A clean energy source: Assessing the energy potential of retrofitting the European hydropower fleet

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Abstract

About 50% of all hydropower plants (HPPs) worldwide were originally commissioned more than 40 years ago, so that the advanced age of the fleet is a major concern across all continents, and especially in Europe. The retrofitting of HPPs can generate several benefits for production, flexibility, safety, management and environment. In this work, the benefits related to energy and flexibility were considered and quantified by conducting a large-scale assessment for the

European Union and Europe, taking into account several retrofitting strategies: dam heightening, head loss reduction in waterways, increase of installed power in run-of-the-river and storage power plants, increase of annual inflow, increase of maximum efficiency and weighted efficiency of electro-mechanical equipment, start and stop improvement, digitalization and inflow forecast, floating photovoltaic and reservoir interconnection. For most of these strategies, an indicator of the additional capacity and/or annual production that could be obtained compared to the current conditions was calculated. Excluding site-specific strategies (e.g. installation of new parallel waterways, increase of withdrawals from existing intakes) the resulting compound value of the indicator is 10.2% for European Union and 12.2% for the whole Europe, plus 4-28.6 TWh achievable by interconnecting reservoirs. This suggests that the retrofitting of HPPs can generate significant benefits in terms of energy and flexibility, minimizing environmental impacts, and should be considered as an important element of both energy transition and water management policies.

Keywords

dam; digitalization; flexibility; refurbishment; turbine; upgrade; water-energy nexus.

CF = capacity factor
d = dam height (m)
E = energy (TWh/y)
H = head (m)
h_p = number of hours at part load
h_p = part load hours
h_v = operating hours calculated from CF
NC = nominal capacity (MW)
P = installed power (MW)
Q = volumetric flow rate or discharge (m^3/s)
V = reservoir volume (m^3)
ΔE_{id} = indicator value (%)
η = efficiency (-)
η_w = weighted efficiency (-)

Acronyms

BEP = best efficiency point
BHA = British Hydropower Association
CFD = Computational Fluid Dynamics
EU = European Union

ESHA = European Small Hydropower Association
EPRI = Electric Power Research Institute
FPV = floating photovoltaic
HP = hydropower
HPP = hydropower plant
IEA = International Energy Agency
IHA = International HydropowerAssociation
JRC = Joint Research Center
PAT = Pump as Turbine
PHS = pumped hydropower storage
PV = photovoltaic
ROR = run of river power plant
SFOE = Swiss Federal Office of Energy
SPP = storage/reservoir power plant
VLH = very low head
WFD = Water Framework Directive

1 Introduction

In 2019, the global installed power of grid-connected hydropower (HP) reached 1308 GW, including 158 GW of pumped hydropower storage (PHS), with an annual generation of 4306 TWh (IHA, 2020). Hydropower also provides 509 MW off-grid hydro electrification services, representing 7.75% of the currently installed distributed electrification capacity, mainly in Africa (31.8%), South America (30.3%) and Asia (25.0%) (Kougias, 2019). Figure 1a depicts the hydropower share, with installed power and annual generation, for each continent, including Europe and the European Union (EU)[1], that are the geographic focus of the present study. East Asia is the continent with the highest hydropower capacity, while the global leader is China with an installed power of 356 GW, 30.3 GW of which are provided by Pumped Hydropower Storage plants (PHS), and an annual generation of 1302 TWh/y.

In 2019, 15.6 GW (1.19% of the global hydropower capacity) of large hydropower (>10 MW) were added (IHA, 2020) and 3.6 GW were under construction in Europe, excluding Turkey (Fig.1b). Although hydropower development in Europe has been relatively slow since 2000, especially in the EU due to the introduction of the Water Framework Directive 2000/60/EC

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[1] Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden. Europe also included (from IHA, 2020): Albania, Andorra, Belarus, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Greenland, Iceland, Kosovo, Liechtenstein, Macedonia, Moldova, Monaco, Montenegro, Norway, San Marino, Serbia, Switzerland, Turkey, Ukraine, United Kingdom.

(WFD) and more restrictive national legislation to preserve the ecological status of European surface waters, hydropower development has not stopped (Kougias, 2019), with a peak in 2011 of almost 10 GW of developed capacity (Figure 1b). The continuous development is due to the benefits of hydropower schemes, especially in terms of ancillary services and water control. In fact, hydropower storage capacity and hydropower flexibility enable electricity to be supplied on demand and to adapt the operation to the grid requirements. In addition, storage capacity allows to better face the modifications of the hydrological regimes and the floods exacerbated by climate change. Therefore, the role of hydropower in the future will be crucial, not least in the context of energy transition and phasing out of combustion-based technologies, which will mainly be replaced by volatile renewables like wind and solar. It is estimated that the HP installed capacity should grow by around 60% by 2050, generating 600,000 skilled jobs over the coming decade for an estimated investment of US$ 1.7 trillion (IHA, 2020).

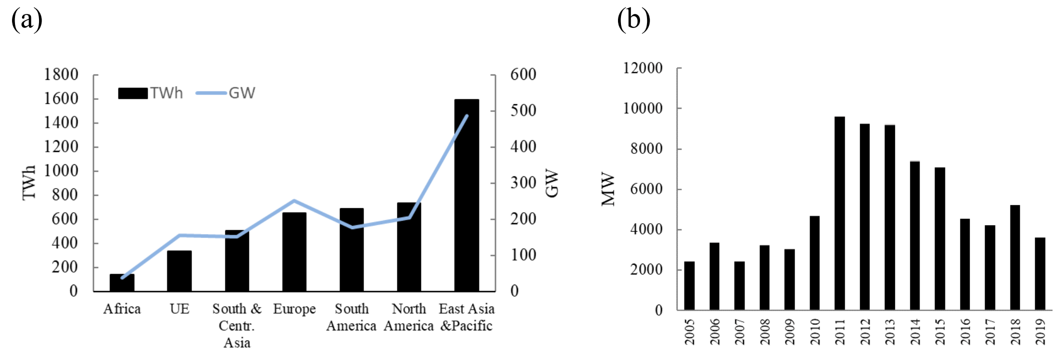

Figure 1. (a) Installed hydropower capacity (GW, right vertical axis) and annual hydroelectric production (TWh, left vertical axis), in 2019, IHA (2020); (b) Installed power in MW under construction since 2005 in Europe (according to World Atlas & Industry Guide 2020, Hydropower & Dams).

However, although a typical hydropower plant (HPP) has an operating life of more than a hundred years if maintained regularly, Fig.2a shows that almost 50% of all hydropower plants worldwide were originally commissioned more than 40 years ago. Hence it is clear that the advanced age of the hydropower fleet is a major concern worldwide (Andritz, 2019) and that the hydropower modernization has a strategic importance at the global scale, especially when considering the above-discussed hydropower benefits. Some examples of the strategic importance of the hydropower modernization can be found in Goldberg and Espeseth Lier (2011) and Van Vuuren (2017) for the African context, in Cohen et al. (2002) for the Ukrainian context, in Lia et al. (2017) for Norway, and in de Podestà Gomes and Bajay (2014) for the Brazilian context.

Uria Martinez et al. (2021) discussed unit expenditures on hydropower and Pumped Hydropower Storage (PHS) power plants modernization and fleet age, showing that Europe has spent more than Africa and some areas of Asia, but less than the other countries, so that it is expected to see an increasing need for the future. Uria Martinez et al. (2021) also showed that only 20% of the European hydropower fleet has been modernized in the last forty years, at an average cost of 50 $/kW (PHS) and 125 $/kW (HPPs without pumping). The European Union (EU) fleet presents a similar situation, as shown in Fig.2b, where the number of hydropower stations commissioned and retrofitted over a 120-year period is presented at a 10-year time-step. The commissioning of the most EU hydro fleet occurred in 1970-1980, with a current HPP average age of 46 years. This estimation does not take into consideration the 18% of the stations that have been modernized, in agreement with the 20% estimated in Uria Martinez et al. (2021) for all of Europe. Assuming that the modernization comes close to a complete overhaul of the HPP, making the year of retrofit a new commissioning date, the average age of the fleet has then decreased by 4 years, to 42 years. This small reduction is due to the fact that approximately half of the interventions took place before 1990. Therefore, under the current market conditions and legislation constraints, modernizing the existing hydropower fleet is of particular interest in the European context, especially when compared with the environmental impacts and conflicts related to the construction of new HPPs on pristine and unregulated rivers.

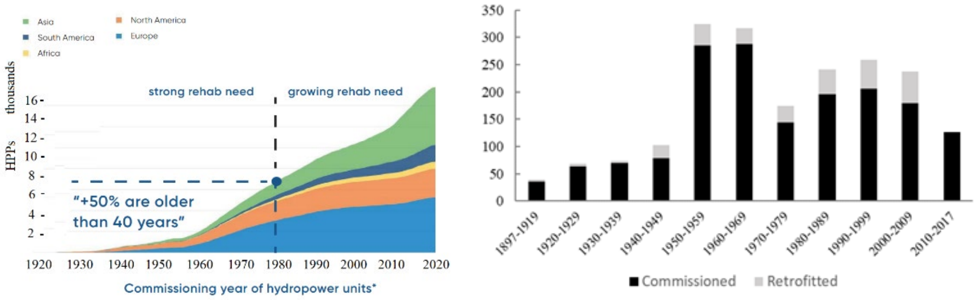

Figure 2. (a) Commissioning year of hydropower stations, cumulative curve (Andritz Hydro, 2019); (b) Hydropower development and retrofitting in the EU, Kougias (2019).

In the context of hydropower modernization, different strategies can be distinguished, depending on their invasive level: retrofitting, upgrading and refurbishing. Retrofitting consists of using recent technologies to improve plant performance, such as control scheme, fault protection, digitalization and monitoring, automation of some auxiliary equipment, and even changing some parts of important equipment, thus improving insulation, which increases the efficiency, while maintaining its capacity. On the other hand, upgrading implies not only changing the side equipment, but also amending the main equipment. This can include the turbine or the generator, or the extension, like increasing inflow from tributaries and the height of the dam, as well as other actions aiming at improving the overall power plant capacity (Bortoni et al., 2019). Refurbishing also requires significant civil works for increasing, for instance, safety. In this work different practices aimed at retrofitting, upgrading and refurbishing are discussed, but retrofitting will be used as a general terminology.

Modernizing the existing HPPs would consolidate and further improve current energy production and grid flexibility (Adams, 2018), while extending the HP lifespan, addressing ownership and operational issues, and increasing the level of safety. Such interventions mainly need to focus on dams and dam safety, the electro-mechanical equipment (i.e. turbine, generator and other auxiliary equipment of the HPP/PHS as valves and gates, transformers, spill ways, trash-racks) and the associated control systems (Kougias et al., 2019). Also related civil infrastructures often need modernization in order to ensure the required plant operational safety especially in view of more severe natural hazards due to climate change. Permits for retrofitting interventions, especially if a concession renewal is involved, can often require the concurrent implementation of mitigation measures to improve the ecological footprint of the HPPs, e.g. improving fish and sediment passage and ecological flow release, as stipulated in the requirements for hydropower in relation to the EU Nature legislation (EU Directorate-General for Environment, 2018) and in the WFD. The modernization can also allow to adapt the HPP operation to the new conditions imposed by climate changes (e.g. the reduction of water availability in some countries, or to be able to use the increased inflow due to climate changes).

Among the different benefits that hydropower modernization can bring, in this study we focused on the energy-related ones, i.e. annual generation and flexibility. The other benefits, e.g. impact mitigation and security, were discussed but not quantitatively addressed. The objective is a screening level quantification of the energy benefits potentially brought by developing hydropower retrofitting as a mainstream solution and a comprehensive strategy at the large scale. This study aimed at posing the basis for future studies and to identify the relevance of the problem in the energy context. T**he performance improvement by cascade operation** and interconnected operation, a strategy for a flexibility improvement within an interconnected market (partially discussed in Gimeno-Gutiérrez and Lacal-Arántegui, 2015), was not here assessed[2]. Different retrofitting practices were investigated (see Method section) and applied at the European and EU scale, considering the hydropower fleet characteristics. For each action an indicator was quantified to show its weight/relevance and its potential contribution at the European and EU scale. The novel technologies that can be implemented for each retrofitting practice, with some case studies, are discussed in the Supplementary Material, that was not conceived to discuss the technical details of these technologies and methodologies, but to derive reasonable and engineering robust assumptions for a bulk assessment of their related energy benefits. In the Method section the main actions that can be implemented to improve the HPP operation within the energy context are reviewed and discussed, and the characteristics of the European hydropower fleet are presented.

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[2] This is not really an issue since there are very few cascade hydropower schemes in Europe which do not belong to the same operator. A cascade hydropower owned by the same operator is today exploited systematically in a coordinated way in order to maximize generation and benefits in view of market demand.

2 Method

Identification of retrofitting actions

Different retrofitting practices can be identified, and classified depending on which terms in Eq.1, expressing the annual production of a hydropower plant, they influence:

$$E = \frac{1}{1000 \cdot 3600} \int \rho g Q H \eta \, dt \quad (1)$$

where E (kWh) is the annual production, ρ=1000 kg/m^3 is the water density, g =9.81 m/s^2 is the acceleration due to gravity, Q is the usable discharge (m^3/s), H is the net head (m), η is the efficiency of power plant equipment and dt is the time step (s). Equation 1 is only a means used to classify the considered retrofitting actions (Q-strategy, H-strategy, η-strategy, t-strategy), since each retrofitting action does not affect the annual production alone. Another relevant metric used in this study is the capacity factor *CF*, defined as the ratio of annual energy production to the energy that would be generated if the plant would always operate at its nominal capacity. For example, the average (*CF*) in Europe is 0.35 (excluding pumped hydro) with significant variations among countries (Kougias, 2019), e.g. in Norway it is 0.5.

Based on the terms in Eq.1, the selected retrofitting actions that can be applied to a certain stand-alone HPP are listed in Tab.1. Table 1 also specifies whether each action involves an increase of nominal capacity (NC+), i.e. an increase in water inflow or geodetic head difference. The identification of these actions was carried out by the authors through a consultation organized by the European Commission Joint Research Centre, focused on discussing hydropower retrofitting procedures, their maturity, challenges, innovative tools and knowledge gaps relevant to their further development. Table 1 also lists some potential impacts upon the aquatic ecosystems related to some typologies of retrofitting interventions. It has to be noticed that for interventions on the dam structures (e.g. dam heightening) or variations in the inflow rate, environmental impact assessment procedures and/or a revision of the current water licenses might be applicable, requiring the implementation of a set of mitigation measures in line with the provisions of the Water Framework Directive – WFD- (such as fish passage solutions, ecological flows, environmentally enhance turbines, e.g. Hogan et al., 2014 and St. Germain, 2018, hydropeaking mitigation measures, e.g. Pérez-Díaz et al., 2012) that could affect the potential increase in energy production and storage capacity. However, a quantification of the energy production losses due to the implementation of these ecological measures is site-specific and cannot be generalized, and therefore, this element was excluded from the assessment.

In order to obtain a quantitative estimation of the energy benefit for each action, the indicator ΔE_{id} was calculated as the ideal increase in the annual production (expressed in % on the present energy production) that could be technically delivered, independently from the market demand and considering all the other conditions to be constant, or analogously, as an increase of the available power that can be used to satisfy the peak demand periods. The value of ΔE_{id} must not be strictly seen as the secure production that will be certainly generated after the action implementation, since the production strictly depends on the available inflow and partly on the market, whose variability will increase in the future. Nevertheless, ΔE_{id} is a robust and physically justified indicator to quantify the potential energy benefits. The higher ΔE_{id} is, the higher the flexibility improvement can be, hence the capacity of producing on demand in high peak periods and for few hours. The current energy production was selected as 360 TWh/y when examining the EU context, and 620 TWh/y for Europe (Kougias, 2019 and IHA, 2020, average of the last five years).

Table 1. Retrofitting actions considered in this work. NC=nominal capacity, u/s=upstream, d/s=downstream. Different HPP types: storage- SPP-, run of river –RoR-, pumped storage –PHS.

Retrofitting action	Notes	Applicable to/ effective at	Main note on production benefit	Additional benefits	Main environmental impacts on the aquatic ecosystem
Dam heightening Supplementary Material 1	NC+ *H*-strategy Increase of nominal capacity	Concrete and embankment dams in mountain regions with hydraulic head of the connected HPPs > 300 m, and open loop PHS plants	Head increase of 2% for a mean dam heightening of 10%. For PHS, only the flow related to the natural runoff should be considered.	Increase of storage volume by 20-30%, allowing to shift more water from one to another season	Construction phase: reduced reservoir level for (parts of) the duration of the works U/s: submergence of riparian areas (impacting related vegetation and habitats) due to the increased water levels; slight reduction of the available lotic habitats along the river reach u/s of the dam D/s: flow regime alterations (timing) in the river reaches d/s of the powerhouse
Reduction of head losses in waterways and penstocks Supplementary Material 2	*H*-*Q*-strategy	SPP plants	Power increase up to 11.6% has been achieved. A value of 5% was assumed.	Damage reduction	Flow regime alterations in the side tributaries due to the increased water withdrawals and in the river reach d/s of the powerhouse (entity and timing)
RoR: increase of installed power (new and/or additional machines) at turbines Supplementary Material 3	*Q*-strategy NC+	For RoR plants without water diversion depending on the number of days for which inflow exceeds nominal i.e. installed discharge capacity	Increase of generation due to reduction of spilling over weir during wet season. Gain depending on the shift of the installed turbine discharge capacity in the inflow duration curve. 5% to 20% for RoR built before 1960.	Flexibility. Increase of power during about 1 hour per day if RoR are installed in series on large streams	n.a.
SPP: Increase of installed power by adding a new parallel waterway system with a new powerhouse	*Q*-strategy NC+	PHS and SPP	Typically, the installed power at high-head SPP can be more than doubled by strongly reducing operation hours per year (typically reduced in projects from 2000 hours below 1000 hours per year)	Some minor gain (<2%) due to lower friction losses in new waterway systems.	n.a.

Supplementary Material 2					
Increase of annual inflow Supplementary Material 3	NC+ Increase of equipment size and hydraulic structure conveyance Q-strategy	Very site specific, needing concession renewal, and, due to climate changes (global reduction of water availability) and environmental constraints, it was not considered feasible at a large scale and not here quantified.	Generation increase but water withdrawal from the river	Increase generation during the peak periods (flexibility)	Variations in the inflow rate.
New electro-mechanical equipment for improved efficiency at BEP Supplementary Material 4	η-strategy	RoR, PHS and Reservoir plants that operate at BEP or full load most of the time	4-6% maximum ideal gain at Best Efficiency Point (BEP) replacing the old deteriorated turbine, depending on turbine type	More available power for peak demand periods	n.a. (no variations in the inflow rate)
More flexible electro-mechanical equipment Supplementary Material 5	η-strategy	RoR, PHS and Reservoir plants that often work at off-design conditions	The goal is to flat the efficiency curve, Francis turbines: weighted efficiency gain of 4-5%.	Damage reduction due to better flow behaviour, and flexible production	Temporary restoration of the “natural” flow regime in the watercourse during the works. Afterwards: n.a. (no variations in the inflow rate)
Start and stop improvement Supplementary Material 6	Increasing operating hours. Flexibility increase t-strategy	RoR, PHS and Reservoir plants	1 start and stop = 15 h of reduced life	Flexibility and less damages	n.a. (no variations in the inflow rate)
Digitalization and inflow forecast Supplementary Material 7	Increasing operating hours. Better control Q-t-strategy	RoR, PHS and Reservoir plants	1% efficiency increase, and increase of generation by a better inflow forecast	Flexibility, better control, inflow forecast and damage prevention	n.a. (no variations in the inflow rate)
Floating Photovoltaic (FPV) Supplementary Material 8	Evaporation reduction Q-strategy	Reservoir and PHS plants	10% of water surface covered would increase the hydro production by reducing evaporation of 70% on the covered area + additional production from the FPV (the latter was not here considered)	Increase of capacity factor	Alteration of thermal and photosynthetic processes related to solar radiation (reduction of the euphotic zone)

Among the Q- strategies, two situations must be distinguished. The first is the increase of the annual inflow, the second is the increase in the maximum flow that can be discharged during the peak hours, but concentrating it during a few hours and letting unchanged the average annual inflow. In both cases, the inflow increase would require an increase of runner size, conveyance capacity of waterways and new hydraulic structures to prevent eventual damages (Vereide et al., 2015; Nogueira et al., 2016). In the first case, the annual inflow extension from side tributaries, neighbor catchments, pumping and transfers among reservoirs will not be addressed here (although some case studies and benefits are provided in the discussion section for completeness), for the following reasons:

1) the annual inflow extension is strictly site-specific and depends on local legislations;
2) a global increase of inflow at the annual scale is only feasible where there are not flow limitations coming from the WFD or environmental legislations, and in countries where water availability will increase in the future (e.g., in Norway, by Lia et al., 2017), while at the global European scale the water availability (and related hydropower potential) is expected to decrease especially after glacier retreat (Terrier et al, 2011; Haeberli et al. 2016; Schaefli et al., 2019).

Instead, the second case would allow to make hydropower plants more flexible, in order to satisfy peak energy demands, to reduce or stop production when there is a surplus of variable renewable energy (VRE) and to reduce spilling during wet periods. This strategy is very site-specific, but an order of magnitude of benefits was proposed based on the author's expertise and literature.

With regards to the η-strategy, i.e. increasing the efficiency of the electro-mechanical equipment, it must be noted that hydropower industry faces an increasing demand of turbine designs that allow a wider range of operations (from deep part-load to full load). Therefore, current research trends aim at improving the overall efficiency on the wide operation range, rather than at the efficiency at Best Efficiency Point (BEP) or at a specific part load value. This overall efficiency is defined as weighted efficiency (Muntean et al., 2016). Supplementary Material 4 and 5 provide detailed information and literature results both for efficiency improvement at BEP and at off-design conditions, temporarily neglecting the weighted efficiency concept, while, in a second step, the results were discussed to derive a reasonable value of the weighted efficiency improvement to be considered as global η-strategy for the electromechanical equipment, rather than considering each operating range (BEP, part load and full load) separately.

As described in Tab.1, each action can be applied in certain contexts, i.e. in a certain HPP type and if equipped with a certain turbine type. Therefore, the following characteristics of the hydropower fleet were estimated in our study:

1) HPP type prevalence (RoR, PHS and SPP) and energy generation from each type. The size of the plant, i.e. small ($\leq$ 10 MW) or large (>10 MW) is only a matter of scale rather than a conceptual issue.

2) Turbine type prevalence (Pelton, Francis, Kaplan-Bulb) and energy generation from each type.
3) Operating hours.
4) Discharged flow rate, head.
5) Basin surface area.

Once the above mentioned five main characteristics are estimated, it is possible to calculate ΔE_{id} for each action described in Tab.1, considering the technical details of each action and the improved performance of modern technology.

In order to determine the above mentioned characteristics of the European Union (EU) and European HP fleet, the main source of information consulted in this study was an open source database (hydropower database) of 4030 European hydropower plants, 2429 of which are located in the European Union (JRC, 2020), with power generally above 1 MW and from now onward called hydropower database. The hydropower database specifies, for each HPP, the country, the type (RoR, SPP, PHS), the installed power (and pumped power for PHS[3]), the head (in most cases, but not for all), the annual energy generation and, for some of them, the reservoir volume. In this database, most of the EU HPPs are included, since the 2429 HPPs represent 130 GW out of the EU total of 155 GW, a statistically representative sample of the whole EU hydropower fleet (the missing 25 GW are related to small hydropower plants and to some countries where data are not available). Therefore, the results related to the above points, presented in relative terms (i.e. expressed in % on the total) and calculated considering the sample of 130 GW are expected to be valid for the whole EU fleet of 155 GW (e.g., the prevalence of RoR plants with respect to the total number of plants, see the Discussion section). The same analysis and calculation was then extended to the whole Europe, of which 194 GW are included in the database with respect to the currently installed 251 GW. The basin surface was instead taken from Hogeboom et al., 2018).

Since the EU hydropower fleet included in the database is almost completely known, the methodology in the following sections was described step by step only referring to the EU.

HPP type prevalence

In the last decade, the annual energy from hydropower in EU has oscillated between 335 and 400 TWh/year depending on the hydrological conditions with the average value being 360 TWh/year. 31.6 TWh come from PHSs (328.4 TWh/y are hence from pure hydropower) that, simultaneously, also consume 36.4 TWh for pumping (averaging the values of 2017, 2018 and 2019 from Eurostat statistics). When considering the 2019 data, 40 TWh are generated by PHS,

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[3] Within the PHS, it is possible to distinguish between closed loop PHS and open loop PHS. The former are made by two reservoirs without natural inflows, where always the same water volume is discharged or pumped. The latter are reservoir plants with an additional lower reservoir, from which (a part of) the discharged water is pumped back to the upper reservoir; the upper and/or lower reservoir either have a natural catchment and/or receive water from neighbouring catchments via intakes and water transfer systems. Since this is not specified in the hydropower database, the authors considered a PHS to be a closed loop one when the turbine and pumping installed power are substantially the same (the authors assumed a reasonable difference of 20% between the turbine and pumping power, to consider the lower pumping efficiency due to head losses).

out of which 56% (22.8 TWh) are mixed PHS (of which 43%, 9.7 TWh, are used for pumping) and 44% are from closed loop PHS.

By analyzing the hydropower database, the EU installed power of RoR, SPP and PHS is estimated in 21.5%, 43.7% and 34.9%, corresponding to 27.9 GW, 57 GW and 45.4 GW, respectively, for a total of 130.4 GW. Considering the size of the plants, 129 GW (99%) are associated to large ones (> 10 MW), 1.14 GW (0.85%) to plants between 1 and 10 MW, and 0.22 GW (0.15%) below 1 MW. For the remaining 25 GW not included in the database, it has been considered that for the whole EU hydropower fleet, 91.8 GW (59.2%) is hosted at large hydropower plants (HPPs) with a nominal power capacity exceeding 10 MW, while a total 10.7 GW (6.9%) is small hydropower (1–10 MW) and the remaining 3.6 GW (2.3%) refers to mini-scale projects (<1 MW), Kougias (2019). Autonomous producers operate 1.9 GW (1.2%), and the remaining of about 47 GW (30.3%) is pumped hydro (Kougias, 2019). In this way, Table 2 is obtained. When instead the focus is on Europe, the installed power is 251 GW (including 55 GW of pumped hydro), with an annual generation in 2019 of 653 TWh (IHA, 2020), and the power gap in the database (57 GW) was filled considering that small hydro below 10 MW is 19.7 GW of installed power (Liu et al., 2019).

Table 2. Generated power (GW) at the EU level related to hydropower plant type (RoR, SPP, PHS) and installed power *P* (MW).

P (MW)	RoR	SPP	PHS	Total (GW)
$P>10$	29.66	62.14	46.97	138.8
$1<P\leq 10$	6.78	3.92	0.03	10.7
$P\leq 1$	5.50	0.00	0.00	5.5
Total	41.94	66.06	47.00	155.0

Within the large scale context of this study, the share of generated energy among the different plant types can be estimated in first approximation by considering that the whole amount of 360 TWh/y proportionally spreads based on a weighted proportion with $P{\cdot}h$, where P is the installed power of each plant type (Tab.2) and h is 2880 operating hours and 4300 hours for SPP and RoR, respectively (see section *Capacity factor and operating hours*), and considering that PHS contribute 31.6 TWh/y on average terms. The results obtained are in line with De Felice (2020), where the EU RoR average annual production (considering data from 2010) is 164 TWh, while the estimated value in Tab.3 is approximately 160 TWh. For Europe, data from de Felice (2020) show that 190 TWh/y are generated from RoR, and 184 TWh7y in our case. The 32 TWh/y generated from PHS in EU corresponds to 37 TWh/y in Europe, proportionally to the installed power (47 GW in EU and 55 GW in Europe of PHS). Further details in Fig.3.

Table 3. Generated energy (TWh) at the EU level, related to hydropower plant type (RoR, SPP, PHS) and installed power (P in MW).

P (MW)	RoR	SPP	PHS	Total (TWh)
$P>10$	112.98	158.55	31.00	302.52
$1<P\leq10$	25.82	10.00	0.70	36.53
$P\leq1$	20.95	0.00	0.00	20.95
Total	159.75	168.55	31.70	360.0

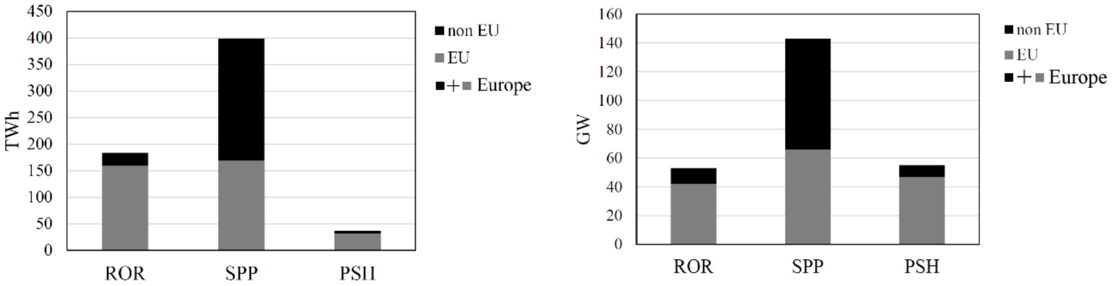

Figure 3. (a) Annual energy generation (a) and installed power (b) in EU and Europe.

Turbine type prevalence

Since the retrofitting challenges and benefits depend on the turbine type, it is necessary to estimate how the total installed power is subdivided among the different turbine types. In the scope of this work, the main turbine types that were considered included Pelton, Francis, Kaplan-Bulb and Pumps. The other turbine types (e.g., Cross Flow and Deriaz) can be considered operating in the same range of Francis ones, and are not so much diffused and representative.

The methodology extrapolated from Quaranta (2019) can be implemented, where a normalized flow rate defined as $Q^{*}= Q\cdot(2gH^{5})^{-1/2}$ can be used to distinguish between Pelton ($Q^{*}<0.00001$), Francis ($Q^{*}<0.001$) and Kaplan-Bulb ($Q^{*}>0.001$), with Q expressed in m^3/s and H in m, and assuming two units for each plant (for safety reasons, the number of units of a large hydropower project is usually greater or equal to two; this enables the maintenance and the greater flexibility in the production program). The calculation of turbine type diffusion, based on the installed power, allowed to estimate the amount of annual production generated by each turbine type, spreading the global hydropower generation of 360 TWh proportionally to the turbine diffusion (Tab. 4). See the discussion section for the validation of this methodology.

In PHS it was assumed that Pumps are the installed turbine type, also used in reverse mode (PAT – Pump As Turbine), although separate units may be used, one for pumping and the other for turbine mode. These details, not taken into account in this study, would not substantially change the results of the large scale assessment. Indeed, since the pump diffusion is 18.8%, while the annual production from PHS is 31.6/360=9%, to assume that all the PHS are equipped with pumps does not appreciably change the value of the benefit indicator. Furthermore, in the context of this study, PHS were excluded from the calculations, except for the benefits related to the dam heightening and the floating PV (that are independent of the turbine type), so that the obtained results will not include any inconsistency in this sense.

Table 4. Turbine type diffusion based on the installed power in EU (PAT = Pump as Turbine).

Turbine	SPP	RoR	SPP TWh/y	ROR TWh/y	Total TWh/y
Francis	53%	28.9%	109	46	156
Kaplan-Bulb	13%	68.9%	27	110	137
Pelton	16%	2.3%	33	4	36
PAT	19%	0.0%	32	0	32

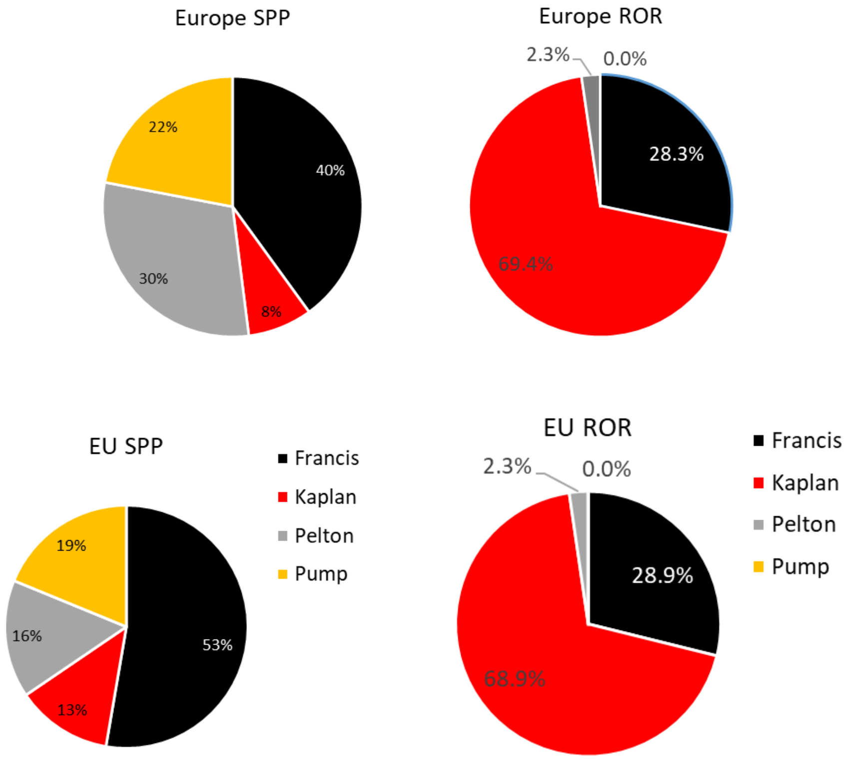

Figure 4. Estimated turbine prevalence in EU and Europe.

Average operational characteristics: operating hours.

Considering an installed power of 108 GW and 328.4 TWh (excluding PHS), it is possible to calculate t = 328.4·1000/108 = 3040 hours, which is the number of hours that, on average across EU, a HPP should operate at its full installed power to generate the same annual amount of energy generated in real conditions. The capacity factor is 0.30, in line with the European average capacity factor of 0.35 (Kougias, 2019). This is higher than values estimated in Lehner et al. (2001), where the average value in 2001 was 1670 h considering Austria, France, Germany, Greece, Italy, Portugal, Spain and Switzerland. The current value is higher due to the performance improvements of HPPs, the increased flexibility and to the higher number of countries considered in this study.

Since a HPP does not always work at its full capacity, the real number of operating hours is higher. In the European Union the average *CF* is low when compared to the almost double *CF* in South America where very large reservoirs (also in Norway) have enough inertia to guarantee a more regular water supply. Nevertheless, a low *CF* in a hydropower fleet with a high share of SPP and PHS, as it is the case in Europe, also means that the fleet has a high flexibility to generate during peak hours of high electricity demand and thus ensuring grid safety.

If data from the hydropower database are used, obtaining h_v=4300 h for RoR and h_v=2880 for SPPs are estimated from the annual generation and installed power. This is in agreement with ESHA (2012) where the estimated number of operating hours, upon which the plant load factor is calculated, ranged from 3000 to 4900 h in operating small hydropower plants across the EU (that typically are RoR), in rough agreement with 4300 h. If a weighted average is calculated using these numbers of hours, averaged with the energy generated from RoR and SPP (Tab.3), the weighted average number of hours would be 3500 h, in line with 3040 h. Although this value may not be sufficiently accurate when considering a single HPP, it is adequately representative at a global European scale.

The above estimated hours assumed the HPP operation at nominal conditions, while the real operation includes also part load working conditions. Therefore, when referring to the hydraulic turbine unit, it is expected that the effective number of hours is higher than 3040. Since turbines rarely work below 30% of the BEP (Landry et al., 2018; Bejarano et al., 2019), it was assumed that an average part load condition is at 60% (average between 90% and 30%) of the BEP, where the efficiency of the Francis turbine is around 10% lower (Muntean, 2016), while that of Kaplan-Bulb and Pelton turbine is practically constant. This is also in line with Russian data (collected by Evgeniia Georgievskaia), that in general, at 60-70% of the nominal power, the efficiency is 10% lower than at BEP, while reduces by more than 20% below 35% of the nominal power.

Therefore a global average part load condition of 60% of the BEP and 10% less efficient was assumed to estimate the real operating hours (Eq.2)

$$P\left(60\% \cdot (1-10\%) \cdot h_p + h_{f+bep}\right) = h_v\, P \qquad (2)$$

where *P* is the power at best efficiency point, h_{f+BEP} the BEP and full load hours. The additional equation to solve Eq.2 considers that h_p = 20 (h_{f+bep} + h_p) for SPP and h_p = 55% (h_{f+bep} + h_p) for ROR (from Spanish data). Considering that h_v is 2880 h for SPP and 4300 h for RoR, respectively. h_p+h_{f+bep} = 5570 h for RoR and 3140 h for SPP, and reasonable changes in the values used in the equation (60% and 10%) do not substantially alter the result for a large-scale context. 3140 and 5570 hours are $\frac{2}{5}$ and $\frac{3}{5}$ of the year, respectively, that could be attributed to the start and stop cycles and inactivity related problems. For large HPPs in Russia, the estimated operating time (in terms of full installed power) is from 1070 to 7185 h (average ~ 4000 h) (Pers. Comm. of Evgeniia Georgievskaia).

Discharge, head and reservoir area

From the hydropower database, the average discharged flow rate for each HPP, Q_{avg}, can be estimated by knowing the annual energy generation, the assumed efficiency of 0.7, the head and the previously estimated number of operating hours (assuming a lower efficiency for the overall operation and a constant head). The global value of Q_{avg} (i.e., $\sum Q_{avg}$) of EU SPPs is 53,263 m^3/s (1,679,620 Mm^3/y), and 96,495 m^3/s (3,043,068 Mm^3/y) for the whole Europe. The average value of Q_{avg} of SPPs is 221 m^3/s and 75 m^3/s for EU and Europe, respectively, while the weighted average value of Q_{avg} is 148 m^3/s for the EU and 116 m^3/s for the Europe, using the SPP power as weight. The average nominal head difference used in SPPs in the EU is 111 m (and 160 m for the European context).

From Lee et al. (2020), with the PV power density of 100 W/m^2 (this value already includes the PV efficiency) installed on 14% of hydropower reservoir surface, floating PV (FPV) potential capacity in Europe was estimated as 729 GW, would correspond to 52,071 km^2 of hydro reservoir[4]. Considering the 198 GW of installed hydro capacity of reservoir and pumped hydro (i.e. plants that have a reservoir), the global average EU value of power density of HPPs is $W_{dens} = \frac{198\ GW}{52{,}071\ km^2} = 3.80\ W/m^2$, in line with Table 8.1 in Supplementary Material 8 (this is a very low value, but it varies greatly from one HPP to another while in the Alps it reaches a much higher value). The value of 52,071 km^2 is in line with the value obtained from Hogeboom et al. (2018), where the surface of the considered 516 European hydropower reservoirs is 13,566 km^2. Considering the hydropower database with 1840 European hydropower reservoirs (SPPs and PHSs), this would linearly correspond to 48,377 km^2, reasonably in line with 52,071 km^2. The results obtained by using this methodology obviously reflect the assumptions made in Lee et al. (2020) to estimate the FPV potential. The analysis of Lee et al. (2020) strictly focused on the FPV potential on hydropower reservoir and consisted in a geospatial analysis, that hence was considered accurate enough to be used to estimate the usable reservoir surfaces.

Calculation of energy benefits of each action

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[4] $\frac{729\ GW}{100\frac{W}{m^2}} \cdot \frac{1}{14\%} = 52{,}071\ km^2$

Table 1 shows the main retrofitting actions, the plant type where they can be applied and the type of turbine concerned to this action. The EU distribution of hydropower plants and turbine types is described in the above sections. From the literature review in the Supplementary Material, it was possible to estimate the benefits that can be obtained from each action. These values are described in the Results section for each retrofitting action.

3 Results

In this section, the main findings better detailed in the Supplementary Material are discussed and summarized, with the aim of supporting the assumptions and performing the calculations of the bulk assessment.

H-strategy = Head increase (dam heightening and head losses reduction in waterways)

The heightening of a dam generates two main and evident benefits: increases in both storage capacity and head. Some dams also need repair, revision and improvements of dam safety issues. It is a good strategy to consider dam heightening at the same time. Obviously, impacts on the upstream environment are generated, such as the submergence of riparian areas due to the increased water level and the transformation into a lentic system of a certain portion of the river reach upstream of the dam, so that this is not always a feasible option, besides involving high investments, which require sufficient high prices at the electricity market during peak hours of demand in the critical season (normally winter half year) to become economically advantageous. Therefore, neglecting for the moment the implicated costs (that may be anyway acceptable if additional storage capacity is also required), it is supposed that the dam heightening could be implemented only in mountainous and non-or sparsely populated environments, where the increase in the upstream water level is not a problem for settlements, environment and infrastructures. These contexts can be easily found in diversion power plants in mountainous environments, where the dam height d is much smaller than the head of the plant H [5].

Based on the work for Swiss dams (Allet and Schleiss, 1990, Felix et al., 2020), well supported by the literature review discussed in Supplementary Material 1, the dam heightening was applied to the SPPs and PHS (only considering the energy produced from the natural runoff) with head $H > 300$ m, and considering that a dam heightening of 10% would correspond to a head increase of 2% in first approximation. From a mathematical point of view, being the dam height d a portion of the hydraulic head H, the head would increase of 2% in correspondence of a dam

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[5] In the Alpine environment, most hydropower plants are diversion plants, where the powerhouse is far below the dam toe, and thus the head H is well above the dam height d. Instead, in the so-called dam powerhouses, where the turbines are located right at the dam toe, the dam height is the main factor that defines the head (this also holds for the typical RoR power plants which typically feature a weir or barrage instead of a large dam), and the effective head increases roughly by the relative dam height increase.

heightening of 10% when d=20%H, that obviously leads to an estimation which should be regarded as a maximum threshold, rather than to a feasible value. It was assumed that the 2% of head increase reflects into an analogous increase of energy generation for the considered plants. This is obviously an idealistic assumption, because actually the head increase would not occur during wet periods when the water level is already at its maximum. Therefore, this is only a way to attribute a reasonable value to ΔE_{id}, indicator that hence should be interpreted as a maximum threshold. Since the head must be known in this calculation, it was applied to the hydropower database, obtaining ΔE_{id} =0.19% for EU and 0.43% for Europe, which is coherent because the share of SPPs in the non-EU countries Norway and Switzerland is particularly high.

The benefit of dam heightening, rather than a significant increase of annual production (maintaining the inflow constant), would determine a pronounced increase in energy storage capacity, which allows to temporally shift water to the season of highest demand (which is winter in the Alpine context and in the Nordics, see Figure A1 in Supplementary Material 1). Assuming typical stage (d) - volume (V) characteristics of Alpine valleys of a power function type $V = \mathrm{a}d^b$, with exponent b = 2 to 3, a relative increase in dam height thus results in an over-proportional relative increase in volume, with an increase in the reservoir surface, but higher modification of the orography. For a 10% increase in dam height, for instance, the reservoir volume typically increases by between 21 and 33%. Practical case studies, with some limitations and related costs are discussed in Supplementary Material 1. It has to be outlined that, for such interventions on the dam structures, environmental impact assessment procedures may be applicable and a revision of the current downstream flow release regime could be requested by the competent authorities, thus affecting to a certain level the potential increase in energy production and storage capacity.

The retrofitting of waterways and penstock can also lead to an increase of power. Indeed, penstocks and waterways reduce their performance over the years, and head losses may increase (e.g. increased friction), with a reduction of the exploited head and maximum flow capacity. Also, the methods used for tunneling has improved over the years, being able to make smoother tunnels. Therefore, their retrofitting can restore the original flow capacity and head. Following the data of Nogueira et al. (2016) (Supplementary Material 2), it can be seen that head losses can be reduced by 25 to 40%, with a power increase between 5% to 11.6%, for a constant geodetic head, that would reflect in an analogous increase of production. By assuming a precautionary power increase by 5% after the retrofitting of waterways and penstocks, ΔE_{id} =2.34% for EU and 3.15% for Europe. Of course the real challenge is to generate a sufficiently greater revenue from this increased technical capability which pays for the revenue lost at outage and the capital cost of the work. The upgrading in itself does not increase annual production, but merely shifts it into a smaller window to trade. Indeed, some efficiency may be lost in the waterways at the greater flows, that however may only be available for short seasonal periods.

Q-strategy: increase of inflow

The *Q*-strategy can consist in either the increase of the annual inflow, or in the increase in the maximum flow that can be discharged during the peak hours, but concentrating it during few hours and leaving unchanged the average annual inflow. Both cases require a larger runner and larger embedded parts, or the installation of additional waterways and powerhouse. In this study, this strategy was not considered, as discussed in the Method section, although the Supplementary Material discusses some literature results and case studies.

As described in the Method section, the former case was not considered, but it may be of high interest in specific countries, e.g. Norway, where water availability has already increased since the majority of the hydropower fleet was constructed, and will increase in the future. An extensive and detailed survey conducted in Norway showed that the average increase in the installed power could be 18% for Francis turbines, 21% for Pelton turbines, and 21% for Kaplan-Bulb turbines (Brunes, 2009).

For RoR on large streams, the increase of installed turbine discharge capacity allows to generate additional energy since spilling over the weir during wet season can be reduced. The gain in generation is achievable mainly for RoR built before 1960, which have a turbine discharge capacity exceeded by the inflow typically over 150 days. Upgrading such old HPP tends today to reduce this value to 60 to 75 days, which results in a gain of generation from 5% to 20% depending on the flow duration curve. For SPP the production can be concentrated during peak hours (Allet and Schleiss, 1990). For a slight increase of the nominal power (<15%) of SPP, also the existing waterways (and surge tank) have to be adapted (Adam et al. 2016, 2018).

η-strategy: new electro-mechanical equipment: improvement of the BEP and weighted efficiency

The mechanical components of hydraulic turbines are prone to ageing after years of operation one (mainly as a consequence of abrasion, erosion, cavitation). As a result, worn mechanical components increase the risk of outage and operation of the hydraulic turbines at a reduced capacity. Replacement and refurbishment of old and aged components can either restore the initial capacity or increase the capacity (upgrading), improving efficiency over wide range domain.

The efficiency improvement can be ensured by the replacement with a modern equipment that is not deteriorated as the old one, and due to the fact that modern equipment is more technologically advanced and exhibit a more optimized design.

When the increase of the BEP efficiency is the aim, for example in HPPs that rarely work at part load, the maximum electromechanical efficiency increase can be 4% for Pelton, Kaplan-Bulb and Francis turbine HPPs (runner, generator, valves, trash racks and bifurcations), plus an increase of 2% (gates and draft tube) for Francis and Kaplan (see Supplementary Material 4).

These values might be realistic for units built more than 60 years ago and never refurbished, while for units built in the last 40 years 1-2% is a reasonable assumption without abrasion.

Nowadays, HPPs frequently work at off-design conditions. Therefore, to estimate the indicator ΔE_{id} for this strategy, the improvement of the weighted efficiency η_w was considered, as discussed in Supplementary Material 5. The increase of the weighted efficiency considers the improvement over the entire range of operation (part load, BEP and full load). Based on data reported in Supplementary Material 5, taken from IEA (2000), the efficiency upgrading after retrofitting the turbine runner, together with runner seal components and the water passage components, is outlined in Table 5. The weighted efficiency improvements of Francis turbines are the following: runner (up to 2.5%), spiral case (up to 0.3%), stay ring (up to 2%), guide vanes (up to 0.5%), draft tube (up to 1%). An overall efficiency contribution of 6.3% is estimated if all components of the hydraulic passage are retrofitted (and all contributions are effective in the same time). However, not all contributions are fully effective in the same time even if all components of the hydraulic passage are refurbished. As a result, a more realistic improvement of the overall weighted efficiency of Francis turbines of 5.5% can be considered for aged hydropower units (>40-50 years, since a lot of hydropower units in Europe are over 40-50 years old). The efficiency curves for Kaplan (on cam operation) and Pelton turbines are flatter than the Francis turbines over a wider operation range, because an efficient flow rate regulation system keeps their efficiency almost constant at off-design conditions. As a result, the weighted runner efficiency of the Kaplan (on-cam operation) and Pelton turbines could be assumed to be smaller up to 1% than the Francis turbines, hence the efficiency of the Francis turbines can be improved more.

With these assumptions, the indicator value is 4.97% for EU and 4.85% for the whole Europe.

Table 5. Weighted efficiency (η_w) improvement and indicator value, considering the sum of the improvements of each equipment. Pump behavior was assumed similar to the Francis one.

Turbine type	η_w increase	ΔE_{id} value for η_w improvement EU	ΔE_{id} value for η_w improvement Europe
Francis	5.5%	2.4%	4.0%
Kaplan	4.5%	1.7%	2.1%
Pelton	4.0%	0.4%	1.8%
Pump	5.5%	0.5%	0.57%

t- strategy: start and stop improvement

Based on literature data described in Supplementary Material 6, 100 start–stop cycles per year can be considered a reasonable current value. One start–stop cycle shortens the refurbishment time period by 15 h. Therefore, assuming a life (before the first important refurbishment) of 30 years, a reservoir HPP will lose 900 h, and a run-of-river plant 45000 hours, or 30 hours per year and 1500 hours per year, respectively. It is expected that start and stop will increase in the future, due to the electricity market, although it is possible to improve unit management and operation in hydraulic short circuit. This action will not be quantified, being very site specific, but hydropower operators should aim at reducing start and stop related problems and transient times, thus increasing the operating hours.

t- strategy and Q-strategy: digitalization and inflow forecast

The digitalization of HPPs, apart from the improvement of predictive maintenance allowing for the prolongation of the lifetime, reduction of the outage time, and addressing cyber-security risks, involves increasing the overall efficiency and, thus, the produced energy, with no additional impacts on the river ecosystems. By analyzing the case studies reported in Supplementary Material 7, it is reasonable to assume that the digitalization can improve the efficiency of existing HPP by 1% (ΔE_{id} =1.0%). By the high quality short and mid-term inflow forecast, spills are reduced and the hours per week to manage manually the operation are reduced, thus the annual generation can improve by 11%, although this is very site-specific (Supplementary Material 7).

Q-strategy: floating PV

The installation of floating PV on the reservoir of HPPs leads to several benefits (Cazzaniga et al., 2019). In this work, the focus was on the energy gain as a consequence of the reduced evaporation, assuming to cover a certain percentage of the basin surface of SPP reservoirs with FPV. As specified in the Supplementary Material 8, it is generally convenient to install a FPV power of the same order of magnitude of the HPP. In Alpine environment, where HPPs are characterized by high heads and low flows (i.e. high power density per unit of reservoir surface), this would require a FPV surface much larger than the HPP reservoir surface. In HPPs characterized by large flows and small heads a small percentage is instead enough to obtain the same power (see Table 8.1 in Appendix 8). The optimal percentage is hence site specific. In this study we assumed 10% of FPV surface in order to reduce the impact on the reservoir and to reduce investment costs, in agreement with Lee et al. (2020). Finally, it must be noted that FPV production dominates the increase of the hydropower generation due to the reduction of evaporation.

From data of Hogeboom et al. (2019) it was estimated that the annual evaporative volume from the examined hydropower reservoirs is 8.1 $\cdot 10^6$ Mm^3 and 9.3 $\cdot 10^6$ Mm^3 for EU and Europe, respectively. The total reservoir surface was 10,586 km^2 and 13,567 km^2, respectively. The weighted average evaporative volume (using the reservoir surface as weight) is V=764 Mm^3 and

V=688 Mm^3 for EU and Europe, respectively. Multiplying these values by 70% (evaporation reduction below the FPV, Zahedi et al., 2020, Scavo et al., 2021; Abdelal, 2021) and by the FPV surface (10%), and considering 3140 h of annual operation, it is possible to obtain V·0.7·0.1/(3,140·3,600) = 4.7 m^3/s and 4.3 m^3/s of additional flow that could be discharged over the 3140 h, on average, for EU and Europe, respectively. This is 3.6% and 4.2% of the weighted average value of Q_{avg} for EU and Europe, respectively, to which it would correspond an equivalent increase in energy generation from SPP, thus to ΔE_{id}=1.7% and 2.7% for EU and Europe. Results are also in line with Sanchez et al. (2021) for the African context, where a 14% coverage would correspond to an increase hydro generation of 2.3%.

Summary

Table 6 summarizes the ΔE_{id} value for each retrofitting action, that can be reasonably interpreted as the additional annual production or peak installed power, depending on the retrofitting action considered, with respect to the current values, independently from the market demand and with constant external conditions. The ideal values of additional capacity can be calculated by multiplying the indicator value by the current installed power (or annual production) in Europe or in the European Union. The global value is ΔE_{id}= 10.2% for EU and 12.2% for Europe (excluding three site-specific strategies, see Table 6), without considering the installed GW recently refurbished. In Table 6, data from Gimeno-Gutiérrez and Lacal-Arántegui (2015) show that the additional storage capacity across Europe can be estimated in 28.6 TWh (and 4.0 TWh in EU) interconnecting existing reservoirs within 20 km distance of one another; the European potential reduced to 198 GWh when considering 5 km. However, this result may be underestimated, since Harby et al. (2013) showed that the hydropower potential could be increased by 20 GW (60 % increase in capacity) in Norway by interconnecting existing reservoirs.

Therefore, results of Table 6 should be interpreted as an indication of which practices lead to higher benefits (in terms of energy). In this analysis we did neither consider the increase of inflow nor the potential generation increase of 5% to 20% for old RoR (built before 1960) by increasing turbine discharge capacity. By assuming an increase of 10% for all the RoR plants (unrealistic aim, but useful to estimate a maximum value), the value of the related ΔE_{id} would be 10%·44% = 4.4%, where 44% is the energy generated from RoR plants in EU, while 3.0% for the Europe. The benefits related to the increase of the annual inflow were not discussed being too site specific. The increase of installed peak power/flow due to new waterways in SPP could not be estimated, being too site specific, but from Supplementary Material it can be seen that it can double.

Table 6. Value of ΔE_{id} for each retrofitting action. The ideal increase of installed power and annual production can be estimated by multiplying the indicator value by the current production in EU and European Union, respectively.

Retrofitting action	ΔE_{id} EU	ΔE_{id} Europe	Interpretation	Comment
Dam heightening – *H- strategy*	0.16%	0.37%	Increase of peak power of 0.25 GW and 0.95 GW	High investments, not always feasible; main benefit in increasing off-season production by larger storage capacity.
Waterways and penstock, *H-Q strategy*	2.3%	3.2%	Increase of peak power of 3.6 GW and 8.2 GW, and annual production of 8.4 TWh and 20 TWh	-
New equipment: weighted efficiency increase over wide range, *η- strategy*	5.0%	4.9%	Increase of peak power of 7.7 GW and 12 GW, and annual production of 17.9 TWh and 30 TWh.	Fish friendly turbines may result in a lower efficiency (2% less) with respect to new standard turbines, thus halving the benefit in the worst case, but they are limited to low heads (< 40 m) and their costs is lower (Dixon and Hogan, 2015).
Digitalization *Q-t- strategy*	1.0%/11%	1.0%/11%	Increase of efficiency of 1%, while annual generation can increase by 11%	Reduced costs and outage time not estimated.
Floating PV *Q-* strategy	1.7%	2.7%	Increase of annual production of 0.36 TWh and 1.2 TWh.	Stability of the floating structure, reservoirs covered by snow and ice and difficult for PV. PV on dam surface is a modern practice. The PV production dominates additional hydro output due to evaporation reduction.
Reservoir interconnection, *Q-strategy*	4 TWh	28.6 TWh	Increase of annual production and more flexibility.	Connecting reservoirs within 20 km, from Gimeno-Gutiérrez and Lacal-Arántegui (2015).
Increase of peak discharge RoR, *Q-strategy*	4.0%	4.0%	Increase of annual production of 14.4 TWh and 24 TWh.	Not quantified, but reasonably estimated
Increase of peak discharge SPP by new waterways, *Q-strategy*	0-100%	0-100%	Increase of peak power	Not quantified, site-specific
Increase of annual inflow, *Q- strategy*	-	-	Increase of annual production	Not quantified, site-specific, may be negative in some regions due to climate change
Overall indicator	10.2%	12.2%		(excluding the last three strategies and reservoir interconnection)

4. Discussion

Increase of hydropower potential and transversal benefits

The retrofitting process of a HPP is a complex procedure and it is unique for each site. Nevertheless, when reasoning at a large-scale (regional, national, continental), it is possible to obtain a representative estimate on the overall energy benefits that could be achieved by retrofitting the existing hydropower fleet, that are flexibility and annual generation. The flexibility increase can be provided in different ways, for example by increasing the installed power (to better satisfy peak electricity demands and to reduce spilling during wet season for RoR power plants), by improving the electro-mechanical performance at off-design conditions, by increasing storage capacity (to deliver balancing power and energy storage at time frames from seconds to days, weeks and months, when needed and during peak demands) and interconnecting more HPPs with one another (Harby et al., 2013; Gimeno-Gutiérrez and Lacal-Arántegui, 2015) or with other energy sources like wind and solar. Hence it is clear that the actions aimed at increasing HPPs flexibility also contribute to ideally increase the capability of the HPP to deliver annual production, and vice-versa.

Table 1 summarizes the practices investigated in this study. For a comparison, the most common actions in the set of 339 upgrading projects developed in the USA in the last decade are replacement or refurbishment of turbine runners (104 projects), generator rewinds (91 projects), installation of digital governors (34 projects), replacement or refurbishment of floodgates (28 projects), and replacement or upgrade of the transformer (16 projects). Many projects combined several of these actions within their scope. Therefore, new equipment, digitalization and waterways resulted the most implemented practices, and these were coherently considered in this study (Uria Martinez et al., 2021).

Table 6 shows the importance of each retrofitting action in terms of energy, but it must be noted that the benefits of retrofitting should not simply be seen within the energy context. Most practices can be implemented on both SPP and ROR, while dam heightening, floating PV and reservoir interconnection are of interest only for SPP.

The dam heightening would only be possible when the increase in the upstream water level is not a matter, and typically refers to concrete dams – but is not limited to these - in mountainous environment. Its ΔE_{id} indicator value resulted very low. The dam heightening should also be considered as a high investment practice, although its benefits are more than additional energy generation. The main benefit lies in shifting water from the peak runoff season (typically spring and summer in European mountainous conditions) to the off-peak season (i.e. winter), enabling seasonal production increases. The bigger storage capacity is one of the main strategies to compensate the hydrological changes induced by climate changes and alteration of water availability, especially in Europe. For a 10% increase in dam height, for instance, the reservoir volume typically increases by between 21 and 33%.

The retrofitting of existing waterways can also lead to a head increase due to the reduction of head losses, mainly in the case of high-head SPP. When seeking for a significant increase of the installed power at existing SPP, a proven option is to build a new waterway (tunnels and shafts) together with a new underground powerhouse which is parallel to the initial scheme and using the same reservoir (see Supplementary Material 3). This allows to ensure high power during very few daily hours of peak demand in the grid, but also during longer stability problems of the grid. The new waterways will have a better efficiency due to the lower friction losses and the generation may also slightly increase as experienced in some projects (see Supplementary Material 3). The refurbishment of the waterways can thus re-establish the original flow rate and head, and thus increase the available power and energy capacity by 5% as maximum improvement, with estimated costs between 400 and 650 \$/m^2 (Nogueira et al., 2016). The increase of the inflow would require updating the water licence, and improved environmental mitigation measures (e-flow, fishway construction, etc.) could be prescribed (Massarutto and Pontoni, 2015; Tonka, 2015).

The replacement of deteriorated equipment by new one reflects in an increased installed power and in a better efficiency at off-design conditions. However, as a mature technology, only the old HPPs exhibit strong design efficiency handicaps (perhaps 5-15%) compared to the modern ones with higher efficiency (Mikhailov et al., 2021). Most of the efficiency reduction undergone by the equipment over the years is mainly due to abrasive water. Ecologically improved turbines can also reduce impacts on fish and ensure better downstream aeration, but their efficiency is generally 2 percentage points lower than standard turbines. Self-aerated and self-lubricated turbines also reduce environmental impacts, minimizing oxygen deficit downstream and oil leakages, respectively (March, 2011; St. Germain, 2018). Another option related to the new equipment is the installation of turbine(s) making use of environmental flow restitution to residual flow stretches of the river, thereby exploiting the head at the water intake, e.g. at weirs of diversion HPPs. This option is strictly site-specific and was not considered, having a negligible effect (few hundred kW per plant, IEA, 2016; Quaranta et al., 2020). In this study, the weighted efficiency concept was used to estimate the energy benefit. However, the efficiency quantity is just a side of the refurbished solution. This quantity is linked with the energy production. The cavitation performance is another side of the refurbished solution, that is linked with both maintenance and repair costs. The improvement of weighted efficiency has to be checked to be in tolerance with cavitation conditions, otherwise, the maintenance and repair costs will be larger than the energy production costs. It must be noted that for retrofitting interventions based on turbines replacement, the use of ecological improved turbines, e.g. the Alden and Minimum Gap Runner turbines, might be considered for providing a reduced impact on downstream migration of fish, especially at low head sites. However, these turbines present a slightly lower efficiency than modern not-ecological ones, therefore limiting the expected increase in energy production, despite their lower cost (Dixon and Hogan, 2015; Hogan, 2014). Recent research showing very promising results in new design of trash racks and guidance structures, to provide fish from being estranged into turbines (Tomanova et al 2021, Fjeldstad et al 2018).

Digitalization is another important practice for the improvement of part load and full load conditions, improvement of turbine response during start and stop cycles, extension of electromechanical equipment life, prevention of failures, ancillary services and reduced maintenance. Not all of these practices necessarily reflect into an increase of power and production. Instead, the short- and mid-term forecast of inflow to hydropower plants allows to avoid spilling of water that cannot be handled by the plant capacity, and also increases the chances at the spot market due to higher generation predictability. Digitalization solutions correlating the operations of a RoR hydropower plant to a real-time monitoring of the available river discharges can allow a more sustainable HPP management, continuously adapted to the water resource availability, particularly relevant when considering climate change scenarios, and to the market demand. Digitalization would also allow to better coordinate multi-reservoir HPP, cascade HPPs and the coordinated operation of more HPPs, maximizing energy generation (Afzali et al., 2008) and optimizing water management (Yalcin and Tigrek, 2019).

The integration of floating PV (FPV) can increase the hydropower fleet generation by 2.7% when 10% of the basin surface is covered with FPV, that linearly varies with the percentage of FPV coverage. The advantages of this hybrid system is in part due to a reduction of the evaporation rate, but mainly to the possibility of using the same infrastructures (in particular the grid connection) and to increase the capacity factor from 3000 to 4000 hours (for comparison, it was estimated from 4000 to 5300 hours in South America). The large increase in energy production of the hybrid system (PV+HPP) allows a better management of HPP plants thanks to the fact the energy production of FPV is in part anti-correlated with that of HPP plant. Furthermore the use of the same grid and infrastructures strongly reduces the costs of the FPV which can be installed in a short time and without any modification of the reservoir conditions. For the future, a power density of W_{dens} = 180 W/m^2 can be reached (higher than that used by Lee et al. (2020), in order to consider future developments and advancements). This value is due to the fact that the raft systems are becoming compact and robust with 400-450 W PV modules (of 2x1 m size). This value should be probably increased in the next future with the increase of PV module efficiency, but a value W_{dens} = 180 W/m^2 was assumed as the most probable, already including PV efficiency. For seasonal deep storage reservoirs which will be full and empty each year, FPV is a challenge considering also the ice cover in high altitude. Thus, FPV application may be limited to reservoirs below 1500 m asl in Alpine environment. As a new trend, PV can also be installed on dam surfaces (gravity and arch dams) resulting in high efficiency due to excellent sun exposition in snow-covered mountains all over the year, since there is no fog in winter most of the time (Kahl et al., 2019). This practice would not only add energy related to the solar panels, but also increase hydro efficiency when being in a hybrid operation with a storage power plant (SPP or PHS). Further details can be found in Kougias et al. (2016). The extension of the coverage area shall be taken into account when assessing the potential impacts on the reservoir ecosystem, since the reduction of the euphotic zone may lead to alterations of thermal and photosynthetic processes related to solar radiation, even though a FPV coverage up to 60% of the lake surface is still deemed acceptable (Haas et al. 2020).

The retrofitting should also aim at reducing the impact of climate changes on the HPP operation. Climate change may reduce water availability and hydropower generation. Patro et al. (2018) in the Alpine-wide study of RoR future perspectives of viability and profitability in Italy, showed that across all basins and all future scenarios, the median decrease in RoR hydropower is −3% (through 2065). Therefore, the retrofitting of the hydropower fleet can help to minimize the reduced potential induced by climate changes that will occur in the long term for some of the regions in Europe (see Supplementary Material 9 for more details). A detailed analysis of eleven representative ROR plants across Switzerland (SCCER SoE, 2019) using the most recent Swiss climate change scenarios CH2018 suggests no change (RCP 2.6 scenario) or only a slight decrease of up to 3% (RCP 8.5 scenario) in the total annual production by mid-century with the present-day installed machinery and residual water flow requirements. More important is the seasonal shift due to the modified water regimes leading to a 5% increased winter production. More winter precipitation will have a positive impact on Swiss HPPs, as less water needs to be spilled (Savelsberg et al., 2018). Also environmental measures to mitigate impacts on aquatic ecosystems may limit hydropower potential, and require hydropower companies to face non negligible construction costs (e.g. retrofitting a dam with fish passage solutions). Innovative materials will also play a central role in the refurbishment projects, although their higher costs with respect to traditional materials may currently limit their economic convenience (Quaranta and Davies, 2021). **Additional considerations on time-frame and environmental challenges are discussed in Supplementary Material 10.**

Sensitivity analysis

In their exploratory intent, the calculations made in this study are referred to hypothetical situations, and as such they cannot be validated. However, the underlying assumptions derive from several case studies and scientific studies. Moreover, the results were benchmarked against the available literature.

The global value of ΔE_{id} is about 10% (excluding reservoir interconnection), which can be reasonably interpreted as the available surplus of energy with respect to the non-retrofitted one. This value is in line with the definition of light rehabilitation discussed in de Podestá Gomes and Vajayfor (2014) the Brazilian context, where, analyzing the literature, it was suggested to classify the modernization into: 1) minimum, when the turbine and generator are repaired to similar conditions as new ones and the performance is back to original values. The average capacity gain in this case is 2.5%. 2) Light, when there is a wider checkup of the main components, with repairs and changes of some of them, in order to improve the power plant performance above the original values. The capacity gain with light rehab can reach 10%. 3) Strong, when the latest hydrological studies provide a new physical condition to the generation unit, and so its energy production is substantially increased (in this case the turbine runner and other components, as well as the main generator parts, are changed and the capacity gain can be about 20%). In our study, the practices related to the light rehabilitation classification were estimated, while the strong ones were discussed and an indicator value roughly estimated.

The EU fleet composition in term of power plant type was also checked versus the data of Kougias (2019), as well as the energy generation estimated from RoR plants versus real data of de Felice (2020). The average number of operating hours was calculated in different ways, as explained in the previous sections, and checked against literature data. All these estimations resulted in line with the aforementioned studies.

The composition of the European and EU and European fleet, in terms of turbine type, was determined based on Quaranta (2019) results, and always assuming two units. Practical considerations are discussed in Supplementary Material 10. These assumptions can be checked with the results of Brunes (2009): 44% of HPPs > 50 MW have been estimated to be equipped with Francis turbines, 14% Kaplan, 31% Pelton, 11% Pump (Brunes, 2009), while from our calculations, 41% of HPPs > 50 MW are equipped with Francis turbines, 15% Kaplan, 25% Pelton, 19% Pumps. Furthermore, based on the installed power, in EU 48.4% were estimated to be Francis, 19.2% Kaplan, 13.6% Pelton, and 18.8% Pumps; this sharing can be compared with the internal database of Voith Hydro for Europe, which estimates that 37.8% are Francis, 24.8% are Kaplan, 15.8% are Pelton, and 18.8% are Pumps, based on the installed power (the remaining percentage is with less traditional turbines).

Although the Francis diffusion is overestimated, in general terms results are in line, considering the simplified approach adopted here, thus this can be considered a satisfactory result. Other examples of turbine share that were found in literature are referred to Saxony (Germany), where the most widely used turbine technology is the Francis turbine contributing to 47% of all hydropower plants. The second turbine technology in Saxony is the Kaplan-Bulb turbine (29%) followed by water wheels (16.5%). The Cross-flow (Ossberger) turbines are more seldom used (6%), whereas only two Pelton turbines are actually in operation (Spänhoff, 2014). In Russia, 37% of HPPs > 50 MW are equipped with Francis turbines, 60% Kaplan, ~3% pump, only one HPP – Pelton (Dvoretskaya et al., 2018). From most Spanish HPPs with an installed power > 50 MW, 68% (Francis), 14% (Pelton), 18% (Kaplan), excluding PHS, while for most Spanish small HPPs, 46% (Francis), 17% (Pelton), 37% (Kaplan+Bulb+Fixed blade propeller); it is not possible to know if these small HPPs are RoR or reservoirs, but it is reasonable to think that most of these small HPPs are ROR. In Switzerland, the turbine share of the high head SPP hydraulic machinery is some 68% and 32% for Pelton and Francis turbines, respectively (Kalberer, 1988). The total

Swiss SPP production share amounts to 56% on a 10-year average (2010-2019), while RoR plants contribute 44%.

Francis, Kaplan-Bulb and Pelton turbines were supposed to also operate in micro plants (nominal capacity below 100 kW) and in very low head sites (< 5 m), that generally are equipped with other turbine types (water wheels, Archimedes screws, Cross flow, Very Low Head- VLH-Turbine), generally installed in existing infrastructures (Bozhinova et al., 2013). In these sites the choice is strictly related to the on-site detailed characteristics. Nevertheless, micro hydro plants play a minor role on the total EU generated electricity.

A sensitivity analysis was carried out in order to estimate the consequences of an error on the estimation of the turbine type prevalence. The diffusion of Francis turbines in RoR plants was changed, by maintaining fixed that of Pelton turbines, and the prevalence of Kaplan-Bulb turbines was adapted correspondingly (the sensitivity analysis of turbine share in SPPs was not performed because it was already proven to be well in agreement with literature data). Table 7 summarizes the results with different combinations of Francis turbine share in RoR plants (as % on the total). It can be seen that a different Francis turbine prevalence does not affect appreciably the results.

We also assumed that the part load operation of SPP is 20% of the total annual operating time. For example, in Switzerland, Austria, Germany, UK, due to volatile markets, even reservoir units operate predominantly on part load due to energy market conditions. If we would have considered 50% instead of 20% (thus, a significant different value), the total number of hours would have been 3630 instead of 3140 h, but this would only affect the FPV benefit.

The values obtained in this study are referred to the European context, but they can be easily calculated for any geographical context, once the characteristics of the HPP fleet is known.

Table 7. ΔE_{id} value of the weighted efficiency improvement strategy by improving the performance of the turbines of all the RoR plants under different scenarios. The current estimated Francis prevalence in EU RoR is 29% and 28% for Europe.

Benefit	Francis RoR diffusion 15%	Francis RoR diffusion 29%	Francis RoR diffusion 50%
ΔE_{id} for EU	4.9%	**5.0%**	5.1%
ΔE_{id} for Europe	4.8%	**4.85%**	4.9%

Cost-benefits

Although the scope of this study is not an economic assessment, in this section some key points are discussed within the economy context. First of all, it is worth to note that flexibility, along with storage, is the benefit according to the market needs that better supports the cost-effectiveness of a hydropower plant new construction or upgrading, and it is the main driver for most of modernization actions as long as safety issues are not involved. Indeed, it may happen that an increase in installed power may be motivated not only by slightly increasing the annual production, but mainly by focusing the generation to the peak hours of demand, profiting of higher prices at the electricity market. Flexibility is important for the economic viability of the plant as it allows better bidding in the balancing market. For example, from the analysis of the operation of several Spanish reservoir hydropower plants, the main source of revenue was found to be the electricity spot market. The revenue from balancing markets is relevant and make a difference so as to make an investment in a new plant or the refurbishment of an old plant feasible. Regarding economic feasibility sufficient high prices have to be ensured by the market during sufficient time to create a business case for investing in upgrading and extension of hydropower (Schleiss, 2006). Increasing the installed power at large SPP by building a new powerhouse and waterway system located mostly underground (parallel to the existing one and using the same reservoir) involves high investment and is motivated by reducing the yearly operational hours allowing to concentrate the generation in periods with high demand, ranging from some hours to several consecutive days (Schleiss, 1997). Such projects do not increase yearly generation and become only interesting if the market remunerates peak energy balancing services over time horizons ranging from milliseconds to weeks, and for providing reserves.

Uria Martinez et al., (2021) showed that in Europe, around $8 billion were spent in 2019 for retrofitting and upgrading. However, the costs related to each retrofitting strategy are rather site specific, and some practical examples can be found in the Supplementary Material. In general, when considering the electro-mechanical equipment, the costs of life extension can be assumed as 60% of greenfield costs, while upgrade costs can be assumed as 90% of greenfield costs. Generally speaking, despite the high investment costs that may incur, benefits are expected to overcome costs. For example, US$ 2.9 billion investment in Africa can unleash benefits of US$ 6.4 billion in present value through life extension. Similarly, for Central America: investments of US$ 1.6 billion can yield benefits of US$ 2.3 billion. For the upgrade scenario, for Africa a US$ 3.9 billion investment would produce a present value benefits of US$ 8.1 billion, while for Central America, a US$ 2 billion of investments yields US$ 3.2 billion in benefits. Therefore, in general, benefits are twice the investment costs (Goldberg and Espeseth Lier, 2011). For example, since 2010, at least $7.8 billion have been invested in the U.S. hydropower and PHS fleet. Almost $2 billion correspond to projects initiated in 2017–2019. The most common items are replacement or refurbishment of turbine runners and generator rewinds.

5. Conclusions

The role of hydropower in the near future will be important for satisfying the rising electricity demand and providing a better water management, flood control and water storage, making use of its significant storage capacities. Furthermore, hydropower will have a main role in providing flexibility and large-scale balancing services to the grid on timeframes ranging from seconds, to hours, weeks and months. This is due to the rapid development of variable renewable energy sources from wind and solar PV, whose technical potential in Europe is estimated to be 5800 TWh/y. There is no other low-carbon solutions to flexibility, storage and large-scale balancing services on timeframes longer than a few hours. Therefore, any retrofitting becomes economically more interesting if at the same time the flexibility of the HPP can be increased. This allows not only to support the energy transition and ensuring grid safety, but also to improve competitiveness of hydro at the spot market (concentrate production on hours with high prices).

In this study several retrofitting strategies were investigated to quantify, by means of a specific indicator, their relevance in terms of realizable additional annual production and installed power. Reality checks of results and sensitivity analyses are provided to prove the consistency of the obtained results. The interpretation of the indicator as theoretical increase in electricity production shows that almost 36.6 TWh (1.3% of current electricity demand) in EU and 75 TWh in Europe could be added by implementing the increase of the dam height, reduction of head losses in waterways, improvement of electro-mechanical efficiency, digitalization and floating photovoltaic. Other strategies, e.g. the inflow increase and the installation of new waterways in combination with new hydraulic machinery, were discussed but not quantified, since their effects are very site specific; the installation of new (e.g., parallel or underground) waterways can double the installed power, providing adequate power during the peak demand periods. Reservoir interconnection is another strategy that could add about 28.6 TWh of storage in Europe, according to a literature study. Results show that the strategies with the highest potential are the reservoir interconnection and the improvement at off-design conditions, whose main benefits are reflected into the flexibility increase of the hydropower fleet. The energy benefit of digitalization was quantified in an efficiency increase by 1%, although spill reduction due to a better inflow forecast can increase annual generation by 11%, and thus become the most convenient strategy in certain contexts.

The other important benefits achievable by implementing the above strategies, e.g. increase of security and reliability, and mitigation of environmental improvements, reduction of outage and failures (by digitalization) were not quantified. These benefits should be addressed in future works, since they play an important role in supporting and justifying retrofitting investments. For example, in Alpine environment, a dam heightening of 10% would increase the head (i.e. the power) of less than 2% on average, but the stored volume would increase by 20-

30% (with benefits on water security and stored energy). The installation of floating PV could increase the hydropower capacity by 2.7%, but the FPV generation could easily increase the global plant capacity factor by 20-50%. The digitalization of a hydropower plant does not only allow to increase the production through a better management and inflow forecast, but also to prevent failure and to reduce maintenance and outage.

This study poses the basis for more specific studies at the country or regional scale, since site-specific limitations were not here considered. The results of this study can prove guidance to policy makers within the strategic policies at the continental scale, especially in Europe, in order to better understand the role of hydropower and the relevance of the problem within the energy market, while the Supplementary Material can instead be of high interest for hydropower companies and scientists to support their retrofitting projects and studies. Although the assessment is carried out for the EU and European contexts, the general methodology and the literature presented in support of the assumptions are easily generalizable, and can be applied at any national or continental scale, as long as the composition of the hydropower fleet is known.

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