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Assessing the energy potential of modernizing 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 modernization of HPPs can generate several benefits in terms of generation, flexibility, safety, operation, and may have neutral or even positive implications for the environment. In this work, we appraise several options for the modernization of existing plants, with the exclusion of measures expected to increase the hydro-morphological pressure on water bodies (e.g. increase of withdrawals or new parallel waterways): dam heightening, head loss reduction in waterways, increase of weighted efficiency of electro-mechanical equipment, digitalization and inflow forecast, and floating photovoltaic (evaporation reduction). We provide an indicative estimation of the additional power and annual generation that could be obtained compared to the current condition. We estimate that the overall energy generation could be increased by 8.4% for European Union and 9.4% for the whole Europe by implementing the above-mentioned strategies. The additional energy gain achievable by increasing the inflow was discussed but not included in the above mentioned overall indicator, because it is very site-specific. The additional energy storage achievable by reservoir interconnection and co-ordinated operation has been estimated in literature as 169 TWh. This suggests that the modernization of HPPs can generate significant benefits in terms of energy, and should be considered as an important element of energy policy, also considering the additional benefits in terms of reliability and flexibility of the energy system that it

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may deliver. The modernization options considered here, insofar as not entailing a worsening of the hydromorphological alterations, are also expected to cause limited or no conflict with the environmental objectives of water policies in Europe.

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 [90]. 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%) [99]. In Europe, the installed power in 2020 reached 251 GW [90], and it was 155 GW in the European Union (EU), that are the geographic focus of the present study[2].

In 2019, 15.6 GW (1.19% of the global hydropower capacity) of large hydropower (>10 MW) were added [90] and 3.6 GW were under construction in Europe, excluding Turkey. Although hydropower development in Europe has been relatively slow since 2000, especially in the EU, partly due to the introduction of the Water Framework Directive 2000/60/EC (WFD) and more restrictive national legislation, hydropower development has not stopped [99], with a peak in 2011 of almost 10 GW of developed capacity. In particular, reservoir hydropower plants remain an important renewable energy source, as their storage capacity enables flexibility of operation and adaptability to the grid requirements. In addition, reservoir plants are less vulnerable to the variability of hydrological regimes induced by climate change [18]. Because of this, it is estimated that the HP installed power should grow by around 60%, with an estimated investment of US$ 1.7 trillion by 2050, generating 600,000 skilled jobs over the coming decades [90].

A typical hydropower plant (HPP) has an operating life of more than a hundred years if maintained regularly. However, almost 50% of all HPPs worldwide were originally commissioned more than 40 years ago, and many are approaching a critical stage of ageing, which is a major concern worldwide [10]. Hence, hydropower fleet modernization has a strategic importance at the global scale (Goldberg and Espeseth Lier [68], Van Vuuren et al. [179], Cohen et al. [42], Lia et al. [110], de Podestà Gomes and Bajay [46]). Uria Martinez et al. [177] showed that only 20% of the European hydropower fleet has been modernized in the last forty years. The European Union (EU) fleet presents a similar situation [99]: most of the EU hydropower fleet was commissioned in 1970–1980, with a current HPP average age of 46 years. This estimation does not take into consideration stations that have been modernized (18% of the plants according to [99], for the EU, or 20% estimated in [177], with half of the interventions before 1990, for Europe). Even assuming that the modernization comes close to a complete overhaul of the HPP, making the year of modernization a new commissioning date, the average age of the fleet remains as high as 42 years, confirming the potential scope for modernizing the existing hydropower fleet in the European context.

Hydropower modernization may lead to retrofitting, upgrading or refurbishing of a plant. 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 the efficiency. Upgrading implies changing the main equipment (turbines, generator), the infrastructure (dam height, intakes) [27]. Refurbishing also requires significant civil works for increasing, for instance, safety.

The increase in energy generation and other benefits that may be associated to modernization may be of great interest, especially if we consider that a modification of existing plants may be free from most of the environmental impacts and conflicts related to the construction of new HPPs on pristine and unregulated rivers. Modernizing the existing HPPs would consolidate and further improve current energy generation and grid flexibility, i.e. hydropower capacity to adapt its operating conditions within short time and support ancillary services, while extending the lifespan, addressing operational issues, increasing the level of safety and reducing environmental impacts [4,100,89]. In this study we propose a screening-level, large-scale quantification of the gains in terms of annual generation and flexibility, that the modernization of the European hydropower fleet might yield. We investigated different modernization practices applied at the European and EU scale, considering the hydropower fleet characteristics, and including all the hydropower plant types (reservoir and run-of-river). For each practice we propose an indicator of the additional energy generation that can be expected, and the potential contribution it may bring at the European and EU scale. Based on estimated characteristics of the European hydropower fleet, which determine the feasibility and effectiveness of the different modernization practices, the technologies available for each modernization practice, supporting the assumptions we make for an aggregated assessment of energy gain, are discussed in detail in the Supplementary Material. We discuss our results also in light of a sensitivity analysis and some reality checks.

2. Methods

2.1. Typologies of modernization practices

The annual generation of a hydropower plant depends on the quantities shown in Eq.1:

$$E = \rho g Q H \eta t \tag{1}$$

where E (kWh) is the annual generation, $\rho = 1000$ 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 t is the annual duration of plant operation. Another relevant metric used in this study is the capacity factor CF, defined as the ratio of annual energy generation 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 [99], e.g. in Norway it is 0.5.

Different modernization practices can be identified depending on which terms in Eq.1 they leverage. Certain practices aim at increasing the usable discharge (Q-strategy), others the net head (H-strategy), the efficiency (η-strategy), or the fraction of the year during which the plant operates (t-strategy).

A Q-strategy may entail either an increase of the annual inflow, or an 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. Increasing the annual inflow is only feasible where we expect climate change to cause an increase of natural discharges, as e.g. in Norway [110], while most of the European fleet is expected to experience a reduction of annual flows particularly in the Alpine region, often as a consequence of glacier retreat [172,73,155]. In

[2] 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.

all other cases, an increase of withdrawals is usually limited by water protection legislation, and it is very site specific. We will therefore focus on the mere concentration of flow during shorter operating windows, without changes in the overall annual inflow. Increasing the inflow entails an increase of runner size, conveyance capacity of waterways and new hydraulic structures to prevent possible damages [182,127], which obviously entails costs. Costs may be justified when these measures make hydropower plants more flexible, capable to satisfy peak energy demands through the increased installed power, while reducing or stopping generation when there is a surplus of variable renewable energy (VRE) and to reduce spilling during wet periods. The feasible *Q*-strategies are the installation of floating PV to reduce evaporation, reducing head losses in water ways and a better management of flow (e.g., when more units operate together) by implementing digitalization.

With regard to the η-strategy, hydropower industry faces an increasing demand of turbine designs that allow a wider range of operations (from part-load to full load), and current research aims 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 [126]. 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.

The *t*-strategy allows to increase the annual operating hours, e.g. by reducing outage and maintenance, reducing manual operation activities and increasing the automatized ones (by implementing digitalization), improving operation under transient conditions and reducing the duration of a start and stop cycle.

The *H*-strategy mainly consists in reducing head losses in waterways and in increasing the dam heightening, although the latter is very site specific.

2.2. Approach to the estimation of energy gains

Fig. 1 shows the procedure we adopt, made of the 4 steps discussed below, namely:

(1) Definition of the modernization practices.
(2) Apportionment of the overall energy generation (*E*) to the part of the HPP fleet on which each practice can be implemented.

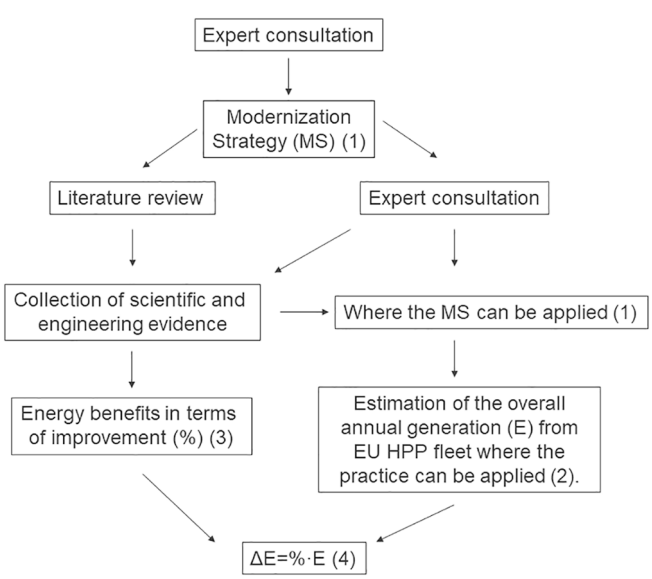

Fig. 1. Procedure and the four steps within parenthesis.

(3) Estimation of a % increase in energy generation for each modernization practice.
(4) Estimation of the overall energy gain ΔE. ΔE was normalized with the average energy generation in EU (360 TWh/y) and Europe (620 TWh/y) obtaining ΔE_{id}.

The first step is the identification of the modernization practices applicable in each context. Based on the terms in Eq.1, the selected modernization practices that can be applied to a certain HPP are listed in Table 1.

The second step requires the estimation of the annual energy generation (*E*) from the subset of the overall HPP fleet to which each modernization practice can be applied. This is done taking into account

Table 1
Modernization practices considered in this work. Different HPP types: storage-SPP-, run of river –RoR-, pumped storage –PHS.

Modernization practice	Strategy Type (Eq.1)	Applicable to/ effective at	Supplementary Material for details
Dam heightening	*H*-strategy	Concrete and embankment dams in mountain regions with hydraulic head of the connected HPPs > 300 m, and open loop PHS plants	2
Reduction of head losses in waterways and penstocks	*H*-*Q*-strategy	SPP plants	3
New electro-mechanical equipment for improved efficiency at BEP	η-strategy	RoR, PHS and Reservoir plants that operate at BEP or full load most of the time	5
More flexible electro-mechanical equipment	η-strategy	RoR, PHS and Reservoir plants that often work at off-design conditions	6
Digitalization and inflow forecast	*Q*-*t*-strategy	RoR, PHS and Reservoir plants	8
Floating Photovoltaic (FPV)	Evaporation reduction, *Q*-*t*-strategy	Reservoir and PHS plants	9
RoR: increase of installed power (new and/or additional machines) at turbines	*Q*-strategy	For RoR plants without water diversion depending on the number of days for which inflow exceeds nominal i.e. installed discharge capacity	4
SPP: increase of installed power by adding a new parallel waterway system with a new powerhouse	*Q*-strategy	PHS and SPP	3
Increase of annual inflow	*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.	4
Start and stop improvement	*t*-strategy	RoR, PHS and Reservoir plants	7

the following characteristics of the hydropower fleet:

1) HPP type: Run-of-River (RoR), Storage/Reservoir (SPP) and Pumped Storage (PHS) and taking into account the contribution of each type of HPP to the generation of electricity. 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 we used (described in the next paragraph), 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).
2) Turbine type (Pelton, Francis, Kaplan-Bulb) and energy generation from each HP fleet equipped with each type.
3) Average operating hours of a European HPP.

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 [93], 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), 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 % of 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 of 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., [81]. We preferred to conduct a bulk assessment rather than a plant-by-plant analysis because the latter option would require site-specific data that we sometimes do not know (e.g., energy generated, evaporation from the reservoir), while the data values at the European scale are known. The main results from this analysis are depicted in Figs. 2 and 3, and better detailed in Supplementary Material 1.

The third step is the quantification of the improvement achievable by each modernization practice (literature review in the Supplementary material+expert consultation), expressed as percentage of improvement. For each practice, a literature review (discussed in the Supplementary Material) was carried out and several case studies were collected to identify the improvements that each practice can bring.

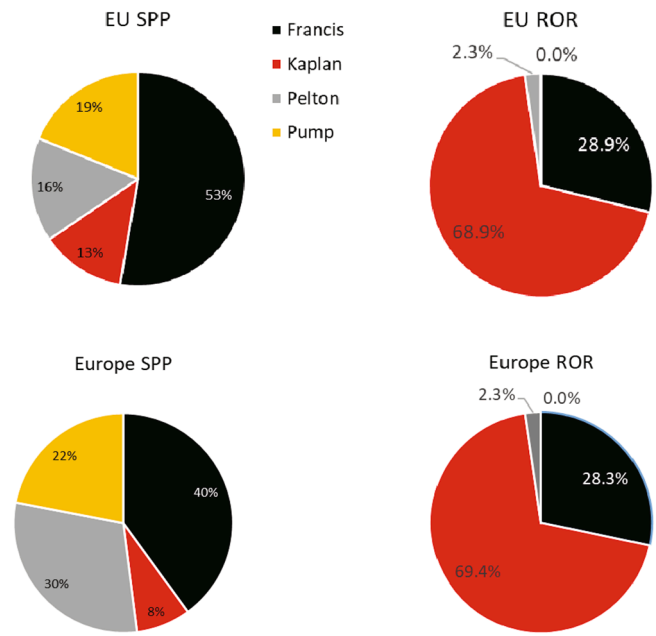

Fig. 3. Estimated turbine prevalence in EU and Europe.

The fourth step is the calculation of the indicator ΔE, i.e. overall energy gain obtained by multiplying the improvement, expressed in %, by *E*. The calculation of the energy gain in terms of annual generation was normalized by the present energy generation, obtaining an indicator of improvement expressed in percentage, ΔE_{id}. This describes the additional energy generation that could be technically delivered, independent of the market demand and all other conditions being constant. ΔE_{id} is a robust and physically justified indicator to quantify the energy gains. ΔE_{id} is also an indicator of the flexibility improvement, i.e. the capacity of producing on demand in high peak periods and for few hours.

3. Results

Table 2 lists the results of the literature review and expert consultation for each modernization practice, that are the basis for the calculation of the energy gains. Each practice can be implemented to certain HPP types, as specified in Table 2, and the share of the related HPP types is shown in Fig. 2. Some potential impacts upon the aquatic ecosystems related to some typologies of modernization interventions are also listed. The effects of the last four practices could not be quantified at the EU and European scale, because too much specific and with possible

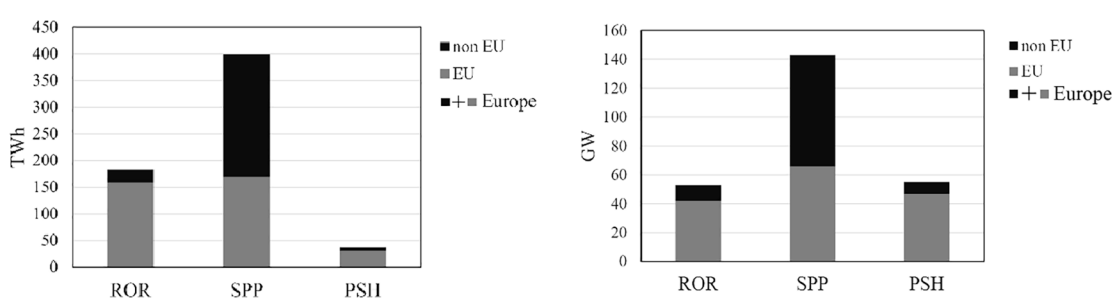

Fig. 2. (a) Annual energy generation (a) and installed power (b) in EU and Europe.

Table 2
Modernization practices considered in this work, u/s = upstream, d/s = downstream. Different HPP types: storage- SPP-, run of river –RoR-, pumped storage –PHS.

Modernization practice	Main note on generation benefit	Additional benefits	Main environmental impacts on the aquatic ecosystem
Dam heightening	Dam heightening of 10%. For PHS, only the flow related to the natural runoff should be considered. Applied to SP with head above 300 m.	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	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)
New electro-mechanical equipment for improved efficiency at BEP	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	The goal is to flat the efficiency curve, weighted efficiency gain of 4–5%.	Damage reduction due to better flow behaviour, and flexible generation	Temporary restoration of the "natural" flow regime in the watercourse during the works. Afterwards: n.a. (no variations in the inflow rate)
Digitalization and inflow forecast	1% efficiency increase, and increase of generation by a better inflow forecast up to 11%.	Flexibility, better control, inflow forecast and damage prevention	n.a. (no variations in the inflow rate)
Floating Photovoltaic (FPV)	10% of water surface covered would increase the hydro generation by reducing evaporation of 70% on the covered area + additional generation 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)
RoR: increase of installed power (new and/or additional machines) at turbines	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 h 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	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 h below 1000 h per year)	Some minor gain (<2%) due to lower friction losses in new waterway systems.	n.a.
Increase of annual inflow	Generation increase but water withdrawal from the river.	Increase generation during the peak periods (flexibility)	Variations in the inflow rate.
Start and stop improvement	1 start and stop = 15 h of reduced life	Flexibility and less damages	n.a. (no variations in the inflow rate)

environmental impacts as discussed above.

3.1. 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. The latter was considered here as directly affecting the available power. We supposed that the dam heightening can be implemented only in mountainous and unpopulated environments, where the increase in the upstream water level is not a problem for settlements, the environment and infrastructure (e.g. roads). 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. 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.

Based on the work for Swiss dams [7,58], well supported by the literature review discussed in Supplementary Material 2, the dam 10% heightening was applied to the SPPs and PHS (only considering the energy produced from the natural runoff) with head $H > 300$ m (in the European context this situation well reflects alpine contexts). The consequent head increase reflects into an analogous increase of installed maximum power for the considered plants, and additional energy

Table 3
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%	2.3%
Kaplan	4.5%	1.7%	1.2%
Pelton	4.0%	0.4%	1.0%
Pump	5.5%	0.5%	0.33%

generation. 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, the calculation was applied to each SPP of the hydropower database with $H > 300$ m, increasing the dam height of 10% and calculating the increase in H and in the related power (a dam height increase of Δd only increases the center of gravity of the reservoir by about $2/3\Delta d$, assuming a triangular reservoir cross section). In this way, $\Delta E_{id} = 0.05\%$ for EU and 0.22% for Europe, which is coherent because the share of SPPs in the non-EU countries Norway and Switzerland is particularly high. In this case, we normalized ΔE_{id} using the EU and EU installed power, respectively (the dam height was estimated as described in Supplementary Material 1).

The benefit of dam heightening, rather than a significant increase of annual generation (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 Fig. A1 in Supplementary Material 2). Assuming typical stage (d) - volume (V) characteristics of Alpine valleys of a power function type $V = ad^b$, with exponent $b = 2$ to 3, a relative increase in dam height thus results in a more than proportional relative increase in volume (for a 10% increase in d, V would increase between 21 and 33%). Practical case studies, with some limitations and related costs are discussed in Supplementary Material 2.

A reduction of the roughness in waterways and penstocks can also lead to an increase of power. Indeed, penstocks and waterways reduce their performance over the years, due to increased friction and consequent head losses due to erosion and sediment deposits. Also, the methods used for tunneling has improved over the years, being able to make smoother tunnels. Therefore, their modernization can restore the original flow capacity and head. Following the data of Nogueira et al. [127] (Supplementary Material 3), it can be seen that head losses can be reduced by 25 to 40%, with a power increase between 5% and 11.6%, for a constant geodetic head, that would reflect in an analogous increase of generation. By assuming a precautionary annual energy increase of 5% after the modernization of SPP waterways and penstocks, $\Delta E_{id} = 2.34\%$ for EU and 3.15% for Europe.

3.2. 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 connected parts (e.g., casing, distributor), or the installation of additional waterways and powerhouse if the maximum flow is higher than the original design one. 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.

Table 4
Value of ΔE_{id} for each modernization practice. The ideal increase of installed power and/or annual generation can be estimated by multiplying the indicator value by the current generation in EU and European Union, respectively.

Modernization practice	ΔE_{id} EU	ΔE_{id} Europe	Interpretation	Comment
Dam heightening – *H- strategy*	0.05%	0.22%	Increase of peak installed power	High investments, not always feasible; main benefit in increasing off-season generation 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 generation 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 generation 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 [48].
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 (evaporation reduction)	0.02%	0.05%	Increase of annual generation equivalent to 500 mini HPP with 100 kW of average power.	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 generation dominates additional hydro output due to evaporation reduction.
Floating PV: solar energy from PV		729 GW	Installed power of floating PV covering 14% of the reservoir surface [105]	This should not be considered an increase in hydro generation.
Reservoir interconnection, *Q-strategy*	4 TWh	28.6 TWh	Increase of energy storage.	Connecting reservoirs within 20 km, from Gimeno-Gutiérrez and Lacal-Arántegui [67].
Virtual reservoir interconnection, *Q-t strategy*		140 TWh	Virtual Energy Storage Gain on 14 year period.	Coordinated operation of HPP within 3000 km, from [187].
Increase of peak discharge RoR, *Q-strategy*	4.4%	3.0%	Increase of annual generation of 15.8 TWh and 18.6 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 generation	Not quantified, site-specific, may be negative in some regions due to climate change
Start and stop improvement	–	–	Increase of annual operating hours and lifespan extension	Not quantified
Overall indicator	8.4%	9.4%		(excluding the last four strategies, reservoir interconnection and coordinated operation, and energy from floating PV)

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 [34].

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 generation can be concentrated during peak hours [7]. For a slight increase of the nominal power (<15%) of SPP, also the existing waterways (and surge tank) have to be adapted [3,2].

3.3. η-strategy: new electro-mechanical equipment: improvement of the Best Efficiency Point and weighted efficiency

The mechanical components of hydraulic turbines are prone to ageing after years of operation (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 power. The modernization of old and aged components can either restore the initial power or increase the power (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 exhibits 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 5). 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.

However, since nowadays, HPPs frequently work at off-design conditions, to estimate the indicator ΔE_{id} for this strategy, the improvement of the weighted efficiency η_w was considered, as discussed in Supplementary Material 6. 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 6, taken from IEA [87], the efficiency gain after modernization of 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 modernized (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, i.e. when velocity triangle theory is satisfied) 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 efficiency improvements in Table 3 were multiplied by the data presented in Table 4 (for EU). The indicator value is 5.0% for EU and 4.85% for the whole Europe.

3.4. t-strategy: start and stop improvement

Based on literature data described in Supplementary Material 7, 100–500 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, the lifespan shortening and the related damages due to start and stop can be considerable. 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 practice 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.

3.5. 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 8, it is reasonable to assume that the digitalization can improve the efficiency of existing HPP by 1% (ΔE_{id} = 1.0%), for example by better distributing the flow among the different turbine units. 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 8).

3.6. t-strategy and Q-strategy: floating PV

The installation of floating PV on the reservoir of HPPs leads to several benefits [38]. 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 9, 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. [105]. Finally, it must be noted that FPV generation dominates the increase of the hydropower generation due to the reduction of evaporation.

From data of Hogeboom et al. [81] it was estimated that the annual evaporative volume from the examined hydropower reservoirs is $2{,}810 \cdot 10^6$ Mm^3 and $3{,}734 \cdot 10^6$ Mm^3 for EU and Europe, respectively. By a linear extrapolation, considering the total reservoir surface in Hogeboom et al. [81] of 10,586 km^2 and 13,567 km^2 (EU and Europe, respectively), and the real ones of 19,374 km^2 and 52,071 km^2, the annual evaporative volume from the SPP reservoirs is $V_e = 5{,}143 \cdot 10^6$ Mm^3 and $V_e = 14{,}332 \cdot 10^6$ Mm^3 for EU and Europe, respectively. Multiplying these values by 70% (evaporation reduction below the FPV, suspended type in [153], and [193]; Abdelal [195]) and by the FPV surface (10%), and considering 3,140 h of annual operation (see Supplementary Material 1), it is possible to obtain $V_e \cdot 0.7 \cdot 0.1/(3{,}140 \cdot 3{,}600) = 89$ m^3/s and 32 m^3/s of additional flow that could be discharged over the 3140 h, on average, for Europe and EU, respectively. The EU value is in line with the estimated evaporation of 9114 m^3/TJ [180]: considering

the estimated EU generation from SPPs of 169 TWh/y, and with the above mentioned assumptions, this would correspond to an equivalent flow rate of 34 m^3/s, in agreement with 32 m^3/s. This is 0.05% and 0.07% of the total Q_{avg}[3] for EU and Europe, respectively, to which it would correspond an equivalent increase in energy generation from SPP, thus to ΔE_{id} = 0.05% and 0.07% for EU and Europe, i.e. 0.02% and 0.05% when normalizing to the whole annual generation (instead of considering only the SPPs). In Sanchez et al. [151], for the African context, a 10% FPV increased the annual hydroelectricity generation by 566 TWh with respect to the 105 TWh (+0.54%, same floating PV type), but the climatic context was different from that of Europe (e.g., 1750 mm/y of evaporation in the considered African SPPs, and 337 mm/y in Europe from data of Hogeboom et al. [81]), thus the order of magnitude of results is in agreement. The reduced evaporation is an additional flow that is added to the main discharged flow, but can also be interpreted as a flow that is available to extend the annual operating hours of the HPP.

3.7. Summary

Table 4 summarizes the ΔE_{id} value for each modernization practice, that can be reasonably interpreted as the additional annual generation, with respect to the current values, independent of the market demand and with constant external conditions. The ideal values of additional generation can be calculated by multiplying the indicator value by the current annual generation in Europe or in the European Union. The overall value is ΔE_{id} = 8.4% for EU and 9.4% for Europe (without considering the installed GW recently refurbished) considering dam heightening, retrofitting of waterways, new electro-mechanical equipment, digitalization and evaporation reduction on 10% of the surface (excluding some *Q*-strategies and reservoir interconnection). This value is in line with the definition of light rehabilitation discussed in de Podestá Gomes and Vajayfor [46].

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 ΔE_{id} = 3.0% for the Europe. The gains related to the increase of the annual inflow were not discussed being too site specific. The increase of installed peak power/flow throughout Europe and EU due to new waterways in SPP could not be estimated, being too site specific, but from Supplementary Material 3 it can be seen that it can double in some cases. Benefits of coordinated operation and reservoir interconnection can be quantified from literature data, but were not included in the overall value of the indicator: the additional energy storage is 28.6 TWh (and 4.0 TWh in EU) interconnecting existing reservoirs within 20 km distance of one another, that reduces to 198 GWh when considering 5 km distance [67]. However, this result may be underestimated, since Harby et al. [77] showed that the hydropower potential could be increased by 20 GW (60 % installed power increase) in Norway by interconnecting existing reservoirs. The interconnected and coordinated (virtual interconnection) SPP operation, can generate a virtual gain of 140 TWh [187].

Therefore, results of Table 4 should be interpreted as an indication of which practices lead to higher energy gains, while the overall value of ΔE_{id} does not include some modernization practices that can significantly increase it (but that are related to more invasive practices and with possible environmental impacts, e.g. increase of annual inflow).

4. Discussion

4.1. Increase of hydropower potential and transversal benefits

The modernization 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 gains that could be achieved by modernization of the existing hydropower fleet, i.e. 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 [77,67,187] or with other energy sources like wind and solar. Hence it is clear that the practices aimed at increasing HPPs flexibility also contribute to ideally increase the capability of the HPP to deliver annual generation, and vice-versa.

Table 3 summarizes the practices investigated in this study, with further details. For a comparison, the most common practices 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 practices within their scope. Therefore, new equipment, digitalization and waterways resulted the most implemented practices, and these were coherently considered in this study [177], and confirmed by a pers. comm. with Enel Green Power).

Table 4 shows the relevance of each modernization practice in terms of energy, but it must be noted that the benefits of modernization 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} value resulted very low. The dam heightening should also be considered as a high investment practice, although its benefits are more than energy gains. 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 generation increases. Increasing the storage capacity is one of the main strategies to compensate hydrological changes induced by climate change. For a 10% increase in dam height, for instance, the reservoir volume may increases more than proportionally between 21 and 33%. 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 in line with the provisions of the Water Framework Directive – WFD- (such as fish passage solutions, ecological flows, environmentally enhance turbines, e.g. [80;167], hydropeaking mitigation measures, e.g. [136] that could affect the potential increase in energy generation and storage capacity. However, a quantification of the energy generation losses due to the implementation of these ecological measures is site-specific and cannot be generalized, and was excluded from our assessment. Since some dams also need repair, revision and improvements of dam safety issues, it is a good practice to consider dam heightening at the same time. Obviously, impacts on the upstream environment (submergence of riparian areas due to the increased water level and transformation into a lentic system of a certain portion of the river reach upstream) may make this option not always feasible. The

[3] 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 total efficiency of 0.7 (Francis and Pump turbines) or 0.8 (Kaplan and Pelton turbines), the head and the previously estimated number of annual operating hours (assuming a lower efficiency for the overall operation and a constant head).

high investments involved require sufficiently high prices at the electricity market during peak hours of demand in the critical season (normally winter) to become economically advantageous.

The modernization 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 4). 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 4). The refurbishment of the waterways can thus re-establish the original flow rate and head, hence increase the available power and energy capacity by 5% as maximum improvement, with estimated costs between 400 and 650 $/m^2 [127]. The increase of the inflow may require updating abstraction permits, and the implementation of additional environmental mitigation measures (higher discharge releases, fish passes, etc.) [118,175].

The replacement of deteriorated equipment by new one reflects in an increased installed power and in a better efficiency at off-design conditions, with an increase in the overall efficiency over a wider operating range. 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 [122]. In this study, the weighted efficiency concept was used to estimate the overall energy gain. Innovative materials will also play a central role in the modernization projects, although their higher costs with respect to traditional materials may currently limit their economic convenience [141]. In order to reduce ecological impacts on downstream migrating fish, the use of ecological improved turbines, e.g. the Alden and Minimum Gap Runner turbines, might be considered, 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 generation, despite their lower cost [48,80]. Recent research has also shown very promising results in new design of trash racks and guidance structures to avoid fish passing through the turbine [59,173]. Self-aerated and self-lubricated turbines also reduce environmental impacts, minimizing oxygen deficit downstream and oil leakages, respectively [116,167]. Another option related to the new equipment is the installation of turbines 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 (some examples at [88,143]).

Digitalization is another important practice for improving the operation and the turbine response during start and stop cycles, that allows to extend the electromechanical equipment life, prevent failures, provide ancillary services and reduce maintenance. Not all of these practices necessarily reflect into an increase of power and generation. Instead, the short- and mid-term inflow forecast allows to avoid spilling of water that cannot be handled by the plant capacity. Digitalization would also allow to better coordinate multi-reservoir HPP, cascade HPPs and the coordinated operation of more HPPs, maximizing energy generation [5] and optimizing water management [190].

The integration of FPV can increase the hydropower fleet generation by less than 0.1% (by reducing evaporation) when 10% of the basin surface is covered with FPV, that linearly varies with the percentage of FPV coverage. This analysis shows as the main benefit of FPV is the energy generation from the PV rather than the evaporation reduction, although an increase of 0.07% of the annual generation from European SPP would correspond to 279 GWh/y, i.e. to a SPP with an average power of 88 MW (3,140 h/y of operation) or to 500 mini hydropower plants with an average power of 100 kW and operating for 5,570 h/y (as estimated in the Supplementary Material 1). The advantages of this hybrid system is mainly due to the possibility of using the same infrastructures (in particular the grid connection) and to increase the capacity factor from 3000 to 4000 h. The large increase in energy generation of the hybrid system (PV + HPP) allows a better management of HPP plants thanks to the fact the energy generation of FPV is in part anti-correlated with that of HPP plant. For the future, a power density of W_{dens} = 180 W/m^2 can be reached, already including PV efficiency (higher than that used by Lee et al. [105], in order to consider future developments and advancements). 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 [94]. Further details can be found in Kougias et al. [101]. 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 [72].

The performance improvement of cascade and multi-reservoir HPPs, and from coordinated/interconnected operation, is also important to increase generation and optimize water management. Marques and Tilmant [117] studied the coordinated operation of the hydropower plants in a single cascade scheme and found that with a proper coordination strategy an energy gain of 3–8% may be obtained. Si et al. [163] analysed the joint operation of the hydropower system in the Upper Yellow river and concluded that, depending on the type of year (dry, normal, wet), the electricity generation might increase by from 1.8% to 14.8% by means of an adequate coordination. Guo et al. [71] dealt with the coordinated operation of two cascade schemes where one river is tributary of the other and found that the electricity generation of the system might increase by 5.7% thanks to the proposed joint operation. However, this was not assessed here at the European scale. In our opinion, 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. In some cases, for instance in Norway, it is mandatory to form a so-called regulation association when there are more than one operator in a catchment or river system. These regulation associations are in charge of operating all the dams and hydropower plants in a coordinated way, to the benefit of all members.

Another strategy, already investigated in literature, is the interconnection of reservoirs that do not belong to the same hydropower scheme. Gimeno-Gutiérrez and Lacal-Arántegui, [67] studied the increase of energy storage capacity by physically interconnecting reservoirs, finding an increase of 28.6 TWh in Europe. Wörman et al. [187] studied the benefits of an interconnected and coordinated (virtual interconnection) SPP operation, finding a virtual gain of 140 TWh. These data are included in Table 4.

The modernization 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. [132] 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). A detailed analysis of eleven representative RoR plants across Switzerland [154] 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 generation by mid-century with the present-day installed machinery and residual water flow requirements [152]. Therefore, the modernization 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 10 for more details). 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). Additional considerations on time-frame and environmental challenges are discussed in Supplementary Material 11.

4.2. Sensitivity analysis and reality checks

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 EU fleet composition in term of power plant type was checked versus the data of Kougias [99], as well as the energy generation estimated from RoR plants versus real data of de Felice [44]. The composition of the European and EU and European fleet, in terms of turbine type, can be compared with literature data: 44% of HPPs > 50 MW have been estimated to be equipped with Francis turbines, 14% Kaplan, 31% Pelton, 11% Pump [34], 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 turbine power, we estimated that in Europe 38.4% were Francis, 12.1% Kaplan, 27.5% Pelton, and 21.9% 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 (the uncovered gap to reach 100% is related to less traditional turbines). 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 [166]. In Russia, 37% of HPPs > 50 MW are equipped with Francis turbines, 60% Kaplan, ~3% pump, only one HPP with Pelton turbine [49]. From most Spanish HPPs with an installed power > 50 MW, 68% are equipped with Francis turbines, 14% with Pelton turbines, 18% with Kaplan turbines, excluding PHS, while for most Spanish small HPPs, 46% are equipped with Francis turbines, 17% with Pelton, 37% with 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 68% and 32% for Pelton and Francis turbines, respectively [95].

Francis, Kaplan-Bulb and Pelton turbines were supposed to also operate in micro plants (nominal power 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 [196]), generally installed in existing infrastructures [28]. 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.

Although results are in line with practical evidence, a sensitivity analysis was carried out in order to estimate the consequences of an error on the estimation of the turbine type prevalence. The share 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 5 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 3,630 instead of 3,140 h, but this would only affect the FPV energy gain.

Table 5
ΔE_{id} value of the weighted efficiency improvement practice 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.

Energy gain	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%

4.3. Costs

Although the economic assessment is not the scope of our study, in this section some economic key points are discussed. First of all, based on the Author expertise, it is possible to say 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 and it is the main driver for most of modernization practices 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 generation, 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. 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. 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., [177] showed that in Europe, around $8 billion were spent in 2019 for modernization, at an average cost of 50 $/kW (PHS) and 125 $/kW (HPPs without pumping). However, the costs related to each modernization practice are rather site specific, and some practical examples can be found in the Supplementary Material. In general, when considering the electro-mechanical equipment, the costs of life extension can be assumed as 60% of greenfield costs, while upgrade costs can be assumed as 90% of greenfield costs. Generally speaking, despite the high investment costs that may incur, benefits are expected to overcome costs. For example, US$ 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 [68]. For example, since 2010, at least $7.8 billion have been invested in the U.S. hydropower and PHS fleet.

5. Conclusions

In this study several modernization strategies were investigated to

quantify, by means of a specific indicator, their relevance in terms of realizable additional annual generation 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 generation shows that about 30 TWh (1.3% of current electricity demand) in EU and 58 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 practices, 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 practice that could add 28.6 TWh of storage in Europe, according to a literature study, while coordinated operation within 3000 km could add 140 TWh. Among the quantified practices, the practice with the highest potential (only considering the energy gain) is the weighted efficiency improvement of electro-mechanical equipment, whose main benefits are reflected into the flexibility increase. The energy gain 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 can become the most convenient practice in certain contexts.

The increase in the annual generation and flexibility allows to support the energy transition and to ensure grid safety, but also to improve competitiveness of hydro at the spot market (concentrate generation on hours with high prices). There is no other low-carbon solutions to flexibility, storage and large-scale balancing services on timeframes longer than a few hours.

The other important benefits achievable by implementing the above practices, 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 modernization 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 reduces evaporation and thus increase the available flow, but to a less extent with respect to the PV generation.

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. The Supplementary Material can instead be of high interest for hydropower companies and scientists to support their modernization projects and studies. Although the assessment is carried out for the EU and European contexts, the general methodology and the assumptions derived from the literature review are easily generalizable, and can be applied at any national or continental scale, as long as the composition of the hydropower fleet is known.

Authors contribution

All the Authors contributed to the paper.

In particular, E.Q. coordinated the consultation, wrote the first draft of the paper and carried out the calculation. A.P. supervised the research and helped to write the paper. All the other authors contributed to collect the literature information, wrote the supplementary material and revised the paper.

Declaration of Competing Interest

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Appendix A. Supplementary data

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