



Is There a Residual and Hidden Potential for Small and Micro Hydropower in Europe? A Screening-Level Regional Assessment

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Abstract

Small hydropower plants (installed power below 10 MW) are generally considered less impacting than larger plants, and this has stimulated their rapid spread, with a developing potential that is not exhausted yet. However, since they can cause environmental impacts, especially in case of cascade installations, there is the need to operate them in a more sustainable way, e.g. considering ecosystem needs and by developing low-impacting technologies. In this paper, an assessment was conducted to estimate how the environmental flow and the plant spatial density affect the small hydropower potential (considering run-of-river schemes, diversion type, DROR) in the European Union. The potential of DROR is 79 TWh/y under the strictest environmental constraints considered, and 1,710 TWh/y under the laxest constraints. The potential of low-impacting micro technologies (< 100 kW) was also assessed, showing that the economic potential of hydrokinetic turbines in rivers is 1.2 TWh/y, that of water wheels in old mills is 1.6 TWh/y, and the hydropower potential of water and wastewater networks is 3.1 TWh/y, at an average investment cost of 5,000 €/kW.

Keywords Environmental flow · European assessment · Hydrokinetic · Mill · Small hydro · Water wheel · Water distribution network

Nomenclature

C_p	Power coefficient (-)
D	Length of grid side (km)

Key Points

- Hydropower potential of DRORs, old mills, water and wastewater networks, and hydrokinetic turbines was assessed throughout EU.
- Different scenarios of environmental flow and plant spatial density were explored.
- DRORs can produce 79 TWh/y under the strictest environmental constraints considered. This may increase up to 1,710 TWh under the laxest constraints.
- The potential of water wheels in old mills, hydrokinetic turbines and turbines in water and wastewater networks is 6 TWh/y; the additional hidden micro hydropower potential estimated in literature ranges between 7 and 8 TWh/y.

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DROR	Diversion run-of-river hydropower plant
<i>dens</i>	Power plant spatial density (km^{-2})
EF	Environmental flow (m^3/s)
EU	European Union
FDC	Flow duration curve
<i>H</i>	Head (m)
HPP	Hydropower plant
HT	Hydrokinetic turbine
<i>L</i>	Withdrawal length (m)
MAF	Mean annual flow (m^3/s)
<i>P</i>	Power (kW)
<i>Q</i>	Flow rate (m^3/s)
ROR	Run of river
S.M.	Supplementary material
SH	Small hydropower
WDN	Water distribution network
WWTP	Wastewater treatment plant
η	Efficiency (-)

1 Introduction

Hydropower is the largest renewable energy source used worldwide, accounting for 1,330 GW of global installed capacity (IHA 2021). Large hydropower (> 10 MW) also contributes to better water management (e.g., flood control), provides storage capacity, supports the spread of variable renewable energy sources (e.g., wind and solar), and provides flexibility to the electric grid (Branche 2017). Small hydropower (< 10 MW) can also contribute to local development, decentralized energy generation and market opportunities in remote areas (Paish 2002). It is estimated that the global installed capacity of small hydropower (SH) is 75 GW, and 173 GW is the untapped potential (Kelly-Richards et al. 2017). Run-of-River (ROR) hydropower accounts for more than 75% of the 3,700 hydropower plants planned or under construction worldwide, especially in Europe (Bejarano et al. 2019; Couto and Olden 2018), which is a market leader of SH technology and scientific research (Wagner et al. 2019; Manzano-Agugliaro et al. 2017). In this paper, the term ROR is used to indicate hydropower plants with no storage capacity.

However, small hydropower plants (SHPs) are not free from environmental impacts, with the interruption of the longitudinal continuity of rivers having potentially far-reaching environmental impacts (Frey and Linke 2002; Moran et al. 2018; Acreman and Ferguson 2010). Therefore, there is a need to develop SHPs in a more sustainable way. Within this context, European directives set mandatory targets, and member states must transpose them into national legislations. Therefore, hydropower operators face different laws for ecological restoration, hydropower operation and public procurement. For example, the Water Framework Directive 60/2000/EC sets common guidelines to preserve and improve the ecological status of rivers (Kallis and Butler 2001), while national and local authorities define specific constraints to hydropower development to reduce the related impacts (Glachant et al. 2014) (see Supplementary Material –S.M.- for more details and examples). Typically, such constraints include a minimum water allowance (“environmental flow” – EF-) and a limitation of the

hydromorphological impacts of stream fragmentation, impoundment and habitat destruction. A way adopted in practice to enforce limitation of such impacts may be a prescription of a minimum required distance between two consecutive barriers (see Supplementary Material for legislation examples and Erikstad et al. 2020 for more insights on the spatial density of hydropower plants). Constraints on SHPs are often defined at the local scale, rather than encoded in generally applicable fixed rules, and can affect hydropower potential appreciably, often undermining the economic feasibility of projects (Bejarano et al. 2019).

When looking at the continental scale (e.g. Europe), understanding of the effects of environmental constraints on hydropower development is essential to help policy makers to define future strategies. However, this nexus is rarely evaluated (Tian et al. 2020). Therefore, the first aim of this paper is to estimate how environmental constraints affect the SH potential in the EU (European Union), focusing on the environmental flow and the spatial density of SHPs. We considered diversion type ROR plants, hereinafter DRORs. DRORs have no storage reservoirs, thus they have been considered ideal for ecologically fragile areas, with a lower disturbance and impact on the stream flow, if an adequate environmental flow remains in the diverted river reach and fish migration across the barrier is possible (Habit et al. 2007; Basso and Botter 2012).

SHPs using technologies that do not need a barrier (e.g., hydrokinetic turbines, Kirke 2019), or SH turbines that can be installed in existing infrastructures and in existing barriers (Hansen et al. 2021) may reduce impacts substantially. Examples of plants exploiting existing infrastructures include water wheels in old mills (Quaranta and Revelli 2018), turbines in pressurized water distribution networks (WDNs) and in wastewater treatment plants (WWTPs) (Mitrovic et al. 2021), and have installed capacity typically below 100 kW (micro hydropower). Technical details of these technologies are provided in the S.M.

Therefore, in this paper we appraise the potential energy production of (1) DROR plants subject to increasingly stringent environmental constraints; (2) hydrokinetic turbines in rivers; (3) water wheels in mills; (4) hydropower in WDNs and WWTPs. After introducing the methods and assumptions for our assessment, we present and discuss the calculated production potential. Based on our results, we suggest criteria for a strategy of small hydropower in EU.

2 Materials and Methods

The potential production through DRORs and hydrokinetic turbines in EU was calculated using a Geographic Information System (GIS)-based model, similar to Palla et al. (2016), Bodis et al. (2014), Goyal et al. (2015). The hydropower potential assessment in water mills was carried out using the EU+UK Restor Hydro database (Punys et al. 2019). The potential in WDNs and in WWTPs was calculated by generalizing the results of Mitrovic et al. (2021) to cover the EU+UK area.

2.1 DRORs

In DRORs, the hydrological regime of the river is not altered, except for a length L between the point where water is withdrawn, and the point where it is discharged from the turbines, where anyway the EF must be respected. The GIS model computes the annual potential energy production (kWh/y) of a DROR plant at a site (x, y) from the frequency of exceedance of discharges (flow duration curve or FDC) and the river slope according to Eq. (1):

$$E(x, y) = \gamma\eta H(x, y)T \int_0^1 \min(Q_{10}, \max(0, Q_{nat}(x, y, \tau) - EF) d\tau \quad (1)$$

where:

- $Q_{nat}(x, y, \tau)$ (m³/s) is the river discharge at the site with frequency of exceedance τ , and T represents the operating annual hours;
- EF is the environmental flow considered (m³/s);
- Q_{10} is the flow with an exceedance frequency of 10% during the year. This is assumed to be the maximum flow allowed through the turbines;
- $H(x, y)$ is the hydraulic head difference (m), assumed independent on the flow (see Eq. (2));
- γ, η represent the specific weight of water (9.81 kN m⁻³) and the overall efficiency of the plant, respectively. The efficiency η depends on the design of the plant, and varies with the flow and head. For the purposes of this assessment we assume it to be a constant equal to 0.65, as in Bódis et al. (2014).

We assumed EF to be a constant discharge each time corresponding to one among the following discharges with a frequency of exceedance of 50% (Q_{50}), 75% (Q_{75}), 90% (Q_{90}), 95% (Q_{95}), 99.7% ($Q_{99.7}$), and also 10% of mean annual flow (0.1MAF), 30% of mean annual flow (0.3MAF), and 50% of mean annual flow (0.5MAF).

We estimated the potential energy production of DRORs at a resolution of 100 m using the SRTM digital elevation model (see Vogt et al. 2007). We refer to FDCs interpolated from available measurements as presented in detail in Persiano et al. (2022). The interpolated FDCs refer to the outlet of sub-basins with a drainage area in the range of a few tens to a few hundreds of km² and we excluded all streams in a non-headwater sub-basin, with a contributing area smaller than 10% of the area at the sub-basin outlet. For the stream network within each sub-basin, we assume the FDC to scale with the ratio $MAF(x,y)/MAF_{basin}(x,y)$, where $MAF(x,y)$ is the local mean annual flow, and $MAF_{basin}(x,y)$ is the mean annual flow at the outlet of the sub-basin where the site (x,y) belongs. The MAF used to scale the interpolated FDCs is obtained from the long-term hydrologic surplus (precipitation minus evapotranspiration as an average over an extended period) obtained from the Budyko equation as discussed in Pistocchi et al. (2019) (further details provided in S.M.). We limited our analysis to that part of the European stream network for which hydrologic information on the FDC is available.

A plant is typically located at a site where a head difference is created either by a knick-point in the stream bed profile, or by an artificial barrier such as a weir. However, the topographic information available at the scale of our analysis does not allow for analysis of these features. In order to estimate the available head difference at each potential site (x,y) , we assume that the stream bed follows an exponential graded profile, for which the slope was computed as Pistocchi (2014):

$$J(x, y) = \theta Z_{max}(x, y) \exp(-K\xi(x, y)) \quad (2)$$

where θ is the exponential profile coefficient, $Z_{max}(x, y)$ (m) is the topographic estimated elevation at the upstream end of the stream segment, placed at a distance $\xi(x, y)$ from site (x,y) , measured along the stream network. $H(x, y)$ is estimated by multiplying the local stream slope $J(x,y)$ by a representative distance L (m) representing the withdrawal length of the stream, comprising the length of the impoundment upstream of a possible barrier at the plant intake, as well as the distance from the intake to the outfall of the plant (extent of the withdrawal). The procedure to estimate K and $J(x,y)$, following the concepts presented in Pistocchi (2014), is outlined in the S.M section.

In order to account for a minimum spatial density that must be respected among hydropower plants within a sub-basin, we superimposed a lattice of regular squares with a side of length D to each sub-basin, to explore different plant spatial densities (Erikstad et al., 2020). Within each polygon deriving from the geometric intersection of the lattice and the sub-basin polygons, we selected only one location (x,y) corresponding to the maximum local value of the product $MAF(x,y)J(x,y)$, representing a stream power scale, and for the assumptions made on the calculation of $H(x,y)$, also a hydropower potential scale. For the sake of exploration we considered $D = 1$ km, $D = 5$ km, and $D = 10$ km, meaning that we would admit no more than one hydropower plant every 1 km², 25 km², or 100 km², respectively. While 1 km² represents an unrealistic scenario (a maximum threshold), 25 km² and 100 km² are in line with the measured values reported in Punys et al. (2019) (between 1 plant every 10 km² and 200 km², depending on the EU country).

2.2 Hydrokinetic Turbines

The kinetic power K (W) in a certain river section can be calculated by Eq. (3):

$$K = \frac{1}{2} \rho Q v^2 \quad (3)$$

where Q (m³/s) is the flow rate, v (m/s) is the flow velocity and ρ is the water density (1,000 kg/m³). Based on the hydraulic geometry relationships presented in Pistocchi and Pennington (2006), we may rewrite Eq. (3) in terms of the river slope and discharge (Eq. (4)).

$$K = 4.14 \cdot J^{0.599} \cdot Q^{1.3806} \quad (4)$$

The stream power resulting from Eqs. (3) and (4) has to be multiplied by the power coefficient $C_p = P/K$, where P is the mechanical power output, to estimate the power output of the hydrokinetic turbine (HT). Our calculations with $C_p = 1$ represent the maximum theoretical potential, and results must be scaled by an appropriate C_p reflecting the performance of HTs (C_p affects the potential linearly). At present, we may assume $C_p = 0.2$ for standard turbines currently available as commercial products, and $C_p = 0.4$ for available well optimized turbines, e.g. with deflectors or enclosed in hydrodynamic structures. In our assessment we calculated the average power potential using both the average flow and the average of the power duration curve, and then calculated the annual energy potential.

The calculated kinetic power K refers to the power available in 100% of the river section. If only a percentage of the cross section is exploited, results have to be multiplied by the swept area percentage. Although the portion of the exploited cross section strictly depends on local factors, we assumed a constant maximum occupation of 25% of the cross section throughout Europe (e.g. Jenkinson and Bomhof 2014). In our study we considered that the turbine occupies the whole water depth (accepting that it will work partially submerged at low water flows). The potential was calculated at 100 m spatial resolution as per the digital elevation map, although it is known that, in order to avoid wake effects and performance reduction, a minimum longitudinal distance between HT installations must be respected. Usually this distance is estimated as $l = 10d$ (d being a reference HT dimension), so some effect is expected for installations on a scale of 10 m or larger. An assessment of the impacts due to this effect would require a detailed analysis far beyond the scope of this paper, hence we anticipate that our estimated potential is in principle overestimated by

neglecting backwater effects and wake effects between installations. An alternate installation on the river banks can mitigate such effects. Within our exploratory intent, we considered HT installations neglecting the presence of barriers and civil structures, and the high kinetic energy at the tail race of hydropower plants.

2.3 Water Wheels in Old Mills

The Restor Hydro database includes location, historical use, restorable conditions, expected mean flow and expected head, for historic weirs in EU+UK. Based on the design guidelines reported in S.M., the following design assumptions were made:

- for each site, the water wheel type was chosen depending on flow and head, and can be horizontal axis (four main types: overshot, middle breastshot, high breastshot or backshot, undershot) (Quaranta and Revelli 2018) and vertical axis type (Quaranta et al. 2021b);
- the maximum wheel width was 2 m for horizontal axis type (thus the exploitable flow rate was limited to this width, although installations with more than one wheel in parallel exist). The maximum diameter was fixed at 6 m for horizontal axis type (hence heads above 6 m were limited to 6 m) and 1.5 m for vertical axis type;
- when more wheel types are suitable, the most powerful one was chosen;
- if the flow is not known, it was assumed to be as equal to the flow that the selected wheel type can discharge, for a wheel width of 2 m;
- the overall plant efficiency was chosen based on the wheel type, as detailed in S.M., and typically ranged between 0.65 and 0.70;
- the ratio diameter/head (D_m/H) was chosen as equal to 4 for undershot wheels, 2.1 for middle breastshot wheels, 1.5 for high breastshot wheels and 0.9 for overshot wheels (Quaranta 2020).

Once that we elaborated all mills with available information on flow Q and head H (total data entries = 8,205), the results were generalized for each country by multiplying the average results by the total number of mills defined in moderate or advanced status (17,587 for the EU), including those with unknown characteristics. The analysis could be further extended to the whole recorded mill database (27,749 sites in EU). Mills in moderate condition are those where some visible remnants remain, e.g. a ruin or other historical building. River obstructions may exist that are in need of restoration or re-creation to bring the site back into service. An advanced condition means that in the site there is a complete, or almost complete, weir or other river blockage.

The cost of horizontal axis water wheels was calculated as $24,500 + 3,628 BD_m$ (€) including civil works (7,000– 20,000€), where B (m) is the wheel width and D_m (m) is the diameter; if civil works are excluded, the cost can be quantified as $19,000 + 2,420 BD_m$ (€) (see S.M. for further details). In this work we included civil works. Instead, for vertical axis water wheels, the cost equation proposed in Quaranta et al. (2021b) was used, excluding civil works.

The water wheel technology was chosen as it was present in the analyzed mills in the past (that means that the site is already conceived to host a water wheel) and because of its higher social acceptance and environmental sustainability. Other turbine types could be installed and, eventually, discharge more water.

2.4 WDNs and WWTPs

In Mitrovic et al. (2021), the hydropower potential in WDNs and WWTPs was calculated for Ireland, Northern Ireland, Scotland, Wales, Portugal and Spain, on the basis of

site-specific data from more than 8,800 locations. These included pressure reducing values, wastewater treatment plants and other locations within these systems suitable for hydro-power installation. The plant efficiency was considered as equal to 50%.

The hydropower potential from WDNs was found to be 2.89 kW per 1000 people in Scotland and 0.29 ± 0.12 kW per 1000 people in the other countries (excluding sites < 2 kW). This may be attributed to the fact that the Scotland territory is highly mountainous. Therefore, the meta-models represented by Eqs. (5) and (6) were derived and used in our analysis:

$$P_w = 0.29 \text{ if } e < 700 \text{ m a.s.l. or } 2.89 \text{ if } e > 700 \text{ m} \tag{5}$$

$$P_{ww} = 44.2p \tag{6}$$

where P_w is the power potential from WDNs for every 1000 people (kW/person), P_{ww} is the power potential from WWTPs (kW), p is the served population (million), and e is the elevation range of each Functional Urban Areas (FUA). A FUA consists of a densely inhabited city and of a surrounding area whose labour market is highly integrated with the city. The largest 671 FUAs in EU + UK were considered, with known population, representing half of the EU + UK population. The elevation e is defined as the difference between the maximum elevation and the minimum one (the Scottish FUAs of Glasgow and Edinburgh value is 751 m and 665 m, respectively). The annual energy generation was calculated multiplying the potential by 8,760 annual hours to obtain a maximum potential. Pumps as Turbines (PATs) are considered the most compact and cost-effective technology in this context (Novara et al. 2019). Furthermore, it must be noted that Eq. (6) refers to regions in non-alpine environment, and the coefficient would be 353 instead of 44.2 to well reproduce the Switzerland estimate of 9.3 GWh/y (9.3 GWh/y corresponds to 8760 h and 35% of average capacity factor, see Discussion section). Therefore, similarly to Eq. (5), these two coefficients were used based on the elevation range (Bousquet et al. 2017).

3 Results

3.1 DROR

Figure 1 shows the potential and the mean usable flow under different EF and plant density values; the left of each figure are those related to the more stringent EFs. By examining the EF effect, the hydropower potential at EF = 0.1% MAF is 2.5 times higher than

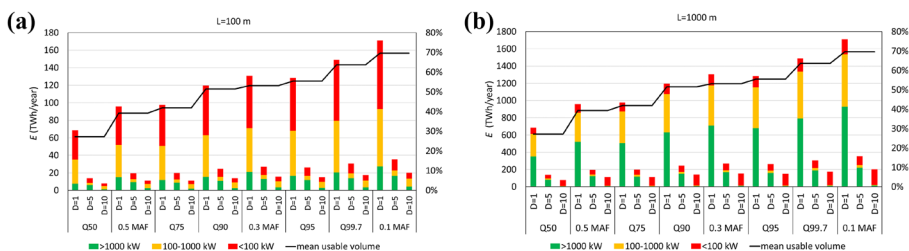


Fig. 1 Cumulative annual production at different EF and D values, for $L = 100$ m (a) and $L = 1000$ m (b). The EF value decreases from left to right, and the mean usable volume of water is shown on the right y-axis

Table 1 Effect of D and L : in the left, changes from the potential at $D = 10$ km ($E_{D=10}$) (for any value of L), and, in the right, from $L = 100$ m ($E_{L=100}$) to $L = 1000$ m ($E_{L=1000}$) at different D

Power class	$D = 10$ km	$D = 5$ km	$D = 1$ km	$D = 10$ km	$D = 5$ km	$D = 1$ km
$P < 100$ kW	$E_{D=10}$	$2 \times E_{D=10}$	$11.4 \times E_{D=10}$	$\frac{E_{L=1000}}{E_{L=100}} = 24\text{-}26$	$\frac{E_{L=1000}}{E_{L=100}} = 8.1$	$\frac{E_{L=1000}}{E_{L=100}} = 2.2$
$100 < P < 1000$ kW	$E_{D=10}$	$2/3 \times E_{D=10}$	$22/3 \times E_{D=10}$	$\frac{E_{L=1000}}{E_{L=100}} = 0.7$	$\frac{E_{L=1000}}{E_{L=100}} = 5.0\text{-}5.2$	$\frac{E_{L=1000}}{E_{L=100}} = 9.2\text{-}9.5$
$P > 1000$ kW	$E_{D=10}$	$3.9\text{-}5 \times E_{D=10}$	$6.2 \times E_{D=10}$	$\frac{E_{L=1000}}{E_{L=100}} = 3.0\text{-}4$	$\frac{E_{L=1000}}{E_{L=100}} = 13.2\text{-}13.6$	$\frac{E_{L=1000}}{E_{L=100}} = 35 - 45$

at $EF = Q_{50}$, that represent the least and most stringent constraint, respectively. $EF = 0.1MAF$ provides the highest annual generation, in agreement with Kuriqi et al. (2019). Results also show that the potential is not so much affected by the EF as it is affected by the D and L (Table 1). The trend of the production versus D is always decreasing, except for the class within 100–1000 kW, whose potential increases from $D = 5$ km to $D = 10$ km as a number of plants shift from above to below 1000 kW. The effect of L is linearly correlated with the production, as expected from the linear increase of head difference with withdrawal length that we assumed. With $L = 100$ m, the majority of the plants have a power < 100 kW, while for $L = 1000$ m the majority have a power > 1000 kW.

Investment costs can be estimated from Ogayar et al. (2009) between 1500 €/kW and 3700 €/kW depending on head and power, and between 0.04 and 0.2 €/kWh (IEA 2021). Costs decrease with the head, since for a certain power the equipment is smaller.

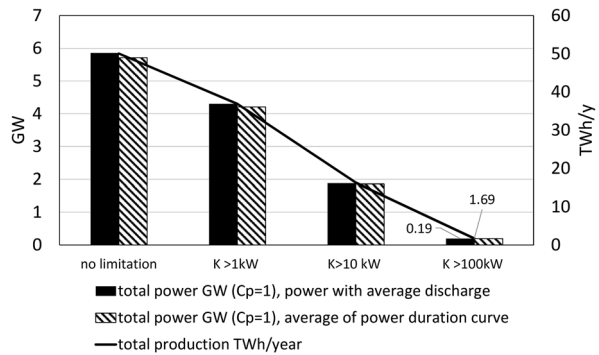
3.2 Hydrokinetic Turbines

For the estimation of hydrokinetic potential, results are shown in Fig. 2 considering different power classes: $K < 1$ kW, $K < 10$ kW, $K < 100$ kW and $K > 100$ kW, where K is the available hydrokinetic power. Figure 2 also shows as using the power duration curve or the power with the average flow does not affect appreciably the results. By assuming $C_p = 1$ and the full exploited river width, the gross hydrokinetic power potential is 5.7 GW. Considering $C_p = 0.3$ and 25% of the river width occupied by the HT array, the potential reduces to 0.43 GW. In an analogous way, the annual hydrokinetic energy potential corresponds to $0.43 \cdot 8,760 = 3.75$ TWh/y, assuming that the turbine is in operation for the whole year (8,760 h).

However, a cost-effective solution should ensure a minimum installed power in order to produce sufficient energy to pay for the investments (e.g., $P > 15$ kW in dos Santos et al. 2019), as very small plants still require a minimum of civil works, and the turbines have a minimum cost that may largely exceed the revenues. Therefore, considering the class $K > 100$ kW, i.e. $P = 7.5$ kW (with $C_p = 0.3$ and 25% of river cross section exploited), the power potential reduces to 0.19 GW (energy potential of 0.17 TWh/y). Considering $K > 10$ kW, thus accepting local installations for private purposes ($P = 0.75\text{-}1$ kW, with $C_p = 0.3$ and 25% of the river width), the power potential becomes 1.85 GW and 1.2 TWh/y of annual generation.

Although the costs for HTs are difficult to estimate (dos Santos et al. 2019), assuming an average installation cost $C = 5,000$ €/kW (Kirke 2019; Munoz et al. 2014), we may expect a payback time of 5.7 years with an operation of 8,760 h/year, for an energy price of 0.1 €/kWh (assumed representative of EU conditions, see S.M.). A LCOE cost of 0.04–0.1 €/

Fig. 2 Power and energy potential for different hydrokinetic power classes



kWh, and 0.3–0.8 \$/kWh, can be assumed for a single or array installation, respectively (see S.M. for further details).

3.3 Water Mills, WDNs and WWTPs

From the Restor Hydro database, the total number of mills is 27,749, and 17,587 are in moderate or advanced status. 8,205 mills are with known data and were used to perform the calculations, whose results were then linearly extended to the 17,587 mills. Table S.M.1 in the S.M. shows the results per member state. The average installed power is 13 kW and France is the country with the largest presence of registered mills. The potential from the 17,587 usable mills is 0.18 GW, and 1.59 TWh/y considering 8,760 h of annual operation. This potential was calculated by assuming the use of the existing structures of the mills, minimizing civil works, thus it can be considered a cost-effective potential. Considering to install water wheels also at the degraded mills (that, anyway, in the past hosted a water wheel), the potential almost doubles, since we should consider 27,749 sites instead of 17,587 sites.

The most used type is the breastshot type, because breastshot wheels are those that can be used in the widest range of conditions of head and flows. The average power is 14.4 kW, 12.9 kW, 21.7 kW, 6.45 kW and 1.30 kW for undershot, breastshot, backshot, overshot and vertical axis water wheels, corresponding to 16%, 30%, 16%, 17% and 21% of total installations. Figure 3 shows the cost per kW as a function of the installed power; the total investment cost is 0.89 billion € for the total usable mills, and an average cost of 4,800 €/kW. The overshot wheel is the type with highest installation cost per kW (7,900 €/kW). Payback times can be estimated assuming an average tariff of 0.10 €/kW (see S.M.) and 8,760 h of operation per year. Payback time ranges between 4 to 6.5 years for undershot wheels, 4 to 9 years for middle breastshot, 3 to 5 years for backshot, 5 to 16 for overshot wheels and 1–3 years for vertical axis wheels.

By applying the metamodels derived in Mitrovic et al. (2021) to the 671 FUA, the estimated potential in WDNs and in WWTPs is 3.0 TWh/y and 0.38 TWh/y, respectively. Use of existing infrastructure replacing pressure reduction valves would imply an average cost of 5,000 €/kW (Garcia et al. 2019; Corcoran et al. 2013), and a payback time between 2 and 10 years (Garcia et al. 2019). Hydropower in WWTPs generally costs 0.1–0.3 €/kWh (Bousquet et al. 2015, 2017).

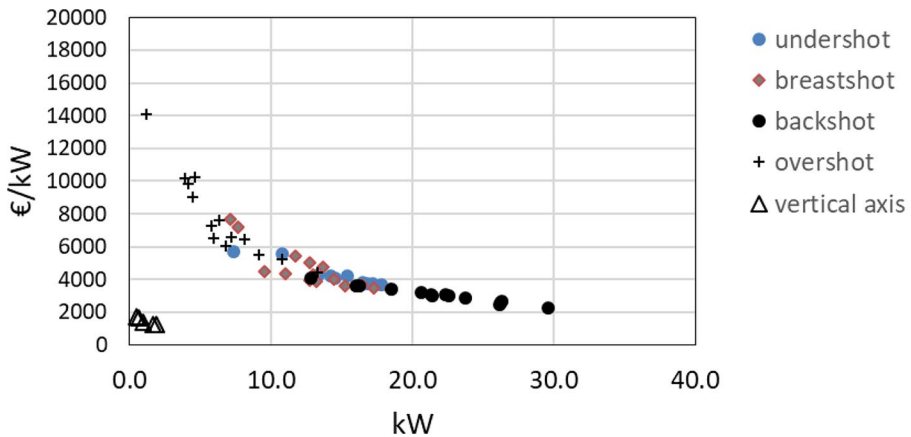


Fig. 3 Estimated investment costs of water wheels. The vertical axis ones do not include civil works

Table 2 summarizes the results and related investment costs, specifying which kind of potential we are referring to (technical or economic). In general, investment costs of SHPs are comparable with those of the other renewable energy sources (S.M.6). The economic potential is the potential that can be developed cost-effectively, while the technical one simply considers the potential that can be developed based on the available technical knowledge, thus it is higher than the economic one. Both potentials reduce when considering environmental constraints.

4 Discussion

Environmental constraints affect small DROR hydropower potential at a large scale, from 79 TWh/y to 1,710 TWh/y. This large variation indicates that the potential for small hydropower is strictly dependent on the objectives of environmental protection set in the permitting of plants. Our estimates consider the actual FDC for each plant, and, correspondingly, 8,760 h/year. However, our estimates suffer from some uncertainty in the hydrological data and the effects of climate change on the hydrology. For example, climate change may reduce the ROR production in alpine environment by 3% (Patro et al. 2018).

Gernaat et al. (2017) estimated that the economic potential is 60% of the technical one for Europe. When considering environmental constraints ($EF = 0.3MAF$) the potential is 70% of the not-constrained one. ESHA (2012) estimated that the EU technically feasible SH potential is 150 TWh and the residual potential available for development is about 50 TWh, that would reduce to 105 TWh and 35 TWh, respectively, when considering environmental constraints according to Gernaat et al. (2017). Therefore, from literature data, the residual potential of SH in EU can be roughly estimated to be below 35 TWh with $EF = 0.3MAF$, although it is not known if this potential already includes the micro hydropower potential in existing infrastructures (the current ROR generation from SH in EU is 47 TWh from Quaranta et al. (2021a), elaborating data of European Commission database, de Felice (2020), also including large plants). The additional potential from the modernization

Table 2 Summary of hydropower potentials and related investment costs

Number	SH technology	Estimated overall potential (TWh/y)	Comment on the potential	Investment costs
1	DROR	79–1,710	Technical potential including environmental constraints. It is 354 TWh/y with $L = 1,000$ m, $EF = 0.1$ MAF and $D = 5$ km, 65% overall plant efficiency, 8,760 annual operating hours and using the FDC. The residual potential has been estimated in literature to be < 35 TWh/y in EU.	1,500–2,000 €/kW, $P > 1,000$ kW 1,700–2,700 €/kW, $250 < P < 1,000$ kW 2,500–3,700 €/kW, $P < 250$ kW 0.04 and 0.2 €/kWh
2	HTs in rivers	0.17–1.2	Lower and upper limit of the economic potential. assuming $C_p = 0.3$ and 25% of the river cross section exploited, 8,760 annual operating hours and the FDC, in EU. However, local limitations (minimum water depth and minimum flow velocity) are not considered due to technological development that HTs can face in the future. HT potential at the tailrace of large hydropower plants was not considered, and under investigation.	Average 5,000 €/kW 0.04–0.1 €/kWh (single installation) and 0.3–0.8 €/kWh for a HT array
3	Water wheels in old mills	1.6	Economic potential. At old mill sites. It may be higher because the database does not include all the European mills. Plant efficiency assumed around 70%, depending on the wheel type, 8,760 annual operating hours and average flow. EU+UK.	Average 4,800 €/kW including civil costs 7,000–20,000 € that may not be necessary at old mill sites, thus costs may be overestimated of 1.3–1.5 times in certain cases
4	PAT in pressurized WDNs and in WWTPs	3.0 + 0.38	Technical potential. Plant efficiency 50%, 8,760 annual operating hours. EU+UK.	Use of existing infrastructure replacing pressure reduction valves. Average 5,000 €/kW (Garcia et al. 2019; Corcoran et al. 2013) 0.1–0.3 €/kWh for WWTPs (Bousquet et al. 2015, 2017)

of the existing hydropower fleet was estimated to be +8% of the current one at the EU scale (Quaranta et al. 2021a).

The potential of HTs in rivers ranges from 0.17 TWh/y to 1.2 TWh/y considering installed power above 7.5 kW and 0.75 kW, respectively, with $C_p = 0.3$ and 25% of the occupied river cross section. We did not consider technical requirements, i.e. that local flow velocities must be above a certain limit (0.5–1 m/s) for a good operation and self-starting of the HT, and that a minimum water depth is required to install HT with enough dimensions. However, it is expected that the requirements of future optimized HTs will be less stringent due to the continuous improvement of this technology, e.g. variable pitch HTs or new bearing types. Hydrokinetic turbine development may be especially relevant for hydrokinetic exploitation of tidal flows (Yuce and Muratoglu 2015) and at the tailrace of large HPPs (Liu and Packey, 2014). The payback time is 5.7 years considering an installation cost of 5,000 €/kW. Maintenance costs were excluded, but can be assumed to be 800 USD/year, with a discount rate of 10% (Munoz et al. 2014), due to the difficult operating environment (local scour and morphological alterations can also be induced by HTs, Hill et al. 2016; Tang et al. 2019). A 5 kW HT would be more competitive with respect to a 5 kW wind turbine if the lifetime of the 5 kW HT is higher than 9 years, and more competitive than solar or diesel generators of the same power (Munoz et al. 2014).

The potential of water wheels in old mills was estimated at 1.6 TWh/y, with a payback time between 1 and 16 years, depending on the wheel type and on the site conditions (if civil works are not needed, costs reduce by 1.3–1.4 times). The potential 1.6 TWh/y is approximately 1/5 of the 8.7 TWh/y estimated by Punys et al. (2019), who studied all the historic non-powered sites from the Restor Hydro project database (64,910 sites), while Kasiulis et al. (2020) studies this for the Baltic States (the potential electricity generation from 835 existing watermill sites in the Baltic States was estimated at 185.6 GWh/y). The installed power of water wheels is generally limited below 30 kW (Fig. 3), so that the plant overall cost usually remains below 70,000 €. Furthermore, water wheels in old mills contribute to the promotion of the cultural heritage, social activities, small economies based on local production sales, and tourism development in the area (Hognogi et al. 2021; Quaranta et al. 2021b). Water wheels exhibit good ecological behavior (Quaranta and Wolter 2020), but with possible acoustic impacts (Quaranta and Müller 2021). The Restor Hydro database provides the mean flow, thus we considered 8,760 h for the estimation of the potential. However, no information is provided on the maximum flow. Since water wheels are generally designed with a design flow slightly below the maximum one, their dimensions here estimated may be smaller. Nevertheless, we expect a small influence on our results, because water wheels can handle large flow variations with high flexibility, and the flow in mill channels is generally quite constant. In this study we only considered mill-related barriers, excluding all the other small barrier types that host additional hydropower potential (5.2 TWh/y according to Punys et al. 2019). We did not consider sites falling into Natura 2000 areas: on average, 18% of the total number of historic sites fall into Natura 2000 areas, and if national protected areas are considered, this percentage increases to 25% (Punys et al. 2019).

The potential in WDNs was estimated as 3 TWh/y, and the average investment cost can be assumed 5,000 €/kW. The cost of hydropower plants in WWTPs can be assumed ranging between 0.1 and 0.3 €/kWh (Bousquet et al. 2015), with a potential of 0.38 TWh/y in the EU+UK. We considered 8,760 of annual operating hours: for WDNs this can be considered quite reasonable, since the flow is almost constant throughout the year, while the average capacity factor of SHPs in WWTPs is 35% (Llácer-Iglesias et al. 2021). Therefore, the hydropower technical potential from WWTPs in EU+UK reduces to 136 GWh. The

Table 3 Hydropower potential (GWh) from literature and that estimated in our study within the parenthesis. As additional example, Gruppo CAP has installed 0.45 kW every 1000 people (60 kW) in the North of Italy

Country	WDN	WWTP	Reference
Ireland	13.7 – 30.4 (58)	1.8 (1)	Mitrovic et al. (2021)
France	188.6 – 548.8 (377)	25.3 (16)	Mitrovic et al. (2021)
Portugal	29.6 – 65.5 (30)	4.0 (2)	Mitrovic et al. (2021)
Spain	135.7 – 300.3 (583)	18.2 (11)	Mitrovic et al. (2021)
Wales + Scotland + North Ireland	29.9 – 152 (70)	4 (2.06)	Mitrovic et al. (2021)
Fribourg (Switzerland)	118 (99) MWh		Samora et al. (2016), but using $\eta = 0.5$
Dublin	5.6 (13.7)		Corcoran et al. (2013), but using $\eta = 0.5$. In Corcoran et al. (2013), sites below 20 kW were not considered, that may add 3 to 4 GW/hy

known developed potential in EU WWTPs is 27 GWh, and 42 GWh including Switzerland (Llàcer-Iglesias et al. 2021). It must be noted that a hydropower plant in a WWTP is economically feasible if its installed power is typically above 3 kW (detail that cannot be taken in our large scale study, where large urban areas are considered for the computation rather than each catchment associated to a potential WWTP in each city). Table 3 shows a comparison between results estimated in our work and literature results, showing that our assessment is accurate within a factor 2. We did not consider pressurized irrigation networks, whose potential was quantified in 0.08 kW/ha, or 2995 kW (6.11 GWh/y, or 0.167 MWh/ha), for 177 sites located in Spain and Portugal (Mitrovic et al. 2021), and the hydropower potential in industries and fish farms, that for example can reach 19 GWh/y in Spain (Mérida García et al. 2021).

5 Conclusions

We estimated the technical potential of DRORs under different scenarios of environmental flow and allowed spatial density of plants, showing how environmental constraints can limit hydropower development at the EU scale to a very significant extent. Our representation of EF is highly schematic, and it is possible that a better compromise between ecosystem protection and energy generation can be found when looking at local situations. Among the various scenarios, the one with $L = 1,000$ m, $EF = 0.1$ MAF and $D = 5$ km yields a potential for small DROR hydropower plants of about 354 TWh/year, including that already developed. In comparison, according to Climate Target Plan analyses (FF55-MIX scenario) wind and solar will increase by 490 and 290 TWh by 2030, respectively.

The second part of the study was focused on estimating the potential of low-impacting micro hydropower technologies and hidden opportunities in existing facilities. We only quantified the potential in terms of energy generation, but they also contribute to R&D, new market opportunities and valorization/optimization of local and existing resources and structures. The economic potential of hydrokinetic turbines in rivers was estimated ranging between 0.17 TWh/y and 1.2 TWh/y. However, despite the performance increase that can be achieved in the future, the potential in undisturbed rivers remains limited, while installations may be of interest if local resources are used, when flow conditions are favorable (e.g. at the tailrace of large hydropower plants the potential may be more relevant) and in specific remote contexts. The economic potential of water wheels in old mills (only considering those in good status) was estimated at 1.6 TWh/y, but the real potential may be higher since water wheels could be installed at any suitable small weir, and the database considered here does not contain all the EU water mills. Significant obstacles to water wheel installations may be long bureaucratic processes for the water concession (despite the small available power) and the need for large diameters, while the possible acoustic impact due to their free surface operation can be mitigated by engineering solutions. On the other side, the retrofitting of old mills can generate additional incomes and benefits not quantified here, e.g. the valorization of the cultural heritage, tourism and electricity for local and remote activities. We only considered mill-related barriers, and other historic weirs could host 5.2 TWh/y. The hydropower potential from WDNs and WWTPs was estimated at 3.38 TWh/y. Some civil infrastructures are already in place and electricity can be used to drive local activities (e.g. remote control of the network), with an almost stable and well predictable production. We did not consider pressurized irrigation networks and hydropower potential from industrial flows and fish farms, that, although may add few hundreds of GWh/y (according to some literature data), can generate local benefits and market opportunities. Therefore, hidden opportunities in existing facilities

should not be simply considered in terms of energy contribution at the large scale, but their multi-purpose benefits should be considered a relevant aspect for the optimal use of water resources and existing infrastructures, while contributing to renewable energy and smart grid development, and without adding substantial impact to the environment.

While this study does not replace specific assessments at the regional and local scale, we show that small hydropower comes with a small but appreciable potential of renewable energy generation. Additional benefits are here discussed, but not specifically quantified. The bulk of this potential is borne by small DROR plants, whose development often conflicts with other environmental objectives and requires defining compatibility criteria for their siting, implementation and operation. This study will help policy makers and environmental authorities in setting the optimal strategies and policies to find the optimal compromise between hydropower development and impact mitigation. Investment costs were also discussed based on literature data, providing a reasonable order of magnitude of required investments.

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Authors Contributions E.Q. and A.P. carried out the calculations, wrote the paper and coordinated the research. In particular, EQ performed the analysis of water wheels and hydropower in WDNs and WWTPs, and the applicability of technologies. AP developed and applied the GIS models for small hydropower and HT potential. All the other authors revised the paper and supported with their experience and literature studies the assumptions of the calculations. E.K. wrote the last section of the Supplementary Material.

Availability of Data and Materials Authors agree with data transparency.

Declarations

Ethical Approval The authors undertake that this article has not been published in any other journal and that no plagiarism has occurred.

Consent to Participate The authors agree to participate in the journal.

Consent to Publish The authors agree to publish in the journal.

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