturbines (W range of power generation) where the relevant works found respond to the use of water distribution by gravity. Relevant examples considering the use of small turbines (kW range of power generation), serve to base the developed forced conduit system and the subsequent experimental analysis of this research with microturbines. Likewise, Table 1 shows that the majority of turbine applications respond to water distribution in both residential and rural applications. The proposal of this study is based on a microturbine application for pressurized conduits, which is a specific novelty. Additionally, this work innovatively proposes a specific experimental system that allows different microturbine proposals to be validated in a validation environment with precision, and scalable results. Likewise, the results are proposed to be relevant not only for a specific irrigation context, but also for different crops and applied to both the context of Spain and the European Union.

Table 1 Synthesis of the bibliographic compilation on the use of excess energy in hydraulic systems using turbines

Reference	Power range	Conduit	Application of the microturbine system
(Christiansen 2016)	S	F	Drinking water
(Azmi et al. 2022)	S	F	Urban buildings
(Kim et al. 2015)	S	F	Residential
(Rodríguez-Pérez et al. 2021b)	S	F	Rural water distribution
(Samora et al. 2016)	S	F	Urban water distribution
(McNabola et al. 2014)	S	F	Industry
(Boroomandnia et al. 2022)	S	G & F	Urban buildings
(Adhikary et al. 2006)	M	G	Rural domestic
(Songad et al. 2022)	M	G	River
(Akshay et al. 2019)	M	G	Rural portable
Author's proposal	M	F	Crop irrigation

S: Small turbines (kW)
M: Pico and microturbines (W)
F: Forced conduit
G: Gravity conduit

2 Materials and Methods

2.1 Analysis and Selection of Irrigated Crops

The irrigated area in Spain exceeds 38,000 km^2, which as increased in the last two nationwide statistics by approximately 1.25% yearly (MAPA, 2021). The greatest area, including almost 30% of the total, is located in the Autonomous Community of Andalusia (southern Spain)". The progressive increase in irrigated area over the last few years has led to the evolution of the different existing irrigation systems. Thus, within the different types of irrigation most widespread, the localized or microirrigation system stands out for water application to crops of approximately 55% of the irrigated area of Spain. Compared to other relevant systems, despite having lower penetration in the country, such as surface, sprinkler or automotive irrigation technology, localized irrigation systems consume less water resources (MITECO, 2015; Ortega et al. 2002; Serra-Wittling et al. 2019). Of all the irrigated area in Spain by microirrigation systems, 42.5% is also located precisely in Andalusia, being 80% within the systems of this region; and increasing its presence by approximately 11% per year in the last decade (MAPA, 2021). This justifies the selection of the Andalusia region as a geographical delimitation of this research.

Once the study area has been delimited, several relevant conditions have been considered to select the crops to be analyzed specifically. The decision factors are as follows:

a) The main crops in Spain are in proportion to the total irrigated area (Fig. 1A).
b) The main crops in the Andalusia region in proportion to the total irrigated area (Fig. 1B).
c) The main crops were selected, based on the two previous criteria, regarding the use of localized or microirrigation systems (Fig. 1C).

The six main irrigated crops in Spain are cereals, olive groves, noncitrus fruit trees, vineyards, citrus fruits and forages, which total more than 80% of the total irrigated area (Fig. 1A). In Andalusia, the main irrigated crop, with more than 62%, is the olive grove. This crop, together with industrial crops, fruit trees, cereals, vegetables and flow-

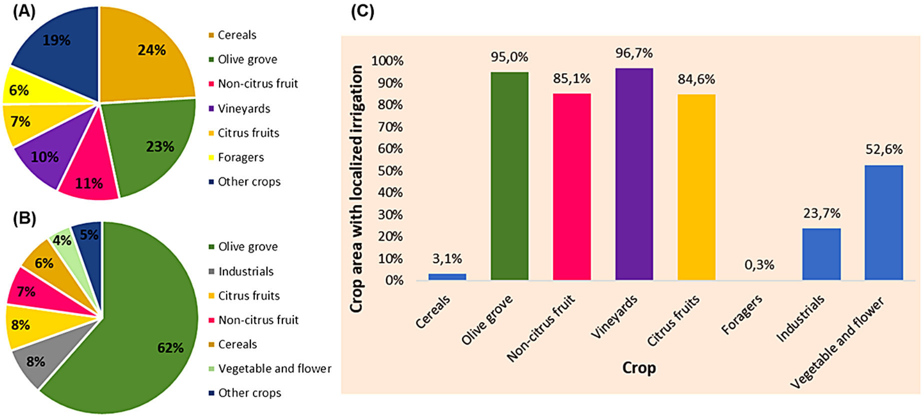

Fig. 1 The main crops in Spain **(A)** and in Andalusia **(B)** in relation to the percentage of the total irrigated area. **(C)** Percentage of irrigated area in Andalusia of selected crops through the localized or microirrigation systems (MAPA, 2021)

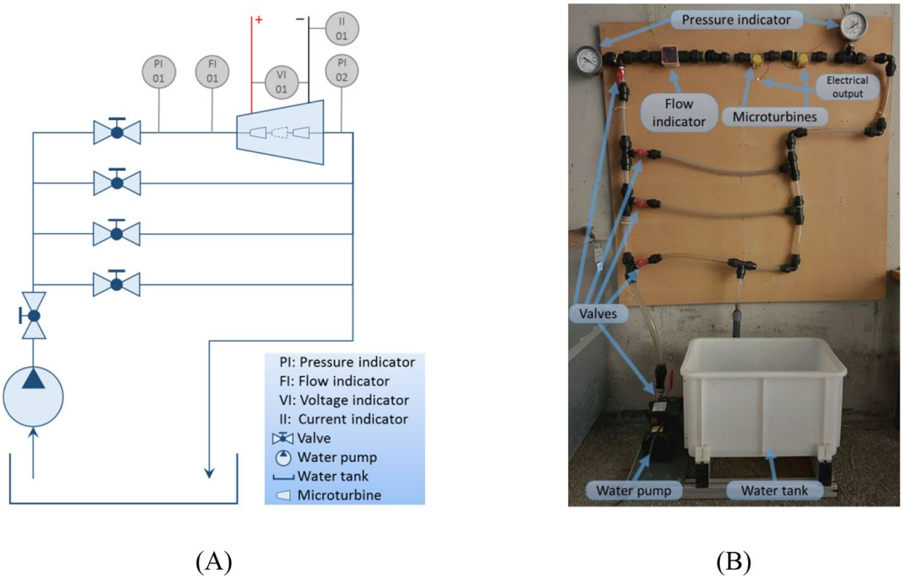

Fig. 2 **(A)** Schematic diagram of the facility, **(B)** View of the completed facility

ers, forms more than 95% of the irrigated croplands of Andalusia (Fig. 1B). Figure 1C shows the proportion of irrigated area in the Andalusia region of these selected crops through the localized or microirrigation systems. Under this criterion, cereals and forages are discarded in this study due to their residual presence in this type of irrigation system. In addition, the contribution of industrial crops or vegetable and flower crops, is also quite small compared to the remaining crops and moreover its nationwide weight is limited. Thus, the four crops that highlight are nationally prevalent, found in the

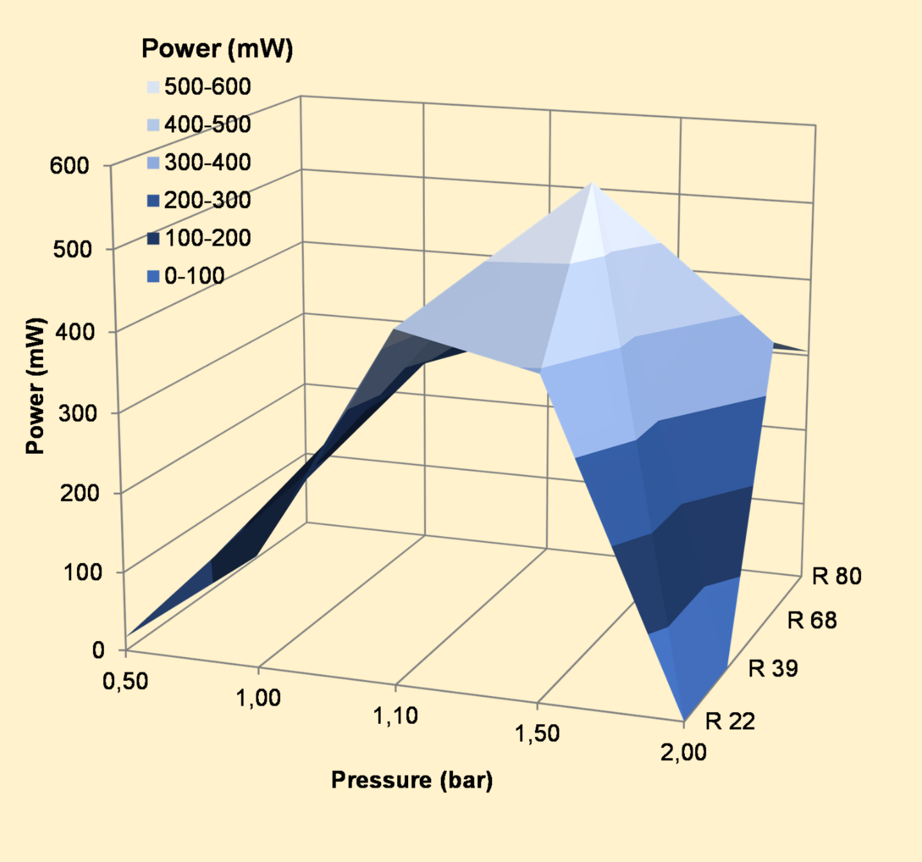

Fig. 3 Power generated (P) against inlet pressure (p) for the 5 V microturbine

Andalusia región, and are amenable to the use of localized or microirrigation systems are: (i) olive groves, (ii) non-Citrus fruit, (iii) citrus fruit and (iv) vineyards. Although the presence of vineyards near the comparing the irrigated area in Andalusia is limited, their presence throughout Spain and its economic relevance justifies consideration of vineyards in this research.

Overpressure in pressurized irrigation systems is the cause of major inconveniences such economic losses, material fatigue and damage or malfunction of the emitters. Microturbine installation allows a double tactic: to avoid the harmful effects of overpressures in the pipe network and to take advantage of this overpressure to obtain economic profitability. Microturbines offer an advantage over pressure-reducing valves of cogenerating energy, rather than dissipating it without any use.

In the present research context, the main objective is to experimentally validate the feasibility of using the excess hydraulic energy (i.e., overpressure) that frequently occurs in localized or microirrigationsystems (i.e., pressurized) through the installation of microturbines. The corresponding electricity generation can power on site applications or provide generation to the grid. As a secondary or instrumental goal, it is

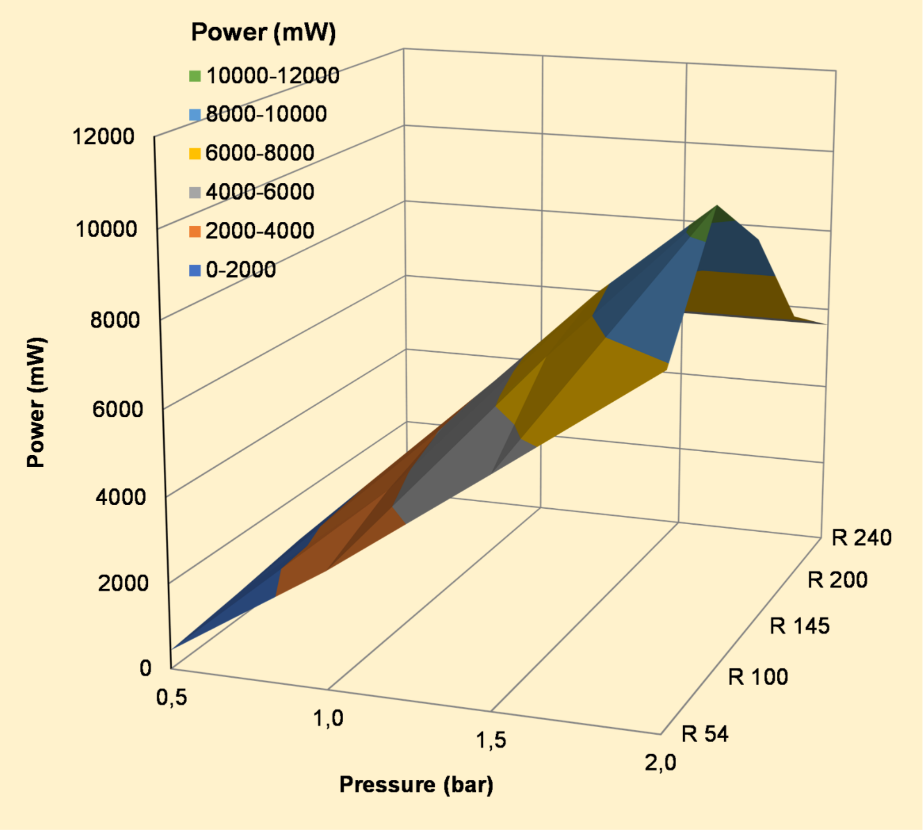

Fig. 4 Power generated (P) against inlet pressure (p) for the 12 V microturbine

necessary to design and execute an experimental laboratory facility that demonstrates suitability for this main purpose. This experimental evaluation will be conducted for selected crops. Different test alternatives are evaluated, testing turbines of different powers as well as with different pressures to determine viable and profitable solutions. The economic feasibility analyses are conducted by calculating the benefit generated by the installed system.

2.2 Design and Implementation of the Experimental Evaluation System

To experimentally evaluate the feasibility of pico and microturbines in localized or microirrigation systems, the following design criteria for an experimental facility are proposed:

1. Enables characterization the operation of microturbines, including generation and efficiency.
2. Allows regulation of the water static pressure at the turbine inlet.
3. Forms a closed circuit so as not to consume water during experimental tests.
4. Is adaptable to different microturbine configurations.

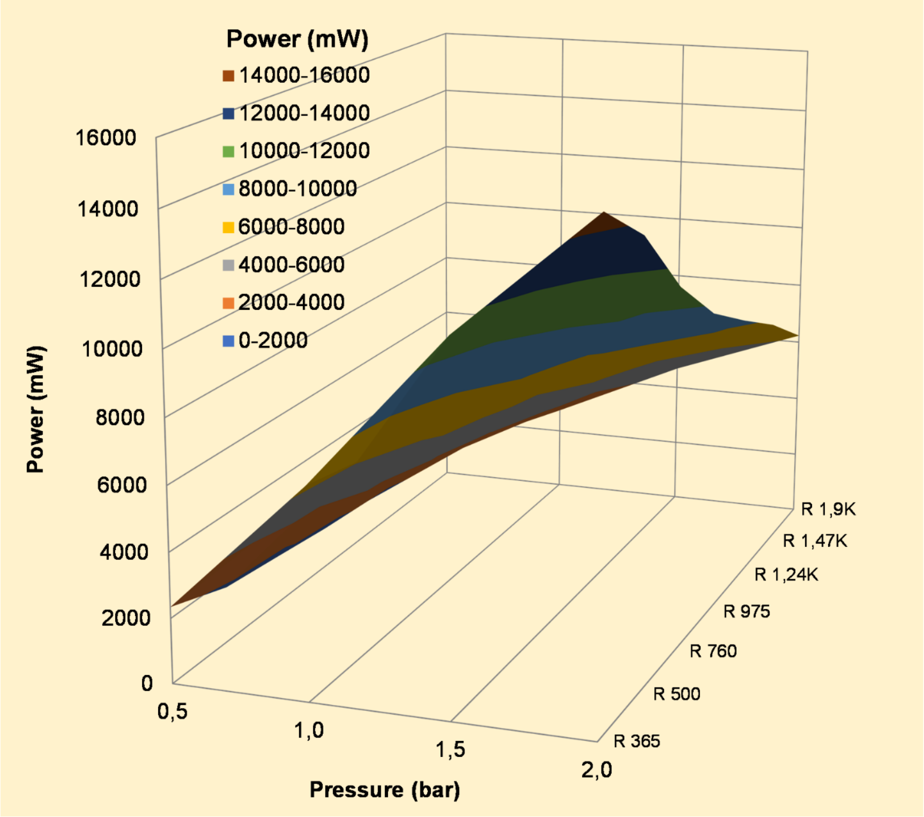

Fig. 5 Power generated (P) against inlet pressure (p) for the 80 V microturbine

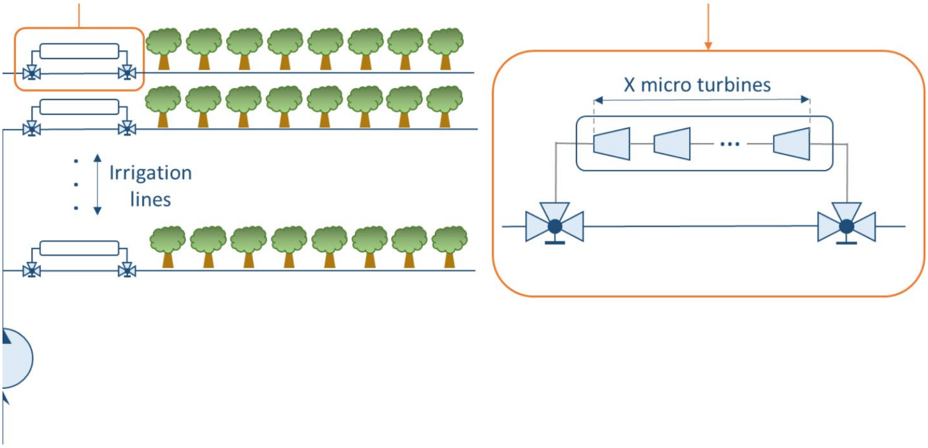

Fig. 6 Schematic diagram of the implantation of the microturbines in the plot

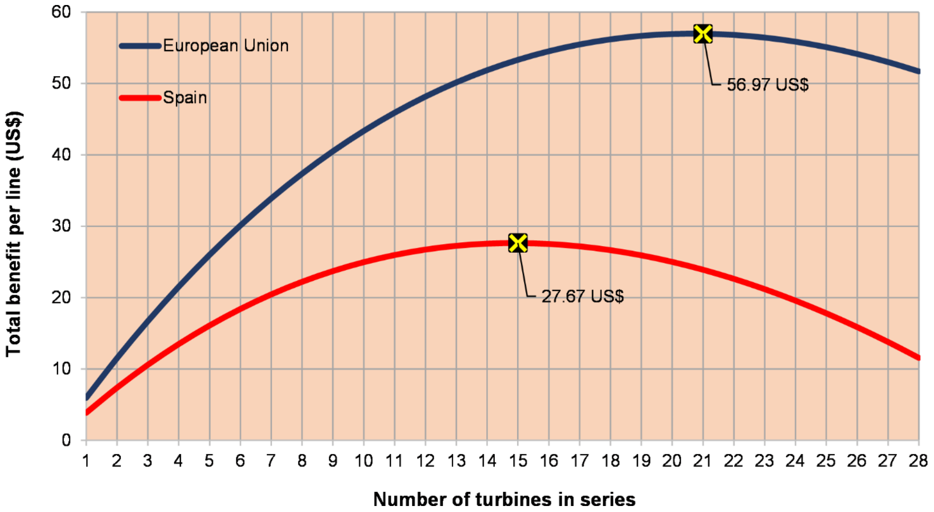

Fig. 7 Benefit ratio against number of turbines coupled in series both in the European Union (EU) and Spain

Table 2 Results for the four selected crops and its three variants considered

Crop and variant	N° of crop irrigation lines	Crop irrigated area (C_a)(ha)	Annual irrigation time (h)	Initial investment + unit maintenance per area (US$/ha)	Marketing benefit (Spain) (US$/ha)	Marketing benefit (EU) (US$/ha)	Installation life (years)
Olive grove 1	16	6.18	547.5	290	71	134	6.4
Olive grove 2	20	6	547.5	373	92	173	6.4
Olive grove 3	80	20	547.5	448	110	207	6.4
Citrus fruit 1	34	6.86	1825	555	137	257	1.9
Citrus fruit 2	35	16	1825	245	60	113	1.9
Citrus fruit 3	25	8	1825	350	86	162	1.9
Not citrus fruit 1	130	2.75	120.5	5294	1304	2451	29
Not citrus fruit 2	160	4	120.5	4480	1104	2074	29
Not citrus fruit 3	124	3.2	120.5	4340	1069	2010	29
Vineyard 1	56	2.41	756	2602	641	1205	4.6
Vineyard 2	74	3.5	756	2368	583	1096	4.6
Vineyard 3	92	4	756	2576	634	1193	4.6

Figure 2 shows the final designed and installed facility The different components of this experimental validation facility are as follows:

- A hydraulic inlet pump that automatically supplies the needed water to the system.
- A water tank from where water is pumped and returned from the system to form a closed circuit for experimental testing. This system can be adapted to open circuits and characterize specific water volume consumption.
- A series of control pressure valves are distributed at the pump outlet, at the inlet of the microturbine, with in three lateral lines configured parallel to the microturbine line. With this spatial arrangement, the desired inlet static pressure to the microturbines is

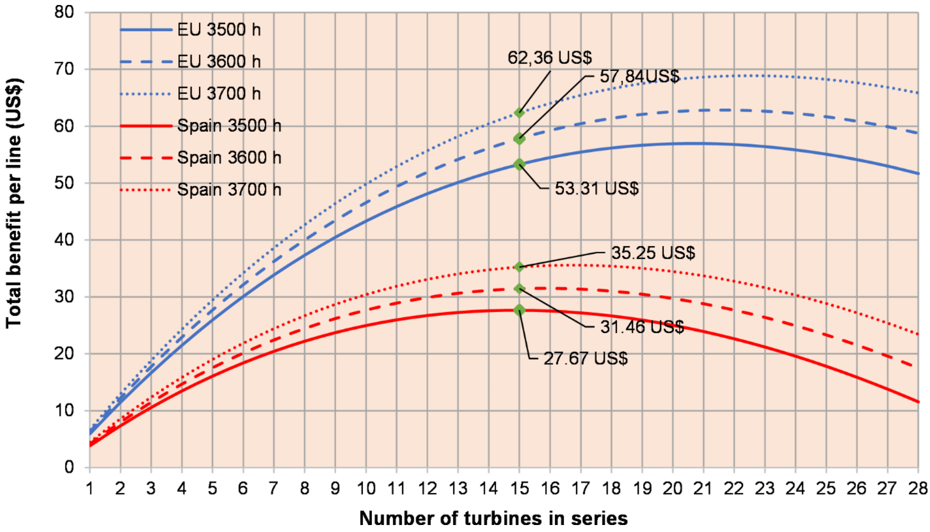

Fig. 8 Profitability ratio regarding the number of microturbines coupled in series and the number of operating hours (3500 h, 3600 h, and 3700 h) both in the EU and Spain

precisely regulated.

- Pressure measuring sensors at the inlet and outlet of microturbines are included to characterize the efficiency of microturbines in terms of static pressure drop. The percentage efficiency responds to the difference in pressure at the outlet compared to the inlet.
- A water flow metre was used to characterize the discharge and pressure ratio.
- Voltage and current sensors to characterize microturbine power generation.
- Connecting pipes, whose diameter is similar to that used in real irrigation systems. Typical nonfixed irrigation joints are used to allow modification to the system, including the number of turbines in the test.

Three models of microturbines are considered (i.e.,5, 12 and 80 V, DC power). The guaranteed operating time of this model of microturbines is 3500 h at maximum performance. Although its real running time is much longer, this value is considered for the characterization and validation conducted in this work. First, the model is characterized by varying the inlet pressures in the turbine from 0.5 bar up to 2 bar (in increments of 0.1 bar). With this it is known when the turbines have a better performance within irrigation water pressures.

3 Results and Discussion

Based on the experimental facility developed, the following variables of the microturbines are analysed:

(1) Efficiency of microturbines with respect to pressure drop. The pressure drop in a single microturbine, using differential pressure sensors previously described, is measured as

3%, successively increasing with the number of turbines coupled in series in the same water line.

(2) Discharge and pressure ratio. This allows us to characterize the piping of the microirrigation systems and unify the analysed crop data into a single parameter. For this study, $Q = 9.672p^{0.653}$ ($R^2 = 1.00$) where Q is the flow discharge (l/min) and p is the pressure at the turbine inlet (bar).

(3) Generation of microturbines. The power generated by the three models of microturbines of different voltages (5 V, 12 and 80 V (Figs. 3, 4 and 5)) was analysed within the typical pressure range of crops where the hydropower system could be applied (between 0.5 bar and 2 bar). For this, the consumption load profile in resistive mode has been adjusted to the output of the microturbine and within the permissible range. The highest power generation is obtained with a power of 14.8 W and using the 80 V microturbine. Figures 3, 4 and 5 show the relation between the maximum power generated by the turbine (P), according to the water pressure (p) and the resistance (R) to control the load applied to the turbine.

With the key of the microturbines characterized and relevant efficiency and generation data obtained, an implementation scheme is proposed in Fig. 6. The circuit starts with a pump, which is part of the existing irrigated area and drives the water throughout the whole irrigation system. The supply or application of the water scheme in the plot is organized from a main distribution line and a series of lateral branch lines. In each of these lateral lines a microturbine system is installed in a parallel or bifurcated way (Fig. 6). This system consists of a set of microturbines coupled in series (the number of coupled microturbines is a matter to be determined in this study), together with a system of manual valves. A valve is installed at the beginning and another at the end of the microturbine section, such that the microturbine line is parallel to a lateral line. Thus, in the case of maintenance requirements or failure in the microturbine system, changing the position of passage in the valves the bifurcation of flow through the microturbines section is cancelled and instead water flows only along the lateral line and water application is never interrupted.

Next, the application of the designed system of microturbines to the four key crops previously selected is analysed. This process compares the parameters corresponding to the economic profitability (related to the benefit) with the time lapse needed to obtain these benefits in relation to the annual irrigation time of each type of crop.

To calculate the energy savings of this investment, we consider the average price of electricity in 2022 (i.e., the last year for which all data are available). A comparison is made between the prices of 2022 in Spain and those of the European Union (EU). For this, we use the data provided by the Iberian Electricity Market Operator (OMIE, www.omie.es). The average price of electricity in 2022 was approximately 210 US$/MWh for Spain, while for the EU in 2022 it was approximately 250 US$/MWh.

For calculating the number of turbines coupled in series per line two scenarios are assumed. The first scenario corresponds to the average price of the EU, while the second scenario concerns the average price in Spain. To determine the optimal number of turbines coupled in series on each line (N), as many turbines as are cost-effective will be installed. To obtain the optimal number of turbines, the following algorithm is applied (by iterative calculation) to maximize profitability:

$$Line\,profit\,for\,N turbines\ (US\$) = \sum_{i=1}^{N} P\eta^{i-1}V_uP_e - C_c - C_m \tag{1}$$

$$Income\,per\,turbine\,(US\$) = P\eta^{i-1}V_uP_e$$

$$Cost\,per\,turbine\,(US\$) = C_c + C_m$$

$$Power\,genertad\,per\,turbine\,(kW) = P\eta^{i-1}$$

where N = number of turbines coupled in series on each line; P = maximum experimental mechanical power of the turbine (14.8 W); η = experimental efficiency of each turbine (0.97 for each turbine, but efficiency is progressively reduced as the number of turbines coupled in series increases); V_u = turbine's design life according to manufacturer (3500 h) (note that this value for the experimental useful life represents a conservative estimate); P_e = average electricity price in 2022 (i.e., 210 US$/MWh in Spain and 250 U$/MWh in the EU); Cc = acquisition cost (6 US$ per turbine + 1 US$ by hydraulic joints); and Cm = maintenance cost (1 US$ per turbine during its lifetime).

The result of applying Eq. (1) to the two electricity price scenarios (i.e., Spain and the EU) are shown in Fig. 7. The benefit is maximized for 15 turbines in the energy price scenario in Spain, as well as for 21 turbines for the energy scenario in the EU. Note that average price of electricity directly affects the maximum point on the curve for each scenario, so in Spain, having a lower price, less benefit will be generated (in relation to the same electricity generated) with each turbine. Applying the most restrictive case, the number of turbines immediately below the lowest maximum number is considered, i.e., 14 turbines. In this case, the 15th turbine produces a marginal benefit (US$0.03). Since its implementation would represent an insignificant profit, its installation is discarded. It is evident that the price of electricity fluctuates greatly. As shown in Fig. 7, comparing 14 and 15 turbines placed in series, the gain is practically negligible.

To assess the validation of the proposed hydropower system in the previously selected crops (i.e., olive grove, fruit trees (citrus and noncitrus) and vineyards), a series of crops is analysed based on the number of lines, crop irrigated area, and annual irrigation time. For comparative purposes, the following variables are calculated for each of the crops:

$$Initial\,investment + unit\,maintainance\,per\,area\left(\frac{US\$}{ha}\right) = \frac{C_c + C_mNL}{C_a} \tag{2}$$

$$Unit\,benefit\,per\,area\left(\frac{US\$}{ha}\right) = \frac{\sum_{i=1}^{N} P\eta^{i-1}V_uP_e - C_c - C_m}{C_a}LL \tag{3}$$

$$Facility's\,operating\,life\,time\,(years) = \frac{V_u}{A_t} \tag{4}$$

where L = number of crop irrigation lateral lines (Fig. 7); Ca = crop irrigated area (ha); and At = annual irrigation time (hours/years), having already defined the other variables.

The Table 2 shows the results for each of the four crops studied and for the three variants assumed for each crop. The range of benefit per hectare generated if the crops were located in Spain or in the rest of the EU is shown. Notably, the price of electricity in Spain is one of the lowest in the EU, therefore, this comparative study represents one of the scenarios that is least economically favourable to microgeneration systems. Finally, the last column shows the number of years needed for the turbines to reach their minimum number of operating hours according to Eq. (4)

The return on investment (ROI) is 28% for Spain and 53% for the EU. Likewise, the benefit that would be obtained for every 100 h above the turbine design life would be 13% (3.6 US$) for Spain and 8% (4.3 US$) for the EU, as shown in Fig. 8.

4 Conclusions

To overcome the contrasting results reported between laboratory tests (using a specially designed facility) and full-scale numerical modelling for four types of irrigated crops in southern Spain, this study considers the application of microturbines to harvest excess hydraulic energy (overpressure). The optimal number of microturbines coupled in series for each lateral irrigation line in a plot has been determined by maximizing the unit benefit according to the electricity prices in Spain and in the European Union. This optimal system is determined to be 15 80 V turbines in series. It is verified that microturbines generate a profitable electrical implementation, with high rates of return on investment, up to 53%, according to the price of electricity. Based on annual irrigation time, the hydropower system is amortized in the least time when used with non-citrus fruit crop (1.9 years). This occurs because this crop requires the most hours of irrigation per year. The crop for which the highest unit benefit is obtained by commercialization of energy is noncitrus fruit (~ 1668 US$/ha). However, because it is a crop that requires a few hours of irrigation per year, it results in the longest amortization period of the hydropower system. The crops with the lowest unit benefit are olive grove and citrus fruits (~ 131 US$/ha, ~ 135 US$/ha). However, since citrus fruits require more than three times the number of irrigation hours per year, their amortization period is lower by the same proportion. Vineyards show a balance between benefit and amortization period (~ 892 US$/ha, 4.6 years), within its limited presence in the context of the study. The system proposes a form of generation that is limited to excess pressure in the water network, since the turbines cause a loss of load. Therefore, the proposed design places them at the end of the installation, which also limits its topology. Additionally, due to this head loss, the maximum benefit is limited to a certain value of turbines. It has been demonstrated that the application of microturbine systems to exploit excess hydraulic energy (overpressures) in the irrigation crops and regions selected in this study, scalable from rural applications in springs to industrial water applications, is a viable and efficient alternative for power generation.

Future work will explore the implementation of our system in different crops to further validate its potential for serving long-term applications.

Acknowledgements CIMEDES Research Center (CeiA3) of University of Almería. Open Access supported by University of Huelva.

Author Contributions Conceptualization and methodology: A.M.R.-P., C.A.R.G. and R.L.; validation, formal analysis, and investigation: C.A.R.G., J.J.C.M. and J.A.H-T.; writing—original draft: A.M.R.-P. and R-L.; writing—review and supervision: C.A.R.G and J.J.C.M. All authors have read and agreed to the published version of the manuscript.

Funding This work has not received any funding.
Funding for open access publishing: Universidad de Huelva/CBUA

Data Availability The necessary data has been obtained through laboratory tests and by survey to different local agricultural companies.

Declarations

Conflict of interest The authors have no conflicts of interest.

References

Adhikary P, Roy PK, Mazumdar A (2006) CFD analysis of micro hydro turbine unit: a case study. ARPN J Eng Appl Sci 11(7):4346–4352

Akshay S, Shinde P, Somavanshi S, SaurabhSarode, Raut M (2019) Energy Generation using Portable Water turbine. Int J Emerg Technol Innovative Res 6(4):197–204. https://www.jetir.org/view?paper=JETIRBB06042

Azmi R, Yazid F, Mahmud N, Hassan F, Azhar A, Salimin S (2022) Modelling of Micro Hydropower System for small load application. J Electron Voltage Application 3:125–132. 1 SE-Articleshttps://publisher.uthm.edu.my/ojs/index.php/jeva/article/view/9250

Boroomandnia A, Rismanchi B, Wu W (2022) A review of micro hydro systems in urban areas: opportunities and challenges. Renew Sustain Energy Rev 169:112866. https://doi.org/10.1016/j.rser.2022.112866

Christiansen C (2016) Culinary and pressure irrigation water system hydroelectric generation. Water Works Engineers, Pleasant Grove City, UT. (United States)

Cordella M et al (2020) Improving material efficiency in the life cycle of products: a review of EU Ecolabel criteria. Int J Life Cycle Assess 25:921–935

e Souza DES, Mesquita ALA, Blanco CJC (2023) Pressure regulation in a water distribution network using pumps as turbines at variable speed for Energy Recovery. Water Resour Manage 37(3):1183–1206

Fetting C (2020) The European Green Deal. ESDN Report, December

Fry J-J, Schleiss AJ, Morris M (2022) Hydropower as a catalyst for the energy transition within the European Green Deal Part I: urgency of the Green Deal and the role of Hydropower. *E3S Web of Conferences*, *346*, 4015

Kijek T (2015) Modelling of eco-innovation diffusion: the EU eco-label. Comp Economic Res Cent East Europe 18(1):65–79

Kim I, James J-A, Crittenden J (2015) The Energy-Efficient, Economical, and Environmental Impacts of Microturbines on Residential Customers. *2015 Seventh Annual IEEE Green Technologies Conference*, 139–146

Lima FA, Córcoles JI, Tarjuelo JM, Martinez Romero A (2019) Análisis Del comportamiento de una red colectiva de riego considerando la programación de riego en parcela. Ingeniería Del Agua 23(2):77–87

MAPA (Ministerio de Agricultura, Pesca y Alimentación) (2021) Encuesta sobre Superficies y Rendimientos Cultivos (ESYRCE): análisis de los regadíos españoles 2021.

McNabola A, Coughlan P, Corcoran L, Power C, Prysor Williams A, Harris I, Gallagher J, Styles D (2014) Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability. Water Policy 16(1):168–183

MITECO (Ministerio para la Transición Ecológica y el Reto Demográfico) (2015) Estrategia para la modernización sostenible de los regadíos, horizonte 2015.

Morar C, Berman L, Unkart S, Erdal S (2021) Sustainable brownfields redevelopment in the European Union: an overview of policy and funding frameworks. J Environ Health 84(4):24

Ortega JF, Tarjuelo JM, De Juan JA (2002) Evaluation of irrigation performance in localized irrigation systems of semiarid regions (Castilla-La Mancha, Spain). *Agricultural Engineering International: CIGR Journal*

Pajula T, Behm K, Vatanen S, Saarivuori E (2017) Managing the life cycle to reduce environmental impacts. *Dynamics of long-life assets: From technology adaptation to upgrading the business model*, 93–113

Pirard T, Kitsikoudis V, Erpicum S, Pirotton M, Archambeau P, Dewals B (2022) Discharge redistribution as a key process for heuristic optimization of energy production with pumps as turbines in a water distribution network. Water Resour Manage 36(4):1237–1250

Rigo A, Andriollo E, Pisani E (2022) Intermediary organizations in Nature Conservation initiatives: the case of the EU-Funded LIFE Programme. Sustainability 14(13):7618

Rodríguez-Pérez Á, Pulido-Calvo I, Cáceres-Ramos P (2021a) A computer program to support the selection of turbines to recover unused energy at Hydraulic Networks. Water 13(4):467

Rodríguez-Pérez ÁM, Pérez-Calañas C, Pulido-Calvo I (2021b) Energy recovery in pressurized hydraulic networks. Water Resour Manage 35:1977–1990

Rodríguez-Pérez ÁM, Pulido-Calvo I (2019) Analysis and viability of microturbines in hydraulic networks: a case study. J Water Supply: Res Technology-Aqua 68(6):474–482

Romero-Marrero L, Pérez-Sánchez M, López-Jiménez PA (2018) Estimation of the characteristic curves of pumped systems working as turbines through their curves operating as pump. Ingeniería Del Agua 22(1):15–26

Samora I, Manso P, Franca M, Schleiss A, Ramos H (2016) Energy Recovery Using Micro-hydropower Technology in Water Supply systems: the Case Study of the City of Fribourg. Water 8(8):344

Serra-Wittling C, Molle B, Cheviron B (2019) Plot level assessment of irrigation water savings due to the shift from sprinkler to localized irrigation systems or to the use of soil hydric status probes. Application in the French context. Agric Water Manage 223:105682

Simionescu M, Păuna CB, Diaconescu T (2020) Renewable energy and economic performance in the context of the European Green Deal. Energies 13(23):6440

Sinagra M, Creaco E, Morreale G, Tucciarelli T (2023) Energy recovery optimization by means of a turbine in a pressure regulation node of a real water network through a data-driven digital twin

Songad C, Kundu AK, Soni D, Patel VS, Abhishek, Sharma C, Kumar V (2022) Energy Generation by using small Hydro Power-An Analysis. Int Res J Eng Technol 09(03):1210–1213

Van der Voet E, Van Oers L, Verboon M, Kuipers K (2019) Environmental implications of future demand scenarios for metals: methodology and application to the case of seven major metals. J Ind Ecol 23(1):141–155

Authors and Affiliations

A. M. Rodríguez-Pérez[1,2] · **C. A. Rodríguez-Gonzalez**[1] · **R. López**[3,4] · **J. A. Hernández-Torres**[1] · **J. J. Caparrós-Mancera**[1]

✉ A. M. Rodríguez-Pérez
angel.rodriguez@dci.uhu.es

C. A. Rodríguez-Gonzalez
cesar@didp.uhu.es

R. López
raul.lopez@udl.cat

J. A. Hernández-Torres
joseantonio.hernandez@dimme.uhu.es

J. J. Caparrós-Mancera
julio.caparros@diesia.uhu.es

[1] University of Huelva, 21007 Huelva, Spain

[2] Department of Engineering, University of Almería, CIMEDES Research Center (CeiA3), 04120 Almería, Spain

[3] Department of Forest and Agricultural Science and Engineering, University of Lleida, 25003 Lleida, Spain

[4] Fluvial Dynamics Research Group (RIUS), University of Lleida, 25003 Lleida, Spain