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Research paper

Is small-scale hydropower energy recovery a viable alternative for climate change mitigation and adaptation? The case of the traditional irrigation system in Valencia (Spain)

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A R T I C L E I N F O

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A B S T R A C T

In the current scenario of climate emergency and energy transition, leveraging knowledge from interdisciplinary fields like the food-water-energy nexus is crucial. Traditional irrigation canals, an integral part of agricultural sustainability, offer untapped potential for small-scale hydropower, providing a decentralized and reliable electricity source. This study estimates the potential for small-scale hydropower production in a medium-scale irrigation system in the Valencia province (Spain). Relevant parameters obtained from local sources (head, water flow, irrigation regimes, etc.) were analysed to select the most appropriate turbine. A total of 8 mills were considered for this branch of the irrigation network. Potential power installable and energy production were estimated using 30 years of historical water flow data from *in situ* measurements. A maximum of 750 MWh/year for the highest head mill was calculated for the year with the highest water flow (2010). For the same year, the total production for all mills together reached nearly 5 GWh/year. These results are consistent with similar case studies in the literature and highlight the untapped capacity of the irrigation network for potential future practical projects. Discussions on the application of the energy produced consider two scenarios: electricity self-consumption and sale to the grid, and hydrogen production for local industrial use. Both scenarios show significant benefits (economic and energy) for the potential installation of hydropower systems. The mitigation potential, particularly for hydrogen production, is shown to depend on the national electricity mix. Opportunities and limitations are considered, highlighting the policy context and the need for further research on economic viability, life cycle assessments, and future climate projections. This work supports decentralized energy models aligned with the EU's carbon neutrality goals and emphasizes the significant potential for micro-hydro installations in irrigation canals as part of a sustainable energy mix.

1. Introduction

Despite global concern over the current earth climate and energy provision resilience (CNN, 2021; Lubchenco and Kerry, 2021), most economic sectors are still relying on non-renewable energy resources, such as fossil fuels. Specifically, in 2022 approximately 61 % of the global primary energy consumption relied on fossil fuels, making the energy sector the largest source of GHG emissions (International Energy Agency, 2021, Our World in Data, 2022). Moreover, in 2020 roughly 60 % of the electricity production (Our World in Data, 2022; Ember - Yearly Electricity Data, 2024; Energy Institute - Statistical Review of World Energy, 2023) was derived from fossil fuels, resulting in 32 % of the total GHG emission. In the path to decarbonisation and cleaner energy supply, renewable energies are the preferred sources since they

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provide renewability, and hence a more long-term vision, as well as a more sustainable low-carbon alternative for the planet. Although this path does not come without concerns and huge drawbacks (Renner and Giampietro, 2020) the EU has started a paramount plan (*Fit for 55*) to reach an emissions reduction by 55 % from 1990 levels by 2030 (European Council, 2024), in line with the worldwide "Energy transition" framework and the *European Green Deal* (European Commission, 2019). In addition, the signatory cities of the Covenant of Mayors for Climate and Energy pledge action to support implementation of the EU 55 % greenhouse gas (GHG) reduction target by 2030 through the development and implementation of a Sustainable Energy and Climate Action Plan (SECAP) (Covenant of Mayors, 2022), containing the main mitigation actions to reduce cities emissions. Both transition to renewable energies and consumption reduction (European Environmental Agency, 2020) are currently the main viable solutions in the face of increasingly scarce fossil-fuel resources (also considering the consequences of the recent Ukraine-Russian conflict) and enhanced GHG concentration in the atmosphere (Nogrady, 2021; Büchs et al., 2023).

Every EU state is managing its decarbonisation path according to local needs and available resources. For example, in Spain, 46.7 % of the electricity generated in 2021 came from renewable energies, with 11.4 % from hydroelectric power (Red Eléctrica Española, 2022). Nuclear energy accounted for 20.8 %, and nearly 30 % of the total electricity was generated using fossil fuels (primarily natural gas at 17.1 %) emitting almost 36 million tons of CO_2 eq. (11.8 % of the total national GHG emissions).

In this context, hydropower is considered one of the cleanest renewable energies available, with the highest Energy Return on Energy Invested (EROEI) (Hall et al., 2014) in case of large installations (i.e., highly energetically viable), albeit not exempt of drawbacks, such as ecological costs, generally difficult to account for (Dorber et al., 2020; Hermoso et al., 2019; Zarfl et al., 2019). When the capacity and installation size diminish to small-scale installations (micro-hydropower, MHP), the ecological disturbances and landscape impact are reduced, while on the other hand the EROEI value drops substantially, depending on the size (Kittner et al., 2016), and overall, it can produce a higher impact in terms of the whole life cycle (Ueda et al., 2019). Few studies related to life-cycle assessment (LCA) of micro-hydropower highlighted these challenges (Gallagher et al., 2015; Suwanit and Gheewala, 2011; Ueda et al., 2019).

According to (Ueda et al., 2019, Suwanit and Gheewala, 2011), in LCA studies of Run-on-river small scale installations, environmental effects can be grouped into several impact categories (such as global warming potential, acidification potential, abiotic resource depletion, fossil fuel depletion potential, Photochemical oxidation, freshwater aquatic ecotoxicity, Human toxicity). Most impacts occur during the construction phase (production of cement, steel, piping, electric equipment, fossil fuel and electricity consumption), material transport, operation and maintenance. Material selection and eco-design can undoubtedly reduce these impacts (Gallagher et al., 2015), while transport is clearly linked to the site of the installation.

Therefore, the selection of new MHP installations needs to simultaneously consider several complex factors, ensuring an environmental benefit compared to conventional sources. Arguably, maintenance and average lifetime of the whole MHP system are critical factors in determining the appropriate technology. Hence, to make it energy-efficient and environmentally cost-effective, the best choice would be durable, low-maintenance equipment, when selecting the turbine, the electric generator and power electronics.

In European countries, potential sites to install new large-scale hydro systems are scarce (Paish, 2002). However small-scale solutions are options that have yet to be thoroughly explored and are in line with decentralised renewable electricity production (Alstone et al., 2015; BOE, 2018, BOE, 2019).MHPs also have the advantage of being suitable for installations in developing countries (Adhau et al., 2012; Butchers et al., 2020; Kittner et al., 2016; Suwanit and Gheewala, 2011; Paish, 2002) or in rural areas where grid connection is lacking (Kittner et al., 2016; Suwanit and Gheewala, 2011).

Energy production, food production and water availability are strongly connected (food-water-energy nexus) and particularly important in this specific context: in the literature, and history in general, there are documented cases where hydroelectric production can support irrigation (Lacombe et al., 2014; Tilmant et al., 2009), as well as instances where energy generation competes with water availability for food production (Zeng et al., 2017). This is a crucial point in the energy provision scenario, as the current path to renewable energy deployment is theoretically taking the world to net zero emissions by 2050 according to the International Energy Agency (IEA) (International Energy Agency, 2021) and the EU (European Commission, 2019).

Micro-hydropower installations within irrigation networks have been shown to represent an option with negligible negative effects on water availability for crops (Butera and Balestra, 2015; Camilo Rosado et al., 2020; Chacón et al., 2018; Chacon et al., 2020; Pérez-Sánchez et al., 2017; Pérez-Sánchez et al., 2020), although literature on this topic is quite scarce. While some studies focus on energy recovery from pressurised irrigation (Camilo Rosado et al., 2020), a relatively limited number of studies centre the attention on the exploitation of irrigation canals for energy harvesting (Adhau et al., 2012; Algieri et al., 2020; Butera and Balestra, 2015; Chacón et al., 2018; Comino et al., 2020; Gallagher et al., 2015; Kamran et al., 2019; Laghari et al., 2013; Paish, 2002; Pérez-Sánchez et al., 2017). Interestingly, according to the environmental impacts listed above, we can speculate that some of the consequences of MHP construction that affect the river ecosystem, may have a minimal effect in case the canal is used for irrigation purposes only (e.g. freshwater aquatic ecotoxicity, acidification potential).

In Table 1 we present a list of most recent works on energy production, primarily from irrigation networks run-on-river/run-on-canal types, with characteristics similar to our case, along with relevant parameters. Most of the studies concentrate on the potential installed power and/or potential energy production, depending on the system's capability, such as the head, available water flow, and the recoverable energy if the irrigation is conducted with a pressurised system.

The studies reported in Table 1 are primarily focused on the technical aspects and lack calculations related to the mitigation potential of the systems and/or to GHG reduction. However, in the present work, the intention is to shift the focus towards the mitigation potential of a small hydropower system and the possibility of using it as an adaptation measure for local communities. Specifically, farmers and irrigation associations. The use of existing technology and infrastructures, such as the irrigation canals and the mills located within, allow these agricultural communities to propose mitigation measures. Moreover, the involvement of local stakeholders and associations is crucial in these processes, and any action plan for a sustainable energy transition needs a multistakeholder approach, as pointed out by Escario-Chust et al. (2023).

As observed previously (Algieri et al., 2020), every case study is highly context specific, and while the table provides a good reference for comparison, each work requires particular focus depending on factors such as the type of exploitable energy (pressurised irrigation or free surface water), the extent of the area under study, the expected maintenance costs etc.

Considering the current climate scenario, water patterns and availability are expected to change, potentially having a profound impact on agriculture and hydroelectric generation. This change, along with the intermittency of other renewables (solar and wind), highlights the importance of energy storage in a future decarbonized scenario based on renewable energies (Zsiborács et al., 2019).

Thus, hydrogen is considered a flexible energy carrier and a promising way to store intermittent renewable electric energy when available in excess (Ball and Weeda, 2015; MITERD (Spanish Ministry for the ecological transition and the demographic challenge), 2022). However, in that direction, scientific results and the real applicability of such

Table 1
Literature review of recent works on MHP energy production from irrigation networks and run-on-river / run-on-canal installations, technically similar to our case study. PAT= Pump as Turbine.

Reference	Type of turbine	Head (m)	Water flow (m^3/s)	Power installed	Energy production	Observations
Butera and Balestra, 2015	Energy recovery (run-on- canal)	-	30.87 m^3/s - 42 m^3/s (decreasing along the channel)	5119 kW (existing) 13665 kW (potential)	-	Diramatore Quintino Sella (DQS) case. Piedmont Region irrigation network (Italy). Channel irrigation Average hydraulic potential of 1.5–2 kW/ha
Chacón et al., 2018	MHP turbines and PATs. Pressurised system	-	-	1 MW (potential)	1GWh (potential)	Aggregation of results for 12 drip irrigation networks. Bembezar MD irrigation district (BMD) - approx. 16,000 ha. Andalusia (Spain)
Pérez-Sánchez et al., 2016	Pressurised system				188.23 MWh (potential)	290.2 ha. Drip irrigation. Valencia (Spain)
	Open irrigation channel – 22 Rotary Hydraulic Pressure Machines	<3 m	0.26	46.42 kW	406.64 MWh/year	Theoretical energy recovery calculated for 67,932 ha of irrigated land
Estrada Tarragó, 2015	PAT Pressurised system	9.6	0.00572	0.24 kW	2124 kWh/year	
Camilo Rosado et al., 2020	Pressurised system	-			545.335 kWh/year (recovered energy)	Theoretical study for the municipal area of Valencia (Spain).
Algieri et al., 2020	PAT	Avg 68.4	Avg 0.287	4.2 MWel	21.14 MWh	Huge variation in head and water flow within the area of the collective irrigation systems under study.
García Morillo et al. 2018	Francis Turbine and PATs. Pressurised system			198.4 kW - 261.4 kW (depending on assumptions on the flow)	205.3 MWh - 270.5 MWh (potential, depending on flow assumptions)	4000 ha Córdoba (Spain)
Comino et al., 2020	MHP - Kaplan	2.40	Avg 10.56	248.6 kW	Avg 1660 GWh/year	
Gallagher et al., 2015	Run-on-river HP	175	0.45	650 kW	1.8–2.1 GWh	
	Run-on-river HP	128	0.1	100 kW	0.4–0.5 GWh	
	Run-on-river HP	105	0.09	50 kW	0.2–0.3 GWh	
Adhau et al., 2012	Run-on-river and irrigation system.	16.6 – 11.0	6.8 – 4.4	750 kW		Dependence on rainfall. Shahnoor Hydro Electric Project
	Run-on-river and irrigation system.	13.9	5.62	500 kW		Purna Hydro Electric Project. Dependence on rainfall.
Kamran et al., 2019	Run-on-canal MHP	8	1.41	79–110 kW	718.05 kWh/year	
Butchers et al., 2020	MHPs: 18 Crossflow and 6 Pelton			18–135 kW		94–1765 households connected
Suwanit and Gheewala, 2011	5 MHP plants	127 m 95 m 106.7 m 137.1 m 98.1 m	6.0 4.36 1.39 2.0 1.73	5100 kW Two sets of 3000 kW Two sets of 1250 kW 2250 kW 1150 kW		"*The flow of rivers changes following seasons—having a rapid flow for 4 months in rainy season, medium flow for 4 months, low flow for 4 months, electricity is generated for only 10 months with varying capacity*"
Rehart Power., 2024	Run-on-river. Archimede Screw Turbine.	2.60	2.00	70.91 kW		Non irrigation purposes. It covers the electric needs of **186 households (4 persons each)**
Landustrie. Linton Lock, 2017.	Run-on-river. Archimede Screw Turbine	3.00	14.5	355 kW		First installation in 2012, with an extension in 2017.

measures are still under debate, and it is not clear whether massive hydrogen storage could offer better advantages compared to battery storage (Nature editorial, 2022). Some disadvantages of hydrogen storage by method are: 1. Gas compression: Low to moderate compression is needed, producing around 15 % of losses (Muthu et al., 2017); because of the low density, high pressure or low temperature is required for storage (Xia et al., 2010) (energy consumption); 2. Liquid hydrogen conversion: around 30 % of energy losses (Muthu et al., 2017); Cooling systems are required (energy consumption) (Reddy et al., 2010); 3. Solid state conversion: Greater weight due to the materials needed to store the hydrogen (metal hydrides) cause weight to increase; greater complexity in storage and use (requires an activation step to release the hydrogen again after being absorbed by the metal hydrides) (Muthu et al., 2017). Additionally, when hydrogen comes into contact with metals such as pipes or storage containers, it can cause structural properties to deteriorate, a phenomenon known as 'embrittlement.' This further complicates the storage and handling of the material (Zvirko et al., 2024).

On the other hand, Hydrogen could be used to address emission reduction targets that, with current technology, are hard to achieve. For example, hydrogen represents an important raw material in refineries and in the manufacture of chemical products, such as plastics, fertilisers and steel (Castelvecchi, 2022; Griffiths et al., 2021; Öhman et al., 2022; Van Renssen, 2020). Spain currently consumes approximately 500,000 t/year of hydrogen, mostly in the manufacturing sector (95 % (MITERD (Spanish Ministry for the ecological transition and the demographic challenge), 2022), and of which 99 % comes from fossil-fuel sources, specifically natural gas (grey hydrogen). If we could substitute that amount for hydrogen produced with renewable sources (green hydrogen), we could avoid emitting between 5 and 8.6 million tons of CO_2 eq. per year (based on the hydrogen emission factors described by Parkinson et al., 2019).

The objective of the present article is to comprehend the opportunities and trade-offs associated with harnessing hydropower energy from irrigation canals through MHP installations. The irrigation network under study is designed in a manner where the potential energy from the gravitational gradient exceeds the requirements for efficient irrigation of all croplands fed by the network. The presence of a surplus of gravitational energy is, in fact, one of the primary motivations behind the development of this study.

The paper will include energy calculations using historical water flow data and carbon accounting, aiming to understand the mitigation potential of such interventions. Additionally, as a potential energy usage scenario, the study will consider the possibility of hydrogen production for industrial use. The potential implications of energy generation and distribution will be discussed, with a specific emphasis on the benefits for local communities through decentralised production and consumption.

2. Methodology and area under study

The methodology followed to carry out the present work is shown in Fig. 1. The study started with the analysis of the case under study, as described in 2.1, to understand the context of the irrigation canals. After that, the measurements of important parameters were collected, specifically the water flow rate (Q) and the locations along the irrigation canals potentially exploitable for turbine installations (2.2). When information was missing, it was either estimated or obtained by third party (such as the heads of the turbine locations, as described below). The water flow data was collected for the last 30 years. The following step was the choice of the most appropriate turbine (intended as the mechanical part of the MHP installation) for the context described previously, as analysed in Section 2.3, by reviewing literature and reports of functional installations.

The electrical power generated per mill is dependent on the water flow (as can be seen later in the text). Therefore, we calculated a first estimation of the potential electrical power with the 30-year average water flow value and total efficiency extracted from literature. For the detailed calculation of the historical potential electrical energy generated we used the daily values of the water flow.

The last step was the calculation of avoidable GHG emissions based on the estimation of the energy produced by each mill on the RAM.

2.1. Study case

The *Real Acequia de Moncada* (RAM) is one of the most important irrigation communities within the traditional hydraulic systems in the region of Valencia (*Comunidad Valenciana*) both for its area and organisation as well as for its history (Guinot Rodriguez, 2007). Its construction, in fact, dates back to the Islamic period between X and XI century (Guinot et al., 1999) and the area subjected to irrigation has not changed substantially. The main channel of the RAM is located at about 8 km north from the city of Valencia and at 7 km from the coast, reaching in total a length of roughly 33 km (map in Fig. 2).

The whole irrigation system of the Valencian area, to which the RAM belongs to, has been recognized in 2019 by the FAO as one of the *Globally important Agricultural Heritage Systems* (GIAHS) (FAO, 2019) for its historical structure, a rich resilient agricultural and irrigation system and a long-standing governance plan for the water as a common good (Ostrom, 1990). At the same time, Valencia presents an actual socio-economic context where decarbonisation is a priority of the political agenda and an ongoing process with a huge potential to strongly reduce the day-to-day impact on the environment for energy production (Gómez-Navarro et al., 2021; Manso-Burgos et al., 2022), food production (Peris-Blanes et al., 2022; Sarabia et al., 2021), transport (Bastida-Molina et al., 2022; Danesin and Linares, 2018) etc.

The geomorphology underlying the spaces irrigated by the RAM determines, in part, the characteristics of both the main channel and its layout, as well as the morphology of the irrigation it feeds. In its head, the canal runs along the Turia riverbed itself and is attached to the cliff formed by the Quaternary terraces and gives rise to what is considered the "dead head" of the canal, in which it runs parallel and at a higher level than the river. A second section begins when the channel abruptly separates from the fluvial course and generates, between it and the riverbed, on the fluvial terraces, the first irrigated spaces (as shown in Fig. 2, as the "bifurcation point"). This section is characterised by its steep slope and a high concentration of mills. It has come to be known as the "stretch of the mills".

In Fig. 2 we show the available mills in the primary channel of the RAM network. In the table embedded in Fig. 2, for each mill, the name, number in the map and the head are reported (Sales Martínez, 2016).

In Fig. 3, we report a contour map showing the water flow in the RAM (Q expressed in m^3/s) day-by-day for the last 30 years. Although the mills receive water every day, with an average flow of 2,32 m^3/s (averaged over 25 years), we can see that there is a high irregularity in the water flow. In periods of drought (1995, 2007–2008, 2015–2016), the water flow is regulated such that it is available for irrigation only every other week. This is a well-known procedure to save water while maintaining at the same time enough irrigation for crops. The other important factor is that water flow is higher during spring-summer months. This fact is counter intuitive, if we compare it with natural water flow in rivers, and it is artificially managed, depending on the weather patterns, to increase water availability during the season in which agriculture is more in need (Sales Martínez, 2016). A Board, composed of various irrigation organizations along the River Turia, determines the amount of water needed for irrigation, according to the downstream crops needs, which sets the river's flow for each period of

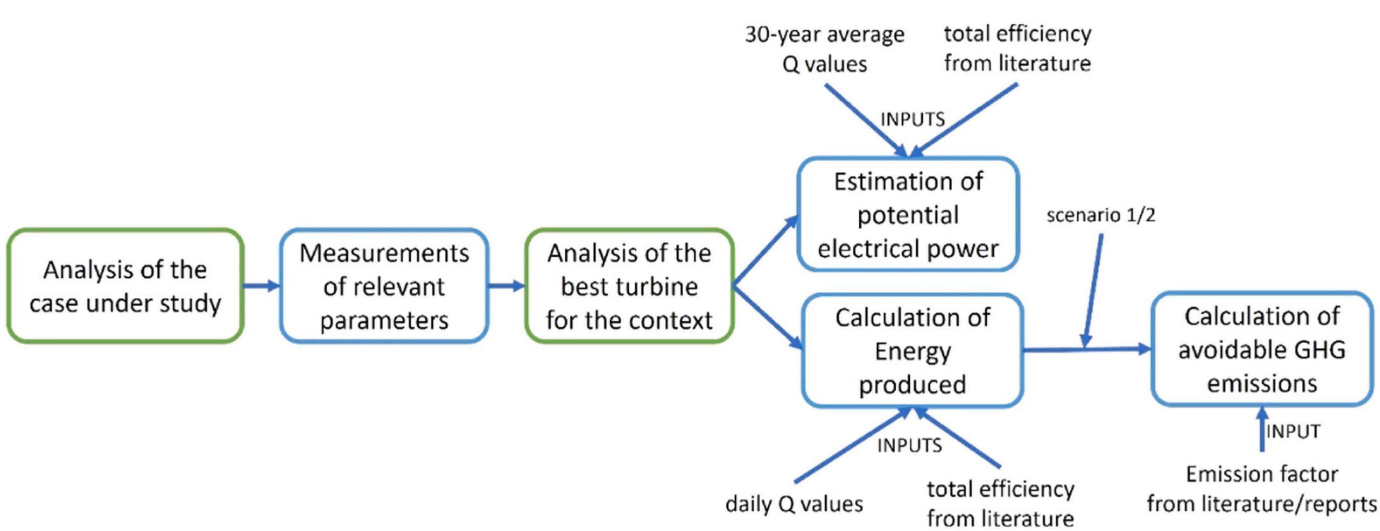

Fig. 1. Flow chart of the methodology followed for the estimation of the energy production and mitigation potential of the irrigation system.

Number	Mill name	Head (m)
1	Testar y Escalaeta	2.5
2	Martinet o de la Vila	2.9
3	Ferrando o del Marqués	2.8
4	Tandera	2.5
5	Batano de Paraires	2.3
6	La Peña	1.8
7	Bonany	1.5
8	Godella	1.5

Fig. 2. Map of the RAM of Moncada. The numbers refer to the mills reported in the embedded table. Below pictures of mill number 4 (Tandera).

the year.

2.2. Measurements

The flow rate of the main channel under study of the *Real Acequia de Moncada* (RAM) is obtained with a piezoresistive level sensor with a 2 m range. The channel is calibrated so that the flow can be calculated from the depth of the water. The signal from this sensor is sent through a remote radio link. Moreover, information regarding the head of the mill was obtained from the irrigation communities. They provided such information from an engineering project carried out in 1985 for remodelling of the RAM's primary channel. A total station was used to conduct

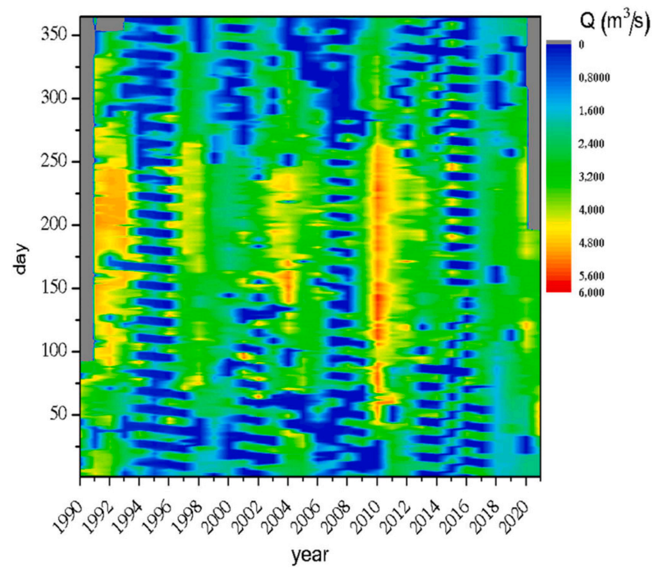

Fig. 3. Contour map reporting the variation of water flow (Q) of the irrigation system depending on the year and the day of the year. It is important to notice that during drought years (1995, 2007–2008, 2015–2016) the amount of water passing in the irrigation canal followed a scheduled weekly alternate behaviour to reduce water wastage.

the topographic survey. The location of mills and primary channel was also obtained by using the cartography created by Sales (Sales Martínez, 2016) which has been integrated in a Geographic Information System (GIS). The cartography has been built in QGIS using topographic maps and aerial photographs. The irrigation canals were mapped by digital drawing with poly-line features from scanned maps of Rustic cadastre of the Geographical and Cadastral Institute of Spain dating from the late 20 s of the 20th century (National Cadastre of Spain, 2022).

2.3. Turbomachinery selection

The choice of the most appropriate turbine is a complex multidimensional problem that needs to consider not only technicalities but also context-related issues. As discussed in the introduction, to increase the lifespan of the turbine, as well as energy and environmentally effectiveness, a low maintenance equipment is the best choice. Regarding the technical demand, we make use of literature (Waters and Aggidis, 2015; Rohmer et al. 2016; YoosefDoost and Lubitz, 2020) and the graph in Fig. 4 adapted from (Schwizer, 2021) to identify the most suitable turbine for the range of Head and flow rate in the RAM.

The Archimedes Screw Turbine (AST) is a relative newcomer to the small-scale hydro power world having only arrived on the scene over the last ten years. They are well known to humanity since very early history (250 BC), as they were used as pumps in irrigation systems to lift water to higher levels (powered either by animals or humans). The working principle is the same as the pump, acting in reverse. AST are generally used on low head with high-medium flow sites. They can work efficiently on heads as low as 1 m and up to 8 m, though practically they are not generally used on heads less than 1.5 m. This translates to power outputs that vary between 5 kW up to 500 kW, as shown in Fig. 4.

When it comes to operational advantages, ASTs have a high debris tolerance and can cope well with varying rates of flow and with suspended solids. In fact, one typical application is in wastewater treatment plants. Therefore, they need relatively low maintenance and present higher robustness when facing disruptive events compared to other hydropower turbines (appearance of small trunks, leaves, mud, litter etc. in the irrigation canal as well as flooding). This means that fine screens are not required at the water intake, and there is no requirement for automatic intake screen cleaners which are normally required on larger low-head hydropower systems, reducing the costs. Overall, costs related to operation and maintenance are lower compared to other

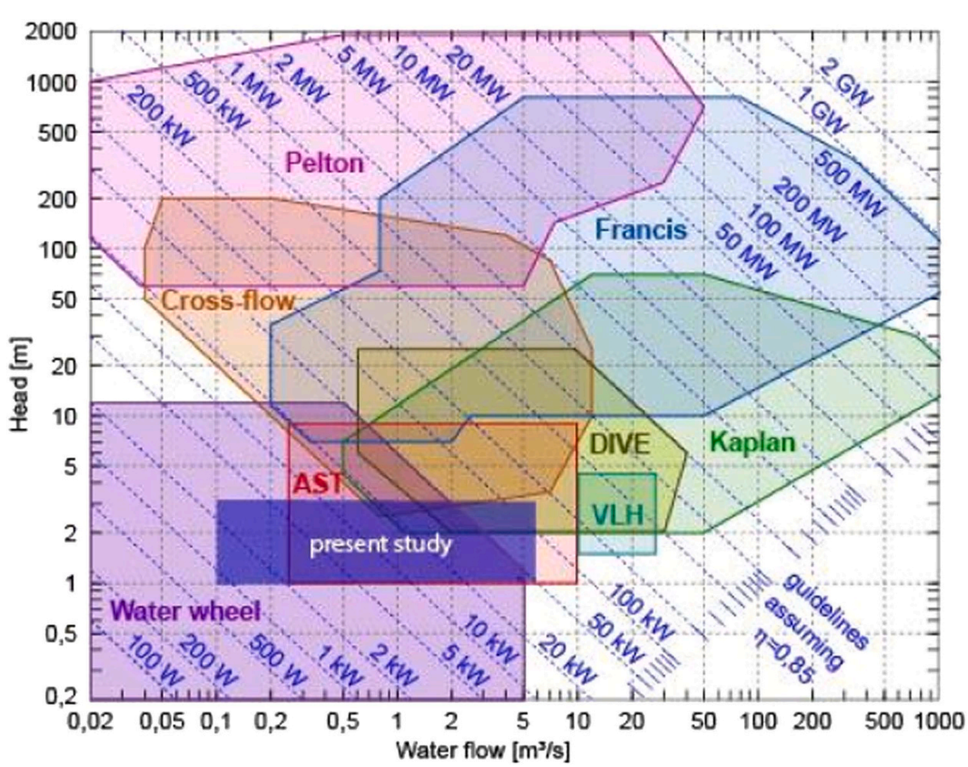

Fig. 4. The range of head and water flow corresponding to the generated power of different types of turbines. The guidelines of generated power have been estimated assuming turbine efficiency of 85 %. The total efficiency of the hydropower system can result in smaller values and dependent on the operating point. Adapted from (Schwizer, 2021).

turbines (ECS, n.d.; YoosefDoost and Lubitz, 2020; Renewable First, 2021; Waters and Aggidis, 2015). The advantage of the low-maintenance is also crucially important when they are installed in remote rural places, and low-resource regions, and when grid-connection is not an option. An AST results in a very robust device due to the fact that it is composed of a single structure and lacks adjustable parts. It has a long lifespan, requiring only re-tipping approximately every 20 years (Waters and Aggidis, 2015; Renewable first, 2021). Thanks to slow screw rotation and relatively big flow passage, wildlife (especially fish) can pass downstream unharmed (Waters and Aggidis, 2015; YoosefDoost and Lubitz, 2020). Therefore, ASTs are generally considered safer for integration into the natural landscape with lower environmental costs. Fish-friendly hydropower technologies are one of the improvement points in nowadays installations (Bai and Zhou, 2021). At last, civil engineering works for the construction of AST installation are relatively simple. Construction costs are also reduced due to the fact that the downstream side of the turbine does not need any discharge sumps or draft tube (Renewable First, 2021).

The main parts of an Archimedes screw used as a hydro generator are shown in Fig. 5a.

The rotational speed is generally low (between 40 and 130 rpm (Dedić-Jandrek and Nižetić, 2019; Rohmer et al. 2016), hence it needs to be increased to be compatible with the electrical generator through the gear box. To maximise cost-effectiveness and efficiency, most ASTs are considered installed at an angle of roughly 20 degrees.

There are several examples of working AST. As reported in (Rohmer et al. 2016; YoosefDoost and Lubitz, 2021), AST can be installed in a different set of conditions, specifically with an ample range of flow rate and head. Installed and currently functioning AST deal with ranges of flow rate between 0,25 m^3/s and 14,5 m^3/s (Landustrie. Linton Lock, 2017; Rehart Power, 2024; Rohmer et al. 2016; YoosefDoost and Lubitz, 2020; YoosefDoost and Lubitz, 2021), while the head range can vary from 1 m up to 10 m (Hydropower screws in Europe, 2024; Rohmer et al. 2016; YoosefDoost and Lubitz, 2021). For a detailed map of working examples of AST installed in Europe, the reader can check the reference (Hydropower screws in Europe, 2024)

2.4. Power estimation and Energy production

For the power and energy production estimation, we used the following simplified formula (Chacón et al., 2018; Rehart Power, 2024), assuming optimised geometrical AST characteristics for the case under study (Rohmer et al. 2016):

$$P = \rho g Q H \eta_{tot} \quad (1)$$

Where P is the electrical power of the MHP, Q the water flow, H the head, and η_{tot} the total efficiency of the turbine, knowing that:

$$\eta_{tot} = \eta_{gen}\eta_{inv}\eta_{gearbox}\eta_{AST}(Q) \quad (2)$$

$\eta_{AST}(Q)$ is the mechanical efficiency of the Archimedes screw, η_{gen} is the efficiency of the electrical generator,η_{inv} the efficiency of the electrical inverter and $\eta_{gearbox}$ the efficiency of the gearbox. According to the reports, gearbox, generator and inverter losses are approximately 15 %, leading to a combined efficiency of 85 % of these three components together ($\eta_{gen}\eta_{inv}\eta_{gearbox} = 0{,}85$) (Renewable First, 2021). As far as $\eta_{AST}(Q)$ is concerned, its value is strongly dependent on water flow according to literature (Rohmer et al. 2016; Dedić-Jandrek and Nižetić, 2019; Lashofer et al., 2012; Renewable First, 2021). In the present work we took this factor into account as the water flow in the RAM suffers great irregularity due to seasonality and droughts as discussed previously. In this respect literature is quite scarce. Hence to express this variability we obtained the dependence of the mechanical efficiency from the percentage of the flow rate with respect to the maximum one for a hypothetical variable-speed AST from reference (Renewable First, 2021). The efficiency is depicted in Fig. 5b, and results are coherent with (Rohmer et al. 2016). We considered as maximum flow rate, the maximum water flow value registered for the RAM in the thirty years analysed (i.e. ~6 m^3/s).

The energy potentially generated (in the form of electricity) with the installation of AST in each mill can however be calculated with the historical daily values of water flow with formula (1). The energy produced was obtained by multiplying the results from formula (1) by the 24 h of the day to obtain the daily energy produced, and by the 365 days to obtain the yearly energy production.

2.5. Estimation of the avoidable GHG emissions in two energy use scenarios

Hydropower, as renewable energy, has the potential to decarbonize the highly emitting sector of electricity production. We developed two decarbonization scenarios to calculate mitigation potential of such a renewable system: 1) decarbonization of the electricity mix generation and 2) green hydrogen production. Thus, we estimate the avoidable GHG emissions of these two possible energy use scenarios. It is difficult to understand and predict future climate scenarios, and it is however out of the scope of the present work. Hence, we considered appropriate to use historical data, as reported above. On the other hand, as the system under study is an irrigation canal, highest and lowest boundaries to energy production are fixed by the maximum and minimum water flow. Lowest production years are the years of alternating water flow

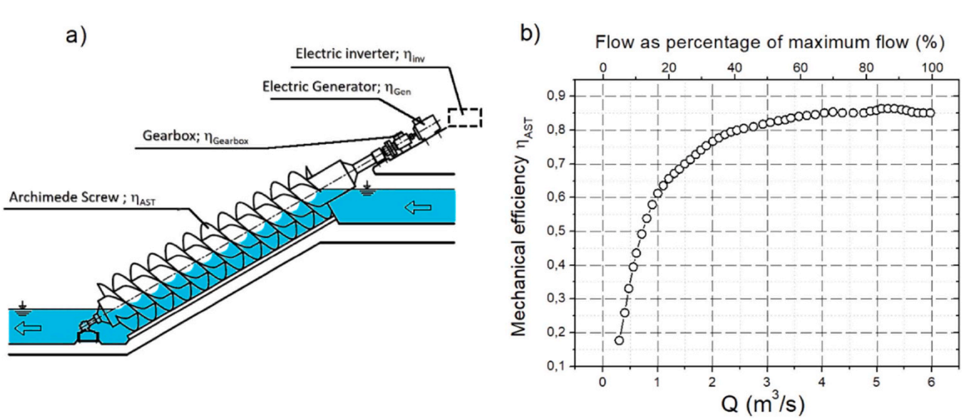

Fig. 5. a) Schematic diagram of the AST. In the image we show the most important components with their relative efficiency factors considered in the calculations. Image under licence CC BY-SA [https://creativecommons.org/licenses/by-sa/3.0/] b) Typical mechanical efficiency curve for a good quality variable-speed AST (η_{AST}) adapted from (Renewable First, 2021). On the lower X-axis the water flow (Q), on the upper X-axis the water flow as percentage of maximum flow, that was chosen as 6 m^3/s, according to historical data.

(historically 1995 and 2007), while highest production years are those with highest water flow (historically 1992 and 2010).

2.5.1. Scenario 1: Decarbonization of electricity mix generation

The estimated hydropower electricity generation described in the present study could contribute to decarbonizing electricity generation by feeding the generated electricity into the electricity grid or by consuming it directly (which would decrease the demand). Thus, avoidable GHG emissions from 1991 to 2020 have been estimated based on the contribution of the hydroelectric energy generated to the decarbonization of the electricity mix generation. For the GHG emissions estimation, we used the following formula:

$$GHG_{emissions} = HP_e \times EF \quad (3)$$

HP_e is the estimated hydropower electricity generation (kWh) and EF is the annual emission factor (g CO_2 eq./kWh) obtained from the national electricity grid (Red Eléctrica Española, 2022). These emission factors are calculated based on: i. amount of fuel consumed by each generation technology; ii. Emission factor of the different fuels; and iii. Degree of annual penetration of each electricity generation technology (Intergovernmental Panel on Climate Change IPCC, 2006). The emissions factors used consider CO_2 and N_2O emissions and its Global Warming Potential (GWP) according to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC (Intergovernmental Panel on Climate Change), 2014).

2.5.2. Scenario 2: Green hydrogen (H_2) generation as raw material in industry

The avoidable GHG emissions of this scenario have been estimated based on the use of hydroelectric energy to produce green hydrogen through electrolysis technology in order to replace grey hydrogen used in industry as raw material. An efficiency of 75 % of the electrolysis technology has been considered (MITERD (Spanish Ministry for the ecological transition and the demographic challenge), 2022). Thus, the production of 1 kg of H_2 requires a consumption of between 49.2 and 56.3 kWh of electricity (kWh$_e$). Finally, the emissions factor (kg CO_2/kg H_2) of replaced grey hydrogen can vary depending on: i. the energy necessary for the storage and ii. distance between generation and consumption (Parkinson et al., 2019). In our estimation, we consider 12.8 as the average value from the literature (Parkinson et al., 2019).

3. Results and discussion

3.1. Energy production

With formula (1) we could calculate a preliminary estimation of the power produced by each mill on the RAM, considering, for the water flow Q values, the 30-year averaged value (2,32 m^3/s) and the corresponding mechanical efficiency from Fig. 5b (η_{AST}=0,79; η_{tot}=0,67). In Fig. 6a), the estimated power of the mills are reported. The standard deviation of the average Q values ($\Delta Q = 1.53$ m^3/s) was used to estimate the deviation propagated in the calculation of the estimated electrical power. As we can observe, the average power per year ranges between 47 and 22 kW. The error bars of calculated powers are substantial as they originate from a huge variation in water flow during the 30 years.

We also report the estimated maximum (and minimum) potentials of the power generated by the ASTs installed depending on the water flows, as shown in Fig. 6b), with reference curves for fixed power. As we can appreciate the AST with the bigger head (*Martinet*), at maximum flow can reach values as high as 100 kW, while the lowest head mill (*Godella*) can reach values of roughly 50 kW. As already pointed out and reported in this graph, output power is strongly dependent on the flow rate in the main channel. This first approximation for the power produced by each mill is a good baseline to understand the potential of each mill, and the variation due to the operating point (mainly due to water flow). However, as described in the methodology part, we are more interested in the calculation of the energy that can be effectively produced with specific historical daily water flow data.

The results of the calculations for the energy produced are reported in Fig. 7. Although the variation year-by-year is substantial, the peak energy generated annually can be as high as 750 MWh for higher head mills.

Moreover, if we consider the overall electricity generation by all the mills (Fig. 8), the values vary from a minimum of 520 MWh up to a maximum of 5.3 GWh. This is coherent with similar interventions in other cities, with values of the same order of magnitudes, such as the case of the *Regio Parco Canal* in Turin, where a mini-hydro power station produced annually around 1.6 GWh and other 4 installations in the municipal area produced between 1 and 4.5 GWh (Comino et al., 2020). At the same time, values of energy production are also similar to hydropower plants in drip irrigation networks, such as the case of Calabria Region with a recovery potential from 0.5 to 4 GWh in each Irrigation Community analysed (Algieri et al., 2020). These results foster the potential of the water-energy-food nexus in traditional irrigation systems, as well as enhancing sustainable transitions in blue infrastructures in

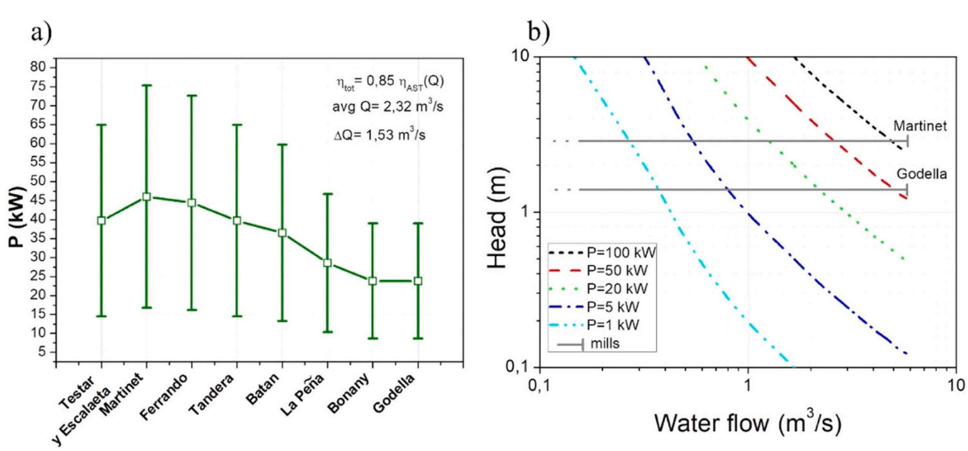

Fig. 6. a) Estimated potential power for each mill under study on the RAM, calculated with water flow averaged over the last 30 years (2,32 m^3/s), the corresponding mechanical efficiency of 0,79 and a total efficiency of 0,67. b) The range of head (H) and flow (Q) of the potential turbine installations of the present study for the maximum head (Martinet) and the minimum head (Godella) mills. Potential output powers are plotted as references and calculated with formula [1].

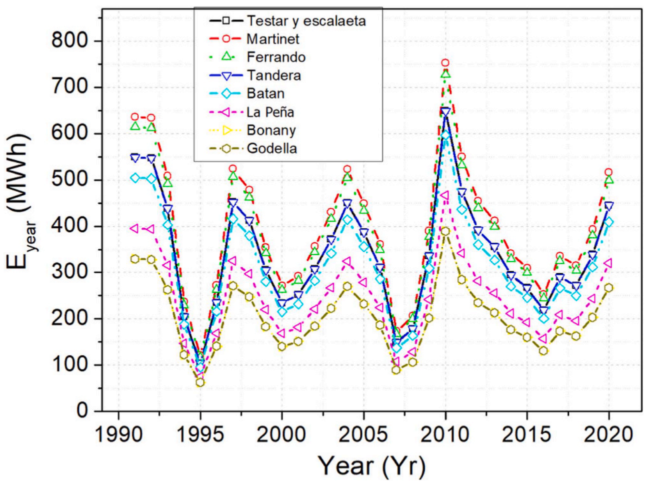

Fig. 7. Variation of the Energy produced year by year by the ASTs installed in each mill. It is easy to spot drought years (e.g. 1995, 2007) and water abundant years (e.g. 1992, 2010). For the years 1990 and 2021 the reduction is due to lack of data.

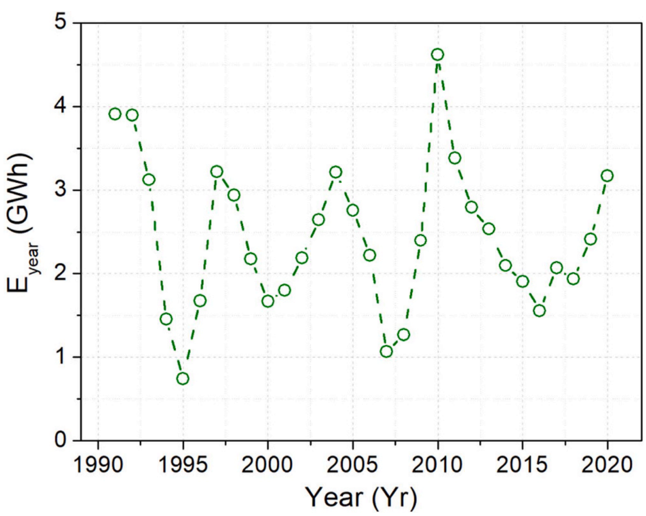

Fig. 8. Overall Energy produced annually if all turbines were installed in all mills. The data are obtained as the sum of all the Energy produced by all turbines.

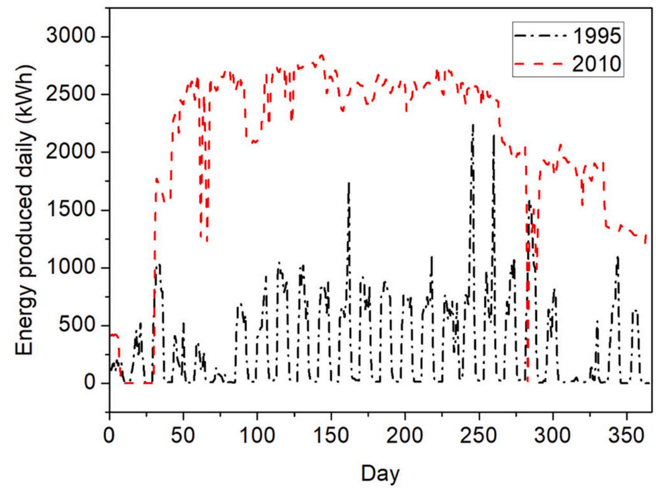

Fig. 9. Potential electrical energy produced daily for the turbine installed at Martinet mill (H=2.9 m), in the years 1995 and 2010, respectively with the lowest and highest water flow.

agreement with (Kamran et al., 2019).

As far as the yearly flow variation is concerned, we show in Fig. 9 the comparison between the lowest and the highest water flow year (respectively 1995 and 2010) for the Martinet mill. As can be observed, during drought years water flows every other week, as a measure to save water. For the year 1995, the potential electrical energy calculated is roughly 66 MWh for *Martinet*.

The implications of flow variability for energy production will depend on the particularities of each irrigation system regarding crop and irrigation practices. In this specific case, irrigation occurs continuously (day and night) during spring and summer (anti-pluviometric regime) with usually a lower flow in winter/autumn. Extreme events also affect irrigation water management: water restrictions are applied during pluri-annual drought periods (reducing energy production potential). This strong link between water and energy production has some implications. Firstly, in agreement with (Neves et al., 2021), in a regular year, the maximum production of energy is generated during spring and summer when it is also the season with more energy requirements in agriculture. But, in drought years, energy production is reduced notably, and when severe restrictions are applied, energy may be produced only once every two weeks. Secondly, this energy source may be more uncertain in the face of a changing climate (as compared to wind and solar) (Bouabdelli et al., 2022).[1]

As a comparison with other renewable sources of energy, the hydropower average annual production estimated in our study is equivalent to 40 % of the annual production of a 3 MW wind turbine. In addition, the estimated average production can be equivalent to the annual production of more than 3400 photovoltaic panels of 250 Wp considering the 2808 solar hours per year in Valencia. Finally, considering an efficiency of between 30 % of a small natural gas generator and 60 % of a modern Combined Cycle Gas Turbine (CCGT) plant, the annual consumption of natural gas to generate the estimated average production of equivalent electricity is between 360,000 and 720,000 m^3 of natural gas respectively.

3.2. Avoidable GHG emissions in energy use scenarios

The emissions that could be avoided using the energy estimated in Section 3.1 in the two scenarios described have been calculated.

3.2.1. Scenario 1: Decarbonization of electricity mix generation

GHG emissions avoidable annually from 1991 to 2020 have been estimated based on the contribution of the hydroelectric energy generated to the decarbonization of the electricity mix generation (Fig. 10). Thus, avoidable annual emissions calculated range between 319 and 1713 t CO_2 eq. The total emissions avoidable in the 30 years-period amounts to 23,447 t CO_2 eq.

The annual average of avoidable emissions (782 t CO_2 eq.) is comparable to the amount of carbon captured annually by all the urban green areas of a large city such as Valencia (Spain, 800,000 inhabitants) (Lorenzo-Sáez et al., 2021). In addition, the avoidable emissions in the years of greatest production are equivalent to 6 % and 8.3 % of all the consumption of urban rail transport and public lighting, respectively, in the same city (Ajuntament de València, 2021).

[1] The degree of uncertainty is certainly linked to water right's allocation and prioritisation rules existing in each river basin. In the Júcar River basin, where this traditional irrigation system is located, urban water supply has the priority in case of water shortage, the following being agricultural users as the 2nd in the order of priority (followed by energy production and industrial uses).

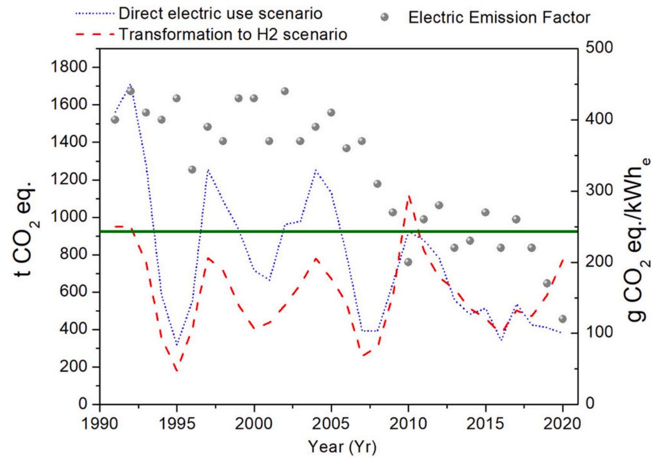

Fig. 10. Avoidable GHG emissions per scenario (primary axis) and electric emissions factor obtained by the Spanish Electrical Grid (REE) per year (secondary axis). Green line identifies emission factor of the electrical mix at 243.23 g CO2 eq./kWhe.

3.2.2. Scenario 2: Green hydrogen (H_2) generation as raw material for industry

Estimated hydroelectric energy used to produce green hydrogen through electrolysis technology would produce between 14 and 88 tons of H_2 annually depending on the energy generated by the mills analysed. This capacity production is equivalent to between 0.003 % and 0.018 % of the total national grey hydrogen consumption. Thus, avoidable annual emissions range between 180 and 1124 t CO_2 eq. with an average of 589 t CO_2 eq. avoidable per year. The total avoidable emissions in the 30-years analysed period are 17,700 t CO_2 eq. (Fig. 10). In Fig. 10 we show the comparison of the GHG emissions avoided for the two cases described. As a reference, we show the variation of the Electric Emission Factor for the REE in the period analysed in the study. As can be seen in the graph, the emission factor for the REE decreases with time because of the decarbonization of energy sources over the years, for the provision of electricity to the Spanish grid.

The comparison of both scenarios (Fig. 10) offers some interesting conclusions. First, the avoidable emissions in the 30-years period analysed by the use of small hydropower electricity produced as a direct use to decarbonize the electrical mix are 32 % higher than if we used this energy to produce green hydrogen as a raw material in industry.

However, it is interesting to note that from an emission factor of the electrical mix lower than 243.23 g CO_2 eq./kWh$_e$ (green continuous line in Fig. 10), the substitution of grey hydrogen by green hydrogen for industrial use as a feedstock avoids more emissions than the decarbonisation of the electricity mix generation. This is an interesting exploitable aspect, primarily because of the decarbonisation process that the Spanish electrical grid is undergoing.

The average annual emissions avoided in the two proposed scenarios (Scenario 1: 782 t CO_2 eq. and Scenario 2: 590 t CO_2 eq.) compared with the 21 mitigation actions that have less impact of the Valencia Sustainable Energy and Climate Action Plan (SECAP) can be seen in Fig. 11. Thus, the scenarios proposed would have a greater impact on mitigating climate change than: Street lighting sector: measures like LED installation in traffic lights (765 t CO_2 eq.), replacement of conventional luminaire for LED luminaire in party lighting (127 t CO_2 eq.) and installation of solar street lights with presence detector (510 t CO_2 eq.); Services sector: replacement of boilers with others that use renewables (287 t CO_2 eq.); Public and municipal transport sector: substitution of vehicles for electric or renewable fuels (600 t CO_2 eq.); Buildings sector: incorporation of frequency inverters in the pumps (301 t CO_2 eq.) and change of pumps for more efficient ones (401 t CO_2 eq.) (Ajuntament de València, 2021).

When comparing the two scenarios calculated with the mitigation actions related to local energy production of SECAP of Valencia, it can be seen that the proposed scenarios have much lower impact in emissions

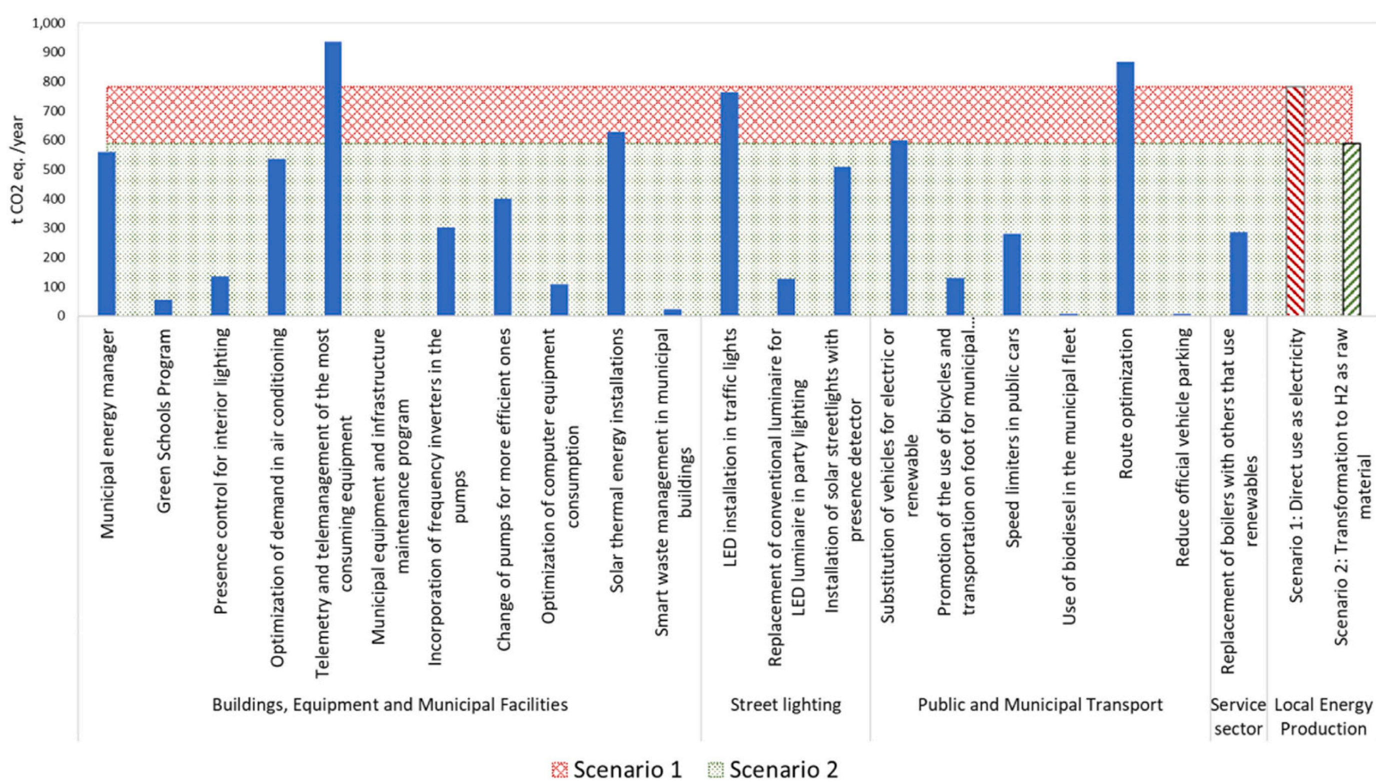

Fig. 11. Comparison of the emissions avoided by the two scenarios calculated with the emissions avoided by the 21 mitigation actions with less impact of SECAP of Valencia.

avoided than other measures such as installation of photovoltaic (100,000 t CO_2 eq. avoided), solar thermal (51,000 t CO_2 eq. avoided), small wind power (33,000 t CO_2 eq. avoided) or geothermal generation (51,000 t CO_2 eq. avoided) (Ajuntament de València, 2021). On the other hand, with the present study our intent is to take advantage of a resource that currently is wasted (gravimetric potential of water in irrigation canals) while providing another essential, non-avoidable service to the society (irrigation and, hence, crop production), and at the same time helping to decarbonise power generation.

3.3. Potential of clean energies in irrigation infrastructures

In this section we seek to stand back and reflect upon the added value associated with the production technique in light of the results presented above, firstly in terms of advances on decarbonisation and green energy production as compared with other renewable techniques, and secondly considering its potential for collective irrigation systems.

3.3.1. Advances compared with other renewable techniques

The analysis reported above delivers a range of advances over other analysis of mitigation measures regarding decarbonisation attempts, including:

(a) The potential of small hydropower plants (and AST) on collective irrigation systems to decarbonize energy consumption using untapped hydropower energy with varying flow rates.
(b) The 'switch' of perspective on hydropower energy production from macro-infrastructure developments with high ecological cost to micro-hydropower production not competing with current water uses for food production (as it is a consumptive use of a flow currently derived for irrigation) and without ecological impact on aquatic ecosystems (as it is installed in a human made artificial system of lined channels, and fish-friendly).
(c) Identification of avoidable emissions (taking into account flow variability) of such technology, a useful indicator to improve decision-making regarding climate mitigation as it allows comparison with other energy mitigation actions at city level.
(d) The possibility to contribute to green energy production generating hydrogen as a raw material for industry.
(e) The intermittency of the electricity production linked with variation in canal water flow is unrelated to the intermittency experienced by solar and wind installations, virtually allowing an integration and compensation of different intermittent sources of renewable energy (Gonzalez et al. 2023). Along the same lines, the decision made by the Board on the amount of the water volume in the river, although intermittent and dependent on external factors (e.g. climate and drought), is still predictable, allowing energy production to be determined in advance.

The figures and analysis presented in this paper show that small-scale hydropower production has obvious potential to contribute to energy transition. Although still to be defined in practical terms, this durable and low-maintenance technology offers potential options to be explored in line with a decentralised energy production (BOE, 2019; Manso-Burgos et al., 2022; Bielig et al., 2022).

3.3.2. Potential for collective irrigation systems

Using the energy potential available in traditional irrigation systems provides not only public goods, but also new opportunities from the collective user's perspective. Having these energy sources available at the 'sluice gate' may reduce energy costs or facilitate the automation of irrigation system elements at a lower cost (than connecting to the closest node of the national electricity grid). Furthermore, feeding the surplus (or the total) electricity into the grid can be a way to compensate for energy operating costs, increasing the competitiveness of traditional irrigation systems. On the other hand, the economic interest of this option depends on the legal framework, which is subject to frequent modifications.

Recent studies stress the importance of internal organisational factors for the success of collective energy projects (Warbroek et al., 2019). Furthermore, 'social capital', plays a key role in understanding social change and energy transition processes (Rogers et al., 2011). Although there is no single definition of 'social capital' it is usually associated with the networks of relationships within a community, trust, reciprocity exchanges, collective solidarity, sense of identity, and shared values (Giacovelli, 2022). In this context, irrigation communities are groups of irrigators, already organised, that share collective water rights and infrastructure. They already have existing institutional arrangements for system's management, decision making and conflict resolution. In the RAM area, existing surface and groundwater irrigation communities are responsible for the entire surface of the system and they are used to adopting new technologies, such as the use of recycled wastewater for irrigation purposes (Ortega-Reig et al., 2014). Therefore, this pre-existent 'social capital' could also be a crucial lever for the creation of energy communities. To own and manage collectively renewable energy assets can facilitate the transition towards a more sustainable and decentralised energy system, enhancing local resilience, and contributing to the achievement of climate goals.

Water use is also linked to the livelihoods of local irrigation communities and crop production. Therefore, increasing the resilience of the water resource, which is a life-threatening issue, would benefit the resilience of a putative energy generation system linked to the flow of water.

In summary, the results discussed in this paper present original significant advancements in decarbonisation and green energy production, especially when compared to other renewable techniques. Small hydropower plants and AST systems integrated within collective irrigation frameworks can effectively utilize untapped hydropower energy, reducing ecological impacts and avoiding competition with water used for food production. Additionally, this technology offers a unique approach to mitigating emissions and generating hydrogen, a crucial industrial raw material. Furthermore, leveraging the energy potential in traditional irrigation systems can offer cost reductions, automation benefits, and increased competitiveness for irrigators. The success of these initiatives also heavily relies on the robust social capital within irrigation communities, which can drive the formation of energy communities and contribute to a more sustainable and decentralized energy system, enhancing local resilience and supporting sustainable transitions.

4. Conclusions

In the current scenario of climate emergency and energy transition, it is quite clear that we need to harness knowledge from interdisciplinary fields (i.e., the food-water-energy nexus (Huntington et al., 2021)) rather than only from very specialised and siloed areas (Nature Energy, 2021). The potential to exploit a resource already used for a different purpose (irrigation) without competition, is an interesting choice that could provide a reliable source of electricity to the energy mix locally, following a decentralised energy production scheme. The intermittency of water flow, and hence in the energy production, makes this solution only a part of a bigger energy mix in electricity production that can compensate for this variability.

The European Union aims to become carbon neutral by 2050 (European Commission, 2019), requiring extensive renewable energy infrastructure across all governance levels (centralised and decentralised). Decentralized energy production and community schemes, as advocated in this work, are promising for this transition. Spanish regulations support a decentralized energy model, simplifying procedures and improving conditions for small producers to enhance consumer participation (BOE, 2018; BOE, 2019). However, policies at various levels (EU, national, regional) undervalue small-scale hydropower, potentially hindering its development.

The calculations obtained from the present work highlight that RAM water resources can be utilized for hydropower electricity production, potentially serving as a tool for mitigation purposes. The results of the present work also show that the installation of MHP systems along the irrigation canals of the RAM can lead to a win-win solution addressing both energy production and stewardship of water resources, particularly in irrigation communities, as an adaptation measure.

Although the economic feasibility and payback time of hydropower installations depend on several factors, this article shows encouraging outcomes for the technical feasibility of MHP installations in the irrigation canals of the RAM, highlighting a notable unexploited capacity for future growth.

There are limitations in the present study, particularly when taking into consideration the future projection of a dynamically changing climate and water/precipitation patterns. Nonetheless, our results can serve as a valuable baseline for future studies about the feasibility of MHP installations according to specific radiative concentration pathways (RCP)(IPCC (Intergovernmental Panel on Climate Change), 2014).

Opportunities for further development of the approach presented in this paper range from broadening the conducted analysis to exploring fundamental issues associated with the policy context. Practical and methodological issues to be further studied include:

- LCA assessment of the practical applications of such a system in a real MHP case scenario (impact of building works, materials, etc.)
- Economic assessment of the investment and its return, in a complex and unstable market, and connections with the potential use as a collective resource (e.g. energy community scheme).
- Assessment of the 'decarbonisation' of the real system embedded in its context.
- Challenges related to unpredictability of meteorological events (climate, precipitation, droughts etc.) for the implementing the intervention,
- Future climate scenario projections, with results feeding back into the economic assessment.

Author statement

As corresponding author, I ask you to consider for publication our manuscript entitled "Is small-scale hydropower energy recovery a viable alternative for climate change mitigation and adaptation? The case of the traditional irrigation system in Valencia (Spain)" written by Tommaso Brazzini, Edgar Lorenzo-Saez, Vicent Sales Martínez, Esther López Pérez, Mar V. Ortega-Reig, Guillermo Palau-Salvador.

We declare no competing interests for the work developed in our group, that led to the production of the manuscript. There was no specific body involved in the financial assistance for the work. We declare no other conflict of interest.

CRediT authorship contribution statement

Guillermo Palau-Salvador: Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Mar Ortega-Reig:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Tommaso Brazzini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Data curation. **Esther López Pérez:** Visualization, Investigation, Formal analysis. **Vicent Sales Martinez:** Resources, Investigation, Formal analysis. **Edgar Lorenzo-Saez:** Writing – review & editing, Writing – original draft, Methodology, Data curation.

Declaration of Competing Interest

We declare no competing interests for the work developed in our group, that led to the production of the manuscript. There was no specific body involved in the financial assistance for the work. We declare no other conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

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References

Adhau, S.P., Moharil, R.M., Adhau, P.G., 2012. Mini-hydro power generation on existing irrigation projects: Case study of Indian sites. Renew. Sustain. Energy Rev. *16*, 4785–4795. https://doi.org/10.1016/j.rser.2012.03.066.

Ajuntament de València, 2021. Sustainable Energy and Climate Action Plan (SECAP) of the city of Valencia. Accessed January 2024, https://www.valencia.es/documents/20142/424002/190415_AYTO_VALENCIA_PACES_Actualizado_.pdf/1cefe22e-7b64-1db9-7f4a-7006aa12bf75.

Algieri, A., Zema, D.A., Nicotra, A., Zimbone, S.M., 2020. Potential energy exploitation in collective irrigation systems using pumps as turbines: a case study in Calabria (Southern Italy). J. Clean. Prod. *257*, 120538 https://doi.org/10.1016/j.jclepro.2020.120538.

Alstone, P., Gershenson, D., Kammen, D.M., 2015. Decentralized energy systems for clean electricity access. Nat. Clim. Change *5* (4), 305–314. https://doi.org/10.1038/nclimate2512.

Bai, L., Zhou, L., 2021. Aiming for fish-friendly hydropower plants. Science *374*, 1062–1063. https://doi.org/10.1126/science.abm8458.

Ball, M., Weeda, M., 2015. The hydrogen economy–vision or reality? Int. J. Hydrog. Energy *40* (25), 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032.

Bastida-Molina, P., Ribó-Pérez, D., Gómez-Navarro, T., Hurtado-Pérez, E., 2022. What is the problem? The obstacles to the electrification of urban mobility in Mediterranean cities. Case study of Valencia, Spain. Renew. Sustain. Energy Rev. *166*, 112649 https://doi.org/10.1016/j.rser.2022.112649.

Bielig, M., Kacperski, C., Kutzner, F., Klingert, S., 2022. Evidence behind the narrative: Critically reviewing the social impact of energy communities in Europe. Energy Res. Soc. Sci. *94*, 102859 https://doi.org/10.1016/j.erss.2022.102859.

BOE, 2018. Real Decreto-ley, 15/2018. https://www.boe.es/eli/es/rdl/2018/10/05/15, 15/2018. https://www.boe.es/eli/es/rdl/2018/10/05/15.

BOE, 2019. Real Decreto 244/2019. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-5089. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-5089.

Bouabdelli, S., Zeroual, A., Meddi, M., Assani, A., 2022. Impact of temperature on agricultural drought occurrence under the effects of climate change. Theor. Appl. Climatol. *148*, 191–209. https://doi.org/10.1007/s00704-022-03935-7.

Büchs, M., Cass, N., Mullen, C., et al., 2023. Emissions savings from equitable energy demand reduction. Nat. Energy 8, 758–769. https://doi.org/10.1038/s41560-023-01283-y.

Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, Bikram, Gautam, B, P., 2020. Understanding sustainable operation of micro-hydropower: a field study in Nepal. Energy Sustain. Dev. *57*, 12–21. https://doi.org/10.1016/j.esd.2020.04.007.

Butera, I., Balestra, R., 2015. Estimation of the hydropower potential of irrigation networks. Renew. Sustain. Energy Rev. *48*, 140–151. https://doi.org/10.1016/j.rser.2015.03.046.

Camilo Rosado, L.E., López-Jiménez, P.A., Sánchez-Romero, F.-J., Conejos Fuertes, P., Pérez-Sánchez, M., 2020. Applied Strategy to Characterize the Energy Improvement Using PATs in a Water Supply System. Water 12, 1818. https://doi.org/10.3390/w12061818.

Castelvecchi, D., 2022. Nature *611*, 440–443. https://doi.org/10.1038/d41586-022-03699-0.

Chacón, M.C., Rodríguez-Díaz, J.A., Morillo, J.G., Gallagher, J., Coughlan, P., McNabola, A., 2018. Potential Energy Recovery Using Micro-Hydropower Technology in Irrigation Networks: Real-World Case Studies in the South of Spain. Proceedings *2*, 679. https://doi.org/10.3390/proceedings2110679.

Chacon, M.C., Rodríguez Díaz, J.A., García Morillo, J., McNabola, A., 2020. Hydropower energy recovery in irrigation networks: Validation of a methodology for flow prediction and pump as turbine selection. Renew. Energy *147*, 1728–1738. https://doi.org/10.1016/j.renene.2019.09.119.

CNN, 2021. Not. a Single G20 Ctry. Is. line Paris Agreem. Clim., Anal. shows. Accessed August 2023, https://edition.cnn.com/2021/09/15/world/climate-pledges-insufficient-cat-intl/index.html.

Comino, E., Dominici, L., Ambrogio, F., Rosso, M., 2020. Mini-hydro power plant for the improvement of urban water-energy nexus toward sustainability-A case study. J. Clean. Prod. 249, 119416 https://doi.org/10.1016/j.jclepro.2019.119416.

Covenant of Mayors, 2022. Object. scope Covenant Mayors Clim. Energy. Accessed January 2024, https://eu-mayors.ec.europa.eu/en/about/objectives-and-key-pillars.

Danesin, A., Linares, P., 2018. The relevance of the local context for assessing the welfare effect of transport decarbonization policies. A study for 5 Spanish metropolitan areas. Energy Policy *118*, 41–57. https://doi.org/10.1016/j.enpol.2017.12.019.

Dedić-Jandrek, H., Nižetić, S., 2019. Small scale archimedes hydro power plant test station: Design and experimental investigation. J. Clean. Prod. *231*, 756–771. https://doi.org/10.1016/j.jclepro.2019.05.234.
Dorber, M., Arvesen, A., Gernaat, D., Verones, F., 2020. Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. Sci. Rep. *10*, 21777 https://doi.org/10.1038/s41598-020-78444-6.
ECS, n.d. Engineering Services. Accessed November 2023, http://www.ecsengineeringservices.com/maintaining-archimedes-screw-pumps/.
Ember - Yearly Electricity Data (2024). The data is collected from multi-country datasets (EIA, Eurostat, Energy Institute, UN) as well as national sources (e.g China data from the National Bureau of Statistics). https://ember-climate.org/data-catalogue/yearly-electricity-data/.
Energy Institute - Statistical Review of World Energy (2023). https://www.energyinst.org/statistical-review.
Escario-Chust, A., Vogelzang, F., Peris-Blanes, J., Palau-Salvador, G., Segura-Calero, S., 2023. Can southern Europe lead an urban energy transition? Insights from the Energy Transition Roundtable in Valencia, Spain. Energy Res. Soc. Sci. *100*, 103047 https://doi.org/10.1016/j.erss.2023.103047.
Estrada Tarragó, F., 2015. Micro-hydro solutions in Alqueva Multipurpose Project (AMP) towards water-energy-environmental efficiency improvements. Bachelor thesis. Universitat Politècnica de Catalunya. Catalunya, Spain. Accessed January 2024, http://hdl.handle.net/2117/77036.
European Commission, 2019. *The European Green Deal. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions*. COM/2019/640 final. Accessed January 2024, https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF; https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
European Council, n.d. *Fit for 55 plan. European Green Deal.* Accessed January 2024, https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.
European Environmental Agency, 2020. Briefing no. 28/2020. Growth without economic growth. HTML – TH-AM-20-028-EN-Q – ISBN 978-92-9480-321-4 – ISSN 2467-3196 – doi: 10.2800/781165 PDF – TH-AM-20-028-EN-N – ISBN 978-92-9480-320-7 – ISSN 2467-3196 – doi: 10.2800/492717 Accessed January 2024, https://www.eea.europa.eu/publications/growth-without-economic-growth. HTML – TH-AM-20-028-EN-Q – ISBN 978-92-9480-321-4 – ISSN 2467-3196 – doi: 10.2800/781165 PDF – TH-AM-20-028-EN-N – ISBN 978-92-9480-320-7 – ISSN 2467-3196 – doi: 10.2800/492717 Accessed January 2024, https://www.eea.europa.eu/publications/growth-without-economic-growth.
FAO, 2019. Globally Important Agricultural Heritage Systems. *Historical Irrigation System at l'Horta de València, Spain*. Accessed. August 2023, https://www.fao.org/giahs/giahsaroundtheworld/designated-sites/europe-and-central-asia/historical-waterscape-of-lhorta-de-valencia/en/.
Gallagher, J., Styles, D., McNabola, A., Williams, A.P., 2015. Current and future environmental balance of small-scale run-of-river hydropower. Environ. Sci. Technol. *40*, 6344–6351. https://doi.org/10.1021/acs.est.5b00716.
García Morillo, J., McNabola, A., Camacho, E., Montesinos, P., Rodríguez Díaz, J.A., 2018. Hydro-power energy recovery in pressurized irrigation networks: A case study of an Irrigation District in the South of Spain. Agric. Water Manag. *204*, 17–27. https://doi.org/10.1016/j.agwat.2018.03.035.
Giacovelli, G., 2022. Social capital and energy transition: a conceptual review. Sustainability *14*, 9253. https://doi.org/10.3390/su14159253.
Gómez-Navarro, T., Brazzini, T., Alfonso-Solar, D., Vargas-Salgado, C., 2021. Analysis of the potential for PV rooftop prosumer production: technical, economic and environmental assessment for the city of Valencia (Spain). Renew. Energy *174*, 372–381. https://doi.org/10.1016/j.renene.2021.04.049.
Gonzalez, J.M., Tomlinson, J.E., Martínez Ceseña, E.A., Basheer, M., Obuobie, E., Padi, P. T., Addo, S., Baisie, R., Etichia, M., Hurford, A., Bottacin-Busolin, A., Matthews, J., Dalton, J., Smith, D.M., Sheffield, J., Panteli, M., Harou, J.J., 2023. Designing diversified renewable energy systems to balance multisector performance. Nat. Sustain. *6*, 415–427. https://doi.org/10.1038/s41893-022-01033-0.
Griffiths, S., Sovacool, B.K., Kim, J., Bazilian, M., Uratani, J.M., 2021. Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. Energy Res. Soc. Sci. *80*, 102208 https://doi.org/10.1016/j.erss.2021.102208.
Guinot, E., Ferri Ramírez, M., Mangue Alférez, I., Martí, J., Martínez, A., Sales Martínez, V. y, Selma Castell, S., 1999. *La Real Acequia de Moncada. Colecció Camins d'Aigua*. Generalitat Valenciana. Conselleria D'Agricultura Pesca i Alimentació, Valencia.
Guinot Rodriguez, E., 2007. Una Historia de La Huerta de Valencia. In: Hermosilla, J. (Ed.), El patrimonio hidráulico del bajo Turia. L'Horta de València, 60-101. Generalitat Valenciana, Valencia.
Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy Policy *64*, 141–152. https://doi.org/10.1016/j.enpol.2013.05.049.
Hermoso, V., Clavero, M., Green, A.J., 2019. Don't let damage to wetlands cancel out the benefits of hydropower. Nature *568*, 171. https://doi.org/10.1038/d41586-019-01140-7.
Huntington, H.P., Schmidt, J.I., Loring, P.A., Whitney, E., Aggarwal, S., Byrd, A.G., Dev, S., Dotson, A.D., Huang, D., Johnson, B., Karenzi, J., Penn, H.J.F., Salmon, A.A., Sambor, D.J., Schnabel, W.E., Wies Jr, R.W., Wilber, M., 2021. Applying the food–energy–water nexus concept at the local scale. Nat. Sustain. *4*, 672–679. https://doi.org/10.1038/s41893-021-00719-1.
Hydropower screws in Europe, n.d. Google Maps. Accessed January 2024, ⟨http://efort.info/AST-Map⟩.
IPCC (Intergovernmental Panel on Climate Change), 2014. Intergovernmental Panel on Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1132 pp. Accessed January 2024, https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf.
Intergovernmental Panel on Climate Change (IPCC), 2006. *Guidelines for national greenhouse gas inventories. Task force on national greenhouse gas inventories (TFI)*.
International Energy Agency, 2021. Net Zero by 2050. A Roadmap for the Global Energy Sector. Accessed November 2021, https://www.iea.org/; https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
Kamran, M., Asghar, R., Mudassar, M., Abid, M.I., 2019. Designing and economic aspects of run-of-canal based micro-hydro system on Balloki-Sulaimanki Link Canal-I for remote villages in Punjab, Pakistan. Renew. Energy *141*, 76–87. https://doi.org/10.1016/j.renene.2019.03.126.
Kittner, N., Gheewala, S.H., Kammen, D.K., 2016. Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. Renew. Energy *99*, 410–419. https://doi.org/10.1016/j.renene.2016.07.023.
Lacombe, G., Douangsavanh, S., Baker, J., Hoanh, C.T., Bartlett, R., Jeuland, M., Phongpachith, C., 2014. Are hydropower and irrigation development complements or substitutes? The example of the Nam Ngum River in the Mekong Basin. Water Int. *39*, 649–670. https://doi.org/10.1080/02508060.2014.956205.
Laghari, J.A., Mokhlis, H., Bakar, A.H.A., Mohammad, H., 2013. A comprehensive overview of new designs in the hydraulic, electrical equipments and controllers of mini hydro power plants making it cost effective technology. Renew. Sustain. Energy Rev. *20*, 279–293. https://doi.org/10.1016/j.rser.2012.12.002.
Landustrie. Linton Lock, 2017. Accessed January 2024, ⟨https://web.archive.org/web/20210804020631/https://www.landustrie.nl/en/products/hydropower/projects/linton-lock.html⟩.
Lashofer, A., Hawle, W., Pelikan, B., 2012. State of technology and design guidelines for the Archimedes screw turbine. In: Hydro 2012 - Innovative Approaches to Global Challenges, Conference paper. Aqua-Media International, Wallington, Surrey, U.K.. Accessed January 2024, https://www.researchgate.net/publication/281347248_State_of_technology_and_design_guidelines_for_the_Archimedes_screw_turbine.
Lorenzo-Sáez, E., Lerma-Arce, V., Coll-Aliaga, E., Oliver-Villanueva, J.V., 2021. Contribution of green urban areas to the achievement of SDGs. Case study in Valencia (Spain). Ecol. Indic. *131*, 108246 https://doi.org/10.1016/j.ecolind.2021.108246.
Lubchenco, J., Kerry, J.F., 2021. Climate science speaks: "Act now. Science *373* (6561), 1285. https://doi.org/10.1126/science.abm3757.
Manso-Burgos, Á., Ribó-Pérez, D., Gómez-Navarro, T., Alcázar-Ortega, M., 2022. Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in Valencia (Spain). Energy Rep. *8*, 10395–10408. https://doi.org/10.1016/j.egyr.2022.08.181.
MITERD (Spanish Ministry for the ecological transition and the demographic challenge), 2022. *Hydrogen Roadmap: a commitment to renewable hydrogen.* Accessed January 2024, https://www.miteco.gob.es/es/ministerio/planes-estrategias/hidrogeno.html.
Muthu, R.N., Rajashabala, S., Kannan, R., 2017. Hydrogen storage performance of lithium borohydride decorated activated hexagonal boron nitride nanocomposite for fuel cell applications. Int. J. Hydrog. Energy 42 (23), 15586–15596.
National Cadastre of Spain, 2022. Accessed January 2024, ⟨https://www1.sedecatastro.gob.es/⟩.
Nature editorial, 2022. *Nature, 611* , 426 https://doi.org/10.1038/d41586-022-03693-6.
Nature Energy, 2021. Come together. Nat. Energy *6*, 765. https://doi.org/10.1038/s41560-021-00897-4.
Neves, M.C., Malmgren, K., Neves, R.M., 2021. Climate-driven variability in the context of the water-energy nexus: A case study in southern Portugal. J. Clean. Prod. *320*, 128828 https://doi.org/10.1016/J.JCLEPRO.2021.128828.
Nogrady, B., 2021. Most fossil-fuel reserves must remain untapped to hit 1.5 °C warming goal. Nature *597*, 316–317. https://doi.org/10.1038/d41586-021-02444-3.
Öhman, A., Karakaya, E., Urban, F., 2022. Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe. Energy Res. Soc. Sci. *84*, 102384 https://doi.org/10.1016/j.erss.2021.102384.
Ortega-Reig, M., Palau-Salvador, G., Cascant i Sempere, Josep, Benitez-Buelga, M., Badiella, J., Trawick, P, D., 2014. The integrated use of surface, ground and recycled waste water in adapting to drought in the traditional irrigation system of Valencia. Agric. Water Manag. *133*, 55–64. https://doi.org/10.1016/j.agwat.2013.11.004.
Ostrom, E., 1990. Governing the Commons. The Evolution of Institution for Collective Action. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511807763.
Our World in Data, 2022. Electr. Prod. Foss. fuels, Nucl. Renew., World. Accessed November 2022, https://ourworldindata.org/grapher/elec-fossil-nuclear-renewables?country=~OWID_WRL.
Paish, O., 2002. Small hydro power: technology and current status. Renew. Sustain. *Energy Rev. 6*, 537–556. https://doi.org/10.1016/S1364-0321(02)00006-0.

Parkinson, B., Balcombe, P., Speirs, J.F., Hawkes, A.D., Hellgardt, K., 2019. Levelized cost of CO2 mitigation from hydrogen production routes. Energy Environ. Sci. 12, 19–40. https://doi.org/10.1039/C8EE02079E.

Pérez-Sánchez, M., Sánchez-Romero, F.J., Ramos, H.M., López-Jiménez, P.A., 2016. Modeling Irrigation Networks for the Quantification of Potential Recovering: A case study. Water *8*, 234. https://doi.org/10.3390/w8060234.

Pérez-Sánchez, M., Sánchez-Romero, F.J., Ramos, H.M., López-Jiménez, P.A., 2017. Energy Recovery in Existing Water Networks: Towards Greater Sustainability. Water *9*, 97. https://doi.org/10.3390/w9020097.

Pérez-Sánchez, M., Sánchez-Romero, F.J., Ramos, H.M., López-Jiménez, P.A., 2020. Improved Planning of Energy Recovery in Water Systems Using a New Analytic Approach to PAT Performance Curves. Water *12*, 468. https://doi.org/10.3390/w12020468.

Peris-Blanes, J., Segura-Calero, S., Sarabia, N., Ribó-Pérez, D., 2022. The role of place in shaping urban transformative capacity. The case of València (Spain). Environ. Innov. Soc. Transit. *42*, 124–137. https://doi.org/10.1016/j.eist.2021.12.006.

Red Eléctrica Española, 2022. Consult. Emiss. Emiss. Factor CO2 eq. Electr. Gener. Accessed June 2022, https://www.ree.es/es/datos/generacion/no-renovables-detalle-emisiones-CO2.

Reddy, A.L.M., Tanur, A.E., Walker, G.C., 2010. Synthesis and hydrogen storage properties of different types of boron nitride nanostructures. Int. J. Hydrog. Energy 35 (9).

Rehart Power, 2024. Hann. Münden CS. Accessed January 2024,.

Renewable First, 2021. Archimedean screw hydro turbine. The Hydro and Wind Company Securing a clean energy future, profitably.

Renner, A., Giampietro, M., 2020. Socio-technical discourses of European electricity decarbonization: contesting narrative credibility and legitimacy with quantitative storytelling. Energy Res. Soc. Sci. *59*, 101279 https://doi.org/10.1016/j.erss.2019.101279.

Rogers, S.H., Halstead, J.M., Gardner, K.H., Carlson, C.H., 2011. Examining Walkability and Social Capital as Indicators of Quality of Life at the Municipal and Neighborhood Scales. Appl. Res. Qual. Life *6*, 201–213. https://doi.org/10.1007/s11482-010-9132-4.

Rohmer, J., Knittel, D., Sturtzer, G., Flieller, D., Renaud, J., 2016. Modeling and experimental results of an Archimedes screw turbine. Renew. Energy *94*, 136–146. https://doi.org/10.1016/j.renene.2016.03.044.

Sales Martínez, V., 2016. *Las ampliaciones modernas en los regadíos históricos. Jovedat y Extremal de la Real Acequia de Moncada.* (Doctoral dissertation, Universitat Politècnica de València. València, Spain.

Sarabia, N., Peris, J., Segura, S., 2021. Transition to agri-food sustainability, assessing accelerators and triggers for transformation: Case study in Valencia, Spain. J. Clean. Prod. *325*, 129228 https://doi.org/10.1016/j.jclepro.2021.129228.

Schwizer, J., 2021. Map of Hydro Turbines, 16. WikiMedia (https://commons.wikimedia.org/wiki/File:Kennfeld_Wasserturbinen.svg).

Suwanit, W., Gheewala, S.H., 2011. Life cycle assessment of mini-hydropower plants in Thailand. Int. J. Life Cycle Assess. *16*, 849–858. https://doi.org/10.1007/s11367-011-0311-9.

Tilmant, A., Goor, Q., Pinte, D., 2009. Agricultural-to-hydropower water transfers: Sharing water and benefits in hydropower-irrigation systems. Hydrol. Earth Syst. Sci. *13*, 1091–1101. https://doi.org/10.5194/hess-13-1091-2009.

Ueda, T., Roberts, E.S., Norton, A., Styles, D., Williams, A.P., Ramos, H.M., Gallagher, J., 2019. A life cycle assessment of the construction phase of eleven micro-hydropower installations in the UK. J. Clean. Prod. *218*, 1–9. https://doi.org/10.1016/j.jclepro.2019.01.267.

Van Renssen, S., 2020. The hydrogen solution? Nat. Clim. Change *10*, 799–801. https://doi.org/10.1038/s41558-020-0891–0 f.

Warbroek, B., Hoppe, T., Bressers, H., Coenen, F., 2019. Testing the social, organizational, and governance factors for success in local low carbon energy initiatives. Energy Res. Soc. Sci. *58*, 101269 https://doi.org/10.1016/j.erss.2019.101269.

Waters, S., Aggidis, G.A., 2015. Over 2000 years in review: Revival of the Archimedes Screw from Pump to Turbine. Renew. Sustain. Energy Rev. *51*, 497–505. https://doi.org/10.1016/j.rser.2015.06.028.

Xia, G., Yu, X., Guo, Y., Wu, Z., Yang, C., Liu, H., Dou, S., 2010. Amminelithium amidoborane Li (NH3) NH2BH3: a new coordination compound with favorable dehydrogenation characteristics. Chemistry 16 (12), 3763–3769.

YoosefDoost, A., Lubitz, W.D., 2020. Archimedes Screw Turbines: A Sustainable Development Solution for Green and Renewable Energy Generation—A Review of Potential and Design Procedures. Sustainability *12*, 7352. https://doi.org/10.3390/su12187352.

YoosefDoost, A., Lubitz, W.D., 2021. Design Guideline for Hydropower Plants Using One or Multiple Archimedes Screws. Processes *9*, 2128. https://doi.org/10.3390/pr9122128.

Zarfl, C., Berlekamp, J., He, F., Jähnig, S.C., Darwall, W., Tockner, K., 2019. Future large hydropower dams impact global freshwater megafauna. Sci. Rep. *9*, 18531 https://doi.org/10.1038/s41598-019-54980-8.

Zeng, R., Cai, X., Ringler, C., Zhu, T., 2017. Hydropower versus irrigation—an analysis of global patterns. Environ. Res. Lett. 12, 034006 https://doi.org/10.1088/1748-9326/aa5f3f.

Zsiborács, H., Baranyai, N.H., Vincze, A., Zentkó, L., Birkner, Z., Máté, K., Pintér, G., 2019. Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040. Electronics 8 (7), 729. https://doi.org/10.3390/electronics8070729.

Zvirko, O., Nykyforchyn, H., Krechkovska, H., Tsyrulnyk, O., Hredil, M., Venhryniuk, O., Tsybailo, I., 2024. Evaluating hydrogen embrittlement susceptibility of operated natural gas pipeline steel intended for hydrogen service. Eng. Fail. Anal. *163*, 108472 https://doi.org/10.1016/j.engfailanal.2024.108472.