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HYDROPOWER AND PUMPED HYDROPOWER STORAGE IN THE EUROPEAN UNION

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS AND MARKETS

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Contents

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Part of results related to future hydropower opportunities were taken from scientific papers published in the context of the SustHydro (Sustainable hydropower to solve the controversy between renewable hydroenergy and ecosystem protection) exploratory activity coordinated by Emanuele Quaranta at the JRC. External scientists were selected to review this report in order to cover most of the several topics related to hydropower and to cover different European countries.

Authors

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Executive Summary

Energy transition and the Green Deal are rapidly progressing in the European Union (EU), with several effects on different sectors, for example on industrial innovation, public and private transport, decarbonisation of the energy sector and energy efficiency. In the electricity sector, the intermittent wind power and photovoltaics, and the hydropower sector with its high flexibility and storage capacity, are key and complementary players.

Hydropower is a complex and challenging sector within the WEFE (Water-Energy-Food-Ecosystem) nexus, especially in the EU (SWOT in Table 1). Hydropower is a renewable and flexible energy source, and its flexible operation and storage capacity allow to integrate the volatile energy production of wind and solar power plants, ensuring grid stability and ancillary services. Therefore, hydropower plays a key role in the long-term decarbonisation scenarios (i.e., the Sustainable Development Scenario and the Net-Zero Emissions Scenario by 2050), contributing to reach the renewable energy targets set in the Renewable Energy Directive (Directive 2009/28/EC, REPowerEU). On the other hand, barriers (not necessarily for hydropower purposes only, but also for, e.g., irrigation and industrial use) in freshwater systems are perceived as a source of impact in the Water Framework Directive (Directive 2000/60/EC), which is aimed at the preservation or recovery of the "good ecological status" of the aquatic environment. The impacts associated to barriers can be of different types, e.g., hydrological and morphological alterations, interruption of river continuity and impoundments, amongst others, and hydropower turbines may cause damages to fish (new hydropower developments in existing barriers and in water infrastructures, and new design concepts, can mitigate these impacts).
Multipurpose hydropower projects can have important additional functions for society, often more important than hydropower generation per se: irrigation and drinking water provision, flood and drought risk management (Flood Directive 2007/60/EC), river navigation and recreation. However, in these projects, civil structures, resources and water reservoirs are shared among different users, and conflicts among different priorities may arise. The challenges of the hydropower sector are also technical. A typical hydropower plant includes the electro-mechanical equipment, the civil structures and the Operation and Maintenance (O&M) equipment to control the system and monitor the status of the components. The operation depends on hydrological conditions, market demand and environmental constraints, amongst others. A significant proportion of investments in the hydropower sector refers to the civil works and associated consultancy services that are very difficult to track.

Despite the high complexity of the sector and its challenges, hydropower is currently the giant of low-carbon and renewable electricity technologies, with 1,360 GW of global installed capacity and 4,250 TWh/y of electricity generation in 2021. The installed capacity in Europe is 254 GW, with an annual energy generation in 2021 of 620 TWh. European hydropower reservoirs provide a storage capacity of 220 TWh (85 TWh are located in Norway). In the EU, the current hydropower capacity is 151 GW, with an average annual generation of 360 TWh/y, which is the highest share from renewable energy sources, beside wind energy. The EU hosts 44 GW of pumped hydropower storage to store water-energy, that is a quarter of the global installed capacity.

Hydropower is a well-affirmed technology, with overall efficiencies generally exceeding 80%, and that can reach 90% (the efficiency of the hydraulic turbine can reach 95%), which is approximately 5-times higher than photovoltaics and 3-times higher than wind technologies. Nevertheless, continuous R&D activities are ongoing to develop novel technologies, innovative mitigation measures and more sustainable solutions to deal with the emerging challenges of the energy market and to mitigate impacts. In terms of scientific publications, the hydropower knowledge production in the EU is the highest, globally, after China. The EU and the U.S. host each about 28% of the innovative companies. Although China is the main patent leader (partially also due to the different patenting procedure in the country), the EU, Japan and South Korea perform almost similarly, and slightly better than the U.S. During the period 2010-2019, the patent activity in EU has registered 471 entities from companies, 18 from non-profit organization or government institutions, 48 from Universities, while 56 are individuals. The EU holds 33% of all high-value inventions globally (2017-2019), with Germany, France and Finland the main contributors. Some low readiness level technologies, that are expected to become established technologies in the next decades, are under investigation. Novel technologies are under investigation and implementation in European hydropower plants, often supported by projects funded by the European Commission (EC) (e.g., Horizon, Interreg projects, among others). Some of these are dedicated to mitigation strategies and less impacting technologies (e.g., FITHYDRO), while others are trying to make hydropower more resilient to climate changes and more flexible (X-FLEX), or aimed at tapping hidden opportunities (e.g., in water distribution networks, REDAWN). Novel technologies are under investigation to integrate hydropower generation with other technologies and energy sources, e.g., floating photovoltaics on hydropower reservoirs, hydrogen generation, hybridization with batteries and waste-heat recovery. Ocean (tidal and wave) energy technology implements several devices adapted from the hydropower sector. Hydropower offers room for digitalization, real-time and remote control, that are emerging strategies to support the EU digital and green transition. Digital solutions can be implemented both for monitoring and enhancing quality of the surrounding environment (e.g.,

water discharge, water temperature and quality, fish habitat, water levels, stability of slopes), for improving the overall efficiency and supporting the Operation and Maintenance sector.

Hydropower systems can contribute towards economic development and social investments. Globally, IRENA estimates that approximately 2.36 million people worked directly in the hydropower sector in 2021, the highest in the last monitored decade. The number of jobs in Europe as a whole is estimated at 120,000. In the EU, the number of direct and indirect jobs in hydropower is estimated to be 99,600 in 2018, with Italy and Austria, located at the heart of the Alps, being the most relevant employers.

Hydropower contribution to the EU+UK annual gross domestic product (GDP) is EUR 25 billion. The EU hydropower market is also very active. Outside China, three EU-based supply companies delivered 73.5% of the total orders in terms of power capacity within the period 2013-2017. The large European operators continue to invest in many hydropower projects outside of Europe, while manufacturer companies have a great export potential. There are several large construction companies which have a worldwide activity in hydropower and dam projects. Many European engineering and consultancy companies offer knowledge, expertise, or consulting to hydropower projects outside of Europe. The global exports within the period 2019-2021 accounted for EUR 2 billion, with EU countries holding 50% of this (China accounted for EUR 376 million of exports in the period 2019-2021). The EU has a significant presence in Russia, Switzerland, Norway, supplying more than 70% of their imports, and in Canada and Chile, contributing to about 40% of their imports. This makes the EU a world leader in hydropower technology (included pumped hydro).

The invested value (early and later stage investments) per inhabitant is 0.03 EUR/person in the EU, while it is 0.25 and 0.01 in the U.S. and China, respectively. European hydropower manufacturers spend more than 5% of annual turnover on R&I, which is more than twice the European industry average. IRENA and World Bank analyses identified hydropower as currently one of the cheapest forms of renewable energy.

Therefore, hydropower is a key sector to maintain a competitive EU in the world, especially in light of the current geopolitical situation and energy crisis. Hydropower catalyses an optimal integration of volatile energy sources (e.g., wind and solar) into the electric grid, and supports the achievement of the renewable energy targets. The multiple services of hydropower reservoirs in the EU can provide additional benefits and mitigate the effects of climate change. Europe is home to more than half of hydro equipment manufacturers and large operators of hydropower. As hydropower global market expands due to increase in global installed hydropower capacity, European operators and manufacturers are an important source of jobs. The export capacity of EU hydropower companies and their innovative characteristics, associated to a lead position in terms of scientific publications, make the EU hydropower a lead sector in the world. The challenges that hamper hydropower deployment and limit its operation are several, most importantly financial, regulatory and environmental. These challenges should serve as a catalyst for a more comprehensive dialog among stakeholders (e.g., industry, academy, associations, citizenry and governmental institutions). The development of hydropower, as well as of all the other renewable energy technologies, must objectively consider benefits and impacts on the short and long-term, in order to mitigate possible conflicts among different Directives and stakeholders, depletion of resources (e.g., water, minerals and materials) and ensure a sustainable growth within the WEFE nexus.

Table 1. SWOT analysis of the hydropower sector.

Strength	**Weakness**
• Mature technology, high efficiency • High flexibility and availability, ensuring supply during peak demand • Long lifespan • Storage capacity (water and energy) • Multipurpose benefits of reservoirs and dams • The lowest Ozone Layer Depletion indicator, the highest Energy Returned on Energy Invested ratio, the lowest pressure on mineral resources and amongst the lowest water footprints during construction and manufacturing • The EU is a leader in scientific research, technological innovation, export and market development	• Environmental and social impacts associated to the construction of new barriers (and high dams) demanding significant and costly mitigation measures (e.g., habitat, fish migration, hydropeaking, hydro-morphological alterations) • Impacts of reservoirs: sedimentation, impoundment, evaporation, carbon and methane emissions (especially, but not limited to, tropical reservoirs) • Most of suitable locations for large reservoirs have already been exploited in Central and Northern EU • Long construction periods of large power plants • Financial support is needed and additional benefits are not remunerated • Moderate public awareness on the benefits of hydropower
Opportunities	**Threats**
• Hidden potential in existing facilities in the water sector (e.g., water network infrastructures) • Attractive for rural and decentralized electrification • Integration of intermittent renewable energy sources with pumped hydropower storage • Modernization of hydropower infrastructure is needed in the EU • Still substantial potential for increasing water pumped hydropower (interconnecting existing reservoirs, sea water plants) • Hybridization with other energy technologies • New reservoirs in high altitude using new lakes created by glacier retreat • Export potential • Safe return on long-term investments in an increasing electricity market	• Substantial uncertainties in long approval processes • Climate changes may change water availability and the available potential (it can increase or decrease, depending on the geographic context, seasonality can also change) • Reduction of generation due to higher requirements regarding environmental flow releases • Loss of reservoir volumes due to sedimentation • In EU, need of improved market rules and to remunerate the additional benefits • Loss of knowledge due to low attraction of traditional engineering fields for young professionals

1 Introduction

1.1 Scope and Context

Water power (or, hydropower) is the oldest renewable energy technology, already used thousands of years ago (e.g., water wheels, see section 2.1). Today, hydropwoer is the largest renewable energy technology, with 1,360 GW of global installed capacity (see section 2.2). The hydropower sector is at the centre of several EU Directives, and, as such, its cross-cutting relevance poses it at the centre of several programmes, debates and challenges within the WEFE nexus. The main European Directives dealing with hydropower are the following ones.

- The European Water Framework Directive (WFD) (Directive 2000/60/EC) gives a focus on the preservation or recovery of the "good ecological status" of the aquatic environment. Hydropower is strictly connected with aquatic ecosystems, due to the impacts it may generate. In 2022, the European Commission published the EU Taxonomy Climate Delegated Act, prompting calls for clarification and consistency in the investment criteria for hydropower.
- EU policies on biodiversity and nature protection are also important for hydropower production and development. Any plan or project that could affect a Natura 2000 site should be subject to an assessment procedure to study the effects in detail, based on Article 6(3) of the Habitats Directive. This is relevant for new hydropower projects and for upgrades or modernizations of existing hydropower plants.
- The Renewable Energy Directive (RED) (Directive 2009/28/EC) claimed for 20% gross energy consumption of every member state based on renewable energy until 2020, and net zero carbon emissions by 2050. As part of the EU´s Climate and Energy Policy 20/20/20, the increase in hydropower production on the energy market (beside an increase of wind and photovoltaics, mainly) will be a consequence of those targets. The energy transition established in REPowerEU, the Green Deal, and the necessity to phase out dependence on Russian supplies, will have a further accelerating effect.
- To reduce risk from imported flexibility, Art. 22 lit. d) of the Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector, requires that every country has to increase the flexibility of the national system, in particular by means of deploying domestic energy sources, demand response and energy storage, and flexibility procurement mainly based on cross-border-exchange [1]. Hydropower plays a key role in this context, since it is the most flexible renewable energy technology and the sector with the highest water-energy storage capacity.
- To cope with natural hazard of floods, the European Parliament released the Floods Directive (Directive 2007/60/EC) in 2007 for managing river systems. Given the severity of floods in Europe (325 major floods in Europe between 1998 and 2004, and more than 200 since 2000), the European Floods Directive addresses the risk analysis and provides operative tasks for the member states. Most of the European river systems are heavily impacted by multiple pressures along the river corridor and/or feature significantly altered conditions in inundation areas. Hydropower can be a source of impact, but also a mitigation strategy, due to its capacity to store water and, therefore, to mitigate floods and droughts.

1.2 Hydropower technology

Water flows from higher altitudes to lower ones, whose difference is called gross hydraulic head. This altitude difference generates the power of water, that can be in the form of potential power (pressure and water level) and kinetic power (water flow velocity). Traditional hydropower is a renewable energy source that converts the hydraulic (water) power into mechanical power by means of a rotating turbine, and into electricity through the connection to an electric generator (Figure 1). Hydropower does not use fuels and it is hence a clean energy source. However, some impacts may be generated, especially when new barriers are installed in freshwater rivers (see section 3.3 for further details).

Hydropower plants can be of four main types (Figure 2):

1. storage power plants (SPP) are facilities that store water in reservoirs behind dams and that can modulate the flow released downstream; reservoirs can be artificial or can exploit existing lakes;
2. run-of-river (ROR) projects utilising the natural flow of water bodies and with limited storage capacity (if storage capacity is below the mean daily inflow, the reservoir is often considered a ROR);
3. pumped hydropower storage (PHS) that is, besides storage power plants, the main procedure of bulk electricity and water storage for power systems, composed of two water bodies (generally, two reservoirs, or a river as lower reservoir) that are connected by a turbine and pump system. PHSs pump water in an upper reservoir in periods of low energy demand and uses it to produce electricity by releasing water to the lower reservoir through the turbines. The reservoirs of closed-loop PHS stations (also known as pure PHS) are not connected to natural watercourses and do not utilise natural (river) inflows. Mixed PHS stations (also known as pump-back facilities), utilise natural inflows from rivers, creeks and groundwater in addition to the pumped water in the upper reservoir.
4. hidden hydropower in water infrastructures for supply, transport and treatment: diversion schemes that utilize the available energy in conveyance systems, e.g., water distribution, irrigation and sewage networks.

In terms of size, hydropower stations are distinguished in large-scale and small-scale, with a typical threshold being an installed power capacity of 10 MW (variations exist). Within the small hydropower context, mini, micro and pico-hydropower refer to installed power below 1 MW, 100 kW and 5 kW, respectively. However, these thresholds are mostly regulatory or administrative, as hydropower exists in a range from some kW to several thousands of MW, and impacts should not necessarily be associated to the size of the power plant.

Hydropower can be classified, depending on the head, into high head, middle head, low head and very low head. Although a clear definition does not exist, it is reasonable to define a very low head when the head is below 5 m (2.5 m in certain cases [2]), low head below 50 m, middle head between 50 m and 100 m, and high head above 100 m [3].

The hydropower sector is rather complex, as it includes the electro-mechanical equipment (turbine, generator, gearbox/transmission, guide vane and wicket gate to control the flow to the turbine, draft tube and casing/volute around the turbine), the civil structures (e.g., weirs, dam, tunnels, pipes, powerhouse, penstocks, fish passages, spillways and canals), and the Operation and Maintenance (O&M) equipment to control the system and monitor the status of the components (Figure 1). The power plant operation depends on the hydrological, environmental and market conditions (e.g., water levels, flow rates, priority on other water uses, energy demand). A significant proportion of investments in the hydropower sector refers to the civil works and associated consultancy services that are very difficult to track. For the sake of simplicity, and because it is very difficult to track all of these aspects, the hydro-turbine is generally considered as a barometer/proxy for some competitiveness indicators (e.g., import/export, market), so that the real amount of the considered competitiveness indicators may be, in most of the cases, underestimated. As a rule of thumb, the electro-mechanical equipment represents typically one third of the investment cost whereas the civil engineering structures represent the major part with the other two thirds, sometimes also reaching 75-80% of the cost share.

Hydropower turbines can be of three main types: action/impulse, reaction, gravity type. Action/impulse turbines exploit either the kinetic energy of a water jet or the kinetic energy of a water stream/river. In the former case, the most used turbine types are Pelton, Turgo and Cross Flow Banki turbines, while in the latter case the most used turbines are hydrokinetic turbines (similar to wind and tidal stream turbines) and stream/floating water wheels (the Vortex turbine has been recently introduced and improved also to work as a reaction type). Reaction turbines exploit both the kinetic energy and the pressure energy, depending on their reaction rate, and the most used types are Francis (including the Pump-as-Turbines[i]), Kaplan (including Bulb, Straflo) and Deriaz turbines. Maximum turbine efficiency commonly range between 80% and 95%, depending on the size and type. In gravity water wheels and Archimedes (or, “hydrodynamic”) screws, the water volume remains in the machine buckets and is released downstream, exerting a hydrostatic pressure on the bucket blades. Therefore, the weight of the water generates the rotation of the machine, with a maximum efficiency commonly ranging between 70% and 90%. The efficiency of the electric generator, driven by the turbine, is generally >92%. Power losses in the waterways between the water intake and the turbine generally account for 5-10% of the gross power, depending on the design, flow rate and length of the waterway. The overall efficiency of hydropower is typically > 80% and can exceed 90% at the optimal operating point, 5-times higher than photovoltaics and 3-times

[i] PATs are Pumps used in reverse mode, i.e. as turbines. They are typically installed in water distribution networks for energy recovery (generally micro-hydropower), replacing pressure regulating valves. PATs are also used in PHS.

higher than wind energy [66].

A dam is a structure designed to retain water from a river. There are two types of dams:

- diversion dams, which use diversion systems to keep water surface at constant level and avoid changing river regime. Diversion dams, also called weirs, are used for ROR, waterways, recreational activities;
- retention dams which create a barrier to store water in a reservoir, thus changing river regime and keeping water surface at a variable level. Retention dams can be built for two types of reservoirs:
    a. supply reservoirs, in which water is extracted from the river for other uses, such as irrigation, navigation, drinking water, industrial use.
    b. regulation reservoir, whose primary function is to regulate water flow. Water is stored and released into the river for different reasons, such as irrigation, flood protection, drought prevention, energy generation, compensation of irregular water releases of upstream power plants or other uses.

The dam structure is composed of a body lying on a foundation built on the riverbed and the banks of the valley. The dam slopes are called upstream and downstream faces, while the crest is the part in-between. There are two main families of dams according to the construction materials, namely embankment and concrete dams. Embankment dams are made of earth or rockfill or a combination of earth and rockfill, while concrete dams are built in conventional concrete or in roller compacted concrete [6].

Hydropower plants exhibits a high hybridization potential with other generation technologies as an integrated unit [4]. Hybrid power plants can occupy a single site or comprise a micro-grid distributed on the territory. In hybrid power plants, hydropower can be combined with solar or wind power to increase the stability and reliability of electricity generation [5]. In an hybrid power plant, PV panels or wind turbines can produce energy when the sun or wind is available, while saving water for hydroelectricity during intermittent times when the sun or wind go down [6]. Photovoltaic systems can be installed as floating solution on hydropower reservoirs [7], reducing PV land use, optimizing the overall efficiency and reducing evaporation. Waste-heat can be extracted from the cooling system of the turbine/generator [8, 9]. Hydropower can be used for hydrogen production [10, 11]. Pumped hydropower storage is the largest energy battery available worldwide and allows to better integrate the volatile energy output of wind and solar power plants. PHS can also work together with batteries [20]. In an hybrid power plant the same electrical infrastructure can be used, thus lowering overall costs. Ocean (tidal and wave) energy implement several technologies derived from the hydropower sector [12].

Figure 1. Sketch of a storage hydropower plant, with focus on the powerhouse. Source: Hydropower Europe [6].

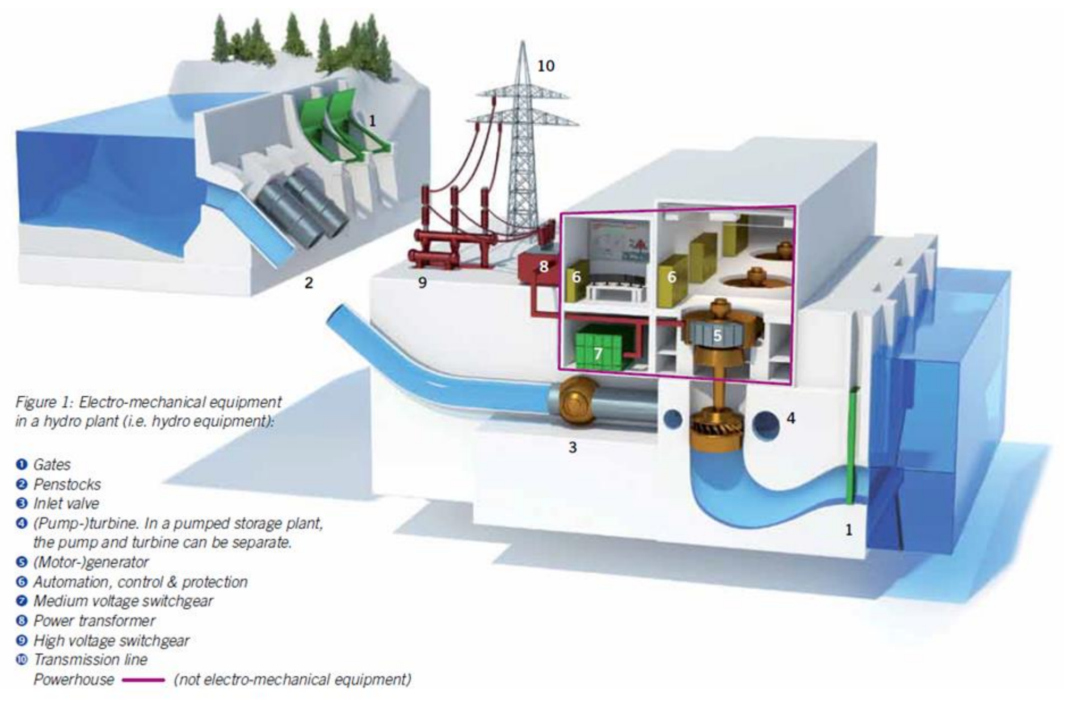
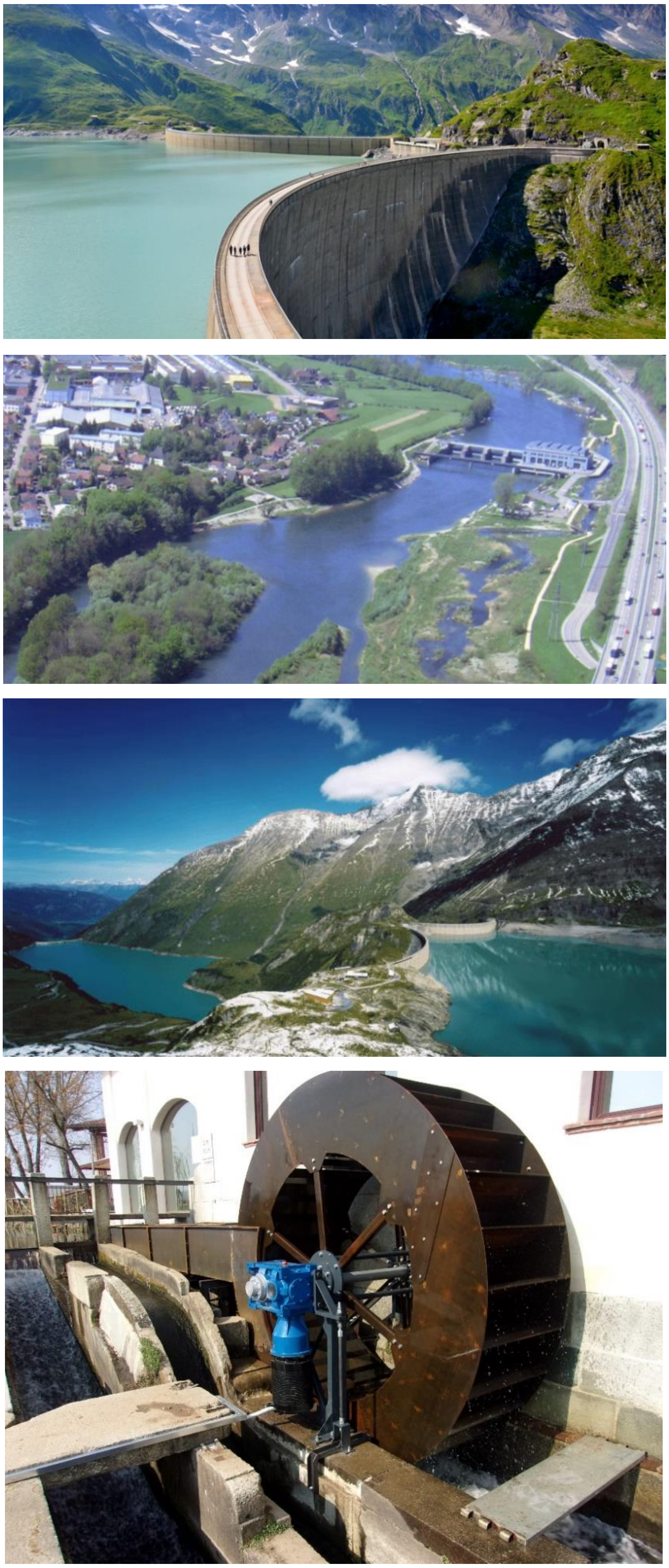


Figure 2. SHP (Mooserboden Dam, Austria, from IEA Hydro report on Annex XIII), ROR plant (Ruppoldingen in Switzerland, with lateral river for fish migration (Courtesy ATEL)), PHS plant with two reservoirs (photo courtesy of Voith Hydro, Limberg II und Kopswerk II, Austria), micro plant with water wheel in a diversion canal (photo courtesy of Gatta srl, Italy).

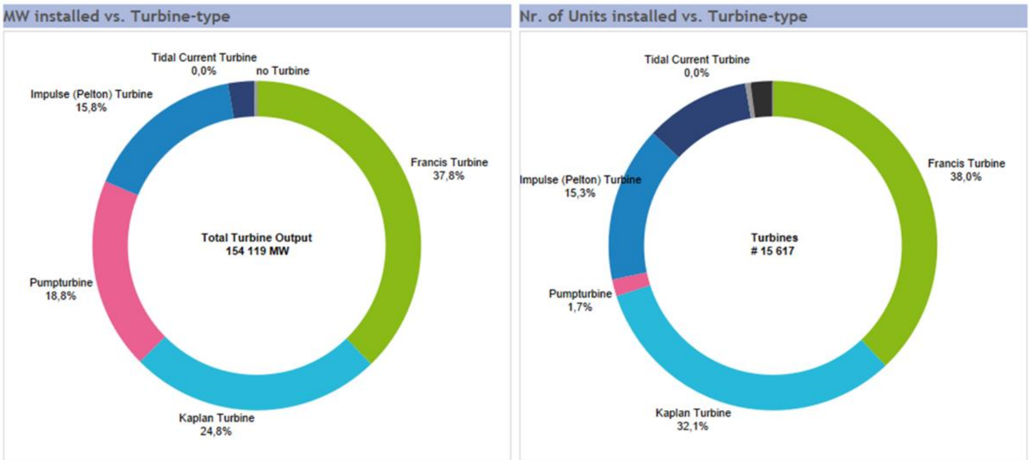


2 Technology state-of-the-art, future developments and trends

2.1 Technology readiness level (TRL)

The history of hydropower began more than 2,000 years ago. The water wheel has been the first hydropower converter in human history, mainly used to lift water and for mechanical activities, e.g., for grinding grain and sawing wood. In the first half of the 19th century, water wheels were widespread in industrial countries around the world, especially in Europe. For example, there were at least 66,000 water wheels operating in France in 1826, and 25,000–30,000 in England in 1850. In Germany 58,000 mills were counted in 1882 and 33,500 water wheels with power outputs ranging from 0.75 to 75 kW were licensed as late as 1925. In Poland, almost 10,500 watermills operated in the late 18th century. For comparison, 55,000 water wheels operated in the United States in 1840, while in Japan water wheels comprised 56% of total power generation[ii] as late as 1886. The EU funded research project RestorHydro collected 65,000 historic low head hydropower sites in Europe (27,000 are old water mills), but the project estimated that 350,000 micro-hydro sites would have existed until one century ago, providing clean energy [13]. At the beginning of the 20th century, the development of modern hydropower exploiting more powerful sites, and fuel engines, marked the decline of water wheels and mills. Between 1940 and 1970, significant hydropower developments took place worldwide responding to increased electricity needs of growing population and economies. From 1970, hydropower development slowed down in Europe due to the fact that the most suitable sites were already exploited and the rise of environmental concerns. Water wheels were again reintroduced in the market few decades ago as cost effective micro-hydropower converters in low head sites [14]. Nowadays, the most used turbines are the Pelton (high heads, low flows), Francis (middle and high heads, middle flows) and Kaplan-Bulb (low heads, high flows). Low-head Francis and Kaplan turbines can also be used as very low head converters. The share of hydraulic turbines in the EU+UK is depicted in Figure 3.

Figure 3. Share of turbine type according to Voith Hydro database, EU+UK [20].



Nowadays hydropower is an established sector and the largest and most flexible renewable energy source, with well-known and robust technologies and construction methodologies (section 1.2). Nevertheless, R&D activities are continuously ongoing and novel technologies are under investigation. Some of these technologies could become stated technologies in the coming decades [15]. Kougias et al., (2019)[15] and Oladosu et al., (2021)[16] reviewed the emerging hydropower technologies. Their implementation potential in the existing hydropower facilities was assessed in Quaranta et al., (2021)[20]. The innovative materials are discussed in Quaranta and Davies (2021)[49], while environmentally enhanced turbines are discussed in Quaranta et al. (2021)[87]. The Technology Readiness Level (TRL) of some emerging technologies is shown in Table 2. Fry et al., (2022)[17], in the EC funded project Hydropower Europe, estimate that between EUR 190 and 324 million are required to be invested by funding schemes in the following topics: flexibility, optimization of operation and maintenance, resilience of electro-mechanical equipment, resilience of infrastructures and operations, developing new

[ii] it is not specified if mechanical or electrical energy.

emerging concepts, environmentally compatible solutions, and mitigation of global warming impacts. Furthermore, in order to respond to the increasing needs for flexibility[iii] of operation, hydropower electro-mechanical equipment needs to reach higher levels of digitalisation. Digitalisation is required to optimise operation, facilitate O&M, reduce costs, and to increase resilience against physical and cyber threats. A future challenge lies on how to incorporate up-to-date advancements of the IT sector on existing and operating stations that currently use obsolete systems. Operational decision-making, integrating lifetime and maintenance planning as well as real-time inflow forecast with operation at liberalised power markets, is also an important challenge particularly concerning existing plants.

Table 2. TRL (Technology Readiness Level) of selected emerging and novel technologies in hydropower equipment [16].

Technical innovations	Barriers addressed	TRL
Matrix-Bulb turbine-generators	Low head, high civil works costs of standard turbines	9
Modular-Bulb turbine	As above	4
Amjet hydropower turbines	As above	4
Very low head turbine	As above	
Hydrodynamic screws and gravity water wheels	As above	5
New water wheels: turbine water wheels	As above	4
Hydrostatic pressure machine	As above	1
Mavel siphon turbine	As above	8
Vertical axis hydrokinetic turbine	Low head	6
Ultralow head turbine-generator	Very low head sites	3
Passive/active water injection with flow feedback method for Francis/Propeller turbines	High variation in hydropower operating conditions	3
Converter-fed synchronous and doubly fed induction machines	Variable head/flow and operation	9
High-efficiency axial flux generators	Low power density	4
High-density polyethylene and fiberglass-reinforced polymer penstock/lining materials	High cost of steel and concrete	7
Precast concrete dams (French System)	High civil works cost, long construction time	
Alden (Francis)	Fish protection	9
Voith minimum gap runner (Kaplan-type turbine)	Fish protection	9
Natel Restoration Hydro Turbine (Kaplan)	Low head, fish protection	4
Auto-Venting turbines	Low dissolved oxygen	8
Digital avatars of units for combined advanced simulations to evaluate transient operations and flexibility	Operation and maintenance cost, dwindling skilled workforce	3

2.2 Installed energy Capacity, Generation/Production

In 2021, the global installed power of grid-connected hydropower reached 1,360 GW, including 165 GW of pumped hydropower storage (PHS), with an annual generation of 4,252 TWh [18]. Hydropower also provides 509 MW of off-grid hydropower electrification services, mainly in Africa (31.8%), South America (30.3%) and Asia (25.0%) [51].

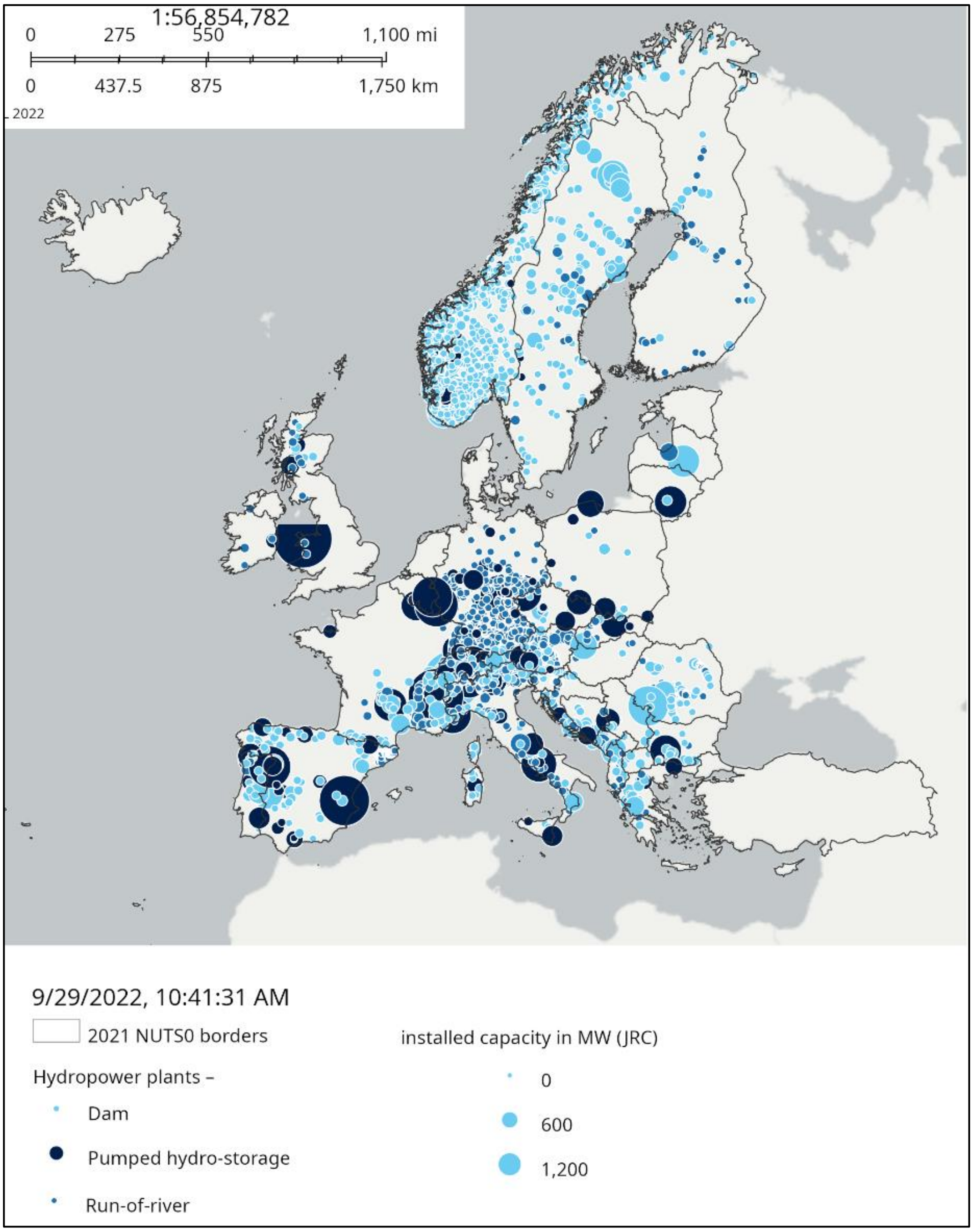
According to Xu et al., (2015)[19], Europe has a hydropower technical potential of 1,121 TWh/y, and, with a current production of 620 TWh/y and installed capacity of 254 GW, has developed 55% of the available technical potential, the highest share, globally (and 65% of developed potential including Turkey). There is still

[iii] The ability of a system to respond to changes in generation and/or load is called system flexibility

untapped technical potential in Europe to be explored with novel technologies[15] and by refurbishing existing plants [20].

In 2021, the hydropower installed capacity was approximately 151 GW in the EU (155 in EU+UK), mostly located in alpine environments (Figure 4). With respect to 2011, this corresponds to + 6 GW of installed capacity. Out of that, 110 GW comprises "traditional" hydropower stations, meaning hydroelectric facilities that solely serve electricity generation (including multipurpose services). Another 22.7 GW refers to closed-loop pumped hydropower storage. The remaining 23 GW is mixed hydropower, meaning typical PHS facilities installed in natural rivers that have the additional feature of electricity storage [21, 22]. The annual generation was 343 TWh in 2021. On average during 2011-2020, 343 TWh/y were generated, of which 83 TWh/y from ROR and 43 TWh/y from PHS (from Eurostat data). For more details on the EU hydropower fleet composition, see Table 3.

Figure 4. Hydropower distribution in Europe according to the JRC hydropower database (194 GW included out of the 254 GW). From: https://energy-industry-geolab.jrc.ec.europa.eu/, and excluding mini-hydropower plants.



Between 2020 and 2021, the European countries with the highest added hydropower capacity have been Turkey (+513 MW), Norway (+396 MW), Austria (+150 MW), Greece (+21 MW), Spain (+16 MW) and Switzerland (+12 MW) (considering data of IHA 2021 and IHA 2022[18]). In the last five years (2015-2019), capacity additions in EU were mainly developed in Portugal, Austria, Italy, and France. This includes some large-scale PHS stations, such as the Frades-II (780 MW), the Foz Tua (270 MW) in Portugal and the Obervermuntwerk-II (360 MW) in Austria. Major rehabilitation and upgrades of existing stations have been, e.g., the La Bâthie, La Coche, and Romanche-Gavet projects in France. Significant PHS development occurred in Switzerland with Linthtal (1200 MW) and Nant de Dranse (900 MW).

Table 3. Installed power (in GW) at the EU level, categorized depending on hydropower plant type (RoR, SPP, PHS) and installed power class *P* (MW), combining data of the JRC hydropower database [20] and Eurostat data.

P (MW)	RoR	SPP	PHS	Total (GW)
$P>10$	23	79	44.1	135.1
$1<P\leq 10$	6.7	3.9	0.03	10.6
$P\leq 1$	5.5	0.0	0.0	5.5
Total	24	83	44	151

In the last decade, the annual energy from hydropower in EU has oscillated between 322 and 398 TWh/y depending on the hydrological conditions with the average value being 363 TWh/y. This is, on average, 12.5% of EU's total net electricity production and represents one-third of the annual renewable electricity generation. In the recent past, the highest EU+UK generation was recorded in 2014 and it was 386.9 TWh.

The EU also owns several multipurpose reservoirs. More than 6,062 large dams higher than 15 m are in Europe (including Ukraine and without Turkey), of which 4,451 are in the EU according to the ICOLD 2020 register of dams. The European hydropower reservoirs store about 440 billion m^3 of water (including Ukraine and without Turkey), 25% of them for multipurpose water use (33% respectively in the EU). Amongst the 6,062 large dams, 2,743 store water for hydropower generation (2,125 in the EU) [23]. EU water reservoirs (including the non-powered ones) are currently able to store approximately 360 TWh/y, roughly the gross energy consumption in Romania. European hydropower reservoirs provide a storage capacity of 220 TWh (that can be increased by heightening of existing dams and new multipurpose reservoirs), which is roughly equivalent to 25 days of the European energy consumption [24]. Norway has almost half (85 TWh) of Europe's reservoir (storage) capacity [25].

A relative comparison shows that the installed power per inhabitant is 0.35 kW/person in the EU, 0.33 kW/person in the U.S. and 0.24 kW/person in China, demonstrating that the EU is a strategic user of hydropower. The European leadership was confirmed in Wagner et al., (2019)[26] for small hydropower and in Manzano-Agugliaro et al., (2017)[27] for the R&D activities.

Hydropower productivity is not uniform across the EU and reflects the climatology, topography and water resources of each region and the power plant type prevalence. This variability is typically shown by the Capacity Factor (CF) that is expressed as the ratio of annual energy generation to the energy that would be generated if the power plant would work throughout the year at the maximum power. The average CF in EU in 2021 was 28%, lower than the global weighted-average of new projects commissioned between 2010 and 2019 that was 48%. The highest CF in EU in the last decade was CF=31% in 2015 and in 2016. Hydropower in the Northern Member States have generally higher productivity than that of countries in Southern Europe (Table 4). Malta and Cyprus have low water resources and the prospects for the development of hydropower plants are low. Storage power plants are usually fitted with relatively high capacity that cannot run at full power throughout the year using only natural inflows. Such plants can supply high capacity during peak electricity demand periods to take advantage of higher prices in liberalised markets thanks to their energy storage capability, resulting in an average yearly CF ranging from 20% to 40%. Storage power plants have typically yearly storage allowing for example in the Alps to store water during summer for electricity production mainly during winter where the demand is higher. Instead, ROR plants have very limited storage capabilities, hence their operating power is typically adjusted to maximise the use of available natural inflows throughout the year. Therefore, the average yearly CF of ROR plants usually ranges from 30% to 60% [72], and the average value in the last decade in EU has been 44%, with a maximum of 52% in 2014. According to the global data presented in [66], the average capacity factor in 2016 of hydropower is 38%, higher than wind (34.7%) and solar (27.2%).

With regards to PHS, the approximately 270 PHS stations worldwide have a total generating power capacity of 165 GW, representing over 90% of the grid scale electricity storage capacity. 160 PHS stations operate in Europe with an overall capacity of 55 GW, and 45 GW in the EU. The productiveness index (Average monthly PHS consumption [GWh] /Average monthly PHS production [GWh]) ranges from 54.8% to 86.8%, with an average EU value equal to 73.9%. PHS stations in most of the countries operate with an average productiveness index of approximately 70-75%. The extreme values refer to Norway (outside of the EU) and Greece. In Norway, PHS plants are operated throughout the day in certain months, followed by periods of low utilization, and this strategy leads to low efficiencies. Greece hosts pump-back stations and their low utilization results in their main operation with river flow, that increases the productiveness index [21].

Averaging the values of 2017, 2018 and 2019 from Eurostat statistics, PHS produced 31.6 TWh, with an average absorbed energy of 36 TWh/y. The overall efficiency of the cycle (electricity provided/electricity absorbed) was of 71% in 2017 and in 2018, and 120% in 2019, probably because of the contribution of natural inflow to the upper reservoirs and because of the plant was more frequently used for production rather than for pumping. When considering the 2019 data, 40 TWh/y were generated by PHS, out of which 56% (22.8 TWh/y) from mixed PHS and 44% from closed loop PHS.

Table 4. Installed power (including PHS), energy generation and capacity factor per member state, for the year 2021 (from IHA, 2022). *(based on 2020 Eurostat data)

Acronym	Country	Installed power GW	PHS Power GW	Annual energy generation TWh	CF	share of total electricity generation*
AT	Austria	14.747	5.596	41	0.32	56.5%
BE	Belarus	0.097	-	0.4	0.47	-
BG	Belgium	1.427	1.307	1.12	0.09	1.3%
CZ	Czechia	2.281	1.172	4	0.20	4.9%
DK	Denmark	0.007	-	0.02	0.33	0.1%
DE	Germany	10.883	6.199	24	0.25	4.2%
EE	Estonia	0.004	-	0.02	0.57	0.3%
IE	Ireland	0.508	0.292	1	0.22	3.1%
EL	Greece	3.421	0.699	6	0.20	12.4%
ES	Spain	20.425	6.117	32	0.18	12.2%
FR	France	25.494	5.837	63	0.28	11.9%
HR	Croatia	2.155	0.281	7	0.37	52.3%
IT	Italy	22.593	7.685	47.98	0.24	17.1%
CY	Cyprus	-	-	-	-	-
LV	Latvia	1.588	-	3	0.22	52.4%
LT	Lithuania	1.028	0.9	0.93	0.10	17.5%
LU	Luxembourg	1.33	1.296	0.95	0.08	42.5%
HU	Hungary	0.058	-	0.21	0.41	0.6%
MT	Malta	-	-	-	-	-
NL	Netherlands	0.038	-	0.06	0.18	0.0%
PL	Poland	2.385	1.78	3	0.14	1.9%
PT	Portugal	7.199	2.829	13	0.21	24.5%
RO	Romania	6.313	0.092	17	0.31	30.4%
SI	Slovenia	1.301	0.18	5	0.44	29.1%
SK	Slovakia	2.522	1.017	4	0.18	13.9%
FI	Finland	3.263	-	16	0.56	23.3%
SE	Sweden	16.478	0.099	71	0.49	43.3%

2.3 Future trends, feasible potential and hidden opportunities including small hydropower and refurbishment

Hydropower is currently the giant of low-carbon electricity technologies and it is the key technology for an optimal integration of volatile energy technologies (e.g., wind and solar energy) into the electric grid. Hydropower installed and storage capacity needs to increase in the near future, but it has to face several environmental constraints. Global cumulative hydropower capacity is expected to expand from about 1,360 GW in 2021 to just over 1,555 GW by 2030 [72], and can reach 2,500 GW in 2050 according to IEA and IRENA.

Long-term strategies provide some estimates on the growth that the hydropower sector is required to undergo to fulfil renewable energy targets. The main priorities for hydropower in the EU are defined in the EU Clean Energy Transition Partnership [28], and are flexibility, storage, digitalization, markets and services of hydropower, sustainable solutions and sediment handling. Several assessments have been carried out to assess the residual opportunities of hydropower, and related trends, in the EU (Table 5). Within this context it is worth to mention the exploratory activity SustHydro carried out at the JRC, *Sustainable hydropower to solve the controversy between renewable hydroenergy and ecosystem protection.* Some of the output are included in Table 5 (Quaranta et al. references).

The EU long-term strategy modelling exercise provides future projections of hydropower development grouped together with wave, tidal, and biomass power [29]. Projections indicate small additions and average hydroelectricity generation of 375 TWh/y, higher than the average generation of 360 TWh/y of the last decade. This increase could be reached by tapping the current potential for green-field projects, that in Europe mainly lies in sites with heads below 200 m [23]. A hidden potential exists in conveyance systems (micro and small hydropower plants), while the modernization of the existing hydropower fleet is an attractive opportunity to make the existing fleet more powerful, efficient and resilient (the average age of the EU fleet is almost 45 years). Quaranta et al., (2021)[20] estimated that the annual electricity generation from the existing hydropower fleet could be increased by approximately 8% (~30 TWh/y)[iv], implementing hydropower digitalisation, modern electro-mechanical equipment and new waterways. Additional strategies to increase generation from the modernisation of aged plants include dam heightening (useful especially to increase storage capacity) and hybridization with other energy technologies. For example, run-of-river plants can produce hydrogen when energy prices fall to zero. Batteries [30] can ensure energy storage for several hours, whilst hydropower can store and release energy for days and weeks, including seasonal transfer, and can be integrated together [31]. Reservoirs can host floating PV, or PV could be installed on dam surfaces [32]. Methane capture processes are under investigation, but R&D is further needed to improve cost-effectiveness (this measure is mainly relevant for tropical reservoirs) [8].

Developing hydropower in existing infrastructures, e.g., in water distribution networks (aqueducts), in existing low head barriers (e.g., water wheels in water mills) and in wastewater treatment plants, as well as hydrokinetic turbines, has been the aim of numerous research and deployment activities. This is due to the considerably lower disruption and impacts compared to conventional reservoir hydropower and the untapped potential in the EU [33, 34]. However, the remaining technical potential associated to these technologies is limited to approximately 10 TWh/y at EU scale. There exists a hidden potential in hydraulic infrastructures in the private water intensive industry, such as mining or energy production (using cooling waters).

In the decade 2000-2010, 22 pumped storage units capable of producing 2,443 MW of rated power were commissioned in the OECD Europe[v]. In the period 2011-2020, 76 pumped storage units capable of producing 11,562 MW (40 MW in the U.S.) were commissioned, under construction, or planned for building and commissioning. The EU long-term projections for PHS show higher deployment rates and 4 GW of new PHS until 2030 in EU (excluding Switzerland, where about 4 GW are ready for approval, pers. comm. Anton Schleiss).

[iv] Under the assumption of the current market and hydrological conditions.

[v] OECD Europe includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom

The anticipated 2030-2050 PHS growth varies between scenarios from 8 GW (Baseline) [35, vi] to 19 GW (ELEC)[vii]. Under the 1.5TECH and 1.5LIFE scenarios[viii], PHS additions are below 2 GW since hydrogen and power-to-gas technologies cover for the storage services.
In September 2020, the Commission presented the Communication "Stepping up Europe's 2030 climate ambition" accompanied by a document that introduces model projections of the EU power system. The share of hydropower is expected to decrease from the current levels (12.5% on average) to 9-10%, depending on the type of scenario. In absolute terms, however, hydroelectric generation will increase by 35 TWh/y across all scenarios. PHS installed capacity, generation and consumption will have to increase. Until 2030, 18-20 GW of PHS will be added reaching up to 65 GW of total installed capacity. Between 2030 and 2050 lower deployment rates are expected, 5-10 GW of PHS additions. A real technical opportunity for PHS is expanding the operating range and application. By introducing smart sensors, variable speed turbines with increased efficiency and system optimization to new or existing PHS, the overall PHS utilization will increase. Countries with redundant PHS potential could look for increasing their potential market share by selling their services to neighbouring countries. Opening up cross-border markets for balancing capacities could also serve as an important incentive to increase the use of the existing PHS capacity [21]. Reservoir interconnection and virtual energy storage gains resulting from the spatio-temporal coordination of hydropower over Europe are opportunities for pumped hydropower and to balance generation variability [36, 37]. One of the most limiting factors in the potential use of large-scale PHS has been that not many locations could offer economically viable deployment. Therefore, examples for a promising change of approach are underwater PHS, low-head energy storage [38] and underground PHS using abandoned mines[ix]. Energy could be stored using existing lakes or small depressions, or retention basins on a terrain in sustainable urban drainage systems. In France, the potential of PHS from small lakes and reservoirs was estimated to be about 33 GWh, which is almost 20% of the current national energy storage capacity [39]. Stocks et al., (2021)[40] estimated that the closed loop PHS potential in EU is 260 TWh, among which 19 TWh are the cheapest sites and 67 TWh refer to the most expensive sites. A key role is, and will be, played by Norway. Presently, Norway has more than 1,000 hydropower reservoirs (85 TWh), more than any EU member states, e.g., Austria (3.2 TWh), France (9.8 TWh), Germany (0.3 TWh), Greece (2.4 TWh), Italy (7.9 TWh), Portugal (2.6 TWh), Spain (18.4 TWh), Sweden (34 TWh) and Finland (5 TWh). Switzerland hosts 8.4 TWh.

Table 5 summarizes the hidden potential in the EU (or Europe) assessed in scientific studies[x].

As example of in-progress hydropower programmes, targets to put 600 MW by 2023 have been set in Sweden. The renovation of the Ffestiniog pumped hydropower storage plant in the U.K. is advancing with more pumped hydropower plants in the UK along with Ireland. A new 240 MW Pelton turbine was launched at La Coche pumped storage station in France, substituting outdated models. Czech Republic and Slovakia are focusing mainly on upgrading facilities. In Italy, an agreement was contracted to fix technological advancements at 33 hydropower plants in the country. In Portugal, the 880 MW Gouvaes pumped storage plant is planned to increase the size and form part of the Tamega Hydroelectric Complex ongoing structure [41]. Norwegian hydropower acts like a battery for balancing variable renewables in neighboring countries. In a press release on 13 October 2014, the EU Commission welcomed the announcement made by the Norwegian government to license the construction of two subsea cables linking Norway to Germany and the United Kingdom (UK). According to the press release, the two 1400 MW subsea cables will enable the three countries to exchange electricity and use the Norwegian hydropower potential. Vice-President of the EU Commission, responsible for Energy, Günther H. Oettinger said: "*This will help enormously to integrate renewable energy in North-West Europe. Germany and UK can sell*

[vi] The baseline scenario is a projection based on the future developments of the EU energy system, transport system and greenhouse gas (GHG) emissions. This scenario acts as a benchmark for new policy initiatives. It reflects policies and market trends used by policymakers as a baseline for the design of policies that can bridge the gap between where EU energy and climate policy stands today and where it aims to be in the medium- and long-term, notably in 2030 and 2050.

[vii] The ELEC scenario is built around a switch from the direct use of fossil fuels to electricity, aiming for a 80% emission reduction. https://www.equilibredesenergies.org/en/16-05-2019-2050-strategy-the-road-towards-decarbonisation-is-being-mapped-now/.

[viii] The 1.5TECH scenario combines several technologies and relies heavily on the deployment of biomass and of carbon capture and storage technology. The 1.5LIFE scenario relies less on technology options and more on changes to consumer preferences and lifestyles in order to achieve a fully circular economy. They aim at carbon neutrality by 2050, which would be the only coherent target with a less than 1.5°C global warming.

[ix] https://www.atlantis-project.eu/

[x] Some of these studies have used the European hydropower database developed by the JRC, including coordinate, type, installed power, and, in most cases, gross head, annual energy generation and water storage capacity. This database has been elaborated in a recent study (Quaranta and Muntean, 2022) with an estimation of turbine type, number of units and turbine rotational speed. Further work is needed to integrate this database with existing ones, e.g., those reporting the dam characteristics, in order to increase the knowledge of the European hydropower fleet.

renewable energy to Norway when weather conditions are such that they produce a lot and Norway can sell electricity from hydropower. This will benefit both sides and balance the system” [25].

Table 5. Potential of different hydropower strategy in EU (in EU when not specified).

Hydropower tapping opportunity	Generation potential	Comment
Closed loop hydropower	260 TWh	Stocks et al., (2021)[40]
Spatio-temporal coordination of reservoirs	140 TWh	Europe, Worman et al., (2022)
Hydropower plant modernization	30 TWh/y	Quaranta et al., (2021), Quaranta and Muntean (2022)[8]
Reservoir interconnection	29 TWh	Gimeno-Gutierrez and Lacal-Arantegu (2015)[37]
Existing historic barriers not mill-related	5.2 TWh/y	EU+UK, Punys et al., (2019)
PAT in pressurized WDNs and WWTPs	3.0+0.1 TWh/y	EU+UK, Quaranta et al., (2022)
Heat recovery from generators	2.9 TWh/y	Quaranta and Muntean (2022)
Water wheels in existing mills	1.6 TWh/y	Quaranta et al., (2022)
Rainfall on building roofs	0.5 TWh/y	Quaranta et al., (2022)[42]
Hydrokinetic turbines in rivers	0.17-1.2 TWh/y	Quaranta et al., (2022)
Pressurized conduits for irrigation and industrial flows	<0.1 TWh/y	EU+UK, Mitrovic et al., (2021)[43]
Floating PV (evaporation reduction)	<0.1 TWh/y	Quaranta et al., (2021), 10% of reservoir surface coverage
Sea water PHS	t.b.d.	Kougias et al., (2019)[15]
PHS in mines	t.b.d.	Menendez et al., (2017)[44]
Floating PV on hydropower reservoirs	139 TWh/y	Kakoulaki et al., (2022)[45], covering 10% of 1,608 km^2 of EU reservoir surface, associated to 49 GW of hydropower installed capacity and 94 TWh/y of hydropower generation.
Floating PV on hydropower reservoirs	729 GWp	Lee et al., (2020)[7], Europe, 14% of reservoir surface coverage

2.4 Technology Cost – Present and Potential Future Trends

Hydropower is financially competitive with other electricity technologies, achieving some of the lowest values of electricity generation costs. IRENA and World Bank analysis identified hydropower as currently one of the cheapest forms of renewable energy [47]. Capacity factors (see Table 4) depend on the hydrology of the site and on market demand. One of the main advantages of hydropower stations is that the low operation cost is generally very stable since it does not depend on fuel cost. Moreover, hydropower stations typically have a long service life (typically assumed 50 years), with the civil works even exceeding 80-100 years. In Europe the average age of the hydropower fleet is almost 45 years, hence hydropower refurbishment is of strategic relevance [20]. However, hydropower is capital intensive, requiring large upfront investments. Licensing and construction periods can be long and complicated especially in large-scale projects (several years and in certain cases even exceeding 10 years). Cost data differentiated by hydropower type (run-of-river and storage) are rather difficult to find. For example, cost data of IRENA are not differentiated by technology. Anyway, the cost per kW can be roughly considered similar between run-of-river and storage power plants [xi, 46]. Table 6 depicts the approximated share (in %) of civil, mechanical, and electrical components in the total capital cost of different hydropower plants.

Table 6. Capital cost breakdowns for the main types of hydro. Civil: Dam, tunnels, piping, powerhouse (overground or underground), roads. Mechanical: Turbine, penstock, gates, valves, hydraulics. Electrical: Generator, transformer, cabling, grid connection. Source: IHA, 2022, based on IHA member input.

Hydropower type	Civil	Mechanical	Electrical
Large-scale Storage hydropower	70%	10%	20%
Large-scale Run of river	50%	30%	20%
Small-scale Run of river	50%	30%	20%
Pumped hydropower storage	30-50%	20-30%	30-40%

Globally, in 2019, the global weighted-average LCOE for new hydropower stations (greenfield projects) was below EUR 40/MWh, 11.5% lower than the values reported for onshore wind and 30% lower than that for photovoltaics (PV) [47]. 98% of the hydropower projects commissioned in 2021 had an LCOE within or lower than the range of newly commissioned fossil-fuel fired capacity cost. Moreover, 85% of the hydropower capacity commissioned in 2021 had a LCOE lower than the cheapest new fossil fuel-fired cost option [47].

The LCOE of new hydropower projects (covering all types) in Europe including Turkey may be 50 EUR/MWh with a range between 30 EUR/MWh (5° percentile) and 140/MWh (95° percentile). Run-of river projects may be situated in the range of 30 EUR/MWh to 80 EUR/MWh with average at 40 EUR/MWh, whereas storage hydropower including pumped storage power plants are in the range of 80 EUR/MWh to 140 EUR/MWh with an average of some 100 EUR/MWh. The generation costs of small hydropower projects (below 10 MW), most often run-of-river, typically are 40% to 60% higher. The difference of hydropower with variable renewable energy sources (RES), such as wind and PV, is that the deployment cost has a slightly increasing trend contrary to the decreasing costs of PV and wind. This is because the best sites for hydropower generation have been exploited and several requirements now exist to respect sustainability criteria and impact mitigations. Besides, almost half of the installation cost (45% on average) of a hydropower project relates to civil works, whose cost typically increases at rates subject to construction cost inflation. When considering refurbishment projects, the cost ranges between 20 and 30 EUR/MWh [23]. Despite registering LCOE levels rather low in 2008 and high in 2010, the overall trend is fairly constant [48]. The LCOE cost in Europe are depicted in Figure 5.

The CAPEX of recent large hydropower projects of all types may be EUR 1,500 per installed kW with a range between 1,000 EUR/kW (5° percentile) and 4,000 EUR/kW (95° percentile). Run-of-river power plant projects may be situated in the range of 1,000 EUR/kW to 1,800 EUR/kW with average at 1,400 EUR/kW, whereas storage hydropower including pumped hydropower storage are in the range of 1,400 EUR/kW to 4,000 EUR/kW with an average of about 2,500 EUR/kW. The CAPEX of small hydropower projects (below 10 MW), most often run-of-river, typically are also some 40% to 60% higher[xii]. Micro-hydropower projects have a typical overall cost of EUR 5,000/kW (e.g., water wheels in old mills, hydrokinetic turbines, turbines in pressurized water networks and low head turbines in existing barriers or weirs). The cost of projects that use parts of established water management infrastructure (e.g., existing reservoirs, non-powered dams and conveyance systems) and brownfield projects that expand operational power plants or replace their equipment (a main future trend in Europe), is typically up to 70% lower than for new ones, as spending goes mainly towards replacing or adding electro-mechanical equipment.

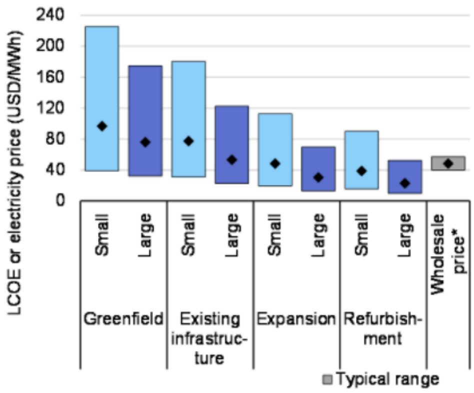
Annual operation and maintenance (O&M) costs are often quoted as a percentage of the investment cost per kW per year, with typical values ranging from 1% to 4%. Operation and salaries take the largest slices of the

[xi] In Patro et al., (2022) equations to estimate the cost of different ROR plants (diversion, in-stream, canal type) are presented. This study showed that the highest LCOE is for diversion type, that is 20% higher than the LCOE of dam-toe and canal-type hydropower plants, but the investment cost mainly depends on the installed power rather than on the plant type.

[xii] pers. comm. of prof. Anton Schleiss.

O&M budget. Maintenance varies from 20% to 61% of total O&M costs, while salaries vary from 13% to 74%. The International Energy Agency (IEA) assumes O&M costs of 2.2% for large hydropower projects and from 2.2% to 3% for smaller projects, with a global average of around 2.5% (IEA, 2021[47]). This would put large-scale hydropower plants in a similar range of O&M costs – expressed as a percentage of total installed costs – as those for wind, although not as low as the O&M costs of photovoltaics. When a series of plants are installed along a river, centralised control, remote management and a dedicated operation team to manage the chain of stations can reduce O&M costs to much lower levels. Materials are estimated to account for around 4% [47].

Figure 5. LCOE costs for the European hydropower [23].



Hydropower stations are location-specific and each project has unique design characteristics, and a clear projection of costs for the next decades is hard to find. Accordingly, in regions where the best locations have already been developed (e.g., in the EU), the remaining technical potential usually refers to less advantageous sites and involves higher installation costs. Europe and North America have the highest hydropower investment costs because of relatively high labour costs, fewer undeveloped economical sites and steep fees to mitigate impacts on the environment and on existing infrastructures. Therefore, installation costs of greenfield hydropower projects may increase in the future. Furthermore, the evolution of this generation and installation costs up to 2050 is mostly influenced by the market inflation. Due to improvement in construction efficiency, mainly of underground works, there may be a tendency that construction costs may be reduced mainly for storage and pumped hydropower storage power plants. Nevertheless, this potential saving will be compensated by the higher costs of environmental mitigation measures, and the expected increase of the investment costs could be better faced if adequate remuneration will be paid for the multiple services and benefits as well as more flexible and integrated solutions provided (e.g., climate change adaptation, different water uses, water-energy-food-environmental nexus). For example, pumping operation of PHS helps to balance excess supply and avoid curtailment; however, grid operators do not currently remunerate this service apart from lower prices, and this service will become increasingly important to avoid renewable curtailment. Current power market conditions show that the revenues attained from the price differential (arbitrage) along with the declining revenues from the provision of the ancillary services are not enough to cover the fixed investment and administrative costs of these units. Several sites have been placed on indefinite hold due to a perceived lack of profitability, including Lago Bianco 1,000 MW and Grimsel III 600 MW in Switzerland, Atdorf 1,400 MW in Germany (IHA, 2022, pers. comm.).

Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, hence investment risks are higher, requiring specific policy instruments and incentives, as well as a longer-term policy perspective and vision. However, renewable energy policy attention in the past two decades has focused primarily on wind and solar PV technology expansion (and lowering their cost), mainly through support schemes such as deployment targets, financial incentives and long-term power purchase contracts. Today, more than 100 countries have introduced short- and long-term targets and financial incentives for wind and solar PV, but fewer than 30 have policies targeting new and existing hydropower plants [72].

2.5 Public R&I funding

Despite hydropower technological maturity, research efforts are still ongoing, with new concepts and technologies [15], novel materials [49] and innovative projects [50]. Recent hydropower research and development (R&D) efforts intend to improve the performance of systems and components and the sustainability and readiness of hydropower for modern power markets. Hydraulic design and mechanical equipment R&D focuses on expanding the flexibility of stations to support a wider range of operation, and to minimize the environmental impacts, like sediment transport and fish migration impairment, hydropeaking and impoundment.

In the last decade (2010-2020), public spending for R&D in the EU ranged between EUR 9 million and EUR 24 million per year (Figure 6), with decreasing trends after peaks. The main hubs of public spending are Austria, Germany, Finland, France, Italy, Poland and Sweden. Annual public spending in hydropower R&D is generally not stable as it follows the implementation of targeted actions, short-term national policies and specific EU calls.

Figure 7 depicts the annual R&D public spending in EU Member States (MS). Furthermore, while in certain MS funding is somewhat stable (Germany, France, Sweden), in several MS it is irregular and dominated by targeted investments in specific years. Hydropower public spending is nearly 18 times lower than that for wind and 15 times lower than that for solar PV in 2019.

Figure 6. EU public R&D investments trend [EUR Million]. Source: JRC based on IEA data, CIndECS2022.

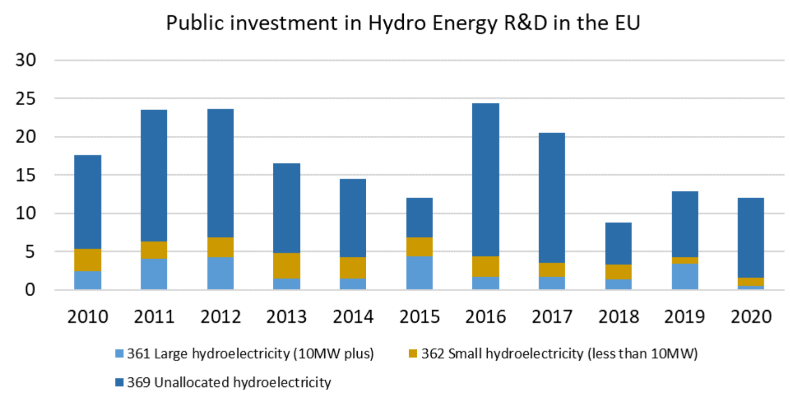
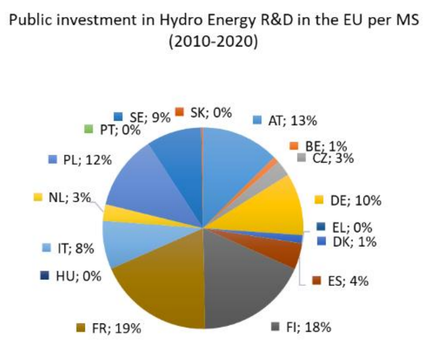


Figure 7. Public R&D investments in hydropower for the main EU member states over the period 2010-2020. Source: CIndECS2022



The average public R&D investment is EUR 14 million on annual basis in the EU (2016-2021), slightly higher than the annual public spending in Canada (approximately EUR 12.7 million annually) and higher than that of Norway (about EUR 10 million) and Switzerland (about EUR 13.95 million). In the U.S., public investments are coordinated by the Water Power Program of the United States Department of Energy. The Water Program (hydropower branch) budget is typically higher than the EU and it is noteworthy that in the recent past (2016-2021) its annual budget was EUR 99 million (source: JRC based on IEA).

The latest analysis within the Low Carbon Energy Observatory [51], in 2019, revealed that thirteen research and innovation projects receive EUR 52.8 million from EU funds, through the Horizon-2020 program (their total budget is EUR 62.3 million). The duration of these projects ranges between 24 and 52 months. Considering the EU funded projects through the H2020 program during 2020 and 2021, EUR 20.5 million were funded, mainly on small-scale hydropower and their interaction with the environment.

2.6 Private R&I funding

The number of identified innovators is rather limited for hydropower and three countries host 60% of active companies. Europe (as the U.S.) hosts 28% of identified companies mostly in countries connected to the Alps such as France, Germany, Italy and Austria (Figure 8). The U.S. (1st) and France (3rd) rely on a relatively strong base of venture capital companies[xiii] while all innovators in Japan (2nd) are corporations.

Figure 8. Innovative companies: share by type (left) and number by country (right).

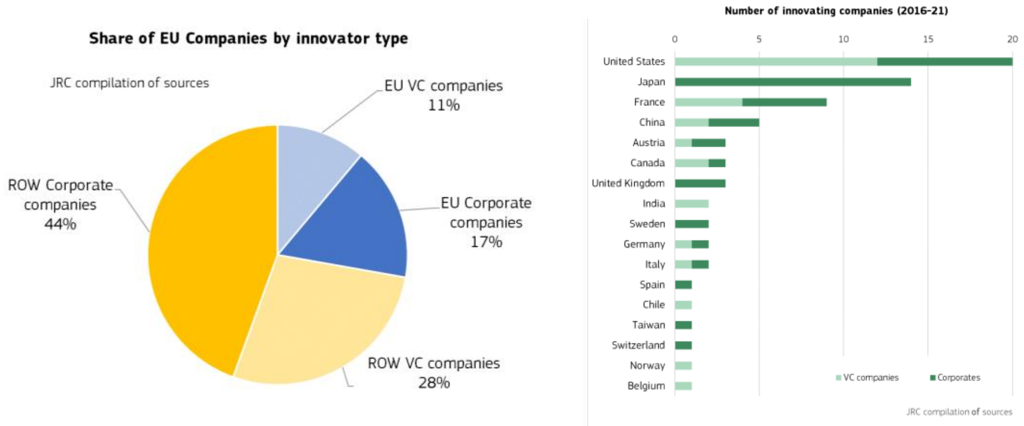


Figure 9 depicts the R&I expenditures of the largest corporate investors and their subsidiaries. These estimates are derived from the patenting activity of those companies, hence the decreasing trend since 2010. This is probably due to the increase of R&D activities and related patenting activities in the other renewable energy sectors.

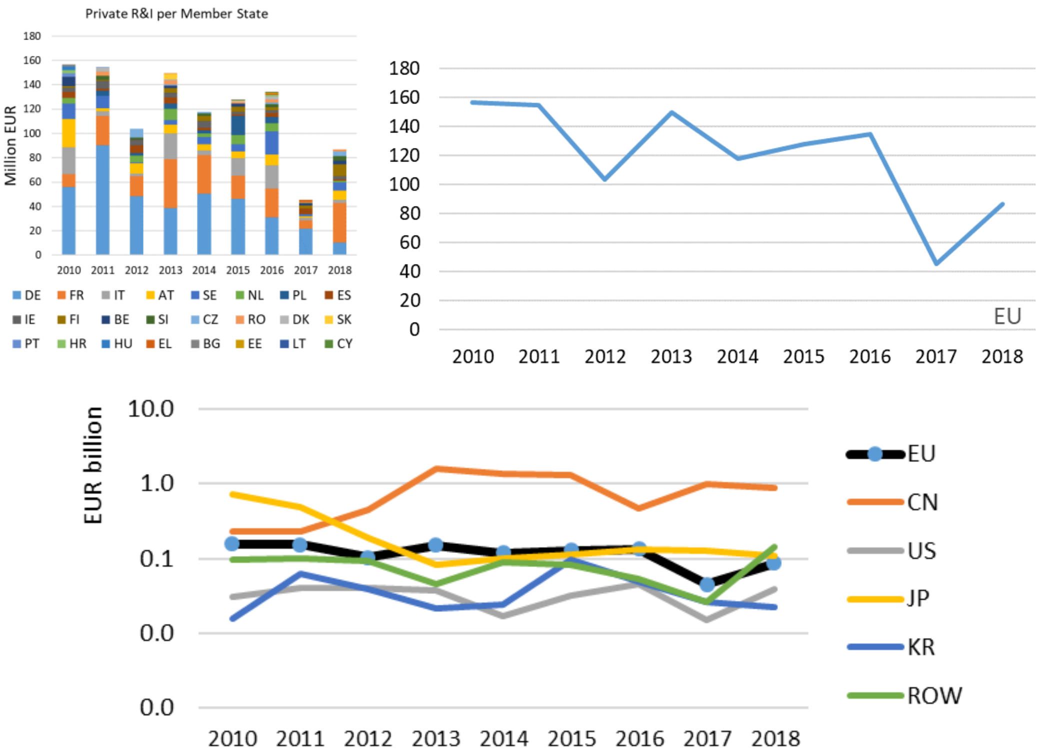
Global level of capital investments in hydropower Venture Capital companies (early and late stages[xiv]) have increased over the 2016-2021 and amount to € 110.5 million (+40% as compared to previous period). While yearly investments have been fluctuating since 2016, investments in 2021 are significantly lower (-40% with regard to 2020) and below the current period average.

Global investments in early ventures only represent 15% of all VC investments over the current period and have decreased towards their lowest levels in over a decade, both in the EU and in the rest or the world, after a peak in 2018. Since 2016, early stage investments amounted to € 17.5 million and the EU accounts for 28% of them. It is worth noting that there are no reported grants for the identified EU based companies while they constitute the essential of investments in the rest of the world (almost 75%).

[xiii] Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. Venture Capital companies are companies that have been at some point part of the portfolio of a VC investment firm (or that have received Angel or Seed funding, or are less than 2 years old and have not received funding).

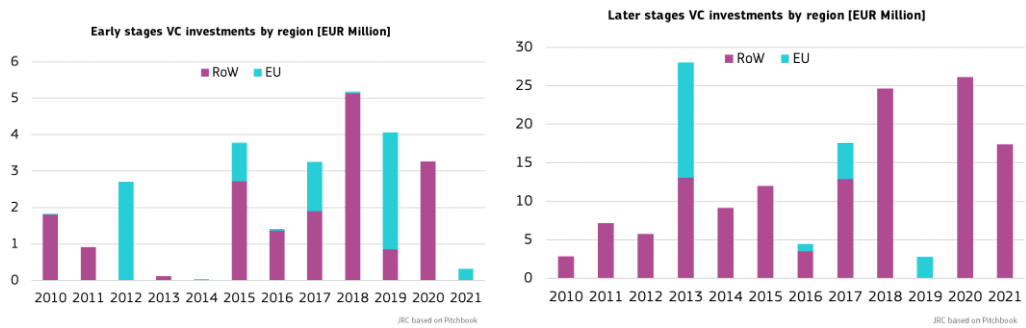
[xiv] Early stages investments include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC investments (it also include public grants). Later stage investments indicator reflect growth investments for the scale-up of start-ups or larger SMEs and include Late Stage VC, Small M&A and Private Equity Growth/Expansion.

Figure 9. Private R&I investments.



Early stage and later stage investments in VC companies are depicted in Figure 10 and compared to the rest of the world. Between 2016 and 2021, the EU early and later stage investments were EUR 4.96 million and EUR 8.48 million, respectively. Considering the total investments, France (EUR 9.78 million) and Belgium (EUR 3.56 million) are placed below the U.S. (EUR 83.38 million) and China (EUR 13.53 million). In the rest of the world, early and later stage investments within the same period were EUR 12.53 million and EUR 84.56 million, respectively. The invested value per inhabitant is EUR 0.03 per person in the EU, while it is 0.25 and 0.01 in USA and China, respectively.

Figure 10. Early stage (left) and later stage (right) investments over the period 2010-2021 [EUR Million]. Source: JRC based on Pitchbook.



2.7 Patenting trends[xv]

The present patent analysis was based on data available from the European Patent Office EPO PATSTAT 2021b (autumn), using the CPC (Coordinated Patent Classification) code Y02B 10/50 (Hydropower) and Y02E 10/20. Details of the analysis are described in dedicated JRC publications [52, 53]. The number of patents for the EU and other major countries are provided in Figure 11, covering the period 2010-2019. China is the main patent leader (partially also due to the different patenting procedure in the country [51]) while EU, Japan and Korea perform almost similarly, and a bit better than the U.S. During the period 2010-2019, 471 patents were registered by companies in the EU, 18 from government no-profit, 48 from Universities, while 56 are individual. Within the EU, Germany is leading in patenting (192), followed by France (85), Italy (37), Austria (27) and Sweden (26), all of them (excluding Sweden) in alpine environments. The EU is the lead region in terms of high-value inventions i.e., EU applicants tend to extend patent families to more than one patent office, although this trend is decreasing over the years (Figure 12), probably because it takes time to extend patent protection to other offices thus especially for years 2018-2019. The EU holds 33% of all high-value inventions globally (2017-2019). Germany, France and Finland are the main contributors.

Figure 11. Patent activity for different owner categories.

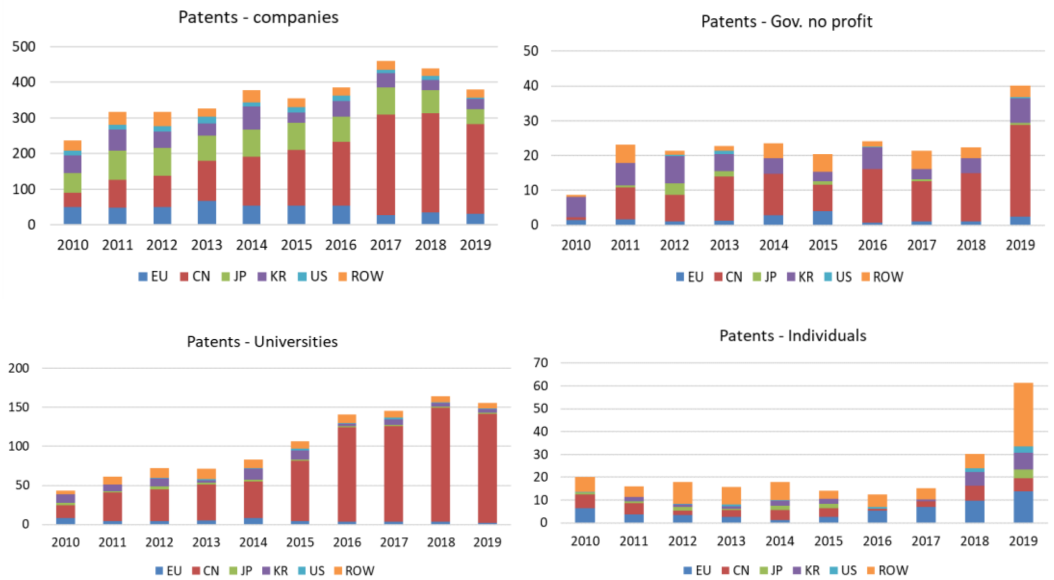
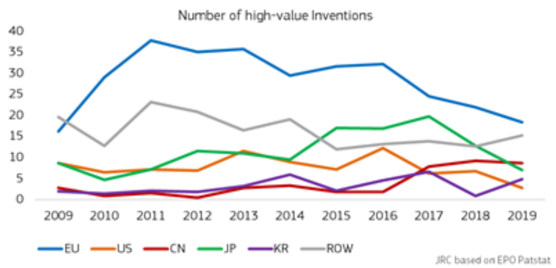
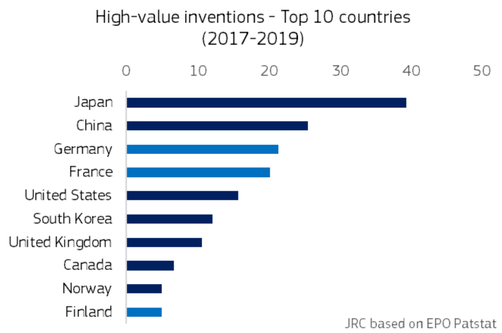


Figure 12. Number of high-value inventions (left) and Top 10 countries (right), Source: JRC based on EPO Patstat.



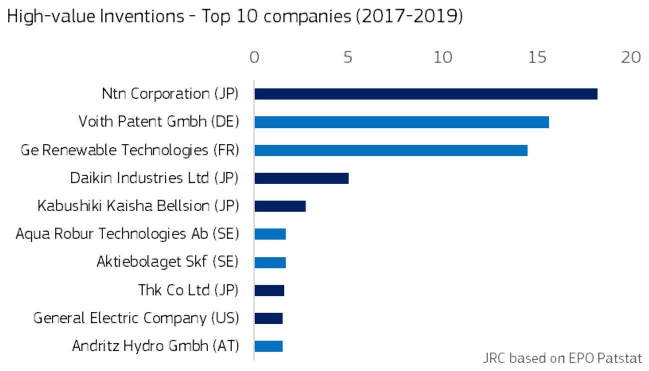


[xv] See Appendix 1.

Figure 13 shows the top 10 companies with high-value invention patenting. 5 companies from the EU are in this top 10: Voith Hydro, GE Renewable Technologies EU branch, Aqua Robur, Aktiebolaget Skf and Andritz Hydro, with Voith and GE within the top-3, sharing together 47% of high-value inventions from the top-10 leader companies worldwide.

R&I expenditures by the subsidiaries of the largest corporate R&I investors, based on patenting activity, are depicted in Figure 9. Expenditures in R&D activities are operational costs and not investments in a company as the late and early stage investments. The trend is decreasing from 2010, probably due to the increase of R&I activities and related patenting activities in the other renewable energy sectors.

Figure 13. Top patenting companies Source: JRC based on EPO Patstat.



2.8 Bibliometric trends/Level of scientific publications

Hydropower research covers a wide range of scientific areas: energy, engineering, environmental and water resource sciences, geology, fisheries and many others. Jiang et al., (2016)[54] observed a rapid growth rate of publications related to hydropower, highlighting the increasing demand for hydropower-related research. Post construction issues of hydropower development are more attractive for scholars than energy technology itself, and an interdisciplinary trend of hydropower research is emerging from the interaction of natural science, social science and engineering hydropower technology [54]. The main hydropower topics researched by EU institutions are described in Manzano-Agugliaro et al., (2017)[27]. Six EU countries are amongst the top ten contributory countries in publishing papers on the topic "Repowering of Small Hydropower Plants" [55].

A bibliometric analysis using the Scopus dataset shows that the number of records (research articles) concerning the word "hydropower" (within the Title, Abstract, Keywords) has been increasing in the past five years (from 1,648 in 2017 to 2,412 in 2021). Between 2017 and 2021, EU institutions participated in the publication of 2,123 articles (out of the total 10,392), led by Germany (405), Italy (268), Spain (255), Sweden (192) and Austria (187), and China is the world leader with 3,879 records (1,187 for the U.S.). Norway (378 publications), Switzerland (304) and the U.K. (506) are also lead scientific contributors, but not included in the EU. EU-based institutions participated in the publication of 70% of the highly cited papers. This is an indication of Europe's important role in driving R&D activities. Leading funding agencies for the period 2016-2020 are various National Foundations in China, the National Council for Scientific and Technological Development and the CAPES in Brazil, the EU (with the H2020 and ERC programs), the NSERC in Canada and the NSF in USA [56].

Furthermore, additional keywords have been selected to better analyse the bibliometric trends: hydropower dam ("hydropower" and "dam" have to be found 3 keywords apart or less), reservoir ("hydropower" and "reservoir" have to be found 3 keywords apart or less), penstock, turbine, draft tube, fish passage, hydropeaking and sediment (including sedimentation and turbine erosion), as proxy on civil structures, electro-mechanical equipment and environmental operation. The keyword "hydropower", or "hydroelectric" or "hydro electric" must also be present in the text, but with no proximity requirements. Table 7 shows the bibliometric trend of the proxy keywords. Comparing the EU with the rest of the world, and considering the difference in population, the EU is a lead region in the analysed sub-topics, with an evident leadership in the sub-topics hydropeaking, fish passages and sediments. The EU is also well positioned when considering the other keywords, having a

publication activity almost similar to the leading country, if the population difference is taken into account. The main concurrence is exerted by China. However, although Chinese hydropower dam developers dominate the global dam industry nowadays [57], their bibliometric indicator is 189 for the keyword dam, thus below EU (350) and the U.S. (453).
Hydropower research covers a wide range of scientific areas, thus the results here presented, based on a few hydropower-related keywords, do not represent the full database, and only work as indicator.

Table 7. Bibliometric trends: number of peer-reviewed publications for some selected keywords and highly cited papers (HCP, top 10% cited normalised per year and field; RoW = rest of the world). 1st extra EU country is not included in the RoW.

	2010-2021						2021			
keyword	EU	1st EU country	1st extra EU country	RoW	HCP EU	HCP extra EU	EU	1st EU country	1st extra EU country	RoW
Hydropower	3,843	743 (Germany)	5,614 (China)	6,699	502	518 (China)	511	89, 89 (Germany and Italy)	706 (China)	972
Dam	350	70 (France)	453 (USA)	882	67	66 (USA)	54	11 (Germany)	65 (USA)	137
Reservoir	221	40 Germany)	270 (China)	618	28	51 (China)	33	9 (Italy)	40 (China)	64
Penstock	33	10 (Austria)	72 (China)	60	2	10 (China)	3	1, 1, 1, 1 (Austria, Germany, Spain, Poland)	5 (China)	9
Draft tube	17	4, 4 (Italy and Spain)	58 (China)	27	0	2 (China)	4	2 (Spain)	10 (China)	4
Turbine	102	15 (Italy)	236 (China)	211	10	30 (China)	17	4 (France)	35 (China)	41
Hydropeaking	81	24 (Italy)	310 (India)	60	13	3 (Switzerland)	13	3, 3 (Italy, Sweden)	63 (India)	7
Fish passage	73	22 (Germany)	81 (USA)	66	7	7 (USA)	14	4 (Sweden)	8 (USA)	8
Sediment	72	24 (France)	50, 46 (China, USA)	113	9	7 (USA)	14	4, 3, 3 (France, Italy, Spain)	13 (China)	19

2.9 Impact and Trends of EU-supported Research and Innovation

The European Union has funded several projects in the field of hydropower. From 2015 to 2022, 41 projects have been found, with a peak in 2018 (10 projects). Figure 14 depicts the received EU contribution for each country, and the total between 2015 and 2022. It is surprising to note that UK, Belgium and the Netherlands, that are flat countries, have received many funds, and this is associated mainly to the development of low head hydropower converters. Italy and France are amongst the most funded countries, probably due to their variegated territory, suitable both for low head hydropower and for high head plants in the Alpine environment. Different extra-EU countries have been involved, thus generating a world global impact, and, in particular: Uzbekistan, Kyrgyzstan, Kenya, Zambia, Mozambique, Ethiopia, Chile, Australia, Brazil, New Zealand, North Macedonia, Colombia, Uganda, Cameroon, Ecuador, Bolivia.

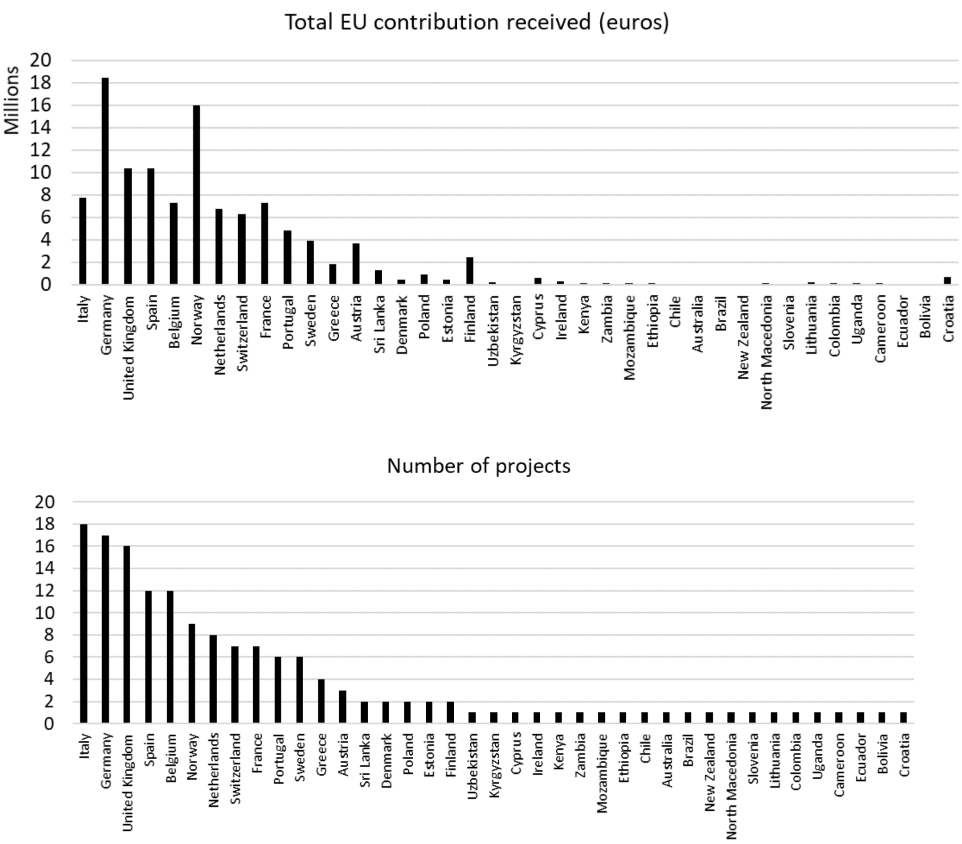
The three most recurrent topics are:

1. flexibility improvement of hydropower plants;
2. improvement of environmental performance, especially fish migration and water resource management;
3. new technologies for low head sites and hydrokinetic energy conversion.

Table 8 lists some of the Horizon and recent EU funded projects, from Cordis database. It is worth mentioning the research project Hydropower Europe. It is a comprehensive project, bringing together stakeholders of the hydropower sector in a forum to develop a Research and Innovation Agenda, and a Strategic Industry Roadmap to support implementation of research and innovation for new hydropower technologies and innovative mitigation measures (the successor of Hydropower Europe, ETIP Hydropower Europe, started in 2022).

The current open Horizon calls deal with hidden hydropower opportunities (see also Quaranta et al., 2022, typically associated to low head hydropower) and hydropower digitalization (typically associated to flexibility, Quaranta et al., 2021, Kougias et al., 2019). These activities are in line with future EU opportunities (see section 2.3). An additional international and comprehensive activity on hydropower, where the JRC and RTD are involved, is the Hydropower Roadmap of the International Energy Agency, in particular the Annexes Hydropower & Fish, Resilience of Hydropower to Climate Changes, Valuing Hydropower Services, and Hidden Hydropower opportunities[xvi]. The exploratory activity SustHydro, coordinated by the Author at the JRC, is aiming at identifying sustainable and hidden hydropower opportunities in the EU to support the previous activities and EU policies (see e.g., Quaranta et al., 2021, Quaranta et al., 2022). Two current Horizon programmes on hydropower deal with the improvement of the existing hydropower fleet and new sustainable capacity additions [xvii, xviii].

Figure 14. Received funds and number of projects by country (Interreg projects not included).



[xvi] https://www.ieahydro.org/work-programme/

[xvii] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d3-03-08

[xviii] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d3-03-11

Table 8. List of some Horizon projects and their main characteristics and EU share (n° of member states).

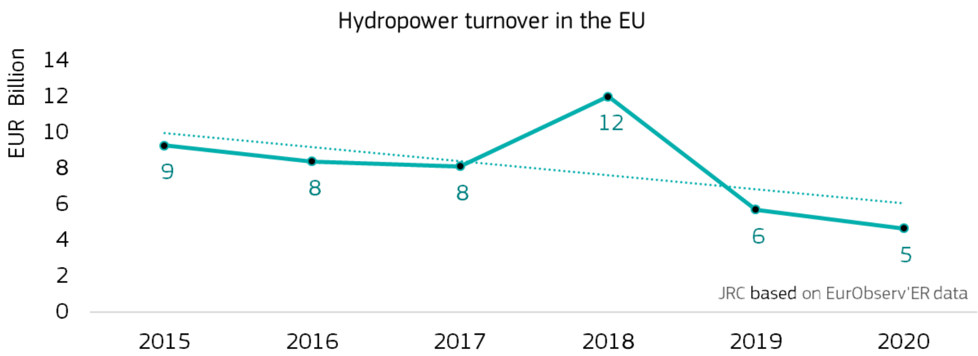
Acronym	Budget (EUR)	Title	Partners	EU share	Improvement aim
AFC4HYDRO	4,711,589	Design, implementation and validation of active flow control systems	6	57%	TRL
ALPHEUS	4,996,825	Augmenting grid stability through Low head Pumped Hydro Energy Utilization & Storage	12	83%	TRL
AMBER	6,238,103	Adaptive Management of Barriers in European Rivers	21	76%	sustainability
BINGO	7,8224,23	Bringing INnovation to onGOing water management – A better future under climate change	20	100%	sustainability
CaFE	3,939,999	Development and experimental validation of computational models for cavitating flows, surface erosion damage and material loss	8	100%	TRL
DAFNE	5,420,223	Use of a Decision-Analytic Framework to explore the water energy food NExus in complex and trans-boundary water resources systems of fast growing developing countries	14	63%	sustainability
DP Renewables	2,877,033	A range of economically viable, innovative & proven hydrokinetic turbines that will enable to exploit the huge potential of clean, predictable energy in the world's rivers, canals and estuaries	1	67%	TRL, cost
EcoCurrent	71,500	Innovative water current pico turbines for the economic and sustainable exploitation of the renewable energy from rivers and estuaries	1	100%	sustainability, TRL, cost
ECO-DRILLING	2,811,875	Environmentally efficient full profile drilling solution	1	70%	sustainability
EUROFLOW	3,923,989	A EUROpean training and research network for environmental FLOW management in river basins	10	100%	sustainability
FitHydro	7,171,550	Fishfriendly Innovative Technologies for Hydropower	26	82%	sustainability
Hydro4U	9,931,160	Hydropower For You - Sustainable small scale hydropower in Central Asia	13	69%	TRL, sustainability
Hydroflex	5,716,989	Increasing the value of Hydropower through increased Flexibility	16	95%	TRL
HydroKinetic-25	71,500	Commercialization of a viable and proven HydroKinetic Turbine that will harness the power of the world's rivers, canals and estuaries in a sustainable, innovative and cost-effective way	1	100%	TRL, cost
HydroLowHead	1,512,893	Profitable low head hydropower	2	70%	TRL, cost
Hydropower Europe	993,570	The new forum giving voice to Europe's hydropower community	14	93%	TRL, cost, sustainability
HyKinetics (2019)	71,500	An innovative axial turbine for conversion of hydro-kinetic energy to electricity for river applications	1	100%	TRL
HyKinetics (2022)	1,534,488	An innovative axial turbine for conversion of hydro-kinetics energy to electricity in rivers and canals	2	100%	TRL
HYPOS	2,397,120	Multi-function software for hydropower data collection and monitoring	5	60%	TRL, sustainability
HYPOSO	2,938,373	European hydropower solutions for a more sustainable world	13	62%	sustainability, potential
HyPump	2,545,390	Enabling Sustainable Irrigation through Hydro-Powered Pumps for Canals	1	70%	Cost, TRL, sustainability
Imprex	7,996,848	IMproving PRedictions and management of hydrological Extremes	23	100%	sustainability
KEEPFISH	135,000	Knowledge Exchange for Efficient Passage of Fishes in the Southern Hemisphere	8	25%	sustainability
Ribes	4,048,220	RIver flow regulation, fish BEhaviour and Status	11	82%	sustainability
RIVER-POWER	71,500	Water flow kinetics energy exploitation for mini/micro hydropower plants	1	100%	TRL
SHYDRO-ALP	180,277	Quantifying ecological effects of small hydropower in Alpine stream ecosystems	1	100%	sustainability
XFlex Hydro	18,162,949	Hydropower Extending Power System Flexibility	20	70	TRL

3 Value change Analysis

3.1 Turnover

The annual turnover of hydropower electricity generation in the EU was approximately EUR 12 billion in 2018[58] (Figure 15). Leading Member States in terms of turnover are Austria (EUR 2.85 billion in 2018), Italy (EUR 2.25 billion), France (EUR 1.55 billion), Spain (EUR 1.18 billion) and Germany (EUR 1.06 billion). European hydropower manufacturers spend more than 5% of annual turnover on R&D, which is more than twice the European industry average[56].

Figure 15. EU turnover.



3.2 Gross value added

With an annual value creation[xix] of approx. EUR 38 billion (in 2015) in Europe, which may grow to some EUR 75 billion to 90 billion by 2030, the hydropower sector makes an important contribution to the European economy, which is similar to the gross domestic product (GDP) of Slovenia. Direct tax contributions are estimated at almost EUR 15 billion annually, or more than one third of total value creation, which is several times more than the limited volume of subsidised payments to small hydropower. A substantial share of this value goes directly to local and regional budgets and helps to foster regional development. Whilst it is difficult to estimate the associated benefits, the multipurpose functions of hydropower represent an additional annual economic value of EUR 10 billion to 20 billion, even when neglecting the potential value of avoided damages from flood events, which may be substantial. These benefits can be expected to increase in the future, for instance due to an increased need for water management and flood control. In the EU+UK, hydropower contributes EUR 25 billion to the GDP, annually. The main part of this contribution derives from hydropower generation with about EUR 20 billion. Exports of hydropower equipment accounts for nearly EUR 1 billion and the remaining amount is tax revenue. Hydropower contribution to EU+UK GDP is expected to increase considerably by 2030 and exceed EUR 40 billion or even reach EUR 50 billion, depending on the renewable scenario[xx] evolution (Diversified Supply or Reference Scenario, respectively) [59].

[xix] Value creation comprises of the contribution of different economic sectors to gross domestic product (GDP)

[xx] The scenario 'Diversified Supply Technologies' follows the EU's long-term decarbonisation pathway and uses a mix of different technologies, including RES. It achieves a significant reduction of carbon emissions in the power sector (> 95% by 2050) and assumes a strong growth of renewables, mainly wind power. In contrast, the ''Reference' scenario' reflects a more conservative development scenario that fails to meet the carbon reduction targets by 2050.

3.3 Environmental and socio-economic sustainability

Sustainable development requires attention to a wide range of economic, social and environmental objectives. Energy and water for sustainable development depend not only on supply choices, but also on how these choices are implemented. Sustainable development is a major challenge for hydropower, because it is an energy technology that involves several stakeholders and challenges related to the environment, the society (especially the large projects), the energy sector and the economy. The complexity of hydropower is well visible in its cross-cutting presence in different European Directives, with its benefits and impacts (see Table 1 and section 1.1). Benefits and impacts are summarized in Figure 16, while Table 9 summarizes the sustainability indicators of hydropower.

Figure 16. Benefits and impacts of hydropower (figure from Branche, 2017) [60].

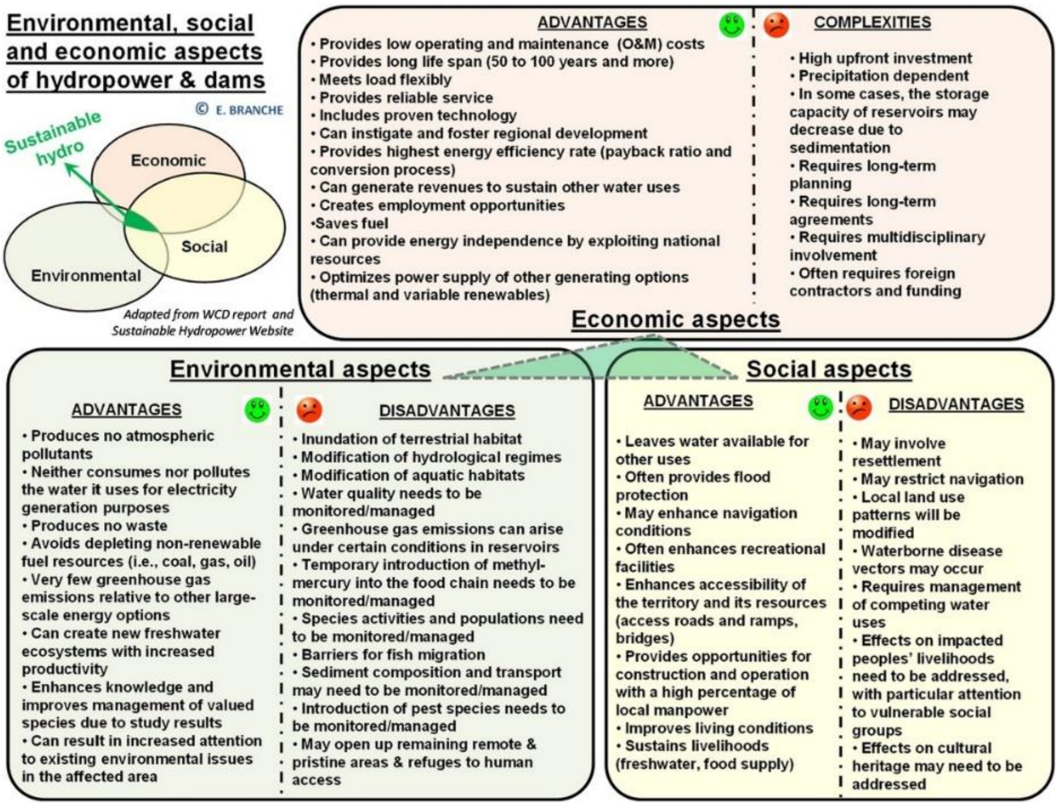


Table 9. Summary table.

Parameter/Indicator	***Input***
Environmental	
LCA standards, PEFCR or best practice, LCI databases	*Y, see* [61, 77, 78, 79]
GHG emissions	*The IPCC states that hydropower has a median greenhouse gas (GHG) emission intensity of 24 gCO_2-eq/kWh (grams of carbon dioxide equivalent per kilowatt-hour of electricity generated allocated over its life-cycle). By comparison, the median figure for gas is 490 gCO_2-eq/kWh. It also depends on the geographic context, e.g., alpine or non-alpine area.*
Energy balance	*EROI = 60-100* [62]*, the highest one amongst energy sources, storage capacity and flexibility.*

Ecosystem and biodiversity impact	*Yes, new barriers can generate several impacts. See the text in this section and* Figure 16.
Water use	*Depends on the power plant and on the head difference. The average flow rate discharged by European hydropower plants is 5,045 m^3/MWh (elaborating data of hydropower database, Quaranta et al., 2021*[20]*). Water is used for energy generation and released downstream in ROR plants, while the natural hydrological regime is significantly altered, and evaporation losses can be relevant, in reservoirs (SPP). The water footprint of hydropower in EU during construction phase is 3.6 m^3/GWh, which is 90-fold less than the solar one (in 2019, but now PV technology is improved and this difference may be slightly attenuated) and similar to the wind one* [63]*. The water footprint for operation (excluding the turbined flow) is almost zero for ROR and 32 m^3/MWh for SPP (evaporation mainly), more than 1-order of magnitude higher than that for PV. Globally, around 507 GW of hydropower competes with irrigation. While hydropower reservoirs might support irrigation, there are well-known cases where it reduces water availability for irrigated food production, e.g., in Portugal* [64]*.*
Air quality	*No pollutant emission, but methane emission from reservoirs* [65]*.*
Land use	*Hydropower densities (W/m^2) vary quite widely across the literature as they are dependent on geographic and topological conditions. Reservoirs include the additional land required for impoundment, but that, generally, serve for multiple purposes. Elaborating data of* [20]*, the density value for reservoir hydropower plants ranges from 0.98 W/m^2 (5° percentile) to 986 W/m^2 (95° percentile) (12 W/m^2 is the 50° percentile) considering the reservoir area as water footprint. These are estimated values with an approximated reservoir area. If the 50° percentile value is multiplied by the capacity factor (0.38), by the power at operating point (90% of the installed one) and by the infrastructure ratio (0.62), the power density becomes 2.3 W/m^2, higher than the average global value ranging from 0.25 to 0.75 W/m^2 calculated in van Zalk and Behrens (2018)*[66]*. The infrastructure ratio (that represents the additional surface for mines, roads, foundations, etc.) is 0.62, higher than wind (0.10) and slightly lower than photovoltaics (0.73-0.91). The ratio of biomass power plants is the highest (0.90)* [66] *(infrastructure ratio =1 is the optimal/ideal value).*
Soil health	*Alteration of sediment transport, possible landslides in big projects, but also improved maintenance and additional monitoring.*
Hazardous materials	*See section 4.3. No critical materials are commonly used.*
Economic	
LCC standards or best practices	*Zakery and Syri (2015)*[67] *found that the annualized life cycle cost (LCC) for PHS ranged between 200 and 270 €/kW/y, half the LCC of batteries. Donnelly et al., (2010)*[68] *found that the LCC was 66 $/MWh for a reservoir hydropower plant, 88 $/MWh for a ROR plant, and 103 $/MWh, 405 $/MWh, 99 $/MWh, 66 $/MWh for a wind, solar, nuclear and coal power plant, respectively.*
Cost of energy	*See section 2.4.*
Critical raw materials	*No, see section 4.3.*
Circular economy, Resource efficiency and recycling	*The lifespan of civil structures is typically 80 years, after that a retrofitting activity is required. However, dams are designed to withstand 1,000 years floods. Electro-mechanical equipment has a lifespan 20-30 years. No critical material is used and the overall efficiency (from water withdrawn to turbine release) is generally above 80% for large plants and above 65% for mini plants, and can reach 90%. Heat losses of generators can be recovered and used for heating, and methane capture technologies are under development to capture degassing methane downstream of the turbines. Reservoirs can have multiple purposes (supporting irrigation, security, fishing, leisure).*
Industry viability and expansion potential	*See section 2.3.*
Trade impacts	*Yes, the hydropower sector involves industry, environment and high financial investments. See section 4.2.*
Market demand	*See section 3.*
Technology lock-in/innovation lock-out	*See section 2.1. Several R&D activities are ongoing, although the main technology is well established. Local materials can be used for the construction.*
Tech-specific permitting requirements	*Several permitting procedures for land and water use* [69]*.*
Sustainability certification schemes	*Yes* [xxi]
Social	

[xxi] https://www.hydrosustainability.org/standard-overview

S-LCA standard or best practice	*Yes, see the text.*
Health	*No direct emissions.*
Public acceptance	*Yes, if people reallocation is not required and if water resources are not depleted.*
Education opportunities and needs	*Yes, especially when hydropower is linked to the industrial heritage and cultural heritage (e.g., water mills)* [33, 70].
Employment and conditions	*For employment data see section 3.5.*
Contribution to GDP	*see section 3.*
Rural development impact	*Yes, especially in case of rural areas that host water mills and hydraulic infrastructures.*
Industrial transition impact	*Yes, hydropower can provide flexibility and can be hybridized with other energy technologies (e.g., floating photovoltaics, hydrogen production, heat generation, wind).*
Affordable energy access (SDG7)	*If well operated, hydropower can provide a better management of water resources and micro-hydropower can be installed in remote localities.*
Safety and (cyber)security	*Digitalization is an emerging strategy to improve generation, extend lifespan and mitigate impacts, and thus cybersecurity is of high relevance. The EU is a lead exporter, thus the EU hydropower is a secure market for the EU, with no dependency from foreign countries, differently from, e.g., the solar sector, where most of the materials (most of them, critical materials) are imported from China.*
Energy security	*Water and energy storage. Energy can be stored in large-scale reservoirs and in PHS in larger quantities with respect to batteries. For example, the stored energy in the Blåsjø PHS reservoir, the Norways's largest reservoir (8 TWh), is equivalent to more than 40,000 times the Hornsdale battery park in Australia.*
Food security	*Several dams are built for irrigation purposes. Hydropower reservoirs serve as water storage for other purposes, e.g., irrigation, industrial and domestic water supply, aquaculture and fire-fighting.*
Responsible material sourcing	*No.*

When developed and operated responsibly, hydropower directly supports the achievement of Sustainable Development Goals (SDG) 6, 7, 9 and 13. Hydropower projects can contribute towards economic development, social investments and environmental outcomes, supporting SDGs 1, 2, 3, 4, 5, 8, 10, 11, 12, 14, 15, 16 and 17.

As a low-carbon energy technology with no direct emissions, hydropower contributes to energy targets and climate change mitigation. Its advantages include the reliability of supply, very high conversion factors (efficiency) and flexibility [71]. Therefore, it can adjust its generation to balance short-term variations in the intra-day market, and support security of supply for seasonal variations. It also supports frequency regulation. Because of this, although its share of total generation remained stable over the last decade due to the growth of wind, solar PV and green hydrogen, hydropower flexibility is critical for integrating rising levels of volatile energy sources into electric systems [72]. Multi-purpose reservoirs can provide additional benefits and water provision for several other uses more than hydropower generation. According to the Hydropower Europe project, hydropower has the best climate indicators, the best performance for storage and flexibility, it is a driver for regional economies and PHS could comply with the objectives of the Taxonomy: climate change mitigation and adaption, protection of water resources, transition to circular economy and pollution prevention.

On the other hand, hydropower can be responsible (or in the case of multipurpose installations, co-responsible) for ecosystem deterioration through diversion and alteration of flow and changes in habitat; new barriers obstruct the natural river flow with ecological, hydrological and morphological consequences. Hydroelectric reservoirs can be responsible for methane and carbon emissions in all climate regions as a consequence of the decomposition of allochthonous or autochthonous organic matter, with a special risk of increasing natural emissions under conditions favourable to methane production (anoxic conditions, large areas of low water depth) [73]. Only 40% of surface water bodies surveyed by the European Environmental Agency was found to be in a good ecological state, despite EU laws and biodiversity protocols [74]. Strict standards and associated legislation were therefore put in place in the EU to protect ecosystems and the environment, meaning that new hydropower development has to fulfil high sustainability requirements. The Hydropower Sustainability Assessment Protocol offers a way to assess the performance of a hydropower project across more than 20 sustainability topics.

It is important to note that, generally speaking, the effects of a hydropower plant are site and waterbody specific and should not be related to the size of a project a priori. Furthermore, benefits and impacts depend on the climatic and geographic context, as well as on the type of hydropower plant and implemented technology. For example, the study of Mahmud et al., (2019)[75, 77] found that the overall LCA[xxii] (Life Cycle Assessment) of hydropower plants (kg CO2eq/kWh) in Europe is lower than outside of Europe (see also [76]), and, overall, hydropower plants in non-alpine regions are responsible for carbon emission with a higher rate than those in alpine ones (Mahmud et al., 2019), due to higher rate of methane biogenic emissions from non-alpine power plants, that typically include larger reservoirs. In Mahmud et al., (2019), it was found that a higher rate of nitrous oxide is emitted by an alpine plant due to more combustion of fossil fuels during the manufacturing, and more combustion of solid waste at the end-of-life waste management because of the more difficult transport and connection with disposal facilities. The construction phase was responsible for most impacts in alpine areas in Europe, whereas the transmission line is the most impactful for non-alpine areas [77]. ROR are not associated to large impoundments and methane emissions from the reservoir [78], but ROR ecosystem services are smaller than those provided by storage hydropower plants ($ 37 million with respect to $ 410 million in the case study described in [61]). However, the situation is very site-specific and any kind of generalization would be misleading and should be avoided.

When speaking about PHS, a comparison with batteries is worthwhile. Batteries do not have to be expensive centralised installations with capacities in the order of magnitude of several GWh. The capacity can be broken down into smaller units and distributed across a number of sites, and have a very fast response. However, batteries have particular requirements with regard to the materials that they are made from, how they can be operated, and how they are decommissioned at their end of life. Most of materials refining is done in China. Batteries are particularly well suited to fast-response short-term balancing requirements, while PHS hold large volumes and can provide long-term storage, with a lifespan of up to 100 years (below 20 years for batteries). PHS are less impacting than batteries, except for natural land transformation, in a LCA analysis performed in[79]. However, batteries would require to occupy an enormous area to be comparable with a PHS, and would not provide additional benefits besides energy storage and flexibility. Hence batteries and PHS should be seen as complementary technologies rather than as substitutes.

3.3.1. Challenges of different water uses and EU Directives

European hydropower reservoirs store about 440 billion m^3 of water (including Ukraine and without Turkey), 25% of them for multipurpose water use (33% respectively in the EU). Amongst the 6,062 large dams, 2,743 store water for hydropower generation (2,125 in the EU) [80]. Multipurpose reservoir plants can have important additional functions for society, often more important than hydropower generation per se: irrigation and drinking water provision, flood and drought risk management, river navigation and recreation, fire-fighting, fishing, leisure. These services can be developed to provide civil society with greater resilience towards climate change impacts. However, a major challenge with multipurpose reservoirs is sharing water, costs and impacts amongst competing users, and to define user priorities. For example, EDF (Electricité de France) and the WWC (World Water Council) have agreed in 2012 to cooperate and launched a program to work on a SHARE concept framework for multi-purpose hydropower reservoirs in order to achieve a higher sustainability. The purpose is to maximise the benefits of the multi-purpose use of hydropower reservoirs by considering the principles of 1) Shared resource, 2) Shared rights and risks, 3) Shared costs and benefits [60, 81].

Another challenge for the hydropower sector is to pursue energy, climate and environmental targets at the same time. As highlighted in section 1.1, hydropower is a major player in several EU Directives and programmes, i.e. the WFD, the Flood Directive, the Renewable Energy Directive (REPowerEU). Therefore, sustainable hydropower needs to achieve a good balance between electricity generation, social benefits and impacts on the ecosystem and biodiversity. The achievement of a trade-off has been the aim of several discussions and studies [82, 83, 84]. Mitigation and sustainable solutions have to be implemented, for example ecological and more environmental-friendly solutions, both at the planning/management level and during the construction and O&M stage [85] (e.g., more fish friendly turbines, racks to avoid fish passage through the turbine, efficient fish passages, better sediment management and hydropeaking mitigation measures [86, 87]). At the planning/management level, an integrated approach is essential to reach a holistic view of the river basin, for example for selecting the optimal power plant location [88]. It is necessary to identify all stakeholders and engage them in the early stages to participate on a voluntary basis to the dialogue. The involvement of local citizens is important, also for small hydropower plants. A survey conducted throughout the EU claimed that ROR plants should be managed as distributed generation rather than viewed as part of a centralized national system like traditional large-scale

[xxii] The Life Cycle assessment (LCA) is a systematic approach to evaluate the effects of a technology/process throughout its lifespan, from raw materials extraction through to processing, transport, operation and end-of-life disposal.

hydropower reservoirs. However, this depends on the site and on the size, and the largest plants should be managed both with a local and national setting. Local involvement (as opposed to centralized planning) can help facilitate community acceptance [89].

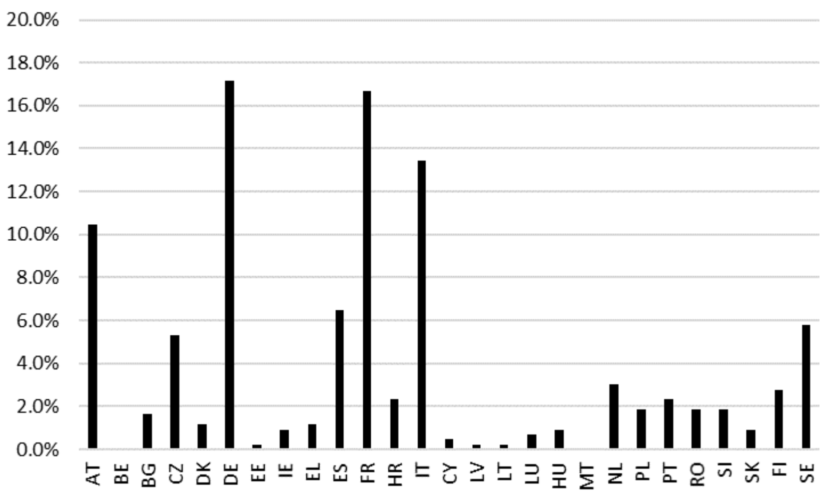
It is essential to provide greater flexibility and adaptability in the way water is allocated among users during the whole lifetime of the reservoir and to take into account all the effects that hydropower can generate on the environment and society, both at the local scale and at the regional/national scale. For example, the studies of Alsaleh and Abdul-Rahim (2021) analysed the interaction between hydropower and environment, human capital, market, innovation ecosystem and economic growth, in the EU+UK from 1990 to 2018 [41]. They suggest that micro-hydropower development can be qualitatively evaluated as sustainable from the perspective of improving community well-being. Environmental planning and advanced design processes can support sustainable trade-offs between the preservation of ecosystem functions and energy production through small hydropower. The same authors showed that carbon dioxide releases in EU+UK can be efficiently lessened through expanding hydropower. Boosting the production of hydropower energy by 1% will lessen the carbon dioxide by 0.809%, while a rise in economic growth by 1% leads to an increase in carbon dioxide releases by 0.113% [90]. On the other hand, growth in hydropower production lessens the water quality, although the highest influence on water quality was estimated to be brought by the increase in population density and economic growth [74]. Fan et al., (2022) found that recently constructed dams were associated with increased Gross Domestic Production (GDP) in North America and urban areas in Europe. However, new dams were associated with decreased GDP and population in the Global South, and with a decreased greenness in nearby areas in Africa [91], where large projects may generate conflicts, corruption and poverty gaps [92].

3.4 Role of EU Companies

A recent JRC research developed a database of EU companies active in the hydropower sector that includes 524 entries [56]. The large part of EU-based companies are commercial companies (85%). These companies are active in the design, manufacture and supply of hydropower equipment, including automation and control systems. They are also active in consultancy, R&D, and the construction of civil works. A smaller number of companies are national (≈10%) and international (≈5%) organizations active in hydropower.

Figure 17 depicts the share of companies in EU Member States, based on data of 438 EU companies available in a different database [93]. It highlights that the main hubs of hydropower activity are in France, Germany and Italy, and that certain countries such as Austria, Spain, Sweden, and Czech Republic host a significant number of hydropower companies.

Figure 17. Number of EU-based hydropower companies per Member State [93].



Hydraulic turbines are important components and a reliable proxy of the investment as they define the power capacity of the station. The market of large-scale units (above 10 MW) is dominated by a small number of companies, while a large number of turbine manufacturers exists in the EU and globally, the majority of which focuses exclusively on small-scale turbines. This section focuses exclusively on the global market of large turbines which are typically hosted in projects worth several EUR hundred million (or even EUR multi-billion investments). In monetary terms, such investments represent a very large share of the global hydropower market. Besides, the small-scale market is not systematically monitored. An additional particularity of the hydropower market is that a significant part of investments is not monitored as it refers to the civil works and the associated consultancy services.

3.5 Employment in value chain incl. R&I employment

Employment in hydropower industry spans various value chain elements as project design, manufacturing, project construction and O&M. The sector employment generally includes engineers, geologists, ecologists, economists, technicians, and skilled workers. It also provides employment to scientists, as well as a wide range of scientists working in corporate and academic R&D activities.

Globally, IRENA calculated that approximately 2.36 million people worked directly in the sector in 2021, the highest in the last monitored decade. Only bioenergy (3.44 million) and photovoltaics (4.29 million) exhibit a higher employment level. Globally, almost two-thirds of these jobs were in manufacturing, 30% in construction and installation activities and about 6% were in O&M services. China was the largest contributor to hydropower direct jobs, accounting for 37% of global employment, even though the pandemic caused delays in completing some projects. India accounted for about 18% of global hydropower employment, followed by Brazil, Viet Nam, Pakistan, the United States, the Russian Federation and Colombia. In 2021, Ethiopia climbed to ninth place amongst hydropower employers, reflecting the construction of large new structures, such as the Grand Ethiopian Renaissance Dam, the largest hydropower project in Africa. Canada rounded out the top ten [94].

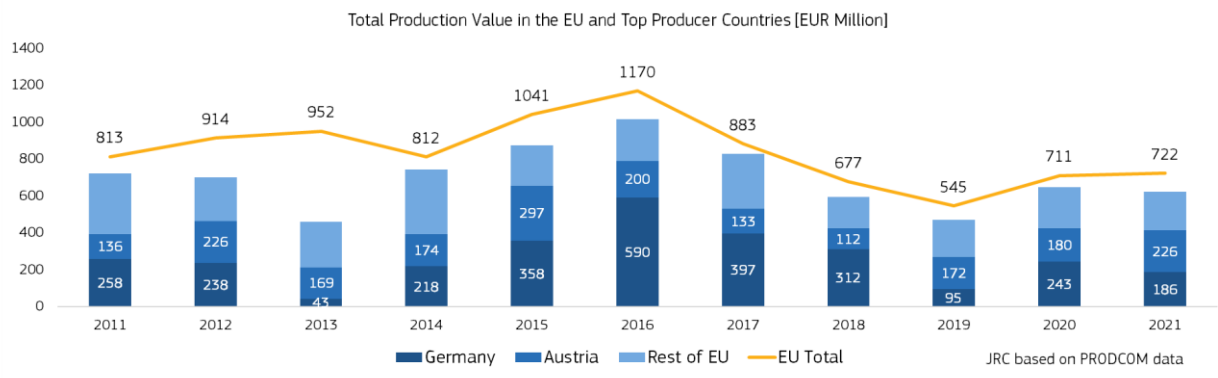
The number of jobs in Europe as a whole is estimated at 120,000. In the EU, the number of direct and indirect jobs in hydropower is estimated to be 99,600 in 2018, with alpine countries Italy and Austria the most relevant employers. The number of direct jobs of hydropower ranges between 74,000 and 87,000 [58], and 89,000 estimated in 2021 by IRENA[94], 7.2% of the direct employment in the renewable energy sector. These numbers correspond to 42,000 Full Time Equivalent (FTE) in O&M and 5,000 FTE in equipment manufacturing. The indirect employment is believed of the same order. This is more than eight times higher than the average in the EU manufacturing sector. A 10% increase of hydropower in the year 2030 would create 27,000 jobs in the EU, mainly outside the hydropower sector itself [59]. EU hydropower employment increased in 2018 with respect to 2015, but with a significant reduction in 2016-2017, probably associated to the reduction of the installed power capacity under construction in 2016-2017 with respect to 2015, from 7,000 MW to 4,000 MW.

Future projections show that hydropower direct employment in EU will remain rather stable between 78,000 and 88,000. According to a different source, hydropower provides 42,000 jobs in power generation and another 5,000 in manufacturing, with almost another 30,000 jobs created in external services of hydropower [56].

3.6 Energy intensity /labour productivity / Production

Hydropower contributes EUR 25 billion to the EU+UK gross domestic product (GDP), annually (electricity generation and exports), that is roughly EUR 500,000 per FTE (Full Time Equivalent). The main part of this contribution (>90%) derives from hydropower generation. When Norway, Switzerland and Turkey are included, the GDP is EUR 38 billion, which may grow to EUR 75-90 EUR billion by 2030. The multipurpose benefits represent an important additional income that, although very difficult to be quantified, may range between EUR 10 and 20 billion, that are expected to increase in the future due to climate change effects. Direct tax contribution are estimated at almost EUR 8.5 and 15 billion, in EU+UK and Europe, respectively, several times higher than the subsides paid to the small hydropower sector [59]. In 2021 the production annual value of hydraulic turbines and their parts was EUR 722 Million within the EU (Figure 18). The energy return on energy invested (EROI) ranges between 60 and 100 [62], the highest one amongst energy sources, 8-fold higher than that of solar and 4-fold higher than the wind one.

Figure 18. Production value



4 EU position and Global competitiveness

4.1 Global & EU market leaders (Market share)

In the recent past, the leading hydropower turbine market has been China, followed by India, Brazil and Ethiopia. Accordingly, China-based technology companies received a large part of orders for hydropower turbines. Between 2013 and 2017, Dongfang Electric and Harbin Electric sold approximately 40 GW of capacity in China. The penetration of EU-based companies in the Chinese market over the same period was significant with Voith Hydro providing 11.5 GW, General Electric 10.5 GW, and Andritz nearly 1 GW of capacity. Accordingly, EU-based companies secured 35% of the total capacity orders in China over the analysed period.

Outside China, the three EU-based companies delivered 73.5% of the total orders in terms of power capacity (2013-2017). Voith delivered 10.7 GW, Andritz 9.1 GW, and General Electric (European headquarter) 6.6 GW. All Chinese manufacturers combined delivered 15.5% of total capacity. This shows the leading role of EU companies. The remaining share was almost equally divided between Japanese, Indian, and Norwegian companies [56].

In terms of number of sold units for large-scale stations worldwide, Andritz, Voith and GE held the leading positions in 2013-2017. In 2017 alone, the three EU companies sold 93 units (>10 MW) or 62% of the total number of sold units. The large European operators (EDF, EDP, ENEL, ENGIE, ENBW, IBERDROLA, PPC, STATKRAFT, UNIPER, VATTENFALL, amongst others) continue to invest in many hydropower projects outside of Europe. Many European engineering and consultancy companies offer knowledge, expertise, or consulting to hydropower projects outside of Europe, where there is considerable growth in the hydropower sector (Artelia, Lombardi, ISL, AFRY -former Pöyry and AF-, Sweco, MESYSolexperts, Tractebel -former Lahmeyer and Coyne et Bellier-, amongst others). Meanwhile, many construction companies (Impregilo, Salini, Skanska, Strabag, Vinci, Walo, amongst others) act as civil contractors or even as EPCs in the framework of turnkey projects [23].

4.2 Trade (Import/export) and trade balance

Despite its relatively low share in the global employment market (4%), the EU industry holds an important share in global exports[xxiii]. Global exports accounted for EUR 2.0 billion over the period 2019-2021 (in 2019 and 2021 accounted for EUR 876 and 356 million, respectively). The EU holds 50% of all global exports and 45% if intra-EU trade is excluded. The major share of global exports by the EU is associated to the big EU hydropower companies. The biggest exporter is China, with 18.7% share, followed by Austria (11%), Italy (8.8%) and Germany (8.6%). The remaining exports are mainly generated by India, Czechia, United States, Slovenia, Brazil and France. EU imports accounted for EUR 393 million from 2019 to 2021. However, 73% of that was intra-EU trade (Figure 19).

The total value of global imports and parts in 2019 accounted for EUR 1 billion (Comext and ComTrade) [51]. This is the lowest value since 2007 and is significantly lower than the average of the previous 10-year period (2009-2018) that was EUR 1,376 million, annually. EU imports accounted for 14% in 2019 (EUR 142 million, out of which EUR 105 million are within EU), and EUR 120 million in 2021 (EUR 84 million within EU). China moved from being the leading import country in 2007 to being almost independent from imports, as the country imported in 2019 equipment of a total value as low as EUR 2 million [95].

For the future, a great opportunity for EU companies is their export potential associated to innovative equipment and small hydropower, as well as assistance in the overall design and operation of hydropower plants.

The EU has a significant presence in Russia, Switzerland, Norway, Canada and Chile, supplying 87%, 79%, 75%, 37% and 43% of all imports, respectively, making the EU the world leader in hydropower technology (included

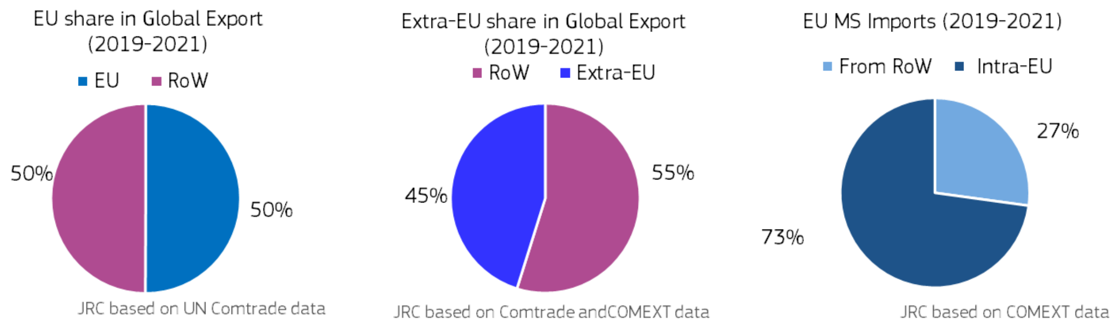
[xxiii] The main categories of goods associated with hydropower technology are: "hydraulic turbines and water wheels" (28112200) and "parts for hydraulic turbines and water wheels" (28113200).

pumped hydro) [96]. Vietnam and Pakistan are the biggest import markets globally; however, the EU has only a 10% market share there in the hydropower sector.

The EU's trade balance has been positive over the period 2011-2020. However, trade surplus has decreased since its peak at EUR 466 million in 2015 to EUR 232 million in 2020 and 211 in 2021. Austria, Germany and Italy have the biggest trade surpluses (EUR million +65, +45, +38, respectively), while Sweden, Latvia and Portugal the biggest negative balances (EUR million -4, -3, -1, respectively).

The total value of imported turbines and components in 2019 accounted for EUR 946 million. This is the lowest value since 2007 and is significantly lower than the average EUR 1,376 million per year of the previous 10-year period (2009-2018). EU imports accounted for 15% in 2019 (EUR 142 million).

Figure 19. EU share in global export (left), Extra-EU share in global export (middle) and EU imports (right) (2018-2020).



4.3 Resources efficiency and dependence in relation to EU competitiveness

Hydropower and pumped hydropower storage are not considered critical sectors. They are of strategic importance to the EU energy system and can contribute to the EU resilience [96].

The hydraulic and mechanical equipment of hydropower is typically made of materials that are available in most parts of the world, such as steel, concrete, and – to a lesser extent – copper, so that hydropower expansion may not be limited by material availability. Concrete is used for dam construction and the required civil works, including the power station. In large-scale stations, concrete may also be used in the construction of tunnels and caverns. The manufacture of mechanical components typically uses steel. The steel used in the turbines and concrete in buildings are crucial for the overall impact of the plant. Local materials are typically used, and this explains the high added value of hydropower to local economies. Copper is used at relatively low quantities in the generator sets. Over the last decade, novel materials have been introduced in the hydropower sector and/or are under testing, e.g., fibre-reinforced composites for small-scale hydropower and hydrokinetic turbines[49].

Hydropower equipment does not contain critical materials such as lithium and cobalt (used in electric vehicles), or neodymium, praseodymium, and dysprosium (used in electric vehicles and wind power plants). Hydropower is the best renewable energy for reducing pressure on mineral resources. The Extraction of Mineral Resources indicator is measured in kilograms of antimony equivalent (kgeq.Sb) per kilogram extracted to take into account existing reserves, the rate of extraction and the "depletion" of each mineral substance: the value for hydropower is 0.017, while it is 0.04 for coal, 0.3 for wind and 14 for solar PV [97]. A relevant concern is related to the use of permanent magnets. The emerging variable speed technology for small projects generally uses permanent magnets, and some micro-hydropower turbines with low rotational speed (water wheels, Archimedes screws) would be more efficient with permanent magnets. However, the material components of permanent magnets may suffer from shortages in the near future, worsened by the Chinese supply monopoly (the EU plays a major role only in the assembly stage, where its share is above 50%) [98, 99]. This should stimulate the development of novel electro-mechanical equipment and the improvement of the lifecycle of such materials (e.g., recycling). However, hydropower development may involve substantial excavation and tunnelling, requiring significant amounts of energy to run the appropriate machinery.

4.4 Threats and opportunities within the current social, energy, geopolitical and climate situation

The entire world is currently facing several challenges, new opportunities to exploit and some threats to fight. In the Twenty-first century, environmental goals such as the reduction of greenhouse gas emissions and the increase of renewables in the energy mix have been the main priority in the policy context. However, the aim of ensuring an energy-independent EU has been somewhat marginalized, and has gained particular importance during the COVID-19 pandemic and the Russia-Ukraine war. These issues are strictly connected with the energy sector and the environment, especially in the EU, highlighting the importance of considering the energy sector and the environment more comprehensively within the WEFE nexus [100]. Hydropower uses water to generate energy, and, when large civil structures are built, significant effects (benefits and impacts) can be generated on the environment, on the economy and on the society, sometimes with non-negligible geopolitical consequences. The consequences may be either a source of impacts or an opportunity for sharing benefits and collaborating, depending on how they are managed.

In this chapter, the interconnection of the EU hydropower sector with COVID-19 and the required independence from Russia are discussed. The EU hydropower sector is compared to that in other countries, in particular China, Russia and the U.S. Some relevant topics within the EU are discussed, e.g. the interconnection of the EU with some European countries and transboundary projects.

Sanitary emergency: COVID-19

The COVID-19 emergency has noticeably affected our society and the energy sector. Resource unavailability and scarcity, and less human resources, have slowed down the construction of new power plants. Other factors that have contributed to slowing down the energy sector have been the reduced electricity demand, slowdown of government processes and work schedules, economic instability, suspension of support programs and changes in policy priorities. Nevertheless, renewable energy production has been less impacted with respect to other energy sectors, thanks to the lower marginal costs of energy generation.

Although the pandemic has not impacted the hydropower sector to the extent witnessed in the oil and gas markets, the impact has been far from insignificant. The electricity consumption reduced during the pandemic and, as a consequence, the energy production. Considering the hydropower generation, as compared to baseline values in 2016 to 2019, hydropower operations in Europe decreased by 21% on average amidst the lockdowns. Generally speaking, in the short-term, widespread uncertainty, currency volatility and liquidity shortages have put financing of many hydropower projects at risk. Greenfield development and critical modernisation projects have been halted due to physical distancing measures and supply chain disruptions. Furthermore, proposed or existing government programmes aimed at supporting the sector have been postponed or could not be implemented [101]. Water Power and Dam Construction (2020)[102] discussed the COVID effects on specific hydropower plants, highlighting that several constructions stopped, as also occurred in the wave and tidal energy context [12]. Hydropower projects that rely on vast quantities of concrete during construction have been unable to meet construction deadlines, due to production being suspended, staff shortages and restrictions on movements [103]. However, this occurred especially in those countries where large investments were in progress on the construction of large hydropower schemes (e.g., Latin America) [104].

On the other hand, COVID-19 brought also some opportunities in the hydropower sector. A survey conducted by IHA showed that several hydropower plant owners digitalized their operation [106]. This is the case of China's Three Gorges and Gezhouba hydropower plants, that set new records by generating more power during COVID-19 lockdowns, also thanks to the digitalization of operation [105]. IHA stated that countries dependent on hydropower had steady electricity for essential workers to use in their job during the pandemic and hydropower was a reliable energy source during the pandemic. IEA affirmed that hydropower has been less affected by the pandemic as compared to other renewable energy sources [106]. In the early stage of the pandemic, a lot of hydropower operators activated their Business Continuity Plans (BCPs). Through this experience, some companies recognized that their BCPs were focused only on natural disasters and others realized that their BCPs only addressed emergencies at one or several of their locations, but were not prepared for a worldwide emergency [107].

The following is an interview made to an engineer, owner of some micro-hydropower plants: "Basically, when the COVID-19 appeared I was running a business in the micro-hydropower sector. The company was running normally. We had components to deliver. So just before the first lockdown, we made as much expeditions as possible. Then we had the first lockdown. At that time I wanted to hire a French guy, living in Milano, and it was not possible to make him come in France for the hiring process. My suppliers were able to deliver only part of the goods. This situation created a short-term problem, we had to pay for the product delivered, but we could not manufacture, thus we could not deliver, with no incomes. When we could travel again, I could not align the salary of the person I wanted to hire. For few months, my prospects had little incomes, they all decided to postpone their investment (many watermills are restaurants, kind of hotel, seminar places). At that time, we did not have enough money to wait one more year. The COVID-19 costed to my company EUR 150,000. There were 6 installations of an average of installed power of 7kW/each that were postponed. Today, for sure 3 of them have not started, but this is planned within 6 months."

Independence from Russia

Over the past decade, EU-Russia relations have undergone a broad set of policy issues, and the energy sector has always played a crucial role, especially the gas supply [108]. The renewable energy targets set by the European Commission, along with the aim of being independent from Russia (REPowerEU), pose some challenges to the growth of the renewable energy sector, highlighting the key role of hydropower.

The exponential growth of volatile renewable energy sources (mainly wind and solar PV) in the EU, to fulfil the abovementioned targets, requires more energy-storage capacity and flexibility [109]. Batteries are not mature and would require an enormous area to provide the same amount of annual energy of a water reservoir. Therefore, hydropower reservoirs and pumped hydropower storage are currently key solutions to compensate for this volatility. For the immediate concerns over security of supply due to the gas shortages, hydropower offers invaluable support to mitigate the volatility experienced in highly gas dependent markets. Furthermore, reservoirs have multiple purposes (see section 3.3). However, hydropower reservoirs generate impacts and there is thus the need of identifying more sustainable solutions (e.g., reservoir interconnection, heightening of existing dams, hybridization of power plants, pumped hydropower in abandoned mines).

The rapid growth of solar photovoltaic, promoted in the REPowerEU program, rises some concerns, because critical materials (e.g., silver and silicon) are used for PV manufacturing (with a high water footprint), and more than 90% of them are imported from China, increasing the EU dependency from China. Batteries require lithium and rare earths are used for wind turbine motors [109].

The Russia-Ukraine conflict has also posed the light on the fact that large hydropower reservoirs are key elements and "gun-points" during conflicts, because of their strategic relevance [110, 111]. Hence, security issues are of strategic relevance. In this context, the digitalization of hydropower plants could contribute to increase safety by real time and remote control, and it is highly promoted across the EU (e.g., the ongoing Horizon project call on hydropower digitalization[xxiv]).

Interconnection and comparison of the EU hydropower sector with external actors

China competitiveness

Europe is home to more than half of global equipment manufacturers. In addition to manufacturers, the largest operators provide investment and knowledge for hydropower projects outside of Europe. Furthermore, the EU represents a promising market for mature hydropower deployment (refurbishment, optimization, conversion to PHS). However, the presence of China in international markets can pose some challenges to the EU, also to the hydropower sector. Without European competition, many of the contracts will continue to be awarded to Chinese contractors for African and Asian hydropower projects. Global sales of hydropower equipment will continue to grow as Asia and African hydropower expands, and European companies will be in direct competition with Chinese manufacturers and contractors (IHA, 2022, pers. comm.). The increasing presence of China in Russia, North Macedonia and Georgia, that are neighbourhood of the EU, may be very bad for the EU's economy (especially the increasing Chinese involvement in dam construction in these regions) [57].

The high competitiveness of China is mainly due to its very large territory, population and gross domestic production. However, when the values of the market and competitiveness (for hydropower) indicators are elaborated considering the population, the EU can be considered more effective in producing knowledge and economy around hydropower, as widely discussed in this report. For example, the installed power per inhabitant

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[xxiv] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d3-03-08

is 0.35 kW/people in the EU and 0.24 kW/people in China. Between 2017 and 2021, EU institutions participated in the publication of 2,123 articles; China is the world leader with 3,879, but China hosts more than 3-times the EU population. The global exports within the period 2019-2021 accounted for EUR 2 billion, with EU countries holding 50% of this, while China accounted for EUR 376 million of exports. The invested value (early and later stage investments) per inhabitant is 0.03 EUR/person in the EU, and 0.01 in China.

Comparison with Russia

When comparing the EU hydropower situation with that of Russia, some considerations are worth to be mentioned. Russia hosts 49.9 GW of hydropower, and expansion of the hydropower sector in Russia is a main goal of the national electric power development. Therefore, Russia is seen like a challenger to the EU hydropower sector, along with Turkey, as they are characterized by high resources, but no links with the EU [xxv, 112]. The current Russian hydropower installed capacity is almost one third of the EU one. However, the installed capacity per inhabitant is almost similar to the EU one. The annual energy generation of Russia is 196 TWh, thus the capacity factor of 44.8% is higher than the EU one, mainly due to the different hydrological and climate context. There are only two pumped storage plants in Russia: the Zagorsk-1 with a capacity of 1,200 MW, which was commissioned back in the Soviet times (1987), and the Zelenchuk power plant with a capacity of 140 MW, which was commissioned in 2016. The relief of the terrain in the European part of Russia (it is particularly this area in which the construction of pumped storage plants is primarily needed) is such that the heads are approximately equal to 100 m, which are not optimal, posing the EU as a strong country in this context [113].

Comparison with the United States

The EU and the U.S. hydropower markets are not strictly connected, and the share of import and export between these countries is marginal. Their hydropower technological advancement status is also similar, and host each about 28% of the innovative companies. The installed power per inhabitant is 0.35 kW/person in the EU and 0.33 kW/person in the U.S. Fisher et al (2012)[114] compared the drivers of pumped storage equipment in the U.S. and OECD (Organisation for Economic Co-operation and Development) Europe. They showed as Europe is investing noticeably more in PHS than the U.S. This is because in Europe there is much more intermittent generation from wind and solar than in the U.S., and the use of gas for generation in Europe was not as attractive as in the U.S., in 2012. The energy arbitrage opportunities due to price spreads for electricity are not as affected by gas generation in Europe as they are and are expected to be in the mid future in the U.S.

The EU performs slightly better than the U.S. in the patenting activity and in scientific publications. Between 2017 and 2021, EU institutions participated in the publication of 2,123 articles on hydropower topics (out of the total 10,392). The U.S. registered 1,187 records.

In the U.S., public investments are coordinated by the Water Power Program of the United States Department of Energy. The Water Program (hydropower branch) budget is typically higher than the EU. Between 2016 and 2021, the EU early and later stage investments were EUR 4.96 million and EUR 8.48 million, respectively. Considering the total investments, France (EUR 9.78 million) and Belgium (EUR 3.56 million) are placed below the U.S. (EUR 83.38 million) and China (EUR 13.53 million). The invested value (early and later stage investments) per inhabitant is 0.03 EUR/person in the EU, and 0.25 EUR/person in the U.S

Transboundary hydropower projects within the EU

More than 70% of the dams under construction, or planned in major basins, have transboundary dimensions[116]. Transboundary hydropower projects are also present within the EU.

Table 10 lists some of EU transboundary hydropower projects. All hydropower plants on the Danube, Rhine and Rhone rivers can also be considered transboundary, as the water flows through several countries. Norway-Sweden has several transboundary rivers with hydropower plants. A recent conflict is that triggered by a new hydropower plant construction between Ukraine and Moldova [115].

[xxv] Depending on the involvement in the EU energy policy and the size of the energy resources, four groups of European countries outside the EU can be distinguished: challengers (e.g., Russia, Turkey — high resources, no links with the EU), outsiders (e.g., Belarus — no links with the EU and low resources), shapers (commitment to EU energy policy and high resources), and followers (members of Energy Community Treaty (ECT) and Iceland). ECT includes the EU, Albania, Bosnia and Herzegovina, the former Yugoslav Republic of Macedonia, Montenegro, Serbia and Kosovo.

Therefore, there is a need to explicitly consider not only aspects related to ownership or sovereignty over natural shared resources, but also the design of schemes that can foster the generation and distribution of benefits to empower the beneficiaries and avoid inequality.

Table 10. Some operating transboundary hydropower projects in Europe [116].

Name	Transboundary Basin	Country	Comment
Iron Gates	Danube	Romania/Serbia	Jointly developed project
Hintrerrhein Kraftwerke	Hinterrhein	Italy/Switzerland	Jointly developed project
Imatra	Vuoksi	Finland	Historical conflicts reported over competing water uses
Chancy Pougny	Rhone	France/Switzerland	Jointly developed project

Interconnection with hydropower-dependent European countries (outside of the EU)

Some non-EU countries, but located in the hearth of the EU area, play an important role in hydropower. Norway and Switzerland, located in the European region, are lead consulting companies for larger hydropower projects worldwide (including specialized equipment), and host a large part of the hydropower reservoirs in Europe. They also play a key role in European research projects, R&D and scientific publication, along with the U.K.
The hydropower share on the national energy mix is about 95% in Norway. Norway has almost half of Europe's reservoir (storage) energy capacity, that will help enormously to integrate renewable energy in North-West Europe. In a press release on 13 October 2014, the EU Commission welcomed the announcement made by the Norwegian government to license the construction of two subsea cables linking Norway to Germany and the United Kingdom.
In Switzerland, the hydropower share on the national energy mix is 57%. The cooperation in the energy market between the EU and Switzerland is important for securing energy supply [117]. Switzerland is highly dependent on electricity imports from the EU in winter, that usually roughly compensates with exports in spring and summer by activating its hydropower resources. However, given the vastness of the European electricity market, Swiss generation capacities play a minor role for meeting European demand. Switzerland thus yields little to no structural power stemming from electricity trade balances with the EU [118], but a key role in scientific and consultancy services.
Albania is fully dependent on hydropower due to its natural conditions, and its hydropower share on the national energy mix is almost 100% (70% of the area is mountainous). However, 50% of the domestic electricity demand is imported from abroad. Although it is a non-EU country, Albania has included in the National Renewable Energy Plan for 2015–2020 entries from the Renewable Energy Directive, which is in force in the EU. Some provisions arising from both the Water Framework Directive and the Birds and Habitats Directive will be implemented [119].

Climate changes

Hydropower is highly interconnected with climate changes [120]. On one hand, hydropower generation depends on water availability, and may suffer of water shortage in long dry periods. On the other hand, optimal management of hydropower reservoirs, along with a better inflow and weather forecast, can help in mitigating droughts and can act as flood control system. Water stored in hydropower reservoirs can also be useful for fire-fighting and agriculture [121].

The scientific literature has widely assessed the effects of climate changes on hydropower potential [xxvi]. For the whole of Europe, the gross hydropower potential [xxvii] is estimated to decline by about 6% by the 2070s, while the developed hydropower generation is expected to decrease by 7–12% (Lehner et al., 2005). Hamududu and Killingtveit (2010) found that generation in whole Europe may decrease by 1-1.8% in Eastern, Western and Southern Europe, and increase by 1.46% in Northern Europe by 2050. The countries most prone to a decrease

[xxvi] For the complete references, see Quaranta et al. (2021).
[xxvii] This is defined as the available hydropower potential simply considering water availability and topography, with no technical and economic limitation

are Portugal and Spain, as well as Ukraine, Bulgaria and Turkey, with decreases of more than 20%. Instead, electricity generation of hydropower stations in Scandinavia is expected to increase by at least 15–30%. In Western and Central Europe, the United Kingdom and Germany will maintain a rather stable developed hydropower potential compared to other European countries (Lehner et al., 2005).

Patro et al., (2018) calculated that the median decrease of generation of ROR hydropower will be −3% in the future, focusing on the Italian Alps. ROR across the Italian Alps thus seems relatively resilient to climate change. Schaefli et al., (2019) calculated that ice mass loss (glacier retreat) can reduce the Swiss hydropower generation by −0.5 TWh/y (−1.4%) in 2050 relatively to the current generation level. Electricity generation has continuously increased since the 1980s due to increased ice melt runoff. Since 1980, 3% to 4% (1.0 to 1.4 TWh/y) of the total Swiss hydropower production was provided by the glacier mass loss.

Gotske and Victoria (2021) estimated that the annual inflow for high (mid)-emission scenarios is going to decrease by 31% (20%) in Southern countries and to increase by 21% (14%) in Northern countries, and more frequent and prolonged droughts in Mediterranean countries are expected. Therefore, an increased seasonality of hydropower operation is required, and this implies an optimal use of the hydropower throughout the year [122]. Instead, in most hydropower schemes in Norway and Sweden, seasonality may decrease as there will be more precipitation in winter (pers. comm. Atle Harby).

The SPPs (storage power plants) in glacierized catchments were thought to have low year-to-year variability in production. Until early 2010, glacier retreat was an important source of water for the increase in SPP production. Due to the combined effect of widespread glacier retreat, reduction in glacier recharge and higher liquid precipitation regime, the flow is significantly reduced in future horizon (2050 onwards) simulations (Patro et al., 2018; Schaefli et al., 2019). Farinotti et al., (2019) suggested that the deglacierizing catchments could make an important contribution in increasing the production in the future (by 2050) if the existing hydropower fleet in such catchments were upgraded by increasing the storage volume (for SPP) or production capacity (for ROR and SPP) [123].

In general, hydropower reservoirs can help to mitigate climate change effects (better water management) in geographic contexts where climate variability is expected to increase (long droughts alternated with intense rainfall events), since they can store and release water in a programmed and controlled way. On the other hand, hydropower plants may suffer during water scarcity periods, while generating more energy in countries where water availability will increase.

5 Conclusions

Hydropower is the largest renewable energy source to date, with a global installed power capacity of 1,360 GW and an annual generation of 4,250 TWh in 2021. Hydropower provides, on average, 360 TWh/y in the EU, and more than a quarter of the global pumped hydropower storage (PHS) capacity is in the EU.

The hydropower sector is characterized by several strengths and advantages with respect to the other renewable technologies. The Energy Return on Investment (EROI) is above 60, the highest one amongst energy technologies. The water footprint of hydropower during the construction phase is noticeably lower than photovoltaics, and hydropower equipment does not use rare and critical materials. Hydropower installation costs are amongst the lowest of the renewable energy technologies. Hydropower reservoirs provide additional services, e.g., water and energy storage for irrigation and fire-fighting, flood control and drought mitigation, and navigation. Furthermore, capacity factors in EU are generally higher than those of photovoltaics and slightly higher than those of the wind sector, while the overall plant efficiency is approximately 5-times and 3-times higher than the efficiency of photovoltaics and wind power plants. Hydropower is the most flexible technology, providing flexibility and stability services to the grid. As the penetration of volatile energy sources (mainly wind and solar power) increases, the flexibility provided by hydropower operation is essential. PHS is a mature technology and, as a result, its technological and manufacturing/market position is considerably more advanced than that of other energy storage technologies (e.g., battery storage, flywheel, thermal and chemical storage). PHS can store water-energy (with daily, monthly and seasonal storage depending on the installed capacity) more cost-effectively than any other option, and can put and adsorb energy available in seconds or few minutes. The annualized life cycle cost for PHS ranges between 200 and 270 €/kW/y, half that of batteries.

However, being at the centre of the Water Energy Food Ecosystem nexus, several obstacles and challenges exist. The first major barrier is the effort to simultaneously pursue renewable energy, climate and environmental goals. These are the aims of different European policies and directives, where hydropower exhibits controversial roles. Depending on the context, hydropower can generate several adverse effects on the environment. The most suitable sites in the EU have been already exploited or are protected by environmental legislation (e.g., protected areas, natural parks) so that new large plants would be installed in less favourable sites, increasing costs, especially for the implementation of environmental mitigation measures. Hydropower development is also affected by climate changes (water availability, seasonality, extremes), but hydropower reservoirs can help to mitigate climate change effects (flood control, drought mitigation). Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, hence have higher financial risk, requiring specific policy instruments and incentives as well as a longer-term policy perspective and vision. The EC Competition Progress Report notes that a cost-effective way to ensure secure and affordable energy supplies is a well-functioning and integrated EU energy market; however, European hydropower operators are not remunerated for all of their services. Therefore, another major challenge is putting a value for all benefits, that is necessary to allow discussions and negotiations between different water users and externalities, and to bridge the gap between financial and economic viability. Therefore, public sector involvement is critical for hydropower expansion [72], and innovative financial mechanisms are crucial for equitable and efficient sharing of benefits among water users. The challenge is to find ways of framing long-term strategies, securing long-term finance sources, and shielding them as effectively as possible from short-term constraints. A significant proportion of investment and activity in the hydropower sector refers to the civil works and associated consultancy services, representing typically two thirds of the construction costs for new power plants. These are very difficult to track, making the collection of data and projections very challenging.

In the long-term up to 2050, the hydropower production in the whole of Europe, including Turkey, can be increased by some 20% (that is some 130 TWh/y) taking into account the 10% potential of upgrading existing hydropower (partly offsetting climate change effects and limitations imposed by environmental legislation) and some 10% by new run-of-river (new hydropower plants in freshwater systems are very controversial) and storage power plants designed as multipurpose projects. Although hydropower is very mature, novel technologies are under investigation and need to be supported and deployed, especially for the refurbishment, upgrading and expansion of the existing fleet, and for the deployment of new pumped hydropower storage plants. In Southern European countries, new reservoirs are urgently needed to mitigate the already visible effects of climate change (floods, droughts and fire, and to compensate hydrological changes due to glacier retreat) [123]. Small-scale hydropower opportunities in rural contexts and integrated in existing facilities can provide decentralized energy when the electric grid is not available, difficult to be connected or to avoid further expansion of the grid. Pico and micro-hydropower plants, e.g., in water supply networks, may be interesting, but can only contribute to the EU energy demand with an additional generation of about 10 TWh/y. Hydropower has also high hybridization potential. Photovoltaic systems can be installed as floating solution on hydropower reservoirs to reduce PV land use and optimize the overall efficiency of the hydro-solar power plant. Due to the different characteristics in response time and storage volume, hydropower and batteries can make a perfect combination in many cases. Waste-heat can be extracted from the cooling system of the generator. Tidal and wave power technologies implement similar freshwater hydropower technologies.

Companies within the EU are very competitive, and are of strategic relevance especially in light of the current geopolitical situation (e.g., the required independence from Russia). European companies own a great export capacity of their products and knowledge in the fields of sustainable and mitigation solutions, new turbine technologies and in the O&M, exerting their consulting services worldwide. 47% of the high-value inventions of the top-10 companies is shared by two EU companies. Furthermore, the EU is well positioned in terms of scientific publications, with the main concurrence of China. The global exports in 2019-2021 accounted for EUR 2 billion with EU countries holding 50% of this. Outside China, the three EU-based companies delivered 73.5% of the total orders in terms of capacity (2013-2017).

Therefore, to keep a competitive EU hydropower sector in an increasingly challenging world (including for energy crises ahead and the competitiveness of China) the strong competence (scientific and industrial) of EU companies and institutions has to be adequately supported. Dialog and cooperation with some non-EU European countries, which highly rely on hydropower, are strongly encouraged, such as Norway and Switzerland. It is essential to increase public awareness about the benefits of hydropower, as a required catalyst for a safe and independent energy transition, that is key to securing the European Green Deal. European National Energy and Climate Plans should include targets for dispatchable low-carbon energy and storage, and consider regulatory and commercial frameworks to implement the targets. Information availability, dialogue with society, and strategies towards social acceptance of associate benefits in different social, technical, environmental and economic contexts are actions that require immediate consideration. On the other hand, hydropower developers must be aware of the hydropower impacts on the environment, and hydropower operation and construction must consider the complex effects on the environment. The hydropower sector includes different types of expertise (e.g., engineers, environmental experts, ecologists, ichthyologists, hydrologists, economists and geologists), thus a better communication between the involved expertise and a transparent process to find a balance between conflicting interests of multi-purpose reservoirs are essential (climate changes may aggravate potential conflicts). Transboundary projects could be a source of conflicts in some cases, but could be an opportunity for a profitable cooperation and sharing of the associated benefits. Hence, a more comprehensive dialog is needed, setting up international discussion tables with institutions, academy, industry and citizenry.

References

[1] Bauhofer, P., & Zoglauer, M. (2021). Safeguarding Climate Targets: Hydropower Flexibility Facilities. Chemie Ingenieur Technik, 93(4), 632-640.

[2] Quaranta, E., Bahreini, A., Riasi, A., & Revelli, R. (2022). The Very Low Head Turbine for hydropower generation in existing hydraulic infrastructures: State of the art and future challenges. Sustainable Energy Technologies and Assessments, 51, 101924.

[3] Andaroodi, M., & Schleiss, A. (2006). Standardization of civil engineering works of small high-head hydropower plants and development of an optimization tool. Communication 26, Laboratory of Hydraulic Constructions (LCH), Ecole polytechnique fédérale de Lausanne (EPFL).

[4] Ramos, H. M., Vargas, B., & Saldanha, J. R. (2022). New Integrated Energy Solution Idealization: Hybrid for Renewable Energy Network (Hy4REN). Energies, 15(11), 3921.

[5] Tan, Q., Wen, X., Sun, Y., Lei, X., Wang, Z., & Qin, G. (2021). Evaluation of the risk and benefit of the complementary operation of the large wind-photovoltaic-hydropower system considering forecast uncertainty. Applied Energy, 285, 116442.

[6] Hydropower Europe (2021). Hydropower Technologies. The State-of-the-Art. https://hydropower-europe.eu/

[7] Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., & Cox, S. (2020). Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renewable Energy, 162, 1415-1427.

[8] Goričanec, D., Pozeb, V., Tomšič, L., & Trop, P. (2014). Exploitation of the waste-heat from hydro power plants. Energy, 77, 220-225.

[9] Quaranta, E., Muntean, S. (2022). Wasted and excess energy in the hydropower sector: a European assessment of tailrace hydrokinetic potential, degassing methane capture and waste-heat recovery. Applied Energy, 329, 120213.

[10] Dolci, F., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny Ordonez, G., Eulaerts, O. and Grabowska, M. (2022). Hydrogen Electrolysis in the European Union – 2022 Clean Energy Technology Observatory Status Report on Technology Development, Trends, Value Chains and Markets, EUR, European Commission, 2022

[11] Valente, A., Iribarren, D., Dufour, J., & Spazzafumo, G. (2015). Life-cycle performance of hydrogen as an energy management solution in hydropower plants: A case study in Central Italy. International Journal of Hydrogen Energy, 40(46), 16660-16672.

[12] Tapoglou, E., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny Ordonez, G., Eulaerts, O. and Grabowska, M. (2022). Ocean energy in the European Union - 2022 Status report on Technology development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/162254, JRC130617.

[13] Quaranta, E., & Wolter, C. (2021). Sustainability assessment of hydropower water wheels with downstream migrating fish and blade strike modelling. Sustainable Energy Technologies and Assessments, 43, 100943.

[14] Quaranta, E., & Revelli, R. (2018). Gravity water wheels as a micro hydropower energy source: A review based on historic data, design methods, efficiencies and modern optimizations. Renewable and Sustainable Energy Reviews, 97, 414-427

[15] Kougias, I., Aggidis, G., Avellan, F., Deniz, S., Lundin, U., Moro, A., ... & Theodossiou, N. (2019). Analysis of emerging technologies in the hydropower sector. Renewable and Sustainable Energy Reviews, 113, 109257

[16] Oladosu, G. A., George, L., & Wells, J. (2021). 2020 Cost Analysis of Hydropower Options at Non-Powered Dams (No. ORNL/TM-2020/1656). Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States).

[17] Fry, J.J., Misech, A., Morris, M., Schleiss, A.J. (2022). Research themes and strategic actions to promote hydropower as a catalyst for the energy transition in Europe. Journal on Hydropower & Dams. 29(3): 37-47.

[18] International Hydropower Association (IHA), (2022). Hydropower Status Report Sector trends and insights, IHA Central Office, United Kingdom.

[19] Xu, J., Ni, T., & Zheng, B. (2015). Hydropower development trends from a technological paradigm perspective. Energy Conversion and Management, 90, 195-206.

[20] Quaranta, E., Aggidis, G., Boes, R. M., Comoglio, C., De Michele, C., Patro, E. R., ... & Pistocchi, A. (2021). Assessing the energy potential of modernizing the European hydropower fleet. Energy Conversion and Management, 246, 114655.

[21] Kougias, I., & Szabó, S. (2017). Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse? Energy, 140, 318-329.

[22] Eurostat (2019). Energy statistics - Supply, transformation and consumption of electricity - annual data 2019.

[23] Hydropower Europe (2021). Strategic Industry Roadmap.

[24] Adamovic, M., Bisselink, B., De Felice, M., De Roo, A., Dorati, C., Ganora, D., Medarac, H., Pistocchi, A., Van De Bund, W. and Vanham, D. (2019). Water-Energy Nexus in Europe, Magagna, D., Bidoglio, G., Hidalgo Gonzalez, I. and Peteves, E. editor(s), EUR 29743 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-03386-8, doi:10.2760/285180, JRC115853.

[25] Graabak, I., Jaehnert, S., Korpås, M., & Mo, B. (2017). Norway as a battery for the future european power system—impacts on the hydropower system. Energies, 10(12), 2054.

[26] Wagner, B., Hauer, C., & Habersack, H. (2019). Current hydropower developments in Europe. Current Opinion in Environmental Sustainability, 37, 41-49.

[27] Manzano-Agugliaro, F., Taher, M., Zapata-Sierra, A., Juaidi, A., & Montoya, F. G. (2017). An overview of research and energy evolution for small hydropower in Europe. Renewable and Sustainable Energy Reviews, 75, 476-489.

[28] Clean Energy Transition Partnership (2020). SET Plan Stakeholder Groups Dialogues Summary Paper Overview of Relevant RDI Challenges identified in the SET Plan Stakeholder Groups Dialogues in preparation of the CETP Strategic Research and Innovation Agenda.

[29] https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en

[30] Bielewski, M., Pfrang, A., Bobba, S., Kronberga, A., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny, G., Eulaerts, O., Grabowska, M. (2022). Batteries for energy storage in the European Union - 2022 Clean Energy Technology Observatory Status Report on Technology Development Trends, Value Chains and Markets, EUR, European Commission, 2022, ISBN 978-92-76-56961-9, doi:10.2760/808352, JRC130724.

[31] Quaranta, E., & Hunt, J. (2022). Retrofitting and Refurbishment of hydropower plants: case studies and novel technologies. In Renewable Energy Production and Distribution, 301-322. Academic Press.

[32] Kougias, I., Bódis, K., Jäger-Waldau, A., Monforti-Ferrario, F., & Szabó, S. (2016). Exploiting existing dams for solar PV system installations. Progress in Photovoltaics: Research and Applications, 24(2), 229-239.

[33] Quaranta, E., Bódis, K., Kasiulis, E., McNabola, A., Pistocchi, A. (2022). Small hydropower potential in Europe: effect of environmental constraints and micro turbines in hydraulic infrastructures and hydrokinetic contexts. Water Resources Management.

[34] Punys, P., Kvaraciejus, A., Dumbrauskas, A., Šilinis, L., & Popa, B. (2019). An assessment of micro-hydropower potential at historic watermill, weir, and non-powered dam sites in selected EU countries. Renewable energy, 133, 1108-1123.

[35] European Commission (2020). Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people, COM/2020/562 final, September 2020

[36] Wörman, A., Uvo, C. B., Brandimarte, L., Busse, S., Crochemore, L., Lopez, M. G., ... & Riml, J. (2020). Virtual energy storage gain resulting from the spatio-temporal coordination of hydropower over Europe. Applied Energy, 272, 115249.

[37] Gimeno-Gutiérrez, M., & Lacal-Arántegui, R. (2015). Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. Renewable energy, 75, 856-868.

[38] Hoffstaedt, J.P., Truijen, D.P.K., Fahlbeck, J., Gans, L.H.A., Qudaih, M., Laguna, A.J., De Kooning, J.D.M., Stockman, K., Nilsson, H., Storli, P.T., Engel, B., Marence, M., Bricker, J.D. (2022). Low-head pumped hydro storage: A review of applicable technologies for design, grid integration, control and modelling, Renewable and Sustainable Energy Reviews, 158, 112119.

[39] Rogeau, A., Girard, R., & Kariniotakis, G. (2017). A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale. Applied energy, 197, 241-253.

[40] Stocks, M., Stocks, R., Lu, B., Cheng, C., & Blakers, A. (2021). Global atlas of closed-loop pumped hydro energy storage. Joule, 5(1), 270-284.

[41] Alsaleh, M., & Abdul-Rahim, A. S. (2021). Do global competitiveness factors effects the industry sustainability practices? Evidence from European hydropower industry. Journal of Cleaner Production, 310, 127492.

[42] Quaranta, E., Tagliaferro, B., Viccione, G. (2022). Harnessing the rainfall on building roofs for micro hydropower generation in the European Union, 3rd IAHR Young Professionals Congress, available from December 2022.

[43] Mitrovic, D., Chacón, M. C., García, A. M., Morillo, J. G., Diaz, J. A. R., Ramos, H. M., ... & McNabola, A. (2021). Multi-country scale assessment of available energy recovery potential using micro-hydropower in drinking, pressurised irrigation and wastewater networks, covering part of the eu. Water, 13(7), 899.

[44] Menéndez, J., Loredo, J., Fernandez, J. M., & Galdo, M. (2017, June). Underground pumped-storage hydro power plants with mine water in abandoned coal mines. In Proceedings of the IMWA 13th international congress, 1, 6-13. Lappeenranta, Finland.

[45] Kakoulaki, G., Gonzalez-Sanchez, R., Gracia Amillo, A., Szabó, S., De Felice, M., Farinosi, F., De Felice, L., Bisselink, B., Seliger, R., Kougias, I., Jäger-Waldau, A. (2022). Benefits of Pairing Floating Solar Photovoltaic with Hydropower Reservoirs in Europe (National and Regional Level). Available at SSRN: https://ssrn.com/abstract=4074448 or http://dx.doi.org/10.2139/ssrn.4074448

[46] Patro, E. R., Kishore, T. S., & Haghighi, A. T. (2022). Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India. Energies, 15(4), 1473.

[47] IRENA. Renewable Power Generation Costs in 2021. International Renewable Energy Agency. Abu Dhabi, UAE: 2020.

[48] European Commission (2020). Energy costs, taxes and the impact of government interventions on investments. Final Report Cost of Energy (LCOE)

[49] Quaranta, E., & Davies, P. (2021). Emerging and Innovative Materials for Hydropower Engineering Applications: Turbines, Bearings, Sealing, Dams and Waterways, and Ocean Power. Engineering, 8, 148-158.

[50] Quaranta, E., Bonjean, M., Cuvato, D., Nicolet, C., Dreyer, M., Gaspoz, A., ... & Bragato, N. (2020). Hydropower case study collection: Innovative low head and ecologically improved turbines, hydropower in existing infrastructures, hydropeaking reduction, digitalization and governing systems. Sustainability, 12(21), 8873.

[51] Kougias, I. (2020). Low carbon Energy Observatory, Hydropower Technology Development Report 2019, European Commission, Ispra, 2020, JRC120763.

[52] Pasimeni, F. et al. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data', World Patent Information. 2019, 59, 101927. doi: 10.1016/j.wpi.2019.101927

[53] Fiorini, A. et al. (2017). Monitoring R&I in Low-Carbon Energy Technologies, EUR 28446 EN, European Commission, Luxembourg, 2017, ISBN 978-92-79-65591-3, doi: 10.2760/434051, JRC 105642.

[54] Jiang, H., Qiang, M., & Lin, P. (2016). A topic modeling based bibliometric exploration of hydropower research. Renewable and Sustainable Energy Reviews, 57, 226-237.

[55] Deliza, E. E. V., de Almeida, F. M., de São, F., Filho, P., da Luz Neto, L. S., Calderaro, I. F. N., & Arenhardt, V. Repowering of Small Hydropower Plants: A bibliometric study in the Scopus Database.

[56] European Commission (2020a). Report from the Commission to the European parliament and the council Council on progress of clean energy competitiveness.

[57] Kirchherr, J., & Matthews, N. (2018). Technology transfer in the hydropower industry: An analysis of Chinese dam developers' undertakings in Europe and Latin America. Energy Policy, 113, 546-558.

[58] EurObserv'ER (2019). The State of Renewable Energies in Europe. 19th EurObserv'ER Rep 2019, 153.

[59] DNV, GL. (2015). The Hydropower sector's Contribution to a sustainable and prosperous Europe.

[60] Branche, E. (2017). The multipurpose water uses of hydropower reservoir: The SHARE concept. Comptes Rendus Physique, 18(7-8), 469-478.

[61] Briones-Hidrovo, A., Uche, J., & Martínez-Gracia, A. (2020). Determining the net environmental performance of hydropower: A new methodological approach by combining life cycle and ecosystem services assessment. Science of the Total Environment, 712, 136369.

[62] Hall, C. A., Lambert, J. G., & Balogh, S. B. (2014). EROI of different fuels and the implications for society. Energy policy, 64, 141-152.

[63] Vanham, D., Medarac, H., Schyns, J. F., Hogeboom, R. J., & Magagna, D. (2019). The consumptive water footprint of the European Union energy sector. Environmental research letters, 14(10), 104016.

[64] Fortes, P., Simoes, S. G., Brás, T. A., & Amorim, F. (2022). Competing water uses between agriculture and energy: Quantifying future climate change impacts for the Portuguese power sector. Journal of Cleaner Production, 371, 133629.

[65] Hertwich, E. G. (2013). Addressing biogenic greenhouse gas emissions from hydropower in LCA. Environmental science & technology, 47(17), 9604-9611.

[66] van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the US. Energy Policy, 123, 83-91.

[67] Zakeri, B., & Syri, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis. Renewable and sustainable energy reviews, 42, 569-596.

[68] Donnelly, C. R., Carias, A., Ali, M., Wood, N., Morgenroth, M., & Bridgeman, A. (2010). An assessment of the life cycle costs and GHG emissions for alternative generation technologies.

[69] Glachant, J. M., Saguan, M., Rious, V., & Douguet, S. (2015). Regimes for granting the right to use hydropower in Europe.

[70] Kuban, N. (2021). Hydroelectric Plants and Dams as Industrial Heritage in the Context of Nature-Culture Interrelation: An Overview of Examples in Turkey. Energies, 14(5), 1281.

[71] Simão, M., & Ramos, H. M. (2020). Hybrid pumped hydro storage energy solutions towards wind and PV integration: Improvement on flexibility, reliability and energy costs. Water, 12(9), 2457.

[72] International Energy Agency (IEA) (2021). Hydropower Special Market Report Analysis and forecast to 2030.

[73] Lu, S., Dai, W., Tang, Y., & Guo, M. (2020). A review of the impact of hydropower reservoirs on global climate change. Science of The Total Environment, 711, 134996.

[74] Alsaleh, M., & Abdul-Rahim, A. S. (2021). Moving toward sustainable environment: The effects of hydropower industry on water quality in EU economies. Energy & Environment, 0958305X211039452.

[75] Mahmud, M. A. P., Huda, N., Farjana, S. H., & Lang, C. (2018, May). Environmental sustainability assessment of hydropower plant in Europe using life cycle assessment. In IOP conference series: Materials science and engineering (Vol. 351, No. 1, p. 012006). IOP Publishing.

[76] Ueda, T., Roberts, E. S., Norton, A., Styles, D., Williams, A. P., Ramos, H. M., & Gallagher, J. (2019). A life cycle assessment of the construction phase of eleven micro-hydropower installations in the UK. Journal of cleaner production, 218, 1-9.

[77] Mahmud, M. P., Huda, N., Farjana, S. H., & Lang, C. (2019). A strategic impact assessment of hydropower plants in alpine and non-alpine areas of Europe. Applied Energy, 250, 198-214.

[78] Dones, R., Bauer, C., Bolliger, R., Burger, B., Faist Emmenegger, M., Frischknecht, R., ... & Tuchschmid, M. (2007). Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Final report ecoinvent data v2.0, 5.

[79] Immendoerfer, A., Tietze, I., Hottenroth, H., & Viere, T. (2017). Life-cycle impacts of pumped hydropower storage and battery storage. International Journal of Energy and Environmental Engineering, 8(3), 231-245.

[80] Hydropower Europe (2021). Strategic Industry Roadmap.

[81] Dupraz, C., & Geisseler, B. (2022). Together in the future: possible approach for new/existing multipurpose reservoirs-From identifying the right partners up to sharing the resource water: operational & legal aspects. In E3S Web of Conferences (Vol. 346, p. 03017). EDP Sciences.

[82] Abazaj, J. (2016). Coherence issues between climate, energy and water in the case of european hydropower: Can we have it all?. In Legal Aspects of Sustainable Development (pp. 347-370). Springer, Cham.

[83] Fruhmann, C., Tuerk, A., Kulmer, V., & Gubina, A. F. (2019). Balancing environmental benefits and damages of small hydropower generation in policy-making: assessing the implementation of a contradicting EU policy framework in Austria and Slovenia. International Journal of Sustainable Energy, 38(1), 37-49.

[84] Kampa, E. (2022). Policy Framework for Hydropower Mitigation. In Novel Developments for Sustainable Hydropower (pp. 1-11). Springer, Cham.

[85] Moran, E. F., Lopez, M. C., Moore, N., Müller, N., & Hyndman, D. W. (2018). Sustainable hydropower in the 21st century. Proceedings of the National Academy of Sciences, 115(47), 11891-11898.

[86] Netzband, A., Brils, J., Brauch, H. J., Liska, I., Miloradov, M., Nachtnebel, H. P., ... & Slob, A. (2007). Sediment management: an essential element of river basin management plans. Journal of Soils and Sediments, 7(2), 117-132.

[87] Quaranta, E., Pérez-Díaz, J. I., Romero–Gomez, P., & Pistocchi, A. (2021). Environmentally Enhanced Turbines for Hydropower Plants: Current Technology and Future Perspective. Frontiers in Energy Research, 592.

[88] Jeftenić, G., Kolaković, S., Panić, M., Kolaković, S., & Mandić, V. (2021). A Methodology Proposal for Selecting the Optimal Location for Small Hydropower Plants. Tehnički vjesnik, 28(5), 1462-1470.

[89] Venus, T. E., Hinzmann, M., Bakken, T. H., Gerdes, H., Godinho, F. N., Hansen, B., ... & Sauer, J. (2020). The public's perception of run-of-the-river hydropower across Europe. Energy Policy, 140, 111422.

[90] Alsaleh, M., & Abdul-Rahim, A. S. (2022). The pathway toward pollution mitigation in EU28 region: Does hydropower growth make a difference?. Renewable Energy, 185, 291-301.

[91] Fan, P., Cho, M. S., Lin, Z., Ouyang, Z., Qi, J., Chen, J., & Moran, E. F. (2022). Recently constructed hydropower dams were associated with reduced economic production, population, and greenness in nearby areas. Proceedings of the National Academy of Sciences, 119(8), e2108038119.

[92] Sovacool, B. K., & Walter, G. (2018). Major hydropower states, sustainable development, and energy security: Insights from a preliminary cross-comparative assessment. Energy, 142, 1074-1082.

[93] Hydropower & Dams (2020). Hydropower & Dams - World Atlas. Int. J. Hydropower Dams, https://www.hydropower-dams.com/industry-guide/?fwp_industry_guide.

[94] IRENA (2022). Renewable Energy and Jobs Annual Review 2022. International Renewable Energy Agency. Abu Dhabi, UAE.

[95] International Trade Center (ITC). Trade statistics for international business development 2020

[96] European Commission (2021). Gérard, F., Gorenstein Dedecca, J., Ying Lee, L., Guevara Opinska, L., Yearwood, J., Hoogland, O. (2021). Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis, European Commission, Brussels, ISBN 978-92-76-38453-3

[97] Fry, J.J., Schleiss, A.J., Morris, M. (2022). Hydropower as a catalyst for the energy transition within the European Green Deal Part I: urgency of the Green Deal and the role of Hydropower. E3S Web of Conferences, Sharing Water: Multi-Purpose of Reservoirs and Innovations, 346, 04015

[98] Bobba, S., Carrara, S., Huisman, J., Matheiux, F., & Pacel, C. (2020). Critical Raw Materials for Strategic technologies and Sectors in the EU. A Foresight Study, Luxembourg, European Union.

[99] Stegen, K. S. (2015). Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. Energy Policy, 79, 1-8.

[100] Jonek-Kowalska, I. (2022). Multi-criteria evaluation of the effectiveness of energy policy in Central and Eastern European countries in a long-term perspective. *Energy Strategy Reviews*, *44*, 100973.

[101] IHA (2020). Strengthening sustainable hydropower to support the Covid-19 recovery.

[102] Water Power and Dam Construction (2020). Hydropower and the impact of COVID 19 https://www.waterpowermagazine.com/features/featurehydropower-and-the-impact-of-covid-19-7929537/

[103] https://www.mottmac.com/views/impact-of-covid-19-on-power-projects

[104] Wadsack, K., Daw, J., Guerra Fernandez, O. J., Heimiller, D., DeGeorge, E., Healey, V., ... & Campos do Prado, J. (2021). Barriers and Opportunities for US Hydropower Industry Engagement in Brazil and Argentina (No. NREL/TP-6A65-78265). National Renewable Energy Lab. (NREL), Golden, CO (United States), Washington State Univ., Pullman, WA (United States).

[105] Mwewa Chikonkolo Mwape (2020). Industry 4.0. Technologies and their Major Disruptive Roles in Hydro Power Systems -A Key to Post COVID Recovery. 30° African Hydro Symposium.

[106] Ope Olabiwonnu, F., Haakon Bakken, T., & Anthony Jnr, B. (2022). The role of hydropower in renewable energy sector toward co2 emission reduction during the COVID-19 pandemic. International Journal of Green Energy, 19(1), 52-61.

[107] https://www.rti.org/insights/covid-19-lessons-hydropower

[108] Belyi, A. (2003). New dimensions of energy security of the enlarging EU and their impact on relations with Russia. European Integration, 25(4), 351-369.

[109] IEA (2022), World Energy Outlook 2022, OECD Publishing, Paris, https://doi.org/10.1787/3a469970-en.

[110] https://www.hydroreview.com/dams-and-civil-structures/russian-forces-capture-kakhovka-hydropower-plant-in-the-ukraine/#gref

[111] https://economictimes.indiatimes.com/news/international/world-news/ukraine-warns-of-threat-to-hydroelectric-power-station/articleshow/90028689.cms

[112] Tomczyk, P., & Wiatkowski, M. (2020). Challenges in the development of hydropower in selected European countries. Water, 12(12), 3542.

[113] Mikhailov, V. E., Ivanchenko, I. P., & Prokopenko, A. N. (2021). Modern state of hydropower and construction of hydro turbines in Russia and abroad. Thermal Engineering, 68(2), 83-93.

[114] Fisher, R. K., Koutnik, J., Meier, L., Loose, V., Engels, K., & Beyer, T. (2012). A comparison of advanced pumped storage equipment drivers in the US and Europe. *Louisville, USA, Hydrovision*.

[115] Efros, I. (2018). Why the Ukrainian hydropower infrastructure on Dniester will destroy Moldova and how to prevent such a disaster. Chișinău: Institutul de Politici Publice. Available online.

[116] Llamosas, C., & Sovacool, B. K. (2021). The future of hydropower? A systematic review of the drivers, benefits and governance dynamics of transboundary dams. Renewable and Sustainable Energy Reviews, 137, 110495.

[117] Heselhaus, S. (2022). The quest for the future energy mix in the EU and in Switzerland. In Swiss energy governance (pp. 49-66). Springer, Cham.

[118] Hofmann, B., Kolcava, D., & Thaler, P. (2022). The Role of Switzerland in European Electricity Governance. In Swiss Energy Governance (pp. 67-92). Springer, Cham.

[119] Tomczyk, P., & Wiatkowski, M. (2020). Challenges in the development of hydropower in selected European countries. Water, 12(12), 3542.

[120] Berga, L. (2016). The role of hydropower in climate change mitigation and adaptation: a review. Engineering, 2(3), 313-318.

[121] Češljar, G., & Stevović, S. (2015). Small reservoirs and their sustainable role in fires protection of forest resources. Renewable and Sustainable Energy Reviews, 47, 496-503.

[122] Gøtske, E. K., & Victoria, M. (2021). Future operation of hydropower in Europe under high renewable penetration and climate change. Iscience, 24(9), 102999.

[123] Farinotti, D., Pistocchi, A., Huss, M. (2016). Dwindling water from glaciers, and the hope in technology. Royal geographical society. JRC101997

List of abbreviations and definitions

CF = capacity factor (-)

EC = European Commission

EROI = Energy Return on Investment

EU = European Union EU27

GDP = Gross Domestic Production

GW = GigaWatt

IEA = International Energy Agency

IHA = International Hydropower Association

IRENA = International Renewable Energy Agency

JRC = Joint Research Centre

O&M = Operation and Maintenance

P = installed power (kW, GW)

PHS = pumped hydropower storage

PV = photovoltaics

R&D = research and development

ROR = run of the river

RoW = Rest of the World

SPP = storage power plant

TRL = Technology Readiness Level

TWh = TeraWatt per hour

U.K. = United Kingdom

U.S. = United States of America

WEFE = Water-Energy-Food-Ecosystem

y = year

Appendix 1.

Patent families (inventions) include all documents relevant to a distinct invention (e.g., applications to multiple authorities).

Statistics are produced based on applicants, considering applications to all offices and routes.

When more than one applicant or technology code is associated with an application, fractional counting is used to proportion effort between applicants or technological areas, thus preventing multiple counting. An invention is considered of high-value when it contains patent applications to more than one office.

Patent applications protected in a country different to the residence of the applicant are considered as international.

High-value considers EU countries separately, while for international inventions European countries are viewed as one macro category.

The CPC classification is not in use with the same degree of consistency across IPOs in Asia. The figures for the total number of inventions for Asian countries should be used with caution. This does not affect statistics for high-value and international inventions.

- Patent families (or inventions) measure the inventive activity. Patent families include all documents relevant to a distinct invention (e.g., applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology.

- High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

- Granted patent families represent the share of granted applications in one family. The share is then associated to the fractional counts in the family.

- Flow of inventions (or destination of patent families) indicates where (in which national patent office) inventions are filed. This can be used to analyse the international flow of inventions.

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