environmental sciences proceedings

MDPI

Proceeding Paper

The Role of Micro-Hydropower Energy Recovery in the Water-Energy-Food Nexus †

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† Presented at the International Conference EWaS5, Naples, Italy, 12–15 July 2022.

Abstract: The potential for the generation of pico- and micro-hydropower through hydraulic energy recovery has been demonstrated across many sectors of the water-energy-food nexus, often termed hidden hydropower. The potential to recover energy from hidden hydropower in water supply, crop production, food processing, and energy production has been demonstrated via numerous in-depth case studies, regional assessments, and physical experiments. This paper presents a holistic overview of the potential role and impacts of micro-hydropower energy recovery on the water-energy-food nexus in the context of climate change. The paper comprises a review and synthesis of the available literature. The paper outlines the potential impacts of hidden hydropower on cost of water supply, energy and food production, considering also the potential impacts on crop yield and food supply. Policy and technological barriers to the exploitation of hidden hydropower resources within the nexus are outlined and recommendations to overcome these are provided. The results of this investigation highlight the potential of micro-hydropower energy recovery in water systems to reduce energy consumption by 0.005–3.7% across various sectors and regions, with consequent impacts in the operating and consumer costs of food, water and energy, as well as on the CO_2 emissions of these activities. This hidden hydropower has the potential to ease the pressures of the water-energy-food nexus and is an important element of the route towards sustainability within the nexus.

Keywords: hidden hydropower; water-energy-food nexus; climate change; micro-hydropower

Citation: McNabola, A.; Mérida García, A.; Rodríguez Díaz, J.A. The Role of Micro-Hydropower Energy Recovery in the Water-Energy-Food Nexus. *Environ. Sci. Proc.* **2022**, *21*, 27. https://doi.org/10.3390/environsciproc2022021027

Academic Editors: Vasilis Kanakoudis, Maurizio Giugni, Evangelos Keramaris and Francesco De Paola

Published: 20 October 2022

1. Introduction

There are numerous interdependencies between water, energy and food resources, as well as their relationship with technological development and management policies [1]. Increased food demand due to population growth, and thus increased pressure on resources, are also directly affected by climate change. Drought reduces water availability for hydropower generation and irrigation, which in turn affects agricultural yields, with direct negative consequences on food and biofuel production. In turn, the fast bioenergy sector development, aiming to promote lower impact energy sources, competes with food production for land and water resources [1]. The unquestionable interconnection between the three sectors requires an integrated and holistic management through cross-sectoral coordination to promote a sustainable development.

Water resources are closely linked to food and energy production, being the main input for agricultural activities, a key resource for numerous industrial processes, and the origin of hydropower generation. Beyond hydropower generation, thermoelectric power generation, oil and gas production, and other renewables such as bioenergy, are vulnerable to reduced production due to water-dependent processes [2]. Regarding hydropower, the global installed capacity in 2020 was around 1300 GW, including 158 GW of pumped storage, representing 13% of the total electricity generated in the EU-27, with 254 GW of installed capacity [3]. However, hydropower may have a substantial land footprint where reservoirs need to be constructed. Small hydropower and run-off-river technologies, installed in existing infrastructures, avoids the construction of large reservoirs, avoiding the significant evaporation, environmental and socio-economic impacts arising from large hydropower projects. The exploitation of these 'hidden' hydropower resources can contribute with an extra green energy input, with a positive impact on decreasing production costs and minimising the environmental impact associated with different sectors, in which water plays an essential role [4].

The objective of this work is to highlight the potential impacts of hidden hydropower on cost of water supply, food and energy production and assess the environmental implications, in a context of climate change. This work also explores the main policy and technological barriers to the development and exploitation of hidden hydropower within the framework of the water-energy-food nexus.

2. Materials and Methods

2.1. Hidden Hydropower Review and Opportunities in the Water Industry Related Sectors

Hidden hydropower exists in hydraulic infrastructure with excess head or pressure, and electricity can be generated from this resource without interfering in the primary function of said infrastructure. This is present in existing hydraulic infrastructure systems such as water supply and treatment, wastewater drainage and treatment, irrigation networks, at existing non-hydropower dams and weirs, at canal locks, and in water-intensive industries (e.g., mining, thermo-electric generation, etc). Generally, research related to hidden hydropower has focused on the assessment of the optimal locations for turbine/pumps as turbines (PATs) installation within networks [5], as well as the resource potential for hidden exploitation [4] in pressurised and non-pressurised water distribution networks. Hidden hydro opportunities have been identified in the drinking water sector [6], irrigation networks [7], wastewater treatment plants [8], water-intensive industrial facilities [9], and rivers [10], among others. The selection of the most suitable available turbines or PATs for energy recovery in water distribution networks [11], new technological developments testing for hidden hydropower [12], or predictions on equipment cost based on available flow and head [13], have also been a key research focus, together with feasibility analysis of hidden hydropower, integrating efficiency, reliability and sustainability criteria [14]. Within these, flow fluctuations is one of the critical aspects in hidden hydropower exploitation, addressed by the development of methodologies based on probabilities and flow distribution in real networks [15].

However, studies in some sectors are still limited, as in the water-intensive industry sector, where most of the evaluations conducted to date cover the potential for energy recovery associated with only industrial waste-water effluents [9], with a severe lack of information about the internal water distribution networks.

This work has estimated hidden hydropower opportunities in Europe considering the previous methodology and results obtained in the REDAWN project (www.redawn.eu). This previous methodology analysed the energy recovery potential for MHP (Equation (1)) in some identified sites in the water industry sector in Ireland, France, Portugal, Spain, and UK, based on the information available for flow and head pressure:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \tag{1}$$

The potential for MHP (P, in W) was calculated considering the density of water (ρ, in kg/m^3), the gravity acceleration (g, in m/s^2), the available flow (Q, in m^3/s), the hydraulic head (H, in m) and the efficiency (η).

The results were then related to the population served by the corresponding installations/facilities analysed (for the drinking water, wastewater and industry sectors), to be then extrapolated to a country scale, considering the total country population and a 24/7 operation time. The extrapolation in the drinking water sector considered 4 different assumptions, due to the lack of data in some countries and the significant differences between those with data [16]. For the wastewater (*WW*) sector, a linear correlation for the *MHP* potential (in kW), based on population served (*X*), with R^2 = 0.78% was used:

$$MHP_{WW} = 4.4222 \times 10^{-5} X - 1.4565 \tag{2}$$

For water-intensive industry, the extrapolation also considered the varying industrial intensity level through its participation in the gross domestic product (GDP) in each country. In the case of the irrigation sector, a ratio between the energy recovery potential per hectare in the analysed networks was considered, extending then the results to the pressurized irrigation areas in Spain and Portugal.

In this work, the previous methodology was extended to provide an overview of the set of the EU-27 countries in their commitment to renewable energies, and in this case, hidden hydropower.

2.2. Strengths of Hiden-Hydro in a Climate Change Context

Hydropower is the most important low-carbon energy source in the world, and serves as the major source of energy storage [17]. The environmental and social impacts of existing hydropower structures already in operation are known, defined and generally accepted. Nevertheless, the installation of new MHP solutions on the existing systems usually saves construction and operation costs and major infrastructure works, while also reducing required time and greenhouse gas (GHG) emissions. Moreover, the energy generated can be consumed on site [18], without the need to transport or store it, decentralising the electricity grid consumption or reducing fossil fuel consumption, in off-grid locations.

These benefits are quantitatively demonstrated and supported by life-cycle assessments (LCA), which provides a suitable methodology for assessing the environmental impact of hydropower installations [19], with possible extra impact reductions identified by carbon and resources savings through eco-design measures [20]. In this work, an estimation of the GHG emissions reduction based on the MHP energy recovery potential identified, and the emission factors for the electricity grid in each country, was addressed, as part of the measurable benefits of hidden-hydro, in a climate change context.

2.3. Potential Impacts on Cost, Food and Energy Production

The use of turbines or PATs for energy recovery in the water industry represents a reduction in the energy dependency, which leads to a reduction of the operating costs. These cost reductions could have direct impacts on the profitability of farmers and producers (principally in the case of agriculture and industry production), on the cost of services (mainly in the water supply and wastewater treatment processes) and final cost of products (agricultural and processed products) for users. In the case of agricultural production, energy is one of the most important inputs, so production can by high energy costs. This occurs when the expected increase in economic benefits due to higher crop yields, does not compensate the extra cost of energy [21,22]. However, the impacts of energy cost on food production and prices are not easily quantifiable in a large scale, and would require the application of complex specific models, integrating information about the crop characteristics and yield pattern, irrigation volumes, energy consumption and prices, production costs and food market prices. In this way, several authors have explored the potential impacts and relations between energy and food prices, using in many cases specific VAR (vector autoregression) models [23]. However, researchers are mainly focused on crude oil and bio-energy as energy sources [24], while interactions related to other energy sources, or even renewable energy production are not explored.

Food production represents between 20% to 30% of the total energy consumption in Europe, from which 15–20% is due to food processing [25]. These figures reveal the significant energy consumption in the primary sector related to food production, representing, as an example, an average between 7 to 10% of the annual input costs for farmers and between 4% and 9% of the total agricultural income in Spain [26], although these figures vary widely between different crops and countries.

In this work, based on the estimations for MHP production, and considering an average cost of energy for the different countries, the potential cost savings through the water sector by hidden-hydro were estimated.

2.4. Policy and Technological Barriers to Exploitation of Hidden Hydro

Significant policy and technological barriers persist to the full exploitation of hidden hydropower resources in existing hydraulic infrastructure systems. These include the varying policies and regulations affecting the production of energy on the micro-scale and the connection of this to the grid. In addition, in the case of existing non-hydropower dams or weirs, environmental consenting for hidden hydropower varies greatly across the EU. The costs associated with these policies and regulations can often be more than the cost of the required hydropower equipment and related civil works. Furthermore, these policies and regulations often treat MHP generation with the same level of rigor as multi-MW plants.

In terms of technological barriers to hidden hydropower exploitation in practice, the cost of hydro-mechanical equipment and return on investment are key. Low-cost technology is required which maintains high efficiency in scenarios which are often low-head containing significant fluctuations in flow rate. Significant research in the hidden hydropower sector has focused on the use of PATs for low-cost power production. The European Commission's Joint Research Centre recently highlighted this trend as well as other trend emerging in hydropower technology development [27].

3. Results

3.1. Hidden Hydropower Opportunities

The analysis conducted under the REDAWN project, estimated a total potential for MHP of 24 MW in the facilities for which data about head pressure and flow was available. From this total, 76% of the MHP potential was identified in the drinking water sector, while 13%, 7%, and 5% corresponded to the irrigation, process industry and wastewater sectors, respectively. However, for some sectors, there was limited initial information. The extrapolations of MHP potential reached a total of 275 MW. This power estimation represented an annual energy recovery potential between 925.1 and 1688.1 GWh, depending on the extrapolation method used [16]. This research considered the regions of Ireland, Spain, Portugal, France and UK.

In this work, these previous results (www.redawn.eu) were used to estimate the potential energy recovery through MHP in the EU-27 member states. Average ratios of energy recovery potential per 1000 inhabitants, for the drinking water sector, between 2.82 to 6.23 MWh/1000 people were obtained, depending on the extrapolation method, reaching a total energy recovery potential through MHP between 1259.1 and 2787.6 GWh/year, for the set of EU-27 countries. For the wastewater sector, a ratio of 0.38 MWh/1000 people and a potential energy recovery of 168.7 GWh/year, were obtained. However, when directly applying the linear correlation previously found for the wastewater sector in REDAWN research, the result was slightly higher, amounting to 172.82 GWh/year. These results were significantly lower than the ones obtained for the drinking water sector, due to calculations are based on discharge volumes, with the difference in height between the treatment plant and the discharge point as available head pressure.

In the case of the industry sector, it was considered the percentage participation of the industrial activity in the GDP, which varied between 10.2% (Malta) and 40.2% (Poland), with an average value of 26.5%. The results of the extrapolation, considering the average

MHP potential ratio of 0.01 MWh/1000 people for each 1% contribution of industry in the GDP, reached for this sector an estimated annual energy recovery potential of 135.9 GWh for the set of EU-27 countries, with the country shares shown in Figure 1. Here, again the estimated potential was based only on the discharge volumes, and not on possible excess pressure in the internal industrial water distribution networks, which could significantly increase this potential.

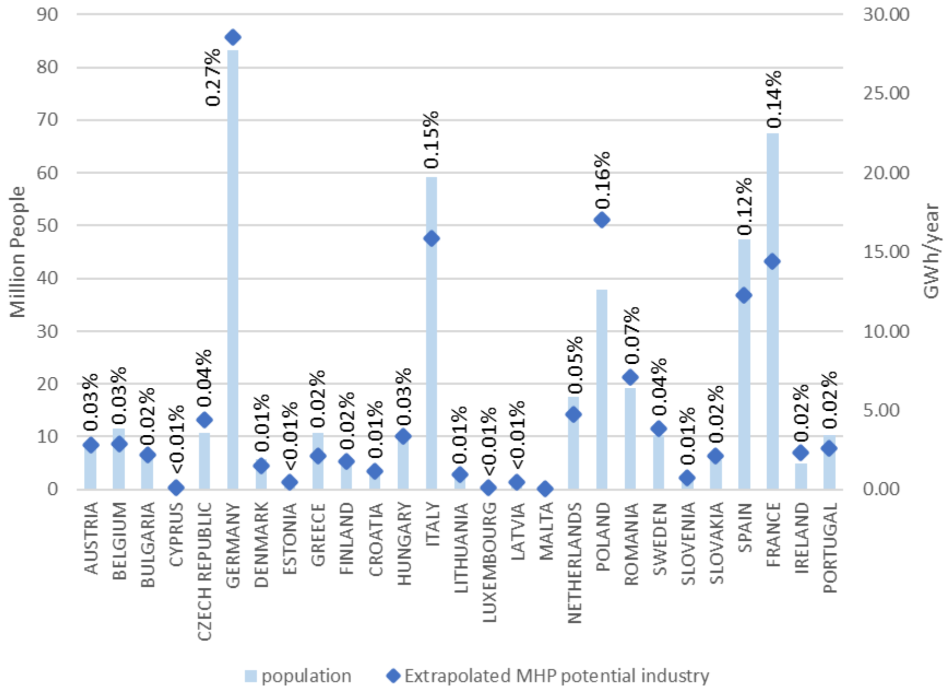

Figure 1. Total population, extrapolated energy recovery potential through hidden hydropower and the industry participation in the GDP for the different EU-27 countries.

The irrigation sector, by contrast, presented difficulties for extrapolation since: the intensity of the agricultural activity depends on the country, and climatic conditions have a significant impact on irrigation needs and techniques. In addition, limited information is available at country level, across Europe. In this sector, the estimation was made considering the MHP potential obtained for Portugal and Spain, and the total volume of water used for irrigation in the different countries, as the ratio related to the irrigated area would give an excessively high and unrealistic total result. Following these steps, the energy recovery potential for the irrigation sector reached a total between 382.1 and 506.9 GWh per year, for the set of EU-27 countries. Nevertheless, this calculation assumed a proportional level of pressurisation of the networks related to the water consumption for irrigation, which suggests a large uncertainty. These results could be more accurate if more objective information on the pressurised irrigated area is obtained, which is not available at the moment.

Considering these results, the total energy recovery potential for the EU-27 area could reach a total annual between 2025.48 (64%, 20%, 9% and 7% for the drinking water, irrigation, wastewater and industry sectors) and 3661.54 GWh (77%, 14%, 5% and 4% for the drinking water, irrigation, wastewater and industry sectors), with the country-distribution shown in Figure 2:

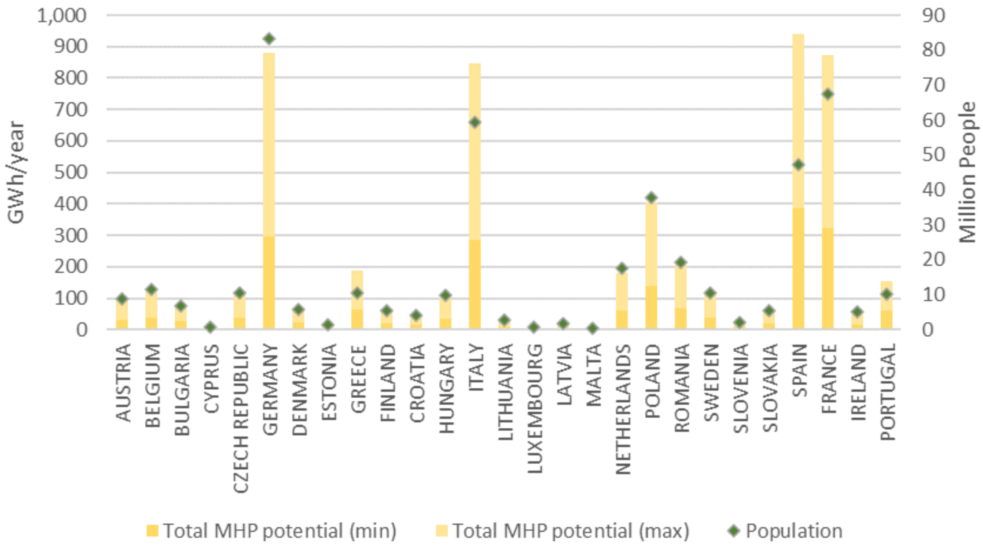

Figure 2. Range of total extrapolated energy recovery potential through MHP and corresponding population for the different EU-27 countries.

3.2. Potential Impacts

Potential impacts of hidden-hydro were here quantified in terms of economic and environmental savings. According to the IEA (International Energy Agency), the energy requirements of the drinking water supply, desalination for municipal use and wastewater treatment in Europe amounted to around 80 TWh in 2014 [28]. On the other hand, following Eurostat statistics [29], the industry sector as a whole achieved an annual consumption in 2020 of around 2600 TWh in the set of EU-27 countries, while agriculture sector reached 283 TWh [30].

For the economic savings assessment, the average price of electricity for 2021 was considered in the different countries [31]. These prices ranged between EUR 0.061 (Sweden) to EUR 0.138 (Ireland), with an average value of EUR 0.087 for non-household consumers; and between EUR 0.100 (Italy) and EUR 0.319 (Germany), with an average value of EUR 0.183, for household consumers (including taxes).

In the case of the environmental impacts, the equivalent GHG emissions related to the electricity grid were considered [32]. These values were very different between countries, with the maximum being represented by Estonia (891 g CO_2/kWh) and the minimum represented by Sweden (8 g CO_2/kWh), with an average value of 279 g CO_2/kWh.

Estimations of hidden hydro carried out in this work represented a potential reduction in energy consumption between 1.8 and 3.7% for the set represented by the drinking water and wastewater sectors, around 0.005% of the industry energy consumption and between 0.14 and 0.18% of the energy consumed in the agriculture sector. Although these percentages may seem low, the reality is that energy consumption in the water sector is high, involving energy-intensive processes. However, exploring the potential for hidden hydro in the water distribution networks in the industry sector, as well as knowing the energy consumption of the irrigation sector, would increase these rates. Considering the maximum and minimum ratios for electricity price for non-household consumers (excluding taxes), hidden hydro could help to save between 87 and 408 MEUR in the set of drinking water and wastewater sectors, between 8 and 19 MEUR in the industry sector and between 23 and 70 MEUR in the agriculture sector. Nevertheless, these figures would reach a total of 1151 MEUR if the highest electricity price for household consumers is considered.

In environmental terms, these figures would represent a total CO_2 emissions savings between 0.54 and 1.01 million tons CO_2 eq per year, if the average emissions ratio is considered, although it would vary between 0.02 and 3.21 million tons CO_2 eq. per year, if the maximum and minimum country ratios are considered.

4. Conclusions

The water-energy-food nexus faces increased pressure from population growth and resource scarcity in a climate change context. The interdependencies between water, energy, and food production mean that changes in one driver can lead to multi-directional consequences.

Hidden hydropower allows green energy generation in water distribution installations, reducing their energy consumption, leading to reduced production costs. However, the quantification of these impacts at a country scale is complex, as the available information is limited. The impacts on food production and prices due to the energy cost reduction requires the use of complex analysis models, since for example, fresh food prices are largely conditioned by the supply/demand rate, thought the year. This paper has estimated the potential for hidden hydro in the water sector, based on previous investigations, as well as the potential economic and environmental impacts associated, for the set of EU-27 countries. The complexity of such a large-scale extrapolation finally resulted in a range of values, which in this case amounted to a total energy recovery potential between 2025 and 3662 GWh per year, which represented economic and environmental savings between 169 and 313 M EUR, and between 0.54 and 1.01 million tons CO_2, respectively, for the set of countries and considering average cost and CO_2 emissions ratios.

However, as pointed out in the methodology and results sections, more in-depth analysis of water distribution networks facilities in water-intensive industries, as well as the collection of the surface areas by type of irrigation in each country, and the application of complex crop productivity models, would allow a better understanding and approximation to the potential of hidden hydroelectricity in the water-energy-food nexus and the impacts in a climate change context.

Author Contributions: Conceptualization, A.M.; methodology, A.M., A.M.G. and J.A.R.D.; resources, A.M.G.; data curation, A.M.G.; writing—original draft preparation, A.M.G.; writing—review and editing, A.M. and J.A.R.D.; supervision, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been carried out as part of the research works of the Postdoctoral Fellowship Margarita Salas (A.M.G.), funded by European Union–NextGenerationEU, through the Spanish Ministry of Universities and the University of Cordoba.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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