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Hydropower and Pumped-Storage Hydropower in the European Union

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

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Contact information
Name: Emanuele Quaranta
Address: Via Enrico Fermi 2749, 21027, Ispra (VA), Italy
Email: Emanuele.quaranta@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

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Contents

Abstract

New developments in the renewable and clean energy sector came on the back of the energy crisis, brought on by the war against Ukraine, and some of the worst droughts Europe has experienced in 2022. Regional electricity prices increased to higher levels than those recorded in 2020. This has resulted in lengthy discussions across Europe about price volatility and security of supply. To strengthen the resilience of the electricity market, the EU has sought ways to optimise the electricity market to tackle price volatility, further accelerate investments in renewables and enhance the flexibility and resilience of the power system. This included the REPowerEU plan of May 2022, which worked to diversify energy supplies and reduce dependence on imported fossil fuels, save energy, and accelerate the rollout of renewables.

Within this context, the European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help addressing the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation. Hydropower is included in the CETO, and it is the topic of this document, that updates the 2023 release[a].

The energy crisis has highlighted the key role of hydropower in providing grid stability and dispatchable generation. Pumped-Storage Hydropower provides more than 90% of energy storage, and hydropower plants equipped with a reservoir can also provide water&energy storage and multi-purpose services. However, dams in freshwater and coastal water systems can cause environmental damages. As the European rivers are severely fragmented, this has led to impediment of fish migration; therefore, achieving the good status of surface waters requires for mitigation measures to also tackle the adverse impact of hydropower on aquatic environment. Sustainable hydropower needs to achieve a good balance between electricity generation and electricity grid services, impacts on ecosystems and benefits for society, supporting the achievement of the Green Deal targets and the objectives of renewable energy and water/environmental policies.

This report highlights that several sustainable hydropower options exist in the European Union, such as: modernization of the existing hydropower fleet, hydropower integration and hybridization with other energy technologies (floating photovoltaics, heat extraction from generators, batteries), exploiting hidden hydropower in water and wastewater distribution networks, hydropower in existing and non-removable barriers (e.g. water mills) and hydrokinetic turbines. New water&energy storage sustainable solutions are also possible, e.g. new pumped-storage hydropower systems created by interconnecting reservoirs or exploiting abandoned open-pit mines. Digitalisation is also emerging as a relevant strategy to mitigate impacts along rivers and to optimize hydropower generation taking into account weather, technical, market and environmental factors. Multi-purpose reservoirs are a potential solution to grapple with climate changes, increased water demand and ensure flexible energy and storage, but they come also with costs and challenges.

The report shows that the European hydropower sector plays a leading role at the global scale, holding the largest share of export and high-value inventions. The EU is very active in scientific publications, and China is the main competitor. Therefore, hydropower is a key sector to strengthen the competitiveness of the EU in an increasingly challenging world (e.g. energy crisis, climate changes, green and digital transition and the competitiveness of emerging economies). The report also tracks the trend of investments, the main EU funded research projects, and critically discusses some socio-economic and sustainability indicators, comparing them with those of the other clean energy technologies. The challenges, especially the environmental and policy ones, are also discussed in order to stimulate future researches and discussions, and to shade more light on the current state of the art of the technology.

[a] https://setis.ec.europa.eu/hydropower-and-pumped-hydropower-storage-european-union-0_en

Foreword

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and innovative technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped-storage hydropower, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- Energy System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Authors

Emanuele QUARANTA, Aliki GEORGAKAKI, Simon LETOUT, Aikaterini MOUNTRAKI, Ela INCE, Juan GEA BERMUDEZ.

Executive Summary

Hydropower is currently the largest low-carbon and renewable electricity technology, with 1416 GW of global installed capacity and 4185 TWh of electricity generation in 2023. Worldwide, pumped-storage hydropower (PSH) currently provides regulation, spinning reserve, and approximately 96% of utility scale energy storage (excluding traditional hydropower reservoirs with no pumping capacity). In the European Union (EU), the hydropower installed capacity in 2023 was 152 GW, and generated approx. 300 TWh (PSH adsorbed and generated approx. 40 TWh in 2022), which is the second highest share from renewable energy sources, after wind energy. Currently, the EU hosts 46 GW of PSH (turbine's power capacity), which is a quarter of the global installed capacity (50.9 GW in China). IRENA's and World Bank's analysis identified hydropower as currently one of the least expensive forms of renewable electricity generation (when looking at the Levelized Cost of Electricity, LCOE, over the lifespan), despite high initial investment costs.

Hydropower is a complex and challenging sector within the Water-Energy-Food-Ecosystem (WEFE) nexus (SWOT in Table 1). Large water reservoirs, not only for hydropower, interact with the hydrosphere, the biosphere, the lithosphere, the anthroposphere and the atmosphere. The crosscutting effects of hydropower, and its interactions with the Earth's spheres, make hydropower relevant to several policies, with often different targets. Therefore, sustainable hydropower needs to achieve a good balance between clean electricity generation and impacts (and benefits) on the environment and on the society.

Hydropower plants are dispatchable, and those with a reservoir can also store inflow water (i.e., energy) and release it later, while PSH can also adsorb the electricity surplus in the grid, allowing to integrate the volatile energy production from non-dispatchable energy sources (e.g. wind and solar power plants). Hence hydropower is a renewable and flexible energy source that contributes to a resilient energy system, ensuring grid stability (preventing blackouts) and ancillary services. Therefore, hydropower plays a key role in the long-term decarbonisation scenarios (i.e. the NZ2050scenario), contributing to reach the renewable energy targets set in the Renewable Energy Directive (Directive 2009/28/EC) and REPowerEU. Furthermore, multi-purpose hydropower projects and large dams/reservoirs can have important additional functions for society: hydropower, irrigation and drinking water provision, flood and drought risk management, river navigation and recreation. In the EU, 30% of large dams are exclusively for hydropower, and 50% of large dams are hydro-powered (including multi-purpose dams where hydropower is not necessarily the first use), according to the International Commission on Large Dams (ICOLD 2023). On the other hand, hydropower barriers installed in freshwater and coastal water systems are a source of impact on aquatic environment. These impacts are regulated in the Water Framework Directive (Directive 2000/60/EC), which is aimed at the preservation or recovery of the "good ecological status"[b] of the water bodies. New barriers can interrupt river continuity (i.e. migration of fish and other aquatic species), reservoirs generate impoundment, with consequent hydrological and morphological alterations, and hydropower turbines may cause damages to fish. In 2020, the AMBER project has identified at least 630,000 (450,000) barriers in European (EU) rivers (but that could be at least 1.2 Million in Europe), while the number of hydropower plants in the EU is estimated slightly below 25,000. 90% of hydropower plants are small, with a cumulative installed power less than 10% of the total, hence the cumulative environmental impact of small hydropower schemes in freshwater systems may be significant.

In the EU, an untapped hydropower potential still exists, e.g. of new PSH, modernization of the existing hydro stations, digitalisation of the operation and small hydropower development in existing infrastructures ("hidden hydropower"). Pumped-storage could complement the operation of existing reservoirs and lakes to enhance water management. Hybridisation with other energy technologies, e.g. floating photovoltaics on hydropower reservoirs, hydrogen generation, hybridization with batteries and waste-heat recovery is growing. Ocean (tidal and wave) power

[b] Ecological status describes the structure and functioning of aquatic ecosystems associated with surface waters. The good status shows for the aquatic environment low levels of distortion resulting from human activity.

plants use turbines adapted from the hydropower sector. Digital solutions, such as forecast modelling, digital twins, real-time and remote control, that are emerging strategies to support the EU digital and green transitions, can be implemented for monitoring and enhancing quality of the surrounding environment, for improving the overall efficiency and energy generation, and for supporting the Operation and Maintenance activities.

The abovementioned challenges and needs require excellence in engineering sciences, environmental management and new innovative planning approaches. Within this context, the European Commission (EC) supported and supports several research projects (on average, EUR 10 Million per year under the Horizon program) that have had an important scientific and technical impact worldwide. Several technologies are emerging and are under development (e.g., variable speed turbines, some digital tools, mitigation solutions). Some of the Horizon projects, funded by the EU, are e.g. FITHYDRO (on mitigation strategies, improvement of fish migration and less impacting technologies), X-FLEX (aimed at increasing flexibility), HYDRO4EU (that aims at demonstrating European small hydropower equipment and technologies in Central Asia) and other projects aimed at tapping hidden opportunities and digitalisation (e.g. iAMP Hydro). REHYDRO started in 2024 on sustainable refurbishment. Other projects aim at unifying the voice of hydropower industry (i.e. intended European Technology & Innovation Platforms –ETIP-Hydropower), to provide consensus-based strategic advice to the European Commission covering analysis of market opportunities, research & development funding needs, biodiversity protection and ecological continuity. Pen@Hydropower aims at improving the networking among hydropower scientists in Europe. Therefore, although hydropower technical maturity is well established, with overall power plant's efficiencies generally exceeding 80%, and that can reach up to 90%, there have been several research programmes in the European hydropower sector.

In terms of scientific publications, the hydropower knowledge production in the EU is the second highest globally, after China. The EU and the United States of America (U.S.) host each about 28% of the innovative hydropower companies (based on investments in R&D). 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 similarly, and slightly better than the U.S. The EU holds 29% of all high-value inventions globally (2019-2021), with Germany, France, Italy and Poland as the main contributors. Some low readiness level technologies, which are expected to become mature technologies in the next decades, are under investigation (e.g. variable speed turbines and very low head turbines). 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 working in corporate and academic R&D activities. IRENA estimates that every 1 MW of community-owned hydropower installed generates ten full-time equivalent jobs in every year of its operation. This is significantly more than any other renewable energy technology. In 2023 there were 3500 employed people in the manufacturing, 98,000 in the construction and 240 in the R&D in the EU (hydropower), with Austria, Germany, France and Italy, mostly located at the heart of the Alps, hosting the largest numbers of employees.

Hydropower contribution to the EU annual gross domestic product (GDP) is approx. EUR 25 Billion considering electricity generation, but if the multi-services associated to hydropower are considered, this value may increase up to EUR 45 Billion. A substantial share of tax value goes directly to local and regional budgets and helps to foster regional development. Approximately EUR 3 Billion additionally come from the Gross Value Added, including trade of turbines. The global exports of large turbines within the period 2021-2023 accounted for EUR 2.1 Billion, with EU countries holding approx. 50% of this (China accounted for EUR 551 Million of exports in the period 2021-2023). However, the Chinese market is increasing significantly. The real dimension of the overall exports are much higher when considering all the equipment (e.g., pipes). A considerable proportion of investments in the hydropower sector refers to the civil works and associated consultancy services that are very difficult to track. The EU's hydropower sector has a significant presence in Russia, Switzerland, Norway, supplying more than 70% of their imports, and in Canada and U.S., contributing to more than 20% of their imports. The large European hydropower operators continue to invest in many hydropower projects outside of Europe. 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 in and outside of Europe. This makes the EU a global leader in hydropower technology (including pumped hydro). The top-10 EU's hydropower operators established the EU Hydropower Alliance, which is committed to advancing sustainable hydropower's role in achieving the EU Green Deal and Fit for 55 ambition. The invested value in hydropower (early and later stage investments) per inhabitant is 0.005 EUR/person for the EU (2018-2023), while it is 0.47 and 0.018 for the U.S. and China, respectively. European hydropower manufacturers spend more than 5% of annual turnover on R&I.

Due to the several benefits of hydropower (flexibility, export capacity, R&D, patenting, employment, multi-purpose when allowed by the license), hydropower can be considered an important sector to maintain a competitive EU in the world. However, the challenges that hamper hydropower deployment and limit its operation are several, most importantly financial, regulatory and environmental, and the declining revenues from the provision of the ancillary services are not enough to cover the fixed investment and administrative costs. These challenges should serve as a catalyst for a more comprehensive dialogue among stakeholders (e.g. industry, academy, associations, citizens and governmental institutions). Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, hence investment risks for large hydropower schemes are higher, requiring specific policy instruments and incentives, as well as a longer-term policy perspective and vision. To gain wide acceptance and to obtain a win-win solution among all stakeholders' needs, the large hydropower infrastructures have to be designed as multi-purpose projects by multidisciplinary teams with a complex system approach. However, renewable energy policy attention in the past two decades has focused primarily on wind and solar PV technology expansion (and lowering their cost). The development of any renewable energy technology must objectively consider benefits and impacts on the short and long-term, in order to mitigate possible conflicts among different targets (e.g. energy and environmental targets) and stakeholders, depletion of resources (e.g. water, minerals and materials) and ensure a sustainable growth within the WEFE nexus and in light of climate changes.

This report updates the 2023 release.

Table 1. CETO SWOT analysis for the competitiveness of the hydropower sector (focus on the EU).

Strength - Mature technology, high efficiency - High flexibility, ensuring supply during peak demand - Grid stabilizer - Long lifespan - Storage capacity (water and energy) of reservoirs - Multi-purpose benefits of reservoirs and dams - The lowest Ozone Layer Depletion indicator, the highest Energy Returned on Energy Invested ratio among electricity technologies, the lowest pressure on mineral resources and amongst the lowest water footprints during construction and manufacturing per GWh - The EU is a leader in scientific research, technological innovation, export - Hydro turbines and generators tend to be much larger and heavier than other generation technologies and thus can play an important role in the frequency stability of the grid.	**Weakness** - Environmental and social impacts associated with the construction of new barriers (and dams), and the mitigation of the existing ones, demand significant and costly mitigation measures (e.g. habitat, fish migration, hydropeaking, hydro-morphological alterations). In reservoirs: sedimentation, impoundment, evaporation, carbon and methane emissions may occur in specific contexts - Limited potential for large hydropower capacity expansion - Long construction periods and large investment needs/risks of large power plants - Additional benefits are not all remunerated
Opportunities - Hidden potential in existing facilities in the water sector (e.g. water network infrastructures) - Attractive for rural and decentralized electrification in developing countries - Integration of intermittent renewable energy sources with pumped-storage hydropower - Modernization of hydropower infrastructure is needed in the EU and can bring additional benefits - Still some potential for increasing pumped-storage hydropower (interconnecting existing reservoirs, abandoned mines) - Potential for hybridization with other energy technologies - New reservoirs in high altitude using new lakes created by glacier retreat - Export potential of electro-mechanical equipment - New reservoirs can support climate change mitigation in drought periods or by mitigating flood events	**Threats** - Substantial uncertainties in long approval processes - Climate changes may increase or decrease water availability and its yearly distribution - Reduction of generation due to higher requirements regarding environmental flow releases - Loss of reservoirs' volume due to sedimentation - In the 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 - Moderate public awareness on the benefits of hydropower

1 Introduction

1.1 Hydropower technology

1.1.1 Types of hydropower plants and definitions

Traditional hydropower is a renewable energy source that converts the hydraulic (water) power (potential and kinetic 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, impacts may be generated when new barriers are installed in freshwater rivers (see section 3.3 for further details). Water power (or hydropower) is the oldest renewable energy technology, which has been used for thousands of years (starting with water wheels, see section 2.1). Today, hydropower is the largest renewable electricity technology, with 1416 GW of global installed capacity worldwide (see section 2.2).

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

1. Reservoir-storage hydropower plants (RSHP) (often called storage hydropower plants, or dam hydropower in some JRC research exercises) are facilities that store water in reservoirs behind dams and that can modulate the flow released downstream and thus electricity generation; reservoirs can be artificial or can exploit existing lakes. They cannot pump water.
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 RSHP is often considered a ROR);
3. Pumped-storage hydropower (PSH) is, beside RSHP, the main water and energy storage technology for power systems, with also pumping capacity. They are composed of two, or more, water bodies (generally, two reservoirs, or a river as lower reservoir) that are connected by a turbine and pump system. A PSH system pumps water into an upper reservoir in periods of low electricity demand (and/or low electricity prices) and uses it to produce electricity by releasing water to the lower reservoir through the turbines. Closed-loop PSH stations (called pure PSH by Eurostat) are composed by reservoirs not connected to natural watercourses and do not utilise natural (river) inflows, except rainfall and some groundwater inclusion. Open-loop PSH stations (also known as pump-back facilities, and called mixed PSH by Eurostat) utilise also natural inflows from rivers, in addition to inflow from rainfall, creeks and groundwater. Pumped storage hydropower represents more than 90% of global energy storage capacity, excluding RSHP[1];
4. Hidden hydropower in water infrastructures: diversion schemes that utilize the available energy in conveyance systems for supply, transport and treatment of water and wastewater.

Traditional hydropower includes RSHP and ROR, while pure hydropower includes RSHP, ROR and energy generated in mixed PSH from natural inflow.

In terms of size, hydropower stations are distinguished in large-scale and small-scale, with a typical threshold of 10 MW (installed power, 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 tens of Watt to several thousands of MW, and impacts should not necessarily be associated to the size of the power plant.

Water flows from higher altitudes to lower ones, and the altitude difference is called gross hydraulic head. The altitude difference generates the power of water, which can be in the form of potential power (pressure and water level) and kinetic power (water flow velocity). 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 250 m, and high head above 250 m (see, e.g. Andaroodi and Schleiss, 2006 [3]).

1.1.2 Components of a hydropower plant

The hydropower sector is rather complex, as it includes the electro-mechanical equipment (turbine, generator, motor generators and pump for PSH), gearbox/transmission (for small hydro applications), guide vanes or wicket gates to control the flow to the turbine, draft tube and spiral casing or distribution pipes, the civil structures (e.g. weirs, the dam, tunnels, surge chambers, the powerhouse, penstocks, fish passages, spillways and canals), and the Control and Instrumentation equipment to monitor the status of the components (Figure 1). The power plant operation depends on the hydrological, environmental and market conditions.

As a rule of thumb, the electro-mechanical equipment represents typically one third of the investment cost (for ROR approx. 50%, for PSH and RSHP with higher heads approx. 20-25%, see section 2.4 for details), whereas the civil engineering structures represent the other two thirds, sometimes also reaching 75-80% of the cost share (see more details in section 2.4). A considerable proportion of investments in the hydropower sector hence refers to the civil works, and the associated consultancy and planning services, which are very difficult to track. Therefore, the hydro-turbine is generally considered as a barometer/proxy to monitor the developments in the hydropower sector (e.g. exports/imports, installed capacity), and the associated market indicators discussed in this report. This means that the real value of the considered competitiveness indicators may be, in most of the cases, underestimated.

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; the maximum turbine efficiency commonly ranges between 80% and 95%, depending on the size and type. In the latter case the most used turbines are hydrokinetic turbines (also used as tidal stream turbines) and stream/floating water wheels (the Vortex turbine has been recently introduced and improved also to work as a reaction type), with maximum efficiency (generally quantified through the power coefficient C_p) up to 30%.
- 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[c]), Kaplan (including Bulb, Straflo) and Deriaz turbines. The maximum turbine efficiency commonly ranges between 80% and 95%, depending on the size and type.
- In gravity turbines (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's blades. Therefore, the weight of the water generates the rotation of the machine, with a maximum machine hydraulic 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 a high-middle head hydropower plant is generally > 80% and can exceed 90% at the optimal operating point, 5-times higher than photovoltaics and 3-times higher than wind farms, while it generally range is between 60% and 80% for a very low head system.

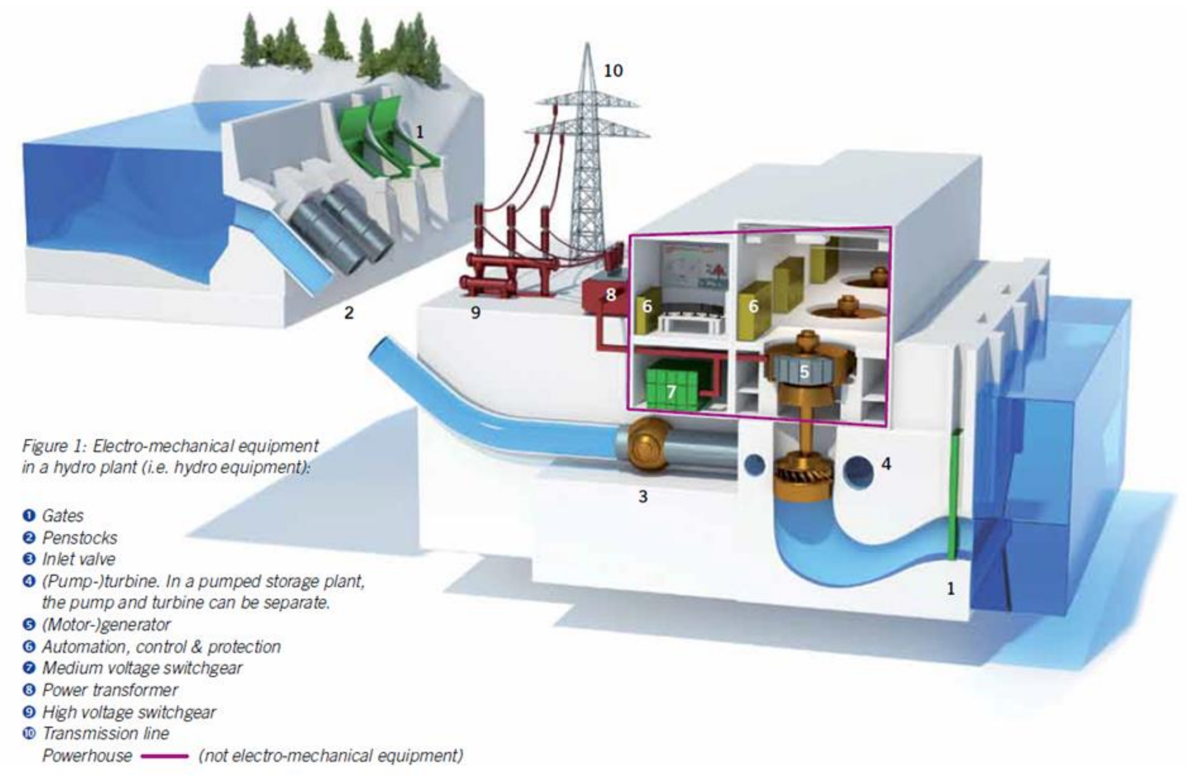
With regards to the civil structures, the dam is one of the main elements, and it is a structure designed to retain water from a river. There are two types of dams:

[c] 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, and are also used in PSH as reversible pump/turbine.

- 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 several 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[11].

Figure 1. Sketch of a reservoir hydropower plant, with focus on the powerhouse.



Source: Hydropower Europe[11].

Figure 2. (a) RSHP (Mooserboden Dam, Austria), (b) ROR plant (Ruppoldingen in Switzerland, with lateral river for fish migration), (c) PSH plant with two reservoirs (Limberg II und Kopswerk II, Austria), (d) micro plant with water wheel in a diversion canal.

(a)

(b)

(c)

(d)

Source: (a) IEA Hydro report on Annex XIII), (b) Courtesy ATEL, (c) courtesy of Voith Hydro, (d) courtesy of Gatta srl, Italy).

1.2 Policy context

The hydropower sector is at the centre of several EU Directives, and, as such, its crosscutting relevance poses it at the centre of several programmes, debates and challenges within the WEFE nexus and the Green Deal. The main European Directives dealing with hydropower are the following ones, related to the environment, energy and climate.

- Environment.

  In the European Union, hydropower plants must comply with the requirements of several environmental Directives: the Environmental Impact Assessment (EIA) Directive, the Habitats and Birds Directives (HD/BD) and the Water Framework Directive (WFD)[d]. These Directives require the developers to identify and assess the significant environmental impacts and risks from such projects and propose relevant measures aiming to prevent and mitigate such impacts and risks. The competent authorities issue permits containing the necessary preventive and mitigation measures. If projects are likely to adversely affect Natura 2000

[d] 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. Less than 10% of barriers in EU's rivers are for hydropower.

sites[e] or water bodies, projects/plans should be subject to an assessment procedure to study the effects in detail, based on Article 6(3) of the Habitats Directive and Article 4(7) of the Water Framework Directive, respectively. The competent authorities may still authorise such projects, provided that compensatory measures are implemented to address significant deterioration or damage and that the projects serve an overriding public interest. The competent authorities still have to properly identify and assess the impacts from hydropower projects and take the necessary measures to prevent, mitigate or compensate significant negative impacts. When Member States (MSs) seek EU co-financing under the Recovery and Resilience Facility (RRF), they must comply with the Do No Significant Harm (DNSH) criteria. The Regulation establishing the Recovery and Resilience Facility (RRF) provides that no measure included in a Recovery and Resilience Plan (RRP) should lead to significant harm to environmental objectives within the meaning of Article 17 (related to the DNSH principle) of the Taxonomy Regulation. The new EU Biodiversity Strategy adopted in 2020, and the Nature Restoration Law, include targets for restoring freshwater ecosystems that are also relevant to activities of hydropower production. The Biodiversity Strategy targets include the restoration of at least 25,000 km of rivers into free-flowing rivers by 2030 and the restoration of degraded ecosystems, like floodplains and wetlands. In addition, water abstraction and impoundment permits should be periodically reviewed in order to achieve good status or potential of all surface waters and good status of all groundwater by 2027 in line with the WFD. Other EU policies which are relevant to the planning, operation and mitigation of impacts of hydropower plans are the EU Eel Regulation, the EU Regulation on Invasive Alien Species as well as the Strategic Environmental Assessment Directive (SEA). The EU Eel Regulation (1100/2007) requires the establishment of measures for the recovery of the stock of the European eel (which is a species impacted by the presence of hydropower), the identification and definition of eel river basins and the set-up of Eel Management Plans to reduce anthropogenic mortalities and improve the escapement of the silver eel to the sea[4].

- Renewable Energy.

  The Renewable Energy Directive (RED) (Directive 2023/2413/EC) fosters the renewable energy transition, also established in REPowerEU and the Green Deal targets, allowing to phase out dependence on Russian supplies: 42.5% of gross final energy consumption has to be produced from renewables in the EU in 2030. Hydropower is included, with a view to ensuring that a potential adverse impact on the water body or water bodies concerned is justified and that all relevant mitigation measures are implemented. The European Commission has included the hydropower technology as a clean technology within the Net Zero Industry Act (NZIA).

- Storage and Flexibility.

  To achieve the Union's climate and energy targets, the energy system is undergoing a profound transformation characterised by improved energy efficiency, the massive and rapid deployment of variable renewable energy generation, more players, more decentralised, digitalised and interconnected systems and increased electrification of the economy. Such a system transformation requires more flexibility and storage capacity: flexibility is the energy system's ability to adapt to changing needs of the grid and manage variability and uncertainty of demand and supply across all relevant timescales (Commission Recommendation of 14.3.2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system).

  To reduce risk from imported flexibility, Art. 22 lit. d) of the Regulation (EU) 2019/941 of the

[e] Natura 2000 is a network of protected areas covering Europe's most valuable and threatened species and habitats. It is the largest coordinated network of protected areas in the world, extending across all 27 EU Member States, both on land and at sea. The sites within Natura 2000 are designated under the Birds and the Habitats Directives.

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 [5]. 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. Hydropower currently provides more than 95% of energy storage in the EU. The EU hosts a quarter of the PSH global turbine capacity. Hydropower is also a flexible and dispatchable energy technology, with response time of the order of seconds to the long-term energy storage capacity at the annual timescale.

In January 2024, the European Parliament and Council reached a provisional agreement to reform the electricity market design, which has now entered into force. This initiative aims to create a buffer between short-term markets and consumers' electricity bills by incentivising longer-term energy contracts. It encourages the use of long-term instruments like power purchase agreements and capacity remuneration mechanisms, although two-way contracts[f] will not be available for reservoir hydropower and PSH, so that they remain fully exposed to market signals.

- Floods.

  To cope with floods, which are the most common and most costly natural disasters in Europe, the Floods Directive (Directive 2007/60/EC) was introduced in 2007 with the aim to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity. The Floods Directive requires all EU countries (1) to assess all areas where significant floods could take place, (2) to map the flood extent and assets and humans at risk in these areas and (3) to take adequate and coordinated measures to reduce this flood risk. 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. Barriers in rivers can be a source of impact, but the capacity to store water in reservoirs can mitigate floods and droughts, if this service is included/specified in the license. Furthermore, an initiative to make water resilient to climate change was recently launched by the European Commission, to design innovative ways to ensure that water management systems are robust enough to respond to the challenges that climate change is already causing.

Threats and opportunities within the current social, energy, geopolitical and climate situation are discussed in the 2022 release of the report and in Quaranta (2023)[6], and in the book chapter Quaranta (2024)[7], with focus on the sanitary COVID-19 emergency, relation with Russia and other external actors (China, U.S., Switzerland, Norway), climate changes and EU transboundary hydropower projects. The role of hydropower to the target of previous Directives is often complex and need to be balanced. There is a promising balancing opportunity to reconcile the friction among climate, energy and environmental law while improving the ecological sustainability of hydropower production[8].

[f] The generator sells the electricity in the market but then settles the difference between the market price and the strike price agreed in advance with the public entity. Any excess revenues shall be distributed to final customers, with some flexibility for member states.

1.3 Link with other CETO technologies

Hydropower plants exhibit a high hybridization potential with other power generation technologies and can operate as an integrated unit [9]. Hybrid power plants can occupy a single site or comprise a micro-grid distributed on the territory. In a hybrid power plant, the same electrical infrastructure can be used, thus lowering overall costs. Hydropower can be combined with solar or wind power to increase the stability and reliability of electricity generation [10]. In a hybrid power plant, PV panels or wind turbines can produce energy when the sun or wind are available [11]. PV systems can be installed as floating solution on hydropower reservoirs [12], reducing PV land use, optimizing the overall efficiency and reducing evaporation, or on dam's surface[82]. Waste-heat can be extracted from the cooling system of the turbine/generator [13, 14]. Hydropower could also be combined with batteries (for e.g. fast reaction in primary regulation [34]) or with hydrogen-electrolyzers in case less demand in the grid is needed and water cannot be stored [15, 16, 171]. Ocean (tidal and wave) energy technologies implement several technologies derived from the hydropower sector [17]. The benefits of hydropower must not only be evaluated in terms of annual energy generation, but especially in terms of provided flexibility, ancillary services, water&energy storage and grid stabilization to support the variable energy generation, which mainly comes with economic and technical burden on hydropower operators[18]. It must be noted that an increase of flexibility for short-term balancing services may cause some impacts, e.g. hydropeaking. Some mitigation measures exist, like regulation reservoirs downstream, integration with batteries, or imposing environmental thresholds on the velocity of the water releases. However, it must also be noted that this flexibility request is the direct consequence of the integration into the grid of highly volatile energy sources.

1.4 Methodology and Data Sources

The report has been written following the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning

The *technology state-of-the-art and future developments and trends* section builds on the:

- technology readiness level
- Installed capacity and electricity production
- Technology costs
- Public and private R&I funding
- Patenting trends
- Scientific publication trends
- Impact of EU R&I

The *value chain analysis* maps the situation of the technology with regard to the:

- Turnover
- Gross Value Added
- Environmental and socio-economic sustainability
- EU companies
- Employment
- Energy intensity and labour productivity
- EU production

The *EU position and global competitiveness* analyses the EU position in the global market according to the:

- Global and EU market leaders
- Trade, imports and exports
- Resources efficiency and dependence

The report uses the following information sources:

- Documents published by the European Commission and international organisations
- Information from EU-funded research projects
- EU and international databases
- EU trade data, trade reports, market research reports and others
- JRC own review and data compilation
- Stakeholders' input
- Scientific publications

Annex 1 provides a summary of the indicators for each aspect, together with the main data sources and gaps.

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

2.1 Technology Readiness Level (TRL)

Nowadays, hydropower is an established sector and the largest and most flexible renewable electricity source, with well-known and robust technologies and construction methodologies (section 1.1). Nevertheless, R&D activities are continuously ongoing and novel technologies are under investigation. Some of these technologies could become established technologies in the coming decades [19]. Kougias et al., (2019)[19] and Oladosu et al., (2021)[20] reviewed the emerging hydropower technologies. Their implementation potential in the existing hydropower facilities was assessed in Quaranta et al., (2021)[34]. The innovative materials are discussed in Quaranta and Davies (2021)[94], while environmentally enhanced turbines are discussed in Quaranta et al. (2021)[127]. Fry et al., (2022)[21], in the EC funded project ETIP Hydropower, estimated 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 operation, environmentally compatible solutions and mitigation of global warming impacts. Furthermore, in order to respond to the increasing needs for flexibility[g] of operation, hydropower electro-mechanical equipment needs to reach higher levels of digitalisation. Digitalisation is required to optimise operation, predict and detect potential future failures, facilitate O&M, reduce operational costs and 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. Digital solution can also be implemented to mitigate environmental impacts[106].

Hydropower's history began more than 2,000 years ago. The water wheel was the first hydropower converter in human history, 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[h]. 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[i] as late as 1886. The EU funded research project RestorHydro identified 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 [22]. 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 [23].

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. Reversible single-stage Francis-

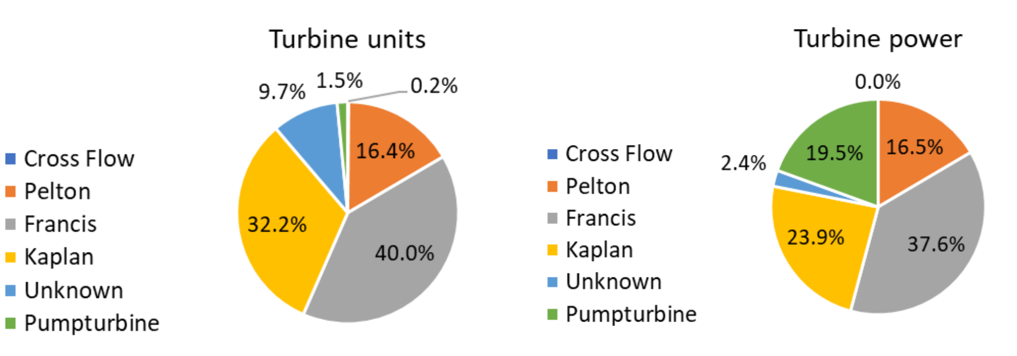
[g] The ability of a system to respond to changes in generation and/or load is called system flexibility.

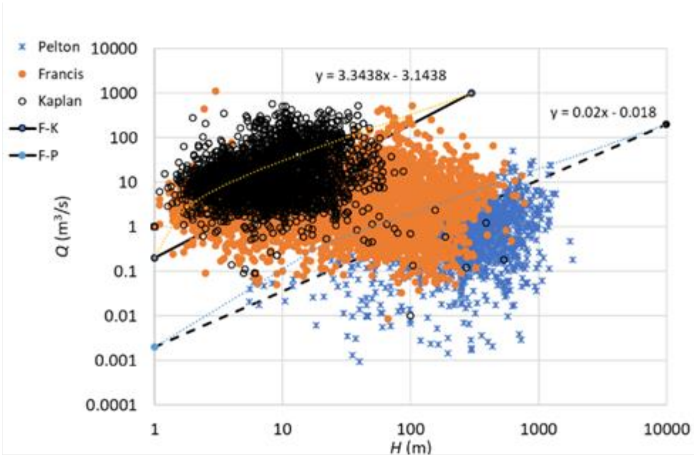
[h] When not specified, Europe includes the EU, Albania, Andorra, Belarus, Bosnia and Herzegovina, Faroe Islands, Greenland, Iceland, Kosovo, Liechtenstein, Macedonia, Moldova, Monaco, Montenegro, Norway, San Marino, Serbia, Switzerland, Turkey, Ukraine, United Kingdom.

[i] it is not specified if mechanical or electric energy.

pump/turbines were developed in the early 1940s and spread in PSH installation with heads up to 700 m. The share of hydraulic turbines and their hydraulic range in the EU is depicted in Figure 3. A negligible share is represented by unconventional turbines, e.g. water wheels, Archimedes screws, Vortex turbines and Very Low Head (VLH) turbines, whose operating range is described in Quaranta et al (2021)[2]. The installed capacity of Archimedes screws is typically below 100 kW and in 2012 around 400 installations were counted worldwide, 71 of them (2.5 MW) in Europe (Lashofer et al., 2012[24]). VLH turbines typically work below 500 kW and their total installed capacity in Europe is around 30 MW (MJ2 Technologies, 2023). Water wheels are generally below 30 kW and with average power of 13 kW in the EU (Quaranta et al., 2022b[65]). In the EU, 12 Vortex turbine installations are in operation, with a cumulative power of 78.1 kW (in Austria, Germany and Belgium)[25]. In the European Union + UK (EU28), according to Voith Hydro database (pers. comm. of Markus Wirth), 24 Banki turbines are installed with a total power of 10.4 MW and maximum head 170 m (updated to 2020).

Figure 3. Share of turbine type in the EU according to Voith Hydro database, and their operating range (as in 2020)[34]. Deriaz, Girard were included into the Francis type (Voith Hydro and Quaranta and Muntean (2023)[14]). In the figure below, F-K means the boundary between the range of Francis and Kaplan turbines, F-P is Francis and Pelton.





Source: Voith Hydro

2.2 Number of power plants, Installed Capacity and Generation

2.2.1 Numbers of barriers and dams

According to the International Commission on Large Dams (ICOLD), more than 59,000 large[j] dams exist in the world, storing 8919 Billion m^3 at full capacity. In the EU there are 4491 large dams according to the ICOLD 2023 register of dams and 33% are for multiple uses. According to ICOLD 2023, in the EU, 46% of single purpose reservoirs are for hydropower (which store 83% of the volume of single-purpose dams), 23% of multiple purpose reservoirs have hydropower as a first use (34% have water supply as first use), 6% of all reservoirs have hydropower as second use and 3.5% as third or fourth use. Overall, 48% of EU reservoirs are powered. EU's large reservoirs[j] store 285 Billion m^3 of water: 124 Billion m^3 are in hydropower reservoirs as single use, while 111 Billion m^3 are in multi-purpose reservoirs equipped with hydropower.

From the AMBER database[26], at least 630,000 barriers were counted in European rivers (450,000 in the EU) and less than 10% are defined as dams (the others include, e.g. weirs, ramps and other transversal barriers with no storage capacity). According to some JRC's estimates based on data from UNIDO, Voith Hydro and the JRC hydropower database, less than 30,000 hydropower plants exist in the EU (also including those in artificial canals, pipes and infrastructures), hence less than 10% of barriers are used for hydropower. 90% of hydropower plants are below 10 MW of installed power, but contribute to a cumulative installed capacity of 10%. For further information on small hydropower in Europe refer to the UNIDO report[27].

In the years 1996–2019, a total of 342 dams were dismantled in Europe, approximately 95% of which are so-called low dams: 54.7% are up to 2.5 m high, 40.6% are 2.5–7.5 m high, 2.3% are dams 7.5–15 m high, and 2.0% are higher than 15 m [28]. According to Dam Removal Europe (DRE), more than 6,000 barriers have been removed in Europe; 325 barriers were removed in 2022, 71% were lower than 2 m and at least 10 hydropower dams were dismantled in England, Finland, France, Norway, Spain and Sweden. In 2023 DRE reported the removal of at least 487 barriers. France was the leader of barrier removal in, followed by Spain, Sweden and Denmark. 46% of the removed barriers were weirs and 36% were culverts. Dams were the next most common type of the removed barriers (12%), followed by ramps, sluices and fords. 78% of the removed barriers were lower than 2 m, 20% were 2-5 m high and 2% were more than 5 m high. More than 4300 km of rivers were reconnected through barrier removals [29]. The newly approved Nature Restoration Law requires Member States to make an inventory of artificial barriers and to identify the barriers that need to be removed.

2.2.2 Installed power capacity and annual generation

In 2023, the global installed power of grid-connected hydropower reached 1416 GW, including 179 GW of pumped-storage hydropower (PSH), with an annual generation of 4185 TWh, lower than the 4408 TWh in 2022 [30, 31]. Hydropower also provides 1.8 GW of off-grid hydropower electrification services, mainly in Africa, South America and Asia [32].

According to Xu et al., (2015)[33], Europe has a hydropower technical potential (thus considering the potential that can be exploited with the existing technology, independently from economic factors) of 1121 TWh per year (hereinafter, TWh/y), and, with a current production of 569 TWh/y and installed capacity of 258 GW, has developed approx. a half of the available technical potential, the highest share, globally. There is still untapped technical potential in Europe to be explored with novel technologies[19] and by refurbishing existing plants [34] (section 2.3).

In this chapter, installed power and annual energy generation are discussed, considering both traditional hydropower and PSH. It must be noted that, while traditional hydropower is classified as renewable energy technology, PSH is classified as energy storage technology. However, mixed PSH,

[j] higher than 15 m, or between 5 and 15 m and with storage capacity higher than 3 Mm^3.

where there is a river inflow and, generally, the annual energy generation is higher than the energy used for pumping, can also be classified as renewable energy technology when considering the net energy generation (energy generation minus energy used for pumping).

Installed power

While in the previous sections data from IHA (2024) were used, from now onward Eurostat data will be used, as they are more focused on the EU, although limited until year 2022. According to Eurostat, in 2022, the hydropower installed capacity was 152.7 GW in the EU, mostly located in alpine environments (Figure 4 and Figure 5). Comparing to 2011, this corresponds to +7 GW of installed capacity. Out of the total installed capacity, 105.8 GW comprises "traditional" hydropower stations, meaning hydroelectric facilities that solely serve electricity generation (including multi-purpose services). Another 22.6 GW refers to closed-loop pumped-storage hydropower. The remaining 24.2 GW is mixed hydropower, meaning typical PSH facilities connected to rivers [35, 36]. In Table 2 the installed capacity of the EU's hydropower fleet is reported, classified by the type of plant and installed power, by analysing several databases (JRC[34], Voith Hydro and UNIDO) updated to 2022[k].
The installed hydropower per inhabitant is 0.34 kW/person in the EU, 0.31 kW/person in the U.S. and 0.30 kW/person in China. The EU is also leader in the small hydro sector (Wagner et al., 2019)[37] and in R&D (Manzano-Agugliaro et al., 2017)[38].

Table 2. Installed turbine power (in % on the total of 152 GW) at the EU level, categorized depending on hydropower plant type (RoR, RSHP, PSH) and installed power class *P* (MW). For PSH the turbine's installed capacity is considered.

	Share (%) on total Power			
P (MW)	RoR	RSHP	PSH	Total
P>10	16.8	44.5	28.4	90.3
1<*P*≤10	4.6	2.8	0.0	7.7
P≤1	2.1	0.0	0.0	1.9
Total	23.9	47.7	28.4	100 %

Source: combination of data of the JRC hydropower database, Voith Database and UNIDO database (year 2022)

Annual energy generation

In the last decade, the annual energy generation from traditional hydropower and PSH (excluding electricity adsorbed for pumping) in the EU has oscillated between 307 and 398 TWh/y depending on the hydrological conditions with the average value being 363 TWh/y. The annual generation was 375 TWh in 2021 including energy from PSH (and excluding pumping, which is 43 TWh in 2022, and 42 TWh of generation), but reduced to 307 TWh in 2022, mainly due to the increase of the other renewables and due to water scarcity in several regions, despite the increase in the total installed capacity. Pure hydropower plants (ROR and RSHP) generated 266 TWh[l]. In 2022, the operation of closed-loop PSH increased by 15%, both in generation and in pumping mode. For further details on PSH refer to section 2.2.3.

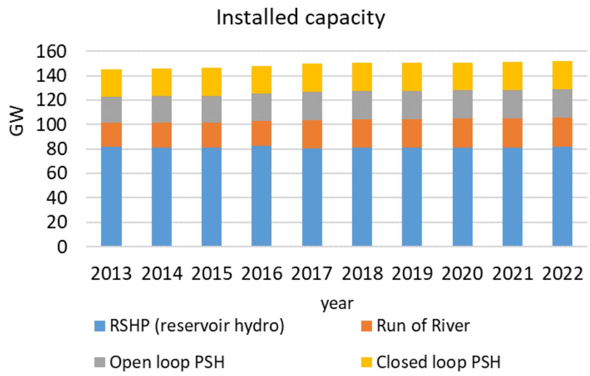
[k] The total installed capacity and the total installed capacity of ROR are higher (+3 GW, +15 GW) than that from other sources (e.g. Eurostat) since it is difficult to track exactly the hydropower fleet composition, and, probably, some hydropower plants with small pondages are considered RoR in the JRC database.
[l] Pure hydropower includes ROR and RSHP. Renewable hydropower includes also hydropower generation from mixed hydropower plants, but only considering the generation associated to the river inflow (thus excluding the water that is turbined after pumping).

Capacity factor

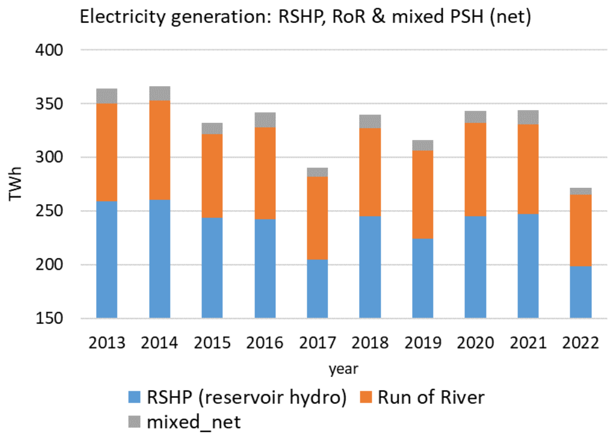
Hydropower productivity is not uniform across the EU and reflects the climatology, topography and water resources of each region and the power plant type prevalence. This variability is typically shown by the Capacity Factor (CF) that is expressed as the ratio of annual electricity generation to the electricity that would be generated if the power plant would work the whole year at nominal power. The average and overall CF in EU in 2021 was 28%, lower than the global weighted-average of new projects commissioned between 2010 and 2019, namely 48%, probably because of smaller rivers and their torrential hydrological regime. The highest CF in EU in the last decade was CF=31% in 2013 and 2014. Hydropower in the Northern Member States generally shows a higher productivity than that of countries in Southern Europe (Table 3). Malta and Cyprus have low water resources and the prospects for the development of hydropower plants are limited, while in the case of Cyprus, where solar energy is available due to prolonged solar radiation, energy storage in the form of PSH has been identified as a possible solution to the problem of supply vs. demand mismatch[39]. Reservoir power plants are usually fitted with relatively high capacity that cannot run at full power throughout the year using only natural inflows. Reservoir 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 57% in 2021 (35% average value in 2021). Reservoir power plants have typically yearly storage, allowing, for example in the Alps, to store water during summer for electricity production mainly during winter. Instead, ROR plants have limited storage capabilities, hence their operating power is typically adjusted to maximise the use of available natural inflows throughout the year. The average yearly CF of ROR plants ranged from 19% to 57% in 2021, and its average value in 2021 in EU was 39%.

Figure 4. Installed turbine capacity (a) and electricity generation in the EU (b and c), including electricity generation from PSH. *Mixed_net* (figure b) means the net electricity generation from mixed (i.e. open-loop) PSH (electricity generation minus adsorbed one for pumping, which is approx. the electricity generated from natural inflow, roughly assuming that pumping and turbining efficiency are approx. the same). In Figure b, the y-axis starts at 150 TWh.

(a)



(b)



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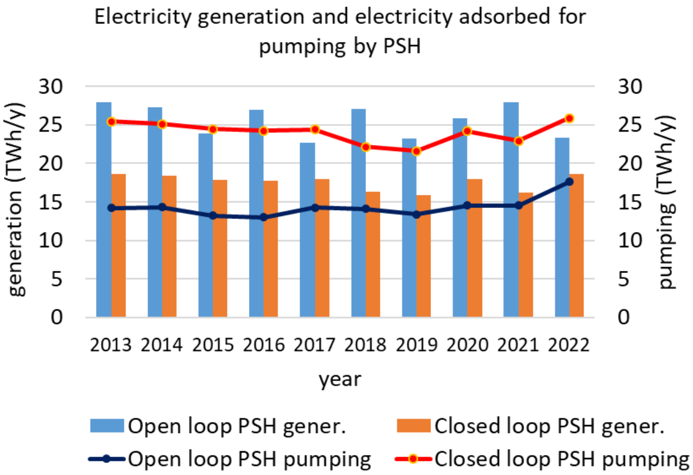
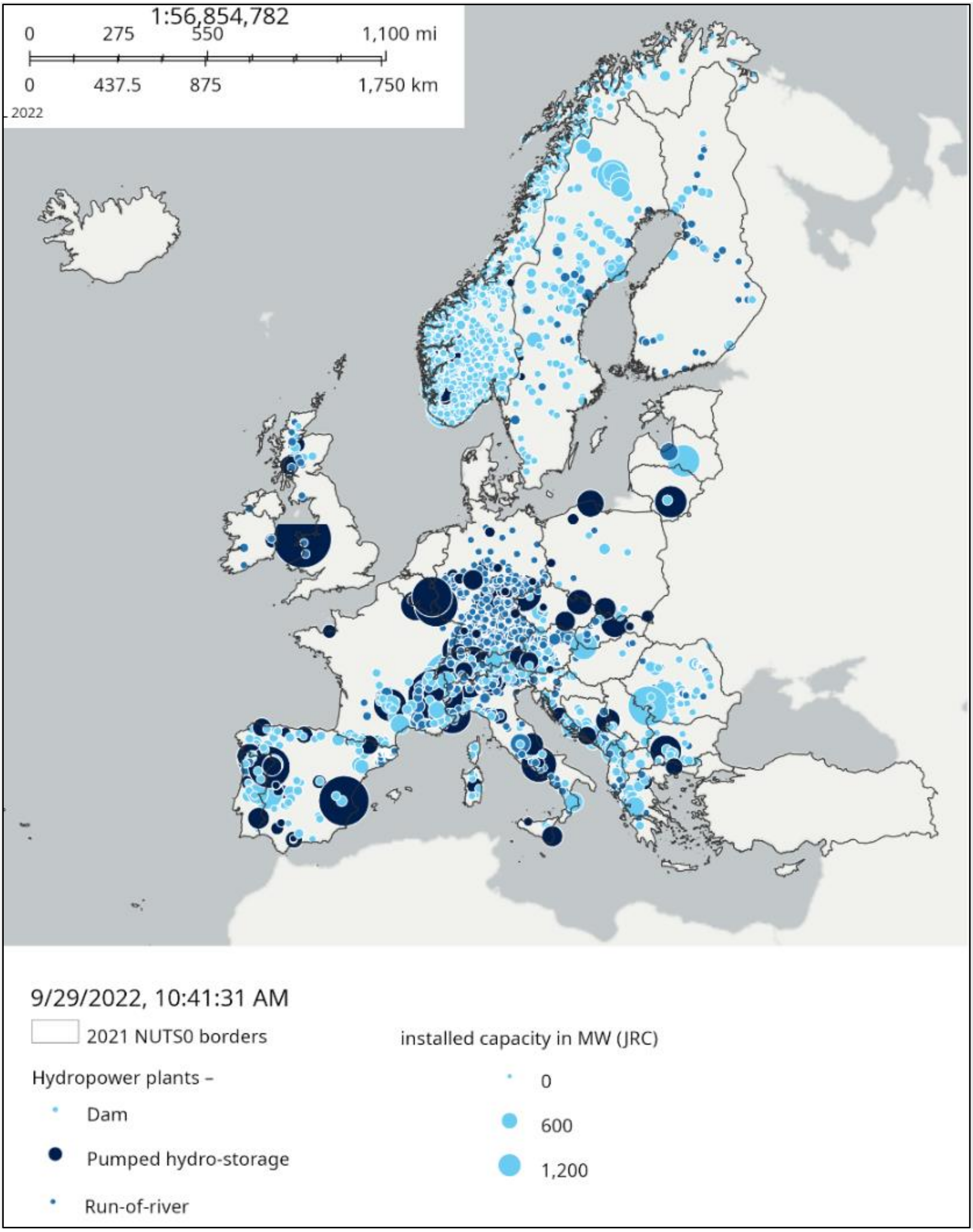


Source: Eurostat

Figure 5. Hydropower distribution in Europe according to the JRC hydropower database (194 GW included out of the 254 GW, year 2019). From: https://energy-industry-geolab.jrc.ec.europa.eu/, and excluding most of the mini-hydropower plants.



Source: JRC

Table 3. Installed turbine power *P* in MW: total and split per category (based on 2022 Eurostat data), including installed capacity of pumps (from IHA's PSH tracking tool), for the year 2022. ROR=run of river, mixed = open-loop, pure = closed-loop, PSH = pumped-storage hydropower, RSHP = reservoir storage hydropower.

Country	acronym	Total	RSHP	ROR	Mixed (Open-loop) PSH (generation)	Mixed (Open-loop) PSH (pumping)	Pure (Closed-loop) PSH (generation)	Pure (Closed-loop) PSH (pumping)
European Union	EU	152,733	81,417	24,434	24,241	16,516	22,641	22,720
Austria	AT	14,923	3497	5631	5795	3751	0	0
Belgium	BE	1430	123	0	0	0	1307	1307
Bulgaria	BG	3390	2377	0	149	147	864	788
Czechia	CZ	2285	1114	0	0	480	1172	669
Denmark	DK	7	7	0	0	0	0	0
Germany	DE	10,974	298	4189	1134	35	5353	5849
Estonia	EE	8	8	0	0	0	0	0
Ireland	IE	529	237	0	0	0	292	292
Greece	EL	3421	2722	0	699	699	0	0
Spain	ES	20,137	11,175	2549	3082	2696	3331	2795
France	FR	25,964	18,864	0	5372	2685	1728	1640
Croatia	HR	2206	1491	440	275	0	0	246
Italy	IT	22,861	9516	6082	3334	1886	3928	4876
Cyprus	CY	0	0	0	0	0	0	0
Latvia	LV	1588	0	1588	0	0	0	0
Lithuania	LT	877	117	0	0	0	760	880
Luxembourg	LU	1330	34	0	0	0	1296	1050
Hungary	HU	60	0	60	0	0	0	0
Malta	MT	0	0	0	0	0	0	0
Netherlands	NL	38	38	0	0	0	0	0
Poland	PL	2407	608	0	376	307	1423	1340
Portugal	PT	8189	1812	2730	3647	3491	0	0
Romania	RO	6663	6293	0	278	68	92	71
Slovenia	SI	1346	0	1166	0	180	180	0
Slovakia	SK	2532	1616	0	0	0	916	917
Finland	FI	3171	3171	0	0	0	0	0
Sweden	SE	16,399	16,300	0	99	91	0	0

Source: Eurostat and IHA

Table 4. Annual energy generation in GWh: total and split per category, including adsorbed electricity for pumping, for the year 2022 (based on 2022 Eurostat data). ROR=run of river, mixed = open-loop, pure = closed-loop, PSH = pumped-storage hydropower, CF = capacity factor for traditional hydropower (excluding PSH) and closed-loop efficiency for closed-loop PSH are also calculated. RSHP = reservoir storage hydropower.

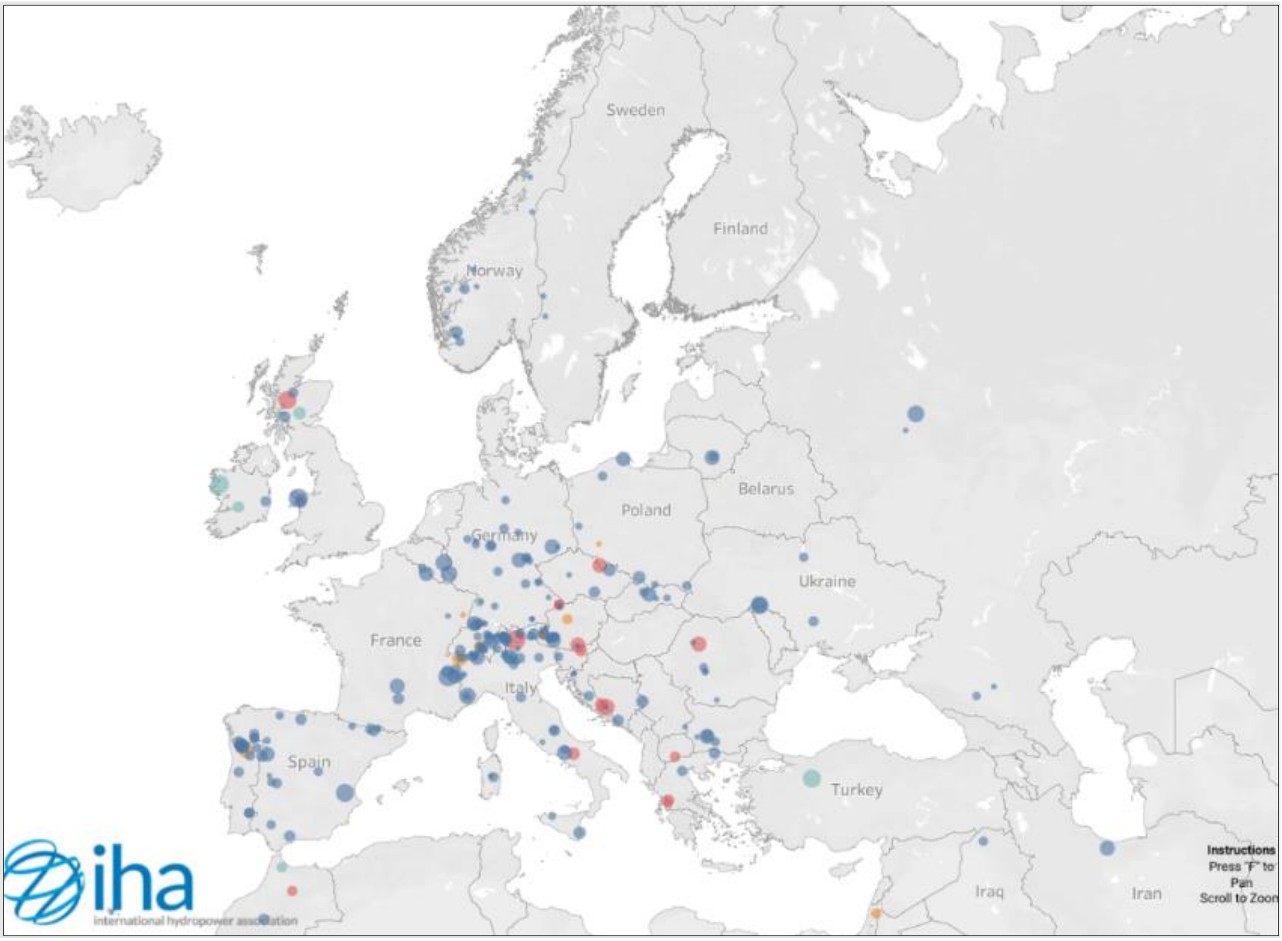
	Total	RSHP	ROR	Mixed or Open-loop (generation)	Mixed or Open-loop (pumping)	Pure or closed-loop (generation)	Pure or closed-loop (pumping)	CF Hydro	Closed loop efficiency
EU	307523	198,693	66,815	23,337	17,624	18,679	25,870	0.29	0.72
AT	39,221	7577	24,663	6982	6451	0	0	0.40	
BE	1646	271	0	0	0	1375	1830	0.25	0.75
BG	3833	3385	0	441	36	7	14	0.16	0.48
CZ	3083	2093	0	0	0	990	1278	0.21	0.77
DK	15	15	0	0	0	0	0	0.26	
DE	23,576	708	16,437	1017	862	5414	8124	0.44	0.67
EE	23	23	0	0	0	0	0	0.33	
IE	948	701	0	0	0	247	403	0.34	0.61
EL	4000	3351	0	648	207	0	0	0.14	
ES	22,102	16,583	0	2353	1845	3166	4247	0.14	0.75
FR	51,049	42,673	0	5875	4268	2502	3183	0.26	0.79
HR	5574	3700	1448	426	163	0	0	0.30	
IT	30,291	13,134	14,310	1409	649	1437	1938	0.20	0.74
CY	0	0	0	0	0	0	0	0.00	
LV	2750	2	2748	0	0	0	0	0.20	
LT	1021	464	0	0	0	556	764	0.45	0.73
LU	1124	64	0	0	0	1059	1417	0.21	0.75
HU	178	0	178	0	0	0	0	0.34	
MT	0	0	0	0	0	0	0	0.00	
NL	50	50	0	0	0	0	0	0.15	
PL	3018	1779	0	233	63	1006	1438	0.33	0.70
PT	8839	1672	3883	3284	2943	0	0	0.14	
RO	14,360	13,466	0	510	0	383	498	0.24	0.77
SI	3401	0	3149	0	0	252	341	0.31	0.74
SK	3963	3678	0	0	0	285	394	0.26	0.72
FI	13,492	13,492	0	0	0	0	0	0.49	
SE	69,967	69,810	0	157	137	0	0	0.49	

Source: Eurostat

2.2.3 Focus on Pumped-storage hydropower

The approximately 270 PSH stations worldwide have a total turbine power capacity of 179 GW, representing over 90% of the global grid-scale electricity storage capacity[40]. 156 PSH stations operate in the EU with an overall turbine capacity of 45 GW (the installed pumping capacity is 39 GW in the EU), and 9 GW are under construction or planned. Several PSH projects were either announced or achieved noticeable progress in Europe during 2023. This technology still has remarkable untapped potential of a few TWh (IHA, 2024), as shown in Table 7.
The productiveness index (average monthly PSH consumption [GWh] /average monthly PSH production [GWh]), considering closed and open-loop stations, ranges from 54.8% to 86.8%, with an average EU value equal to 73.9%. PSH 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, PSH plants are operated throughout the day in certain months, followed by periods of low utilization, and this strategy leads to low productiveness index. Greece hosts pump-back stations and their low utilization results in their main operation with river flow, that increases the productiveness index [35]. The energy stored in EU's PSH is 1300 GWh, elaborating data of IHA according to Quaranta et al. (2024).
Table 5 lists the installed power capacity of large PSH (over 1000 MW) systems by country[41], while Figure 6 depicts the European distribution of PSH systems.

Figure 6. Distribution of PSH plants (source: PSH forum of the International Hydropower Association[42]). Blue = operating, Orange = under construction or planned.



Source: IHA

Table 5. Installed power capacity of large PSH (over 1000 MW) systems by country (year 2023).

Country	In Operation	Under Construction	Total
China	40,648	69,550	110,198
Japan	15,307	2820	18,127
U.S.	13,731	0	13,731
EU (as a whole)	13,514	0	13,514
Italy	4200	0	4200
Australia	1800	2250	4050
Ukraine	2531	900	3431
Taiwan	2608	0	2608
United Kingdom	2500	0	2500
Egypt	0	2400	2400
South Africa	2332	0	2332
India	0	2200	2200
Germany	2105	0	2105
Switzerland	1000	900	1900
France	1800	0	1800
Spain	1770	0	1770
Serbia	1300	0	1300
Luxembourg	1300	0	1300
Russia	1216	0	1216
Vietnam	0	1200	1200
Czech Republic	1175	0	1175
Belgium	1164	0	1164
Iran	1040	0	1040
Indonesia	0	1040	1040
South Korea	1000	0	1000

Source: Nikolaos et al. (2023)

2.2.4 Energy storage in PSH and RSHP

Water storage and water reservoirs are key to the Water-Energy-Food-Ecosystem (WEFE) nexus, i.e. to the interdependence of water, energy, food security and ecosystems – hence the synergies of water, energy, environmental and agricultural policies. Water storage in reservoirs can be exploited as energy storage in two main types of hydropower plants: 1) reservoir hydropower (RSHP) - when the reservoir is coupled with hydro turbines, - and 2) pumped-storage hydropower (PSH) - when the reservoir is coupled with both hydro turbines and pumps (or with reversible pump-turbines) and with a second reservoir. Furthermore, PSH can be classified into 1) open-loop – when at least one of the reservoirs is connected to a river - and 2) closed-loop- when both reservoirs are stand-alone systems. The key metric of energy storage for both types of plants is the energy storage capacity (expressed in GWh), which can be defined as the energy that is stored in the upper reservoir and that can be used to generate electricity in a single generation cycle (when two reservoirs are connected in a closed-loop, the smaller reservoir limits the capacity). One generation cycle together with one pumping cycle forms one complete PSH cycle. The flexibility provided by PSH and RSHP is highly important; furthermore, by reducing the number of operating hours as base load, it is possible to let more water stored and use it during peak hours, hence improving flexibility.

Energy storage in reservoir hydropower[m] RSHP and PSH is the largest source of energy storage today and is the only mature technology for long duration energy storage (IEA, 2023b[43], World Bank, 2024[44]). Globally, reservoir hydropower has a storage capacity of about 1500 TWh, which is about 170 times more than the global fleet of PSH and almost 2200 times more than the Li-Ion battery capacity of both stationary and automotive applications (IEA 2021[45]). Excluding reservoir hydropower, more than 90% of the remaining energy storage in the world is in PSH (IHA, 2024[46]).

Quaranta et al., (2024) estimated that the available theoretical potential of energy storage is 55 TWh[n] in the EU's hydropower reservoirs (excluding PSH and neglecting the cascade effect[o] of reservoirs, that, for example, in Sweden increases energy storage from 8 TWh to 30 TWh). The theoretical energy storage in PSH is 6.3 TWh. Results reported in Graabak et al., (2017)[47] show that in the EU the energy stored in water reservoirs is approx. 90 TWh, which is higher than the one estimated above of 55+6.3=61 TWh, and this is probably due to the cascade effect considered in the Swedish estimate. The abovementioned estimates refer to the maximum available theoretical storage, that use the maximum net head and the full reservoir volume for the storage calculation. In real operating conditions, i.e. the technical potential, the head reduces as the upper reservoir empties (as well as the efficiency, as the turbines move away from their design condition), and not the whole reservoir's volume is used for safety and practical reasons. Furthermore, the smaller reservoir limits the potential. Based on these factors, the technical usable storage capacity of PSH reservoirs was finally estimated in around 500-600 GWh from Quaranta et al. (2024) for PSH, and in 25 TWh for RSHP (without cascade effect).

When considering Europe as a whole, it is estimated that European hydropower reservoirs provide a theoretical storage capacity between 180[72] TWh and 220 TWh[48]. Norway has the largest (85 TWh) storage capacity in Europe, more than any EU Member State. Switzerland hosts 8.4 TWh. Norwegian hydropower acts like a battery for balancing variable renewables in neighbouring countries, with more than 1000 reservoirs (Graabak et al., 2017)[47].

Quaranta et al. (2024) also reviewed the scientific assessments on possible future developments (e.g., new sustainable PSH development such as reservoir interconnection, refurbishment, exploiting abandoned mines) and contextualized them within the current situation, showing the relevance of each potential strategy. The results of Stocks et al. (2021) and Hunt et al. (2020), better discussed in Quaranta et al. (2024), showed a quite high remaining potential for PSH, although the installation costs could be quite high due to the fact that they would be built in the most expensive sites (the most suitable are already exploited) and also because of environmental mitigation measures to be implemented, or environmental restrictions that limit the potential. Gimeno-Gutiérrez and Lacal-Arántegui (2015) and Weber et al. (2024) assessed the potential of interconnecting reservoirs and exploiting abandoned mines, respectively, whose Capital Expenditure (CAPEX) and environmental impacts would be noticeably lower than those of new greenfield projects. The estimated potential that could be realized would be 0.8 TWh and 3 TWh (considering the most economic sites), which is more than 50% of the current theoretical one of PSH. These latter studies do not require the construction of new dams and already included in their analysis some economic criteria (see also Table 10).

[m] reservoir hydropower= a particular type of hydropower system that uses a reservoir and that is not provided with pumping capacity;
hydropower reservoir: term that specifically refers to a reservoir with single use hydropower
[n] calculated by *head* x *stored volume* x *coef*., thus assuming: *head* >> dam height and constant at its maximum value while the reservoir empties, and the full design volume (*coef*. is the conversion factor to obtain TWh). The larger reservoir is used for the calculations, since we are referring to the maximum theoretical one and because from ICOLD only the larger reservoir is generally traceable.
[o] defined as an operation where downstream reservoirs store and release water coming from upstream reservoirs, in a combined, integrated and optimized system

Recent developments

Year 2022

According to IHA (2023)[30], in 2022 the most relevant hydropower development in the EU were realized in Austria, France, Italy, Ireland, Poland, Portugal, Romania and Bulgaria. Portugal (+998 MW) and Austria (+89 MW) were those with the largest capacity addition. As a comparison, Switzerland added 900 MW, Turkey 558 MW and Norway 163 MW. The Gemeinschaftskraftwerk Inn power plant was created as a joint project between the Swiss municipality of Valsot and the Austrian municipality of Prutz. The system offers 89 MW of installed capacity located on the river Inn and generates almost 440 GWh/y of electricity. It is the largest newly built run-of-river power station in the Alpine region and costed EUR 600 Million. Financing included contributions from the European Investment Bank (EUR 150 Million) and KfW IPEX-Bank (EUR 90 Million). In Ireland, the Silvermines hydropower plant will receive EUR 4.3 Million for researching and setting up a pumped-storage facility at a historic mining. In Portugal, construction continues to complete the Alto Tâmega power plant, which is part of the Tâmega Giga Battery project. The reservoir filling operations are expected in October 2023. This is the last stage prior to completion expected in mid-2024 of the Tâmega Giga Battery project. The project includes the construction of three power plants: Daivões, Gouvães and Alto Tâmega with a total installed capacity of 1158 MW. Daivões was inaugurated in July 2022 and is a 118 MW Reservoir Plant. Gouvães was inaugurated in July 2022 and is an 880 MW pumped-storage plant. Finally, Alto Tâmega with a cost of around EUR 1.5 Billion, will have a storage capacity of 20 GWh and is expected to save 1.2 Million tonnes of CO2 emissions annually. Targets to put 600 MW by 2023 have been set in Sweden. A new 240 MW Pelton turbine was launched at La Coche pumped-storage station in France, substituting outdated models. Czechia 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[49].

Year 2023

According to IHA (2024), Austria dominated the capacity addition in 2023 in the EU (+120 MW), followed by Germany (+91 MW) and Finland (+5 MW). Austria continues to be a leader in PSH development. The local pipeline
currently accounts for almost 2.17GW of hydropower and PSH schemes, of which over 1GW is currently under
construction. For Estonia, The Zero Terrain Paldiski underground PSH project, developed by Energislav, was granted permits in January 2023 and is ready for construction. In June 2023 it secured an additional EUR 11 Million of private funds from a group of Baltic companies. This new 500MW/6GWh scheme is one of the EU "projects of common interest" and is supported by the EU's Connecting Europe Facility. In Finland, Kemijoki Oy is reviewing options for developing Ailangantunturi, a 550MW PSH plant in Eastern Lapland. Up to three small-scale PSH plants, for a total capacity of more than 100MW and a total investment of up to EUR 300 Million, are in planning. The expansion and conversion of the Rudolf Fettweis hydropower plant in Forbach reached a final investment decision in May 2023. The existing conventional reservoir power plant will be modernised and converted into a PSH plant. Owners Energie Baden-Württemberg estimate that the conversion cost will be EUR 280 Million, including the construction of a new powerhouse to accommodate the 57MW pumping facility, the modernisation of existing electromechanical equipment (71MW), and the modification of the existing Forbach basin to serve as the lower reservoir of the scheme. The Italian utility Edison has inaugurated the Quassolo hydropower plant, boasting a capacity of 2.7MW on the Dora river. In Spain, in January 2023, the Chiara PSH plant in Gran Canaria received EUR 90 Million in grant support from the European Regional Development Fund. This project is being developed by the local system operator, a unique ownership structure for Europe. Upon completion, the plant will boast a 200MW capacity in turbine mode, 220MW in pumping mode, and a total storage capacity of 3.6GWh. It will also be linked with a seawater desalination plant. In March 2023, Iberdrola obtained approval from the Spanish Government for

the Valdecañas PSH project. This plant will have a total power output of 275MW and is a hybrid system including chemical batteries with a capacity of 15MW, storing up to 7.5MWh of energy. The combined energy storage of the battery and hydraulic units will be 210GWh. In Sweden, Vattenfall has announced ambitious plans to enhance its hydropower capacity by constructing an additional 720MW (IHA, 2024).
It is worth to mention the 15 dam projects negotiated with NGO's in Switzerland which will/should contribute with +2000 GWh/year to the supply safety in the critical winter half year[50].

2.3 Future trends, sustainable potential and hidden opportunities

2.3.1 Introduction

Hydropower is currently the giant of low-carbon electricity technologies and it is the key technology for an optimal integration of volatile energy sources (e.g. wind energy and photovoltaics) into the electric grid. Hydropower (together with water & energy storage) capacity needs to increase in the near future, but it faces several environmental constraints and barriers. Global cumulative hydropower capacity is expected to expand from 1416 GW in 2023[30] to about 1560 GW in 2030 and up to 1800 GW in 2050 according to the Global CETO 2°C scenario 2024 calculated with the POLES-JRC model (see Annex 4). For 2030, these capacity projections are well aligned with IEA and IRENA's projections[110] while these organisations have more bullish projections in 2050, reaching 2500 GW of global hydropower installed capacity. According the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), both estimate a need for around double the amount of hydropower that is currently installed in their net zero scenarios for 2050. IRENA's 2050 net zero scenario has more than 2,900GW total hydropower capacity, of which almost 420GW is PSH. To bridge the gap between current installed capacity and future projections, there is the need to add more than 50 GW per year. The 100 largest greenfield projects in the pipeline, including PSH projects and excluding the Grand Inga project in the Democratic Republic of the Congo from the analysis, as it is so large it would skew the results, totalise 280GW. Europe hosts 7.5 GW of these 100 projects (IHA, 2024).

In the EU, the outlook for the expansion of hydropower is less bright, due to several barriers that are extensively discussed throughout the report and in Table 6[51]. Some projects are planned to go ahead anyway (Figure 9). The main priorities for hydropower in the EU are defined in the EU Clean Energy Transition Partnership[52], and are flexibility, storage, digitalisation, services of hydropower, sustainable solutions and sediment handling. The most important challenges are the following ones: 1) the regulatory context requires stringent environmental, climate and wildlife standards that entail administrative hurdles (see Section 3.3); 2) the most suitable locations for hydropower projects have already been exploited or are environmentally protected areas [53]; 3) new large greenfield hydropower plants face high investment costs and/or long construction times that expose them to risk and to complex financing processes; 4) remuneration of hydropower plants especially in the long-term is challenged by the expected reduction of electricity prices, especially due to the penetration of more renewable energy. Ad-hoc policy interventions and robust implementation of the Electricity Market Design (EMD) reform are needed to tackle these barriers that undermine the full exploitation of the hydropower potential in the EU, which is so critical to the accomplishment of the EU carbon neutrality objective.

Table 6. Challenges for hydropower development in Member States.

Austria	Seasonal variability of water flow
Belgium	Limited hydro potential due to topography
Bulgaria	Relatively low hydroelectric potential
Croatia	Environmental concerns over river ecosystems
Cyprus	No significant hydro resources, but potential for new PSH
Czech Republic	Limited suitable locations for hydro plants
Denmark	Almost no hydroelectric resources
Estonia	Very low hydroelectric potential
Finland	Protecting natural waterways and fish habitats
France	Regulatory constraints for new hydro developments
Germany	Environmental and regulatory constraints
Greece	Droughts affecting water levels for hydro
Hungary	Minimal hydroelectric resources
Ireland	Limited potential for large-scale hydro, except in a few sites, including PSH
Italy	Regulatory barriers for new hydro projects
Latvia	Concerns over damming rivers for hydro
Lithuania	Environmental impact on river ecosystems
Luxemburg	Very limited hydroelectric capacity
Malta	No significant hydroelectric resources
Neterlands	Low elevation limits hydroelectric options
Poland	Limited hydroelectric potential, one PSH planned.
Portugal	Seasonal water flow variability
Romania	Regulatory approval processes for hydro
Slovakia	Hydroelectric growth limited by environmental concerns
Slovenia	Water management conflicts with neighboring countries
Spain	Competing water usage for agriculture vs. hydro power
Sweden	Balancing hydro production with environmental concerns

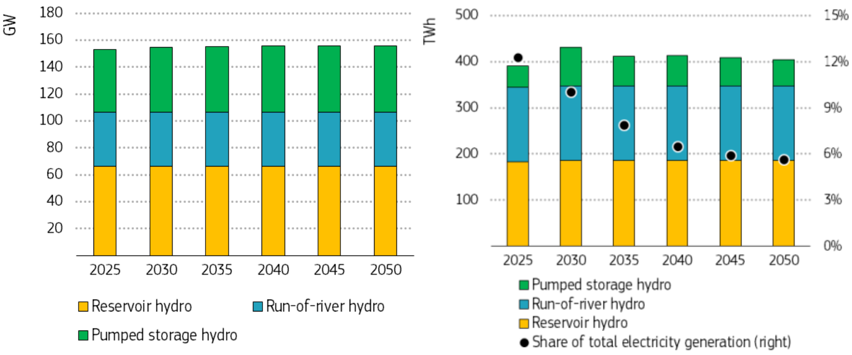
Source: Hassan et al. (2024)

2.3.2 **POTEnCIA's CETO** 2024 Scenario projections

According to POTEnCIA's CETO 2024 Scenario[54, 55] (see Annex 4 for more details on the POTEnCIA model), hydropower installed capacity in the EU is assumed to remain almost stable in the future, but still growing with +3 GW of new PSH in 2050 (see Figure 7). Closed-loop PSH generation (plus that from the pumped water in open-loop PSH) will produce an additional +56 TWh in 2030 with respect to 2020 (but that also adsorbs an almost similar quantity of electricity mainly providing storage and flexibility rather than net electricity generation); RoR will produce + 16 TWh/y and RSHP generation will decrease by 16 TWh. After 2035, hydro electricity generation is projected to slightly reduce again, while remaining higher than 2020 levels, due to the growing competition with other electricity storage technologies and more flexible load from consumers willing to provide demand-response (e.g. smart charging from electric vehicles or flexible hydrogen generation from electrolyzers). These analyses are based primarily on techno-economic considerations and the surrounding political framework. However, they do not consider future water availability, because of the high uncertainty and complexity of projecting future the impact of climate change.

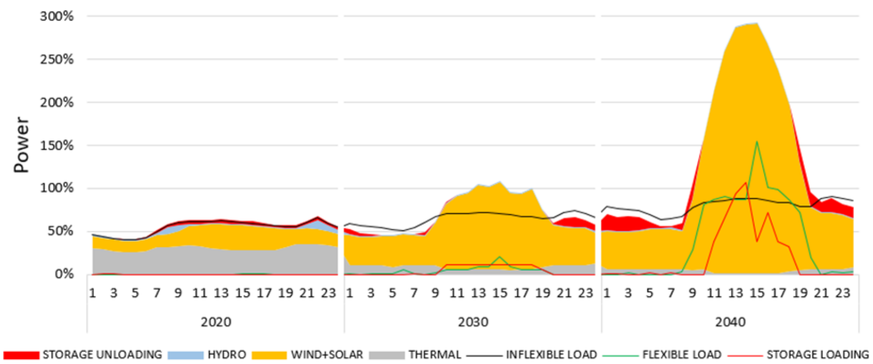
Figure 8 shows how the hourly generation pattern of pumping in PSH changes towards 2050. This is a consequence of the change of paradigm in the electricity system. In 2020, the electricity system is dominated by inelastic hourly demand (i.e. demand that will not change regardless of the electricity price) and thermal-based generation (nuclear, fossil fuels, etc.). In 2020, hydro pumping performs energy arbitrage by loading electricity in the hours with low inelastic demand (and hence low electricity price), and unloads it in the hours with high inelastic demand (and hence high electricity price). However, towards 2050, the system becomes more and more dominated by variable renewable electricity generation and increasing volumes of flexible demand (i.e. demand that is willing to adapt its consumption pattern to benefit from lower electricity prices). As a consequence, the hours with low electricity prices (where hydro pumping loads) tend to shift to those hours where variable renewable generation is the highest (predominantly those in the middle of the day due to PV as shown in Figure 8). On the other hand, the increasing volumes of flexible demand reduce the need for flexibility from hydro pumping units, decreasing its overall contribution to the system.

Figure 7. Hydropower installed capacity and electricity generation in the EU, 2025-2050. PSH generation includes closed-loop PSH and that from the pumped water in open-loop PSH.



Source: POTEnCIA CETO 2024 Scenario (see Annex 4)

Figure 8. Hourly power generation (stacked area) and load (unstacked lines) in 2020, 2030, 2040, relative to 2020's hourly average load (put as 100% as reference condition) aggregated by type, in a spring day in a South European country. Storage unloading = generation. Storage includes PSH, but also batteries after 2030.



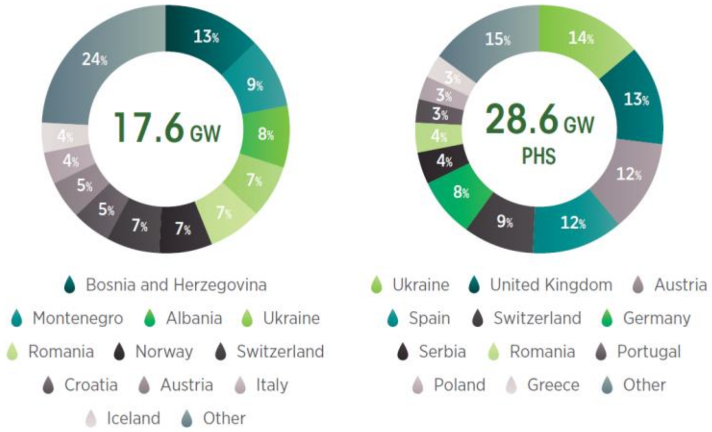
Source: POTEnCIA CETO 2024

Tarvydas (2022) [56] projected an increase of hydropower generation up to about 420 TWh/y in 2050 (including PSH), thus an increase of about 60 TWh/y with respect to the average annual generation recorded in the last 10 years (+17%). By further elaborating results of Calheiros et al. (2024)[57], by 2040 traditional hydropower generation (TWh/y) may increase by 27%, by 2060 by 16%, while predictions are highly uncertain beyond 2060. According to Schmitt and Rosa (2024)[58], who elaborated data of IEA, in OECD Europe the demand for hydropower installed capacity (GW) may increase by 30% by 2050.

2.3.3 Ongoing projects

Table *7* and Figure 9 list the hydropower projects and PSH under construction and planning in Europe.

Figure 9. Hydropower project pipeline in Europe, 2022-2037[59].



Source: IRENA

Table 7. PSH under construction/planning/almost ready (in 2022). Empty cell = unavailable data

Member state	Turbine MW	Pump MW	GWh/y annual generation
AT	45	45	
AT	480	480	850
AT	170	170	460
AT	170	190	216
AT	170	150	
AT	1015	400	785
DE	18	16	
DE	300	300	
EE	506	509	1100
EE	225	225	
EL	220	234	264
EL	460	496	552
ES	200	220	
ES	570		
IE	360	360	650
LT	110	77	
PL	750	804	1275
PT	880	880	1468
SL	400		777

Source: Hydropower and Dams

Table 8 lists the large dams under construction, according to the World Atlas of Hydropower & Dams 2022[60]. It is worth noting that by 2017, in many of the South-Eastern European countries, the number of projects that were being implemented was, however, far behind the total number of planned hydropower projects. For example, by 2017, only 9% of the projects were under construction in these countries, with a percentage of 3.5% and 6% for Serbia and Bosnia and Herzegovina (that are not EU's members), respectively[61]. This is probably due to the long authorization processes and environmental restrictions.

Table 8. Very large dams (>60 m high) under construction/planning/almost ready (2022). H = hydropower, S = water supply, I = Irrigation, reg = regulation/detention, div = diversion. A diversion dam is a dam that diverts all or a portion of the flow of a river from its natural course. Diversion dams do not generally impound water in a reservoir; regulation dams regulate the water flow in areas below the dam.

Member state	Dam's Height	Purpose
AT	113	H
EL	76	S
EL	150	H
EL	72	I,S
EL	60	S,I
EL	145	H,I,S, div
ES	65	S,I
ES	91	reg,I
ES	59	S,I
GR	60	I
IT	78	I
IT	60	I,S
IT	88	I,S
PT	106.5	H
RO	67	H
RO	62	S
RO	103	H,S
RO	91	H,S

Source: Hydropower & Dams

2.3.4 Sustainable potential for hydropower and PSH

Sustainable hydropower needs to achieve a good balance between electricity generation, social benefits and impacts on the ecosystem and biodiversity. In the European Union, most of hydropower development will be based on the optimization and retrofitting of existing infrastructures.

The modernization of the existing hydropower fleet is an attractive opportunity to increase efficiency, production, flexibility, sustainability and resilience to climate changes (the average age of the EU' hydropower fleet is almost 45 years. Modernizing all of the hydropower fleet with the best technologies to increase efficiency (and not the design flow, nor the gross head), and assuming that all hydropower plants need to be modernized, Quaranta et al., (2021) estimated that the annual electricity generation from the existing hydropower EU's fleet could be increased by approximately 10% (~40 TWh/y)[p], implementing new tools for hydropower digitalisation, modern electro-mechanical equipment (to replace deteriorated equipment, increase its flexibility and a bit the best efficiency point), and by optimizing the waterways (e.g., reducing friction and head losses). This is evidently an upper threshold, but does not consider additional gains in case of increase of flow or head (e.g., dam heightening), as well as the transversal benefits that flexibility can deliver to the

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

grid. Additional strategies to increase generation from the modernisation of aged plants include dam heightening (useful especially to increase storage capacity), new waterways to increase the peak installed capacity and a better reservoir management to reduce spills (the latter, with possible increase of annual revenue up to 10%). Modernization should also aim at improving resilience to climate changes and to optimize hydropower operation to better deal with future energy needs, market dynamics and new hydrological time series (more floods and droughts).

Hydropower is also affected by climate change. On one hand, hydropower generation depends on water availability, and may suffer from water shortages 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 a flood control system. Gøtske and Victoria (2021)[62] 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 (especially in winter periods), and more frequent and prolonged droughts in Mediterranean countries are expected. The median decrease of generation of ROR hydropower will be −3% in the future on the Italian Alps. For further details see the 2022 CETO report. Farinotti et al., (2016)[78] suggested that the deglacierizing catchments (catchments where glaciers are disappearing) 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 RSHP) or production capacity (for ROR and RSHP). New development should also aim at increasing storage capacity of existing reservoirs, by de-sedimentation; the average annual sediment inflow into European reservoir is 0.7% of the reservoir volume. Prevention and mitigation solutions (e.g. bypasses) [63] can help in mitigating this issue; dredging is also an option, but costs several billions EUR per year in the EU[64], and has adverse impact on surface waters (both changes in morphological characteristics and increased chemical pressure because of possible contaminated sediments).

Developing hydropower in existing infrastructures (generally, small hydropower, even micro hydropower), e.g. in water distribution networks (aqueducts), in existing low head barriers (e.g. water wheels in water mills) and in wastewater treatment plants has been the aim of numerous research and deployment activities. This is due to the lower impacts compared to conventional greenfield hydropower in freshwater systems, and the untapped potential in the EU [65, 66] (Punys et al., 2019; Quaranta et al., 2022). Small-scale hydropower opportunities 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 (e.g., some alpine areas, mountain refugees). The technical potential associated with these strategies is limited to approximately 10 TWh/y in the EU. There also exists a hidden potential in hydraulic infrastructures in the private water intensive industry, such as mining or energy production (using cooling waters). Hydrokinetic turbines exhibit a low potential, but could represent an interesting strategy when installed at the hydropower plant tailrace as kinetic energy dissipation devices (Quaranta and Muntean, 2023)[14]. New small hydropower plants that involve the construction of new weirs/dams are rather controversial, due to their impacts and limited annual energy generation with respect to the existing hydropower fleet. Bodis et al. (2015)[67] identified that the potential in the EU is 111 TWh/y, which is approx. 40 TWh/y more than the current one, but without considering local technical limitations. Quaranta et al. (2022) updated the analysis by considering different scenarios of environmental flow, spatial density of installations and withdrawal length, showing that the theoretical potential (that does not consider local and site-specific constraints) may vary noticeably.

The EU long-term projections and potential estimation for PSH and new dams are instead more challenging, as they are facing environmental and financial challenges. In the decade 2000-2010, 22 pumped-storage units capable of producing 2,443 MW of rated power were commissioned in the OECD Europe[q]. In the period 2011-2020, 76 pumped-storage units capable of producing 11,562 MW (for comparison, 40 MW in the U.S.) were commissioned, under construction, or planned for

[q] 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.

building and commissioning. Some projections foresee deployment rates of 4 GW of new PSH until 2030 in the EU (in Switzerland, about 4 GW are ready for approval, pers. comm. Anton Schleiss), and an increase in PSH capacity up to 70-75 GW by 2050 [68, 69]. However, POTEnCIA (Annex 4) assumes a rather stable installed power (but an increasing use of PSH), and most of the power capacity of new storage technologies is assumed to be mainly from batteries.

Several studies have quantified the energy storage potential in new PSH, with different levels of constraints (see Quaranta et al., 2024[70], for details on theoretical and technical potential definitions, and for a complete review). When just looking at the feasible technical potential, Stocks et al., (2021)[71] estimated that for the EU, the theoretical energy storage potential is 339 TWh in closed-loop PSH, out of which 25 TWh are below 1000 US$/kW and 88 TWh are above 2000 US$/kW. Hunt et al. (2020) identified 50 TWh of seasonal energy storage in EU by open-loop PSH, and 173 TWh by considering cascade effect (i.e., a downstream reservoir can store and release water coming from the upstream ones). Cascade effect was also found to reduce energy storage cost by 30%. The assessments of Stocks et al. (2021) and Hunt et al. (2020) did not consider restrictions on population, land use, biodiversity, transmission, etc., so they present the existing potential and not its viability. Therefore, a real technical opportunity for PSH expansion is first of all expanding the operating range of the existing ones, e.g. by introducing smart sensors, variable speed turbines with increased efficiency and system optimization.

Since one of the most limiting factors in the potential use of large-scale greenfield PSH with two reservoirs is that not many locations could offer economically viable deployment, new strategies that do not require the construction of new dams are under investigation. Reservoir interconnection, abandoned mines, virtual energy storage gains resulting from the spatio-temporal coordination of hydropower across Europe (especially the connection with the Norwegian grid) and the upgrading of existing PSH (including dam heightening) are opportunities for pumped-storage hydropower and to balance generation variability[72,73]. The realisable potential achievable by interconnecting reservoirs within 20 km distance is +4 TWh in the EU (Gimeno-Gutiérrez and Lacal-Arántegui, 2017). When a maximum distance of 5 km is considered, the realisable energy storage potential reduces to 141 GWh in the EU. Spatio-temporal coordination can reduce the energy storage demand by 140 TWh in Europe over 3-5 years (Wörman et al., 2020). Underwater PSH, low-head energy storage [74] and underground PSH using abandoned mines[r] are under investigation, and the associated potential of the third one (i.e. abandoned mines) is approx. 5 TWh (3 TWh the least expensive sites). Energy could be stored using existing lakes, small depressions or retention basins on a terrain in sustainable urban drainage systems. In France, the potential of PSH from small lakes and reservoirs was estimated to be about 33 GWh, which, according to Quaranta et al. (2024), is approximately 38% of the current national technical energy storage capacity of PSH [75]. Existing reservoirs can be paired to new reservoirs at higher altitudes. In Switzerland, dam heightening implemented at the national scale would increase storage capacity by 30%[76].

Countries with redundant PSH potential could look for increasing their potential market share by selling their services to neighboring countries. Opening cross-border markets for balancing capacities could also serve as an important incentive to increase the use of the existing PSH capacity[35].

The role of pumped-storage in the energy transition should not only focus on energy storage. Pumped-storage should complement the operation of existing reservoirs and lakes to enhance water management. The frequency of floods and droughts in Europe is increasing with climate change. Apart from mitigating climate change, PSH could increase adaptation to climate change by providing valuable long-term water storage, storing water during flood events, and using the water during drought periods. Also, they can store energy on a seasonal scale, storing excess solar power during summer to generate electricity during winter [77]. In Southern European countries, new reservoirs could mitigate the already visible effects of climate change (floods, droughts and fire, and to compensate hydrological changes due to glacier retreat [78]).

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

A recent study of Stocks et al. (2024)[79], better detailed in Appendix 5, found the following results for the potential of PSH in the EU (Table 9), considering both options in unprotected and protected natural areas.

Table 9. Energy Potential [Gigawatt-hours] of Non-overlapping PSH Sites (European Union). All" is not equal to the sum of protected potential and unprotected potential, because some sites in protected areas may overlap with sites outside protected areas (see Annex 5).

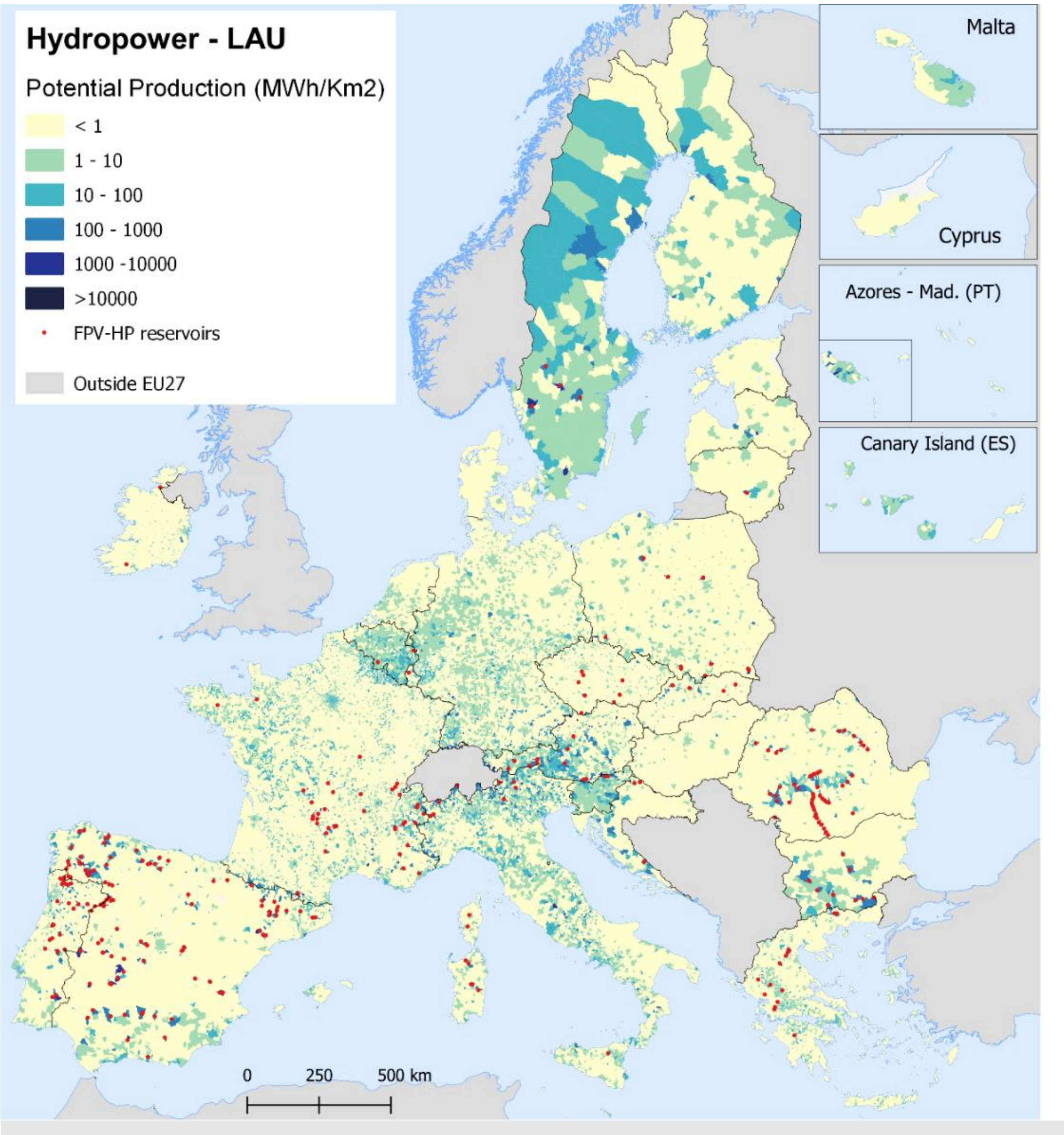
Atlas Type	Unprotected areas	Protected areas	All
Greenfield	507,327	1,461,208	1,774,220
Bluefield	64,150	88,102	113,024
Brownfield	2347	3427	4240
Ocean	114,599	301,449	416,048
Turkey	91,738	435,897	514,107
Totals	654,788	1,799,980	2,246,795

Source: Annex 5

Additional strategies to increase generation include hybridization with other energy technologies. For example, run-of-river plants can produce hydrogen when energy prices fall to zero. Batteries [80] can ensure energy storage for several hours, whilst hydropower can store and release energy for days and weeks, including seasonal transfer, and batteries and hydropower can be integrated together [81]. Reservoirs can host floating PV, or PV could be installed on dam surfaces [82]. Methane capture processes are under investigation, but R&D is further needed to improve cost-effectiveness (this measure is especially relevant for tropical reservoirs, while not very relevant in European reservoirs, with a few local exceptions)[14].
Figure 10 shows the potential for additional energy generation (from hydropower) in the EU, with focus on modernization and hidden hydropower in Water Distribution Networks (WDNs), wastewater Treatment Plants (WWTPs) and water mills. For further details refer to Perpiña Castillo et al. (2024). Table 10 summarizes the hidden potential in the EU (or Europe) assessed in scientific studies[s].

[s] Some of these studies have used the European hydropower database developed by the JRC, including coordinates, type, installed power, and, in most cases, gross head, annual energy generation and water storage capacity. This database was used in a recent study (Quaranta and Muntean, 2023) with an estimation of turbine type, number of units and turbine's rotational speed. Further work is needed to integrate this database with existing ones.

Figure 10 Hydropower additional potential production in EU's municipalities estimated from modernization of aged plants, new development in water distribution networks, wastewater systems and water mills. Potential is shown by municipality unit area. Red dots represent suitable hydropower reservoirs for FPV systems. LAU is Local Administrative Unit. For further details refer to Perpiña Castillo et al., (2024).



Source: JRC

Table 10. Potential of different hydropower and PSH strategies (in the EU when not specified).

Hydropower strategy	Potential	Comment
Closed-loop pumped-storage hydropower (PSH)	339 TWh (25 TWh the cheapest sites)	Stocks et al., (2021)[71], EU, theoretical energy storage
Open-loop (or, mixed) seasonal PSH	50 TWh (10 TWh the cheapest sites), or 173 TWh with cascade effect	Hunt et al., (2020)[83], EU, theoretical energy storage
Spatio-temporal coordination of hydropower reservoirs	140 TWh	Wörman et al., (2022)[72], interconnection between 1200 km and 3000 km, Europe, reduction of energy storage demand over 3-5 years
Reservoir interconnection	29 TWh in Europe, 4 TWh in the EU (max 20 km distance among reservoirs), 198 GWh and 141 GWh, respectively (max 5 km distance).	Gimeno-Gutierrez and Lacal-Arantegu (2015)[73], theoretical energy storage
Sea water PSH	t.b.d.	Kougias et al., (2019)[19]
PSH in mines, underground PSH and low-head PSH	5 TWh of PSH in mines	Menendez et al., (2017)[84], Hoffstaedt et al. (2022), Weber et al. (2024)[85], more details in Quaranta et al. (2024)[70]
Hydropower plant modernization	40 TWh/y	Quaranta et al., (2021)[34], Quaranta and Muntean (2023)[14], additional energy generation
New reservoir-hydropower in deglaciarized areas	11 (0.76) TWh/y	Farinotti et al. (2019)[86], energy generation from all (and from the most suitable) sites
Powering of Non-Powered Dams (NPDs)	1.75 GW	Garrett et al., (2021)[87], Europe
New RoR small hydropower plants	10^1 TWh	tens of TWh/y, Quaranta et al., (2022), and Bodis et al., (2015)
Existing historic barriers not mill-related	5.2 TWh/y	EU+UK, Punys et al., (2019)
Water Utilities (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 (2023)[14]
Water wheels in existing mills	1.6 TWh/y	Quaranta et al., (2022)[65]
Rainfall on building roofs	0.5 TWh/y	Quaranta et al., (2022)[88]
Hydrokinetic turbines in rivers	0.17-1.2 TWh/y	Quaranta et al., (2022)[65]
Pressurized conduits for irrigation and industrial flows	<0.1 TWh/y	EU+UK, Mitrovic et al., (2021)[89]
Floating PV (evaporation reduction)	<0.1 TWh/y	Quaranta et al., (2021)[34], 10% of reservoir surface coverage
Floating PV (FPV) on hydropower reservoirs	139 TWh/y/729 GWp	Kakoulaki et al., (2022)[90], covering 10% of 1608 km^2 of EU's reservoir surface, associated to 49 GW of hydropower installed capacity and 94 TWh/y of hydropower generation / Lee et al., (2020)[12], Europe, 14% of reservoir's surface coverage

Source: scientific literature

2.3.5 The role of the European Investment Bank in the hydropower sector

The European Investment Bank (EIB) is the lending arm of the European Union and the largest multilateral bank of the world[t]. EIB investments are driven by the EU's priorities; any project the Bank funds has to comply with EU rules and standards, whether it is inside or outside the Union. Over the last decade, the EIB has contributed substantially to the development of the hydropower sector globally, investing nearly EUR 3.4 Billion across 63 hydro operations that have resulted in almost 10 GW of new hydropower capacity. The Bank has an ambitious pipeline of more than 40 new hydro operations across the world, representing over EUR 7 Billion in investments in the sector and approximately 23 GW of additional hydro capacity.

The EIB has played a pivotal role in promoting sustainable, flexible, and reliable hydropower projects across the EU, committing EUR 2.3 Billion in financing for these efforts between 2012 and 2021. With the 2021-2025 Climate Bank Roadmap[u] and in the context of the energy crisis, the EIB has scaled up support to renewable energy projects, helping to meet the objectives of the REPowerEU program, which is designed to reduce dependence on fossil fuels and limit energy market disruption.

The EIB currently has 13 new hydropower operations under appraisal across the EU. They are expected to support EUR 2.1 Billion in future investments. These projects have a combined planned capacity of 4.5 GW, including both new build and rehabilitation of existing infrastructure. When including potential hydropower investments in EU's Candidate Countries, the Bank's total European hydro lending volume sums up to EUR 3.2 Billion, which could support 8.35 GW of future hydro capacity.

The analysis of the EIB's hydropower portfolio from 2012 to 2021 shows that during this decade the Bank financed 31 hydropower projects in the EU. These projects include a mix of small to medium size run-of-the river schemes, as well as the construction of three large PSH – two in Austria (Reisseck II 450 MW and Obervermuntwerk II 360 MW) and one in Portugal (Gouvães 880 MW, part of the Tamega scheme).

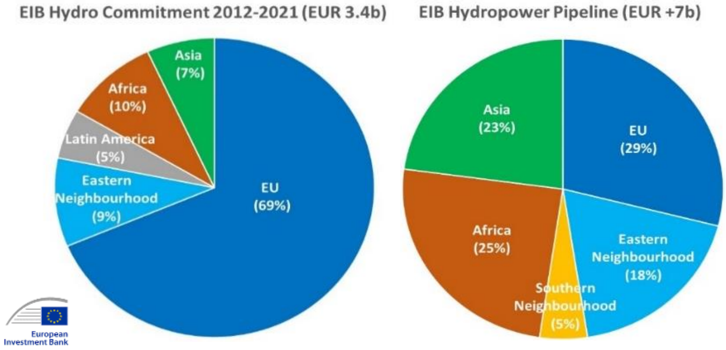
The EU's future hydropower pipeline demonstrates a clear shift, with 9 out of 13 new projects being pump-storage plants (PHS). The Bank is responding to the increasing demand for flexible, ancillary services from the grid. Hydropower, especially pump-storage, is seen as a cost-effective solution to address the flexibility challenges facing the EU's interconnected energy system. At the sub-regional scale, the ability of PHS to absorb overgeneration from intermittent renewables like wind (36% of the EU renewable energy mix) and solar (14%)[v] has further driven the EIB's pipeline towards pumped-storage projects. It has also established the EIB as a leading financier of PHS developments.

Significant future investment in pumped-storage includes the construction of the 200 MW Salto de Chira PHS in the Canary Islands (Spain) and the upgrading of the 1010 MW Kruonis PHS in Lithuania. The construction of the new 680 MW Amfilochia PHS in Greece is also being considered for EIB support. Additionally, the hydropower pipeline indicates a substantial increase of requests for EIB funding from EU Candidate Countries, such as Albania, Serbia, Ukraine and Georgia. These countries have embraced the ambitious renewable targets of the Union and see the EIB as a strategic and technically knowledgeable partner.

The pipeline of EIB hydropower projects demonstrates a more even distribution across regions compared to past commitments (Figure 11). Sub-Saharan Africa and Southern Neighbourhood Countries (such as Tunisia and Morocco) now account for a combined share that nearly equals that of EU countries. The EIB's increased global presence in sectors like energy infrastructure, as well as the change in its hydropower portfolio, is linked to the catalysing effect of the EU's Global Gateway Initiative. This initiative aims to combat climate change and eradicate poverty worldwide.

[t] Source: Multilateral Development Bank (MDB): Types And Examples (investopedia.com)
[u] The EIB Group Climate Bank Roadmap 2021-2025
[v] Source: E. Quaranta, The future of sustainable hydropower in the EU: challenges, projections and opportunities, European Commission Joint Research Centre, Italy

Figure 11. EIB Hydropower Portfolio by Regions. Past Commitment vs. Pipeline.



Source: EIB

Most new hydropower projects have been proposed in the last two years, and the EIB has been able to quickly provide financing inside the EU. The Bank supports hydropower projects that meet its energy lending criteria[w] and comply with its environmental, climate and social guidelines for hydropower development[x].

The EIB Group is playing a crucial role in accelerating Europe's shift to green energy. Hydropower is a key part of this energy transition, as it provides flexibility to the power grid and allows for greater adoption of other renewable sources. As the EU's "Climate Bank", the EIB is fully committed to financing modern, sustainable hydropower projects. This is essential for helping Europe achieve its goal of becoming climate-neutral by 2050.

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 (LCOE). IRENA and the World Bank's analysis identified hydropower as currently one of the most economical forms (in the long term, considering the life span) of renewable electricity generation [91]. One of the main advantages of hydropower stations is that the operating cost is low and generally very stable since it does not depend on fuel cost. Moreover, hydropower stations have a long service life (assumed 40-50 years), with the civil works even reaching 80-100 years (in Europe the average age of the hydropower fleet is almost 45 years, hence hydropower refurbishment is of strategic relevance [34]). However, new large hydropower projects are 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).

Table 11 depicts the approximated share (in %) of civil, mechanical and electrical components in the total capital cost of different hydropower plants.

[w] https://www.eib.org/attachments/lucalli/20230164_eib_energy_lending_policy_en.pdf
[x] https://www.eib.org/attachments/publications/eib_guidelines_on_hydropower_development_en.pdf

Table 11. Capital cost breakdowns for the main types of hydro in Europe, 2021. Civil: Dam, tunnels, piping, powerhouse (aboveground or underground), roads. Mechanical: turbine, penstock, gates, valves, hydraulics. Electric: generator, transformer, cabling, grid connection.

Hydropower type	Civil	Mechanical	Electric
Large-scale Reservoir hydropower	70%	10%	20%
Run of river (Large-scale and small-scale)	50%	30%	20%
Pumped-storage hydropower	50-70%	15-20%	15-30%

Source: IRENA, 2022

In 2022, the global weighted-average (based on the power) LCOE for new hydropower stations (greenfield projects) was EUR 57/MWh, 18% higher than in 2021 (and EUR 30/ MWh for onshore wind and EUR 45/MWh for PV) [91]. However, the economic benefits associated to the multiple services provided by hydropower are not included in the LCOE (flexibility, ancillary services, water management and supply of reservoirs, among others). 96% of the hydropower projects commissioned in 2021 had an LCOE 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 [91].

The LCOE of new hydropower projects (covering all types) in Europe including Turkey is approx. 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 reservoir hydropower including pumped-storage power plants are in the range of 80 EUR/MWh to 140 EUR/MWh with an average around 100 EUR/MWh. The generation costs of small hydropower projects (below 10 MW), generally run-of-river, typically are 40% to 60% higher. When considering refurbishment projects, the cost ranges between 20 and 30 EUR/MWh[11].

The difference of hydropower with variable renewable energy sources (RES), such as wind and PV, is that the deployment cost is exhibiting 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, a big share of the installation cost of a hydropower project is for the civil works, whose cost typically increases at rates subject to construction cost inflation[92]. The LCOE cost in Europe are depicted in Figure 12.

The CAPEX of recent large hydropower projects of all types may be EUR 1500 per installed kW (including civil works) with a range between 1000 EUR/kW (5° percentile) and 4000 EUR/kW (95° percentile). Run-of-river power plant projects may be situated in the range of 1000 EUR/kW to 1800 EUR/kW with average at 1400 EUR/kW, whereas reservoir hydropower including pumped-storage hydropower are in the range of 1400 EUR/kW to 4000 EUR/kW with an average of about 2500 EUR/kW. The CAPEX of small hydropower projects (below 10 MW), generally run-of-river, typically are 40% to 60% higher[y]. The cost per kW of run-of-river power plants is investigated in detail in Patro et al. (2022) [z, 93]. Micro-hydropower projects exhibit an usual overall cost of EUR 5000/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 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.

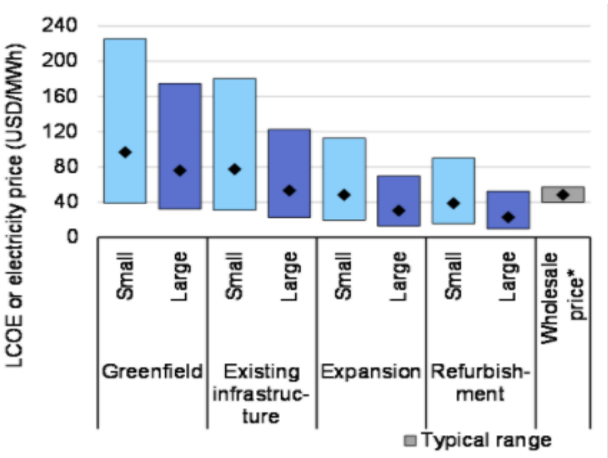
Annual operation and maintenance (O&M) costs are often quoted as a percentage of the

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

[z] In Patro et al., (2022) equations to estimate the cost of different ROR plants (diversion, in-stream, canal type) are presented. They 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.

investment cost per kW per year, with typical values ranging from 1% to 4%. Operation and salaries take the largest slices of the O&M budget. Maintenance varies from 20% to 61% of total O&M costs, while salaries vary from 13% to 74%[91]. 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[91]). 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 and increase generation[aa]. Materials are estimated to account for around 4% [91].

Figure 12. LCOE costs and wholesale price of hydropower in the European Union[11].



Source: ETIP Hydropower

Hydropower plants are site-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 exploited (e.g. in the EU), the remaining technical potential usually refers to less advantageous sites with 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 generation and installation costs up to 2050 is mostly influenced by the market inflation. Due to improvement in construction efficiency, mainly of underground works, construction costs may be reduced for reservoir and pumped-storage hydropower 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. For example, pumping operation of PSH 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 1000 MW and Grimsel III 600 MW in Switzerland, Atdorf 1400 MW and Waldeck II plus 300 MW in Germany (IHA, 2022, Voith

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

Hydro, 2023, pers. comm.).

Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, hence investment risks for large hydropower schemes 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. As of 2022, 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 [110].

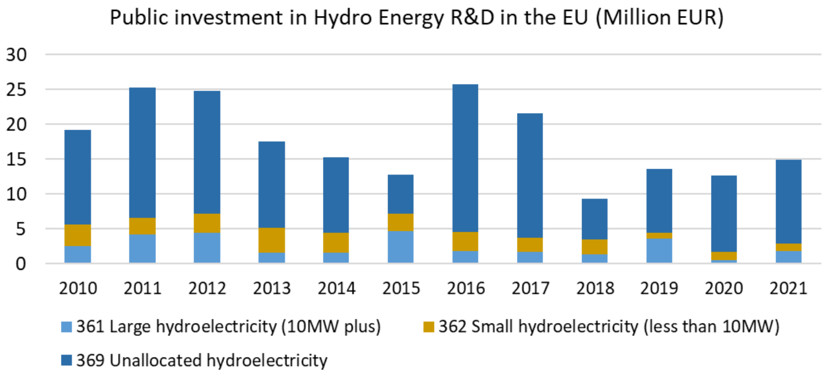
2.5 Public R&I funding

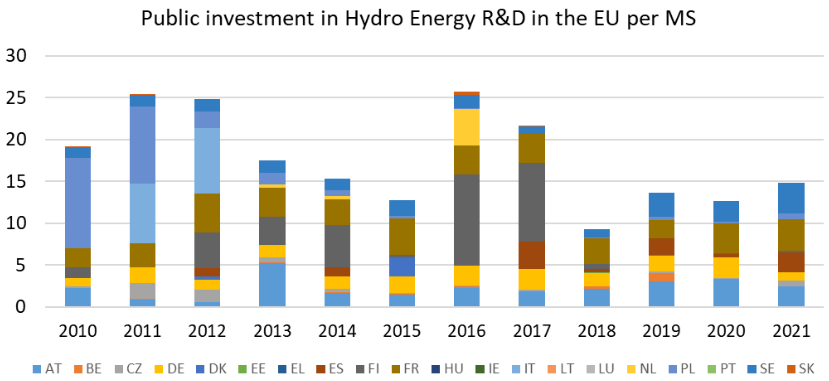
Despite hydropower technological maturity, research efforts are still ongoing to develop new concepts and technologies [19], novel materials [94] and innovative projects [95]. Recent hydropower research and development (R&D) efforts mainly aim at improving the performance of systems and components, sustainability and readiness of hydropower for modern power markets. Hydraulic design and mechanical equipment R&D focus on expanding the flexibility of stations to support a wider range of operation, increasing efficiency levels, and to minimize the environmental impacts, like sediment transport, fish migration impairment and hydropeaking.

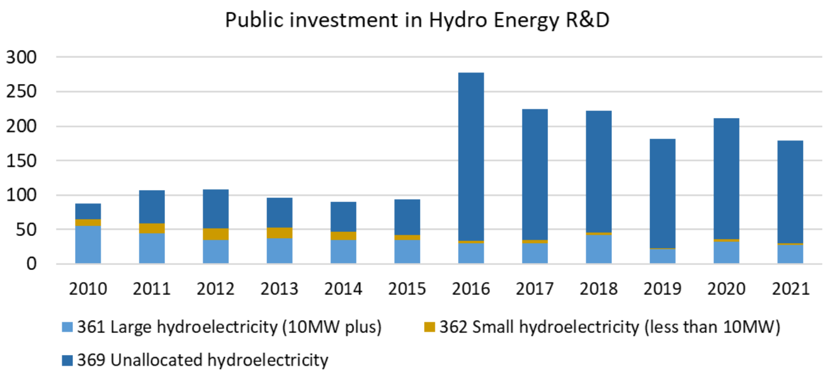
In the last decade (2012-2021), public spending for R&D on hydropower in the EU ranged between EUR 15 Million and EUR 26 Million per year (Figure 13), with decreasing trends after peaks. The main hubs of public spending are Austria, Germany, Finland, France, Italy, Poland and Sweden. Annual public spending 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 14 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 was nearly 12 times lower than that for wind and 20 times lower than that for solar PV in 2021.

Figure 13. EU public R&D investments [EUR Million]. Source: JRC based on IEA data, CIndECS2022. Unallocated=not specified.

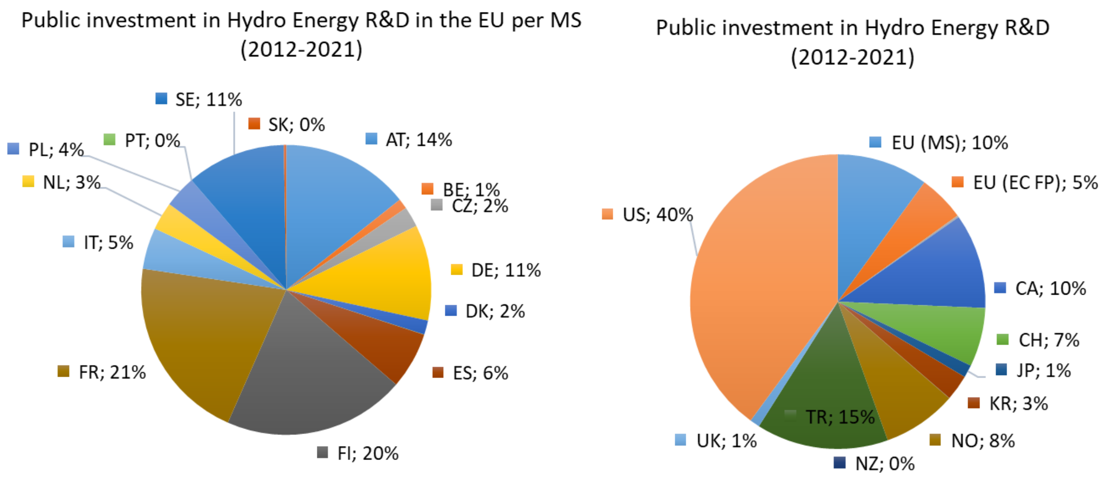






Source: JRC

Figure 14. Public R&D investments in hydropower for the EU member states over the period 2012-2021. Source: CIndECS2022. For the non-EU acronyms, see the Nomenclature list. EU (EC FP) indicates funding form EU framework programmes (H2020) and is only available from 2014 onwards.



Source: JRC

The average public R&D investment is EUR 17 Million on annual basis in the EU (2012-2021), 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., one of the largest sources of public R&D investment for hydropower is coordinated by the Water Power Technologies Office of the United States Department of Energy. The three major federal hydropower owners, the US Bureau of Reclamation, the US Army Corps of Engineers, and the Tennessee Valley Authority, also have R&D programs. The U.S. Department of Energy's Hydropower Program 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[bb]). According to the Water Power Technologies Office Budget | Department of Energy[96], the hydropower budget in 2023 was $59 Million and $120 Million for marine energy. The average over 2016-2021 was $33 Million for hydropower and $77 Million for marine energy. The Bipartisan Infrastructure Law, which passed in 2021, provided an additional $36 Million for U.S. hydropower R&D to be spent between 2022-2025.

2.6 Private R&D funding

Two types of investments are here considered.

(1) Early / late stage investments in companies. Those companies are (or have been) start-ups and growth companies. Investments do not reflect expenditures by those companies. See Annex 2 for further details.

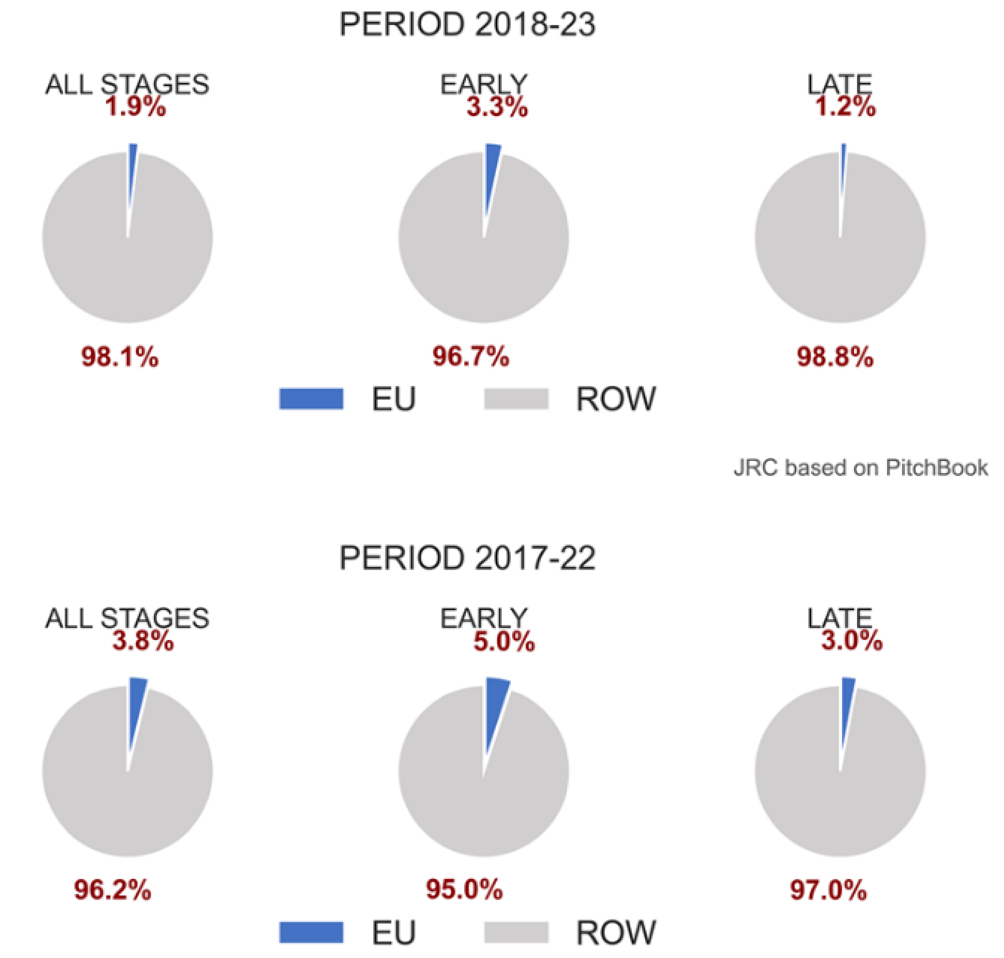
(2) R&D expenditures by the subsidiaries of the largest corporate R&D investors. Expenditures in R&D activities are operational costs and not investments in a company as in (1). Private R&D figures are estimated using patenting output as a proxy.

[bb] Data for the US is available up to 2015. After 2015, we have included old IEA calculations/data. The IEA is in the process of revising this data in cooperation with the US authorities.

There is no connection between (1) the early / late stage investments indicators and (2) the private R&D expenditures indicator, and the population of companies addressed in (1) is totally different from the population of companies addressed in (2).

The early and later stages investments in VC companies over the considered period are depicted in the following figures. The EU hosts 4.5% of investments, mostly in countries connected to the Alps such as France, Germany, Italy and Austria. The U.S. (1st) and France (5rd) rely on a relatively strong base of venture capital companies[cc]. The trend over time is depicted in Figure 16 and Figure 17.

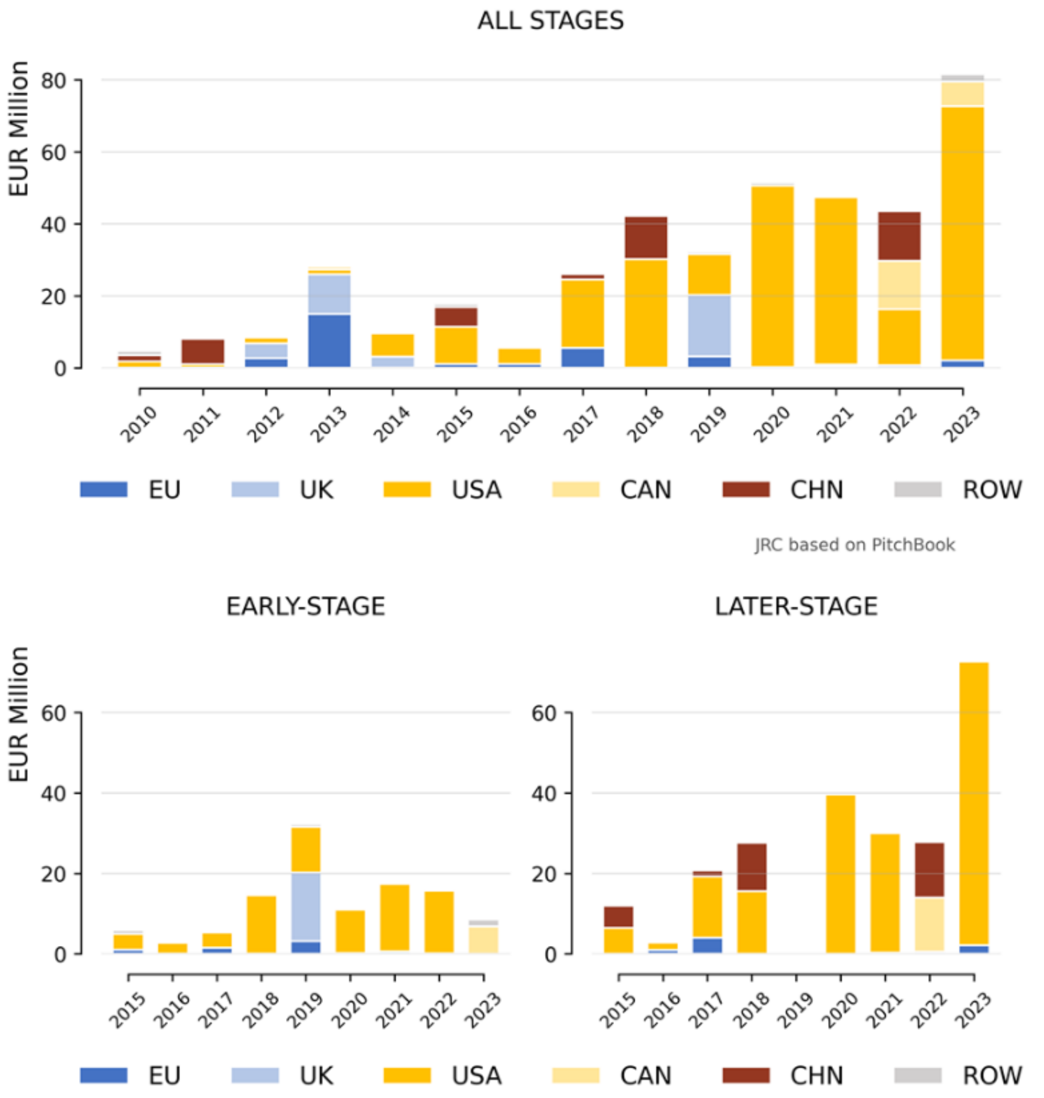
Figure 15. Venture Capital investments. JRC based on Pitchbook.



Source: JRC based on Pitchbook

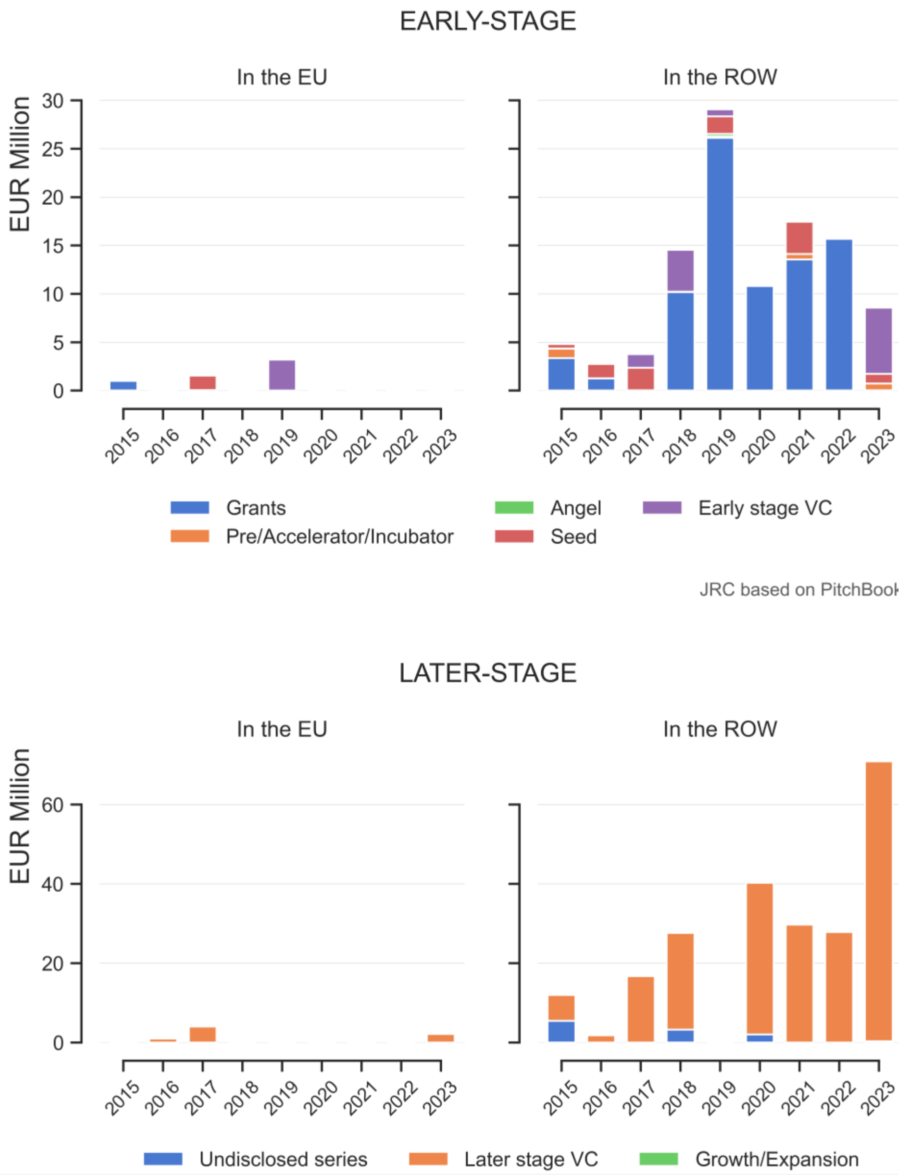
[cc] Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. Venture Capital companies are companies that have been at some point part of the portfolio of a VC investment firm (or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

Figure 16. Trend of early and later stage investments.



Source: JRC based on Pitchbook

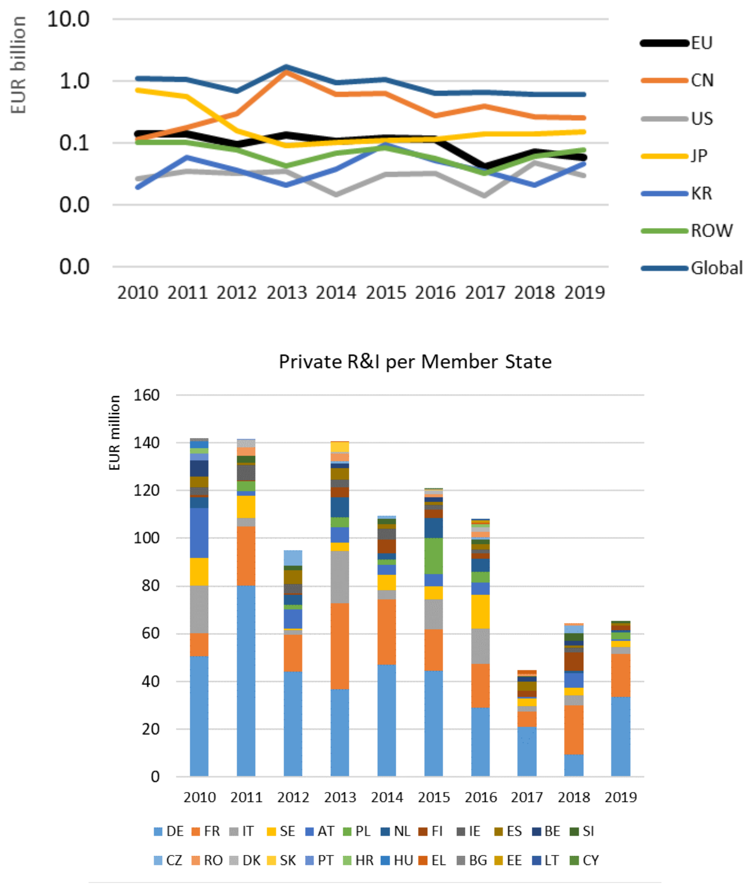
Figure 17. VC/PE (venture capital/private equity) investment by deal type, in the EU (left) and in the ROW (right), for early-stage deals (top) and later-stage deals (bottom).



Source: JRC based on Pitchbook

Considering the R&D investments, Figure 18 shows that China is leading the sector and the global trend follows the Chinese one. In the EU, Germany, France, Italy and Sweden are the member states with the largest contribution. The lead companies are Voith Hydro GMBH (DE), GE Renewable Technologies (FR), Mahle International GMBH (DE), Aktiebolaget SKF (SE), Electricite De France (FR), DIVE Turbinen GmbH Co KG (DE), Andritz Hydro GMBH (AT), Alstom Renewable Technologies (FR), Rehart GmbH (DE), Minesto AB (SE), and Voith Hydro GMBH and GE Renewable Technologies also appear in the top-20 global list.

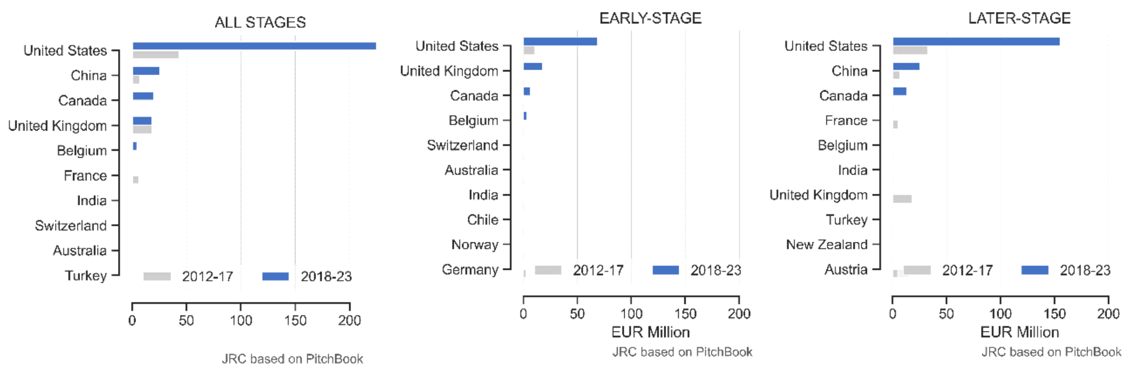
Figure 18. R&D investments.



Source: JRC

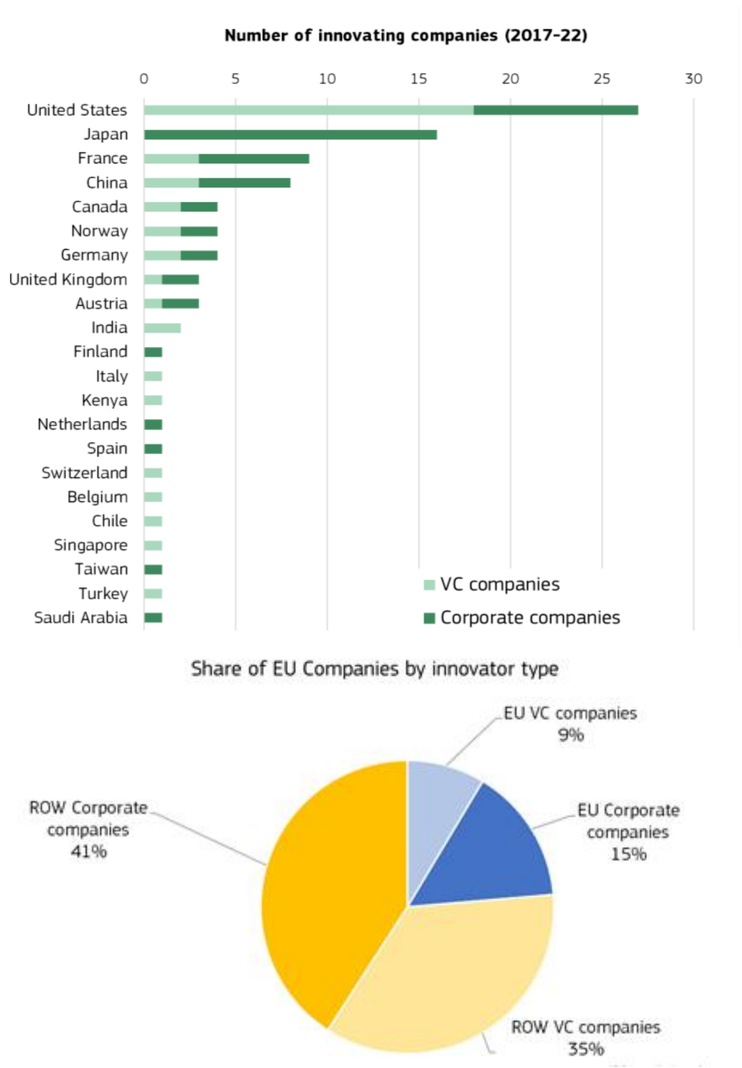
Based on investments, innovative companies can be identified, and Figure 19 shows this data (see Annex 2 for details) aggregated at the country level, while Figure 20 the countries with the largest number of innovative companies.

Figure 19. VC/PE investment in top 10 beneficiary countries, by period for all deals, early-stage deals and later-stage deals.



Source: JRC based on Pitchbook

Figure 20. Innovative companies.



Source: JRC

2.7 Patenting trends

The present patent analysis is 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 [97, 98] and in Annex 3. The number of patents for the EU and other major countries are provided in Figure 21, covering the period 2011-2020. China is the main patent leader (partially also due to the different patenting procedure in the country) while EU, Japan and Korea perform similarly, and better than the U.S.

During the period 2010-2021, 669 patents were registered by companies in the EU, 327 were high-value inventions (i.e. applicants of the EU tend to extend patent families to more than one patent office). Within the EU, Germany is leading in patenting (227), followed by France (111), Italy (59), Poland (59), Sweden (31) and Austria (28). The EU holds 29% of all high-value inventions globally (2019-2021). Germany, France and Italy are the main contributors (Table 12). Therefore, the EU is the lead region in terms of high-value inventions, although this trend is decreasing over the years

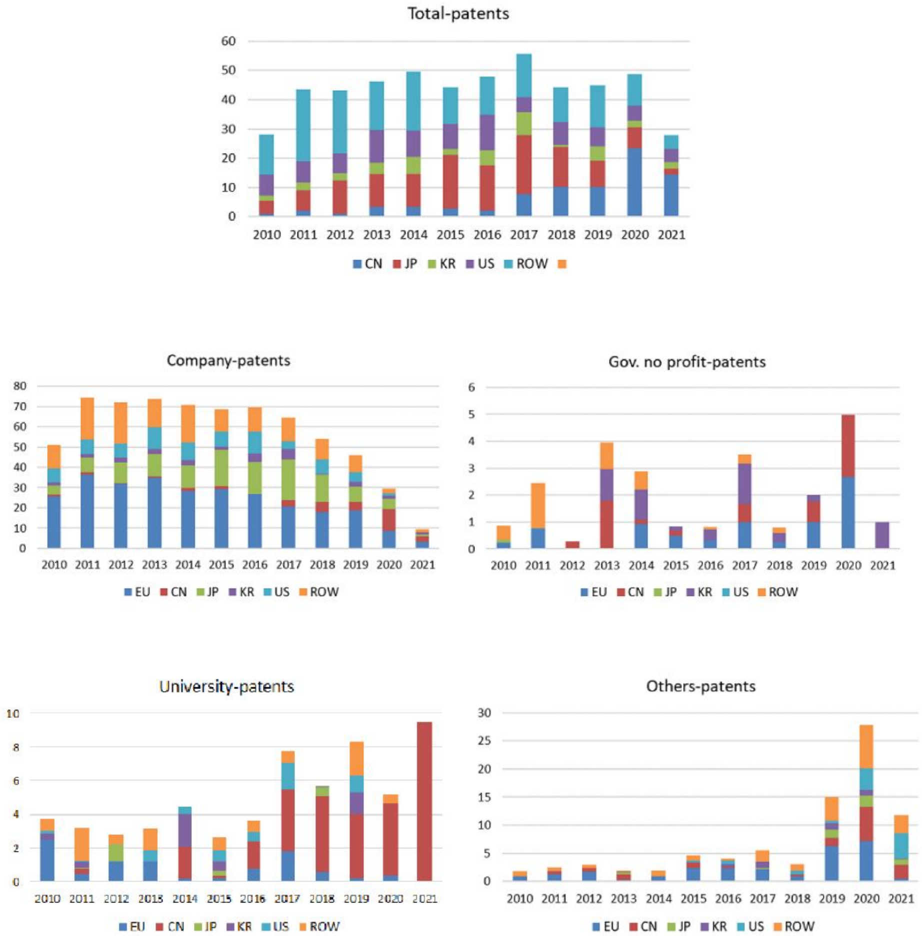
(Figure 21 and Figure 22), probably because it takes time to extend patent protection to other offices.

Table 12. Number of inventions and share of high-value inventions and international activity (2019-2021). Percentages on the total are also calculated.

Number of inventions and share of high-value and international activity (2019-2021)						
	Total	High-value	International	Total	High value	International
ROW	139	30	24	139	22%	18%
JP	193	18	24	193	9%	13%
KR	201	10	20	201	5%	10%
CN	2198	48	17	2198	2%	1%
US	46	16	17	46	35%	37%
EU	116	49	20	116	42%	17%
	EU share	29%	16%			

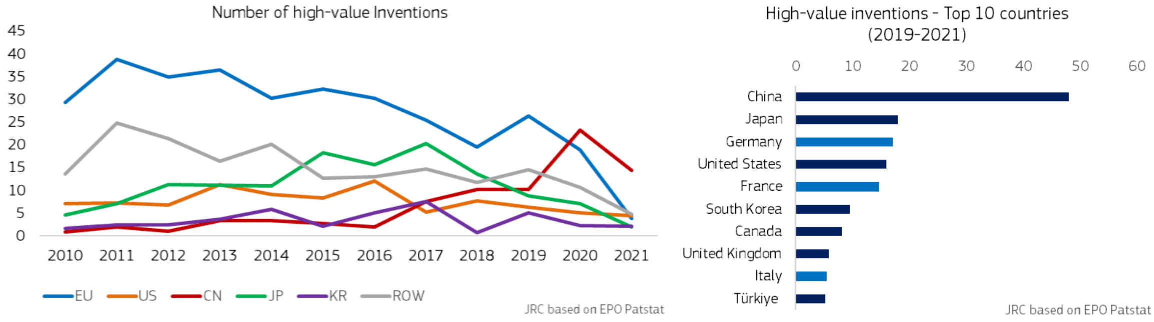
Source: JRC

Figure 21. Patent activity for different owner categories (high-value inventions).



Source: JRC

Figure 22. Number of high-value inventions (left) and Top 10 countries (right).

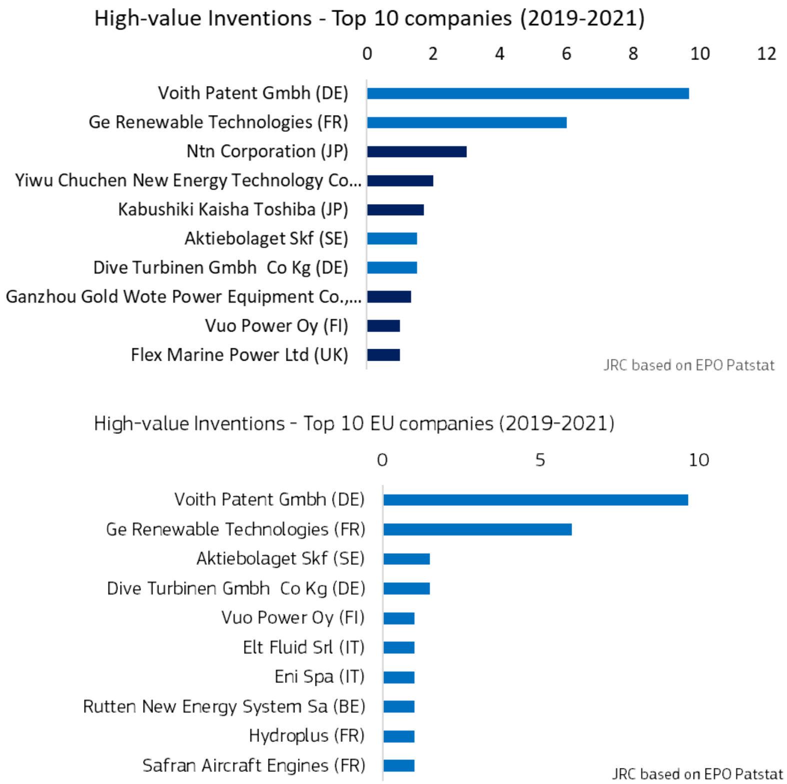


Source: JRC based on EPO Patstat

Figure 23 shows the top-10 companies with high-value invention patenting. Five companies from the EU are in this top-10: Voith Hydro, GE Renewable Technologies (EU branch), Aktiebolaget Skf, Dive Turbinen, Vuo Power Oy, with Voith and GE within the top-3, sharing together 53% of high-value inventions from the top-10 leader companies worldwide.

R&D expenditures by the subsidiaries of the largest corporate R&D investors, based on patenting activity, are depicted in Figure 18. Expenditures in R&D activities are operational costs and not investments in a company as the late and early stage investments (section 2.6). The trend is decreasing from 2010, probably due to the increase of R&D activities and related patenting activities in the other renewable energy sectors.

Figure 23. Top patenting companies.



Source: JRC based on Pitchbook

2.8 Scientific publication trend

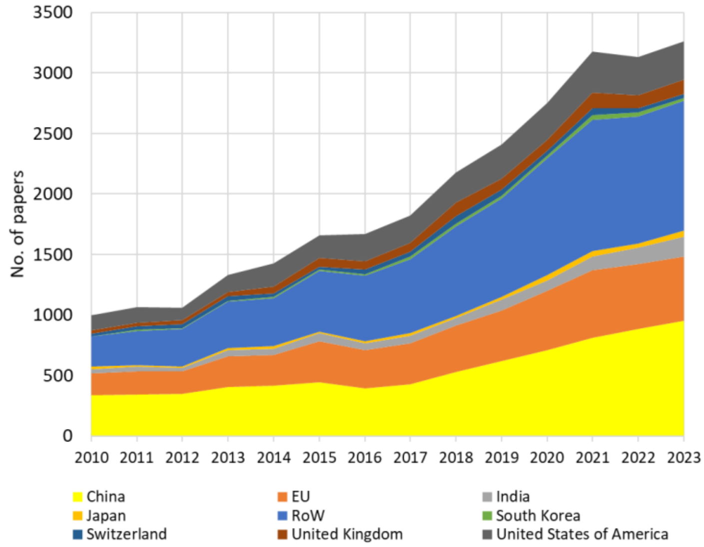
Hydropower research covers a wide range of scientific areas: energy, engineering, environmental and water resource sciences, geology, fisheries and many others. Jiang et al., (2016)[99] observed a rapid growth rate of publications related to hydropower, highlighting the increasing demand for hydropower-related research (Figure 24). 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 [99]. The main hydropower topics researched by EU's institutions are described in Manzano-Agugliaro et al., (2017)[38] (dam and penstock, turbines, social and environmental aspects and control strategies). Six EU countries are amongst the top-ten contributory countries in publishing papers on the topic "Repowering of Small Hydropower Plants" (France, Austria, Spain, Portugal, Poland, Germany) [100]. The same countries, including Italy, appear in the top-ten countries also in other specific topics described in that reference.

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 (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) in Brazil, the EU (with the H2020 and ERC programs), the NSERC (Natural Sciences and Engineering Research Council) in Canada and the NSF (National Science Foundation) in the U.S. [101].

According to Figure 24 and Figure 25, EU's institutions are leading the publication trend, together with China, and this may reflect the leading position of the EU in high-value inventions. In the 2022 CETO report, additional keywords were selected to better analyse the bibliometric trends: "dam" ("hydropower" and "dam" have to be found 3 keywords apart or less in the title or in the abstract), "reservoir" ("hydropower" and "reservoir" have to be found 3 keywords apart or less in the title or in the abstract), 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 of the 2022 CETO report shows the bibliometric trend of these keywords. Comparing the EU with the rest of the world, 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 is taken into account (i.e. number of publications per inhabitant). The main concurrence is exerted by China: Chinese hydropower dam developers dominate the global dam industry nowadays [102]. The percentage of highly cited papers is similar among countries (Table 13).

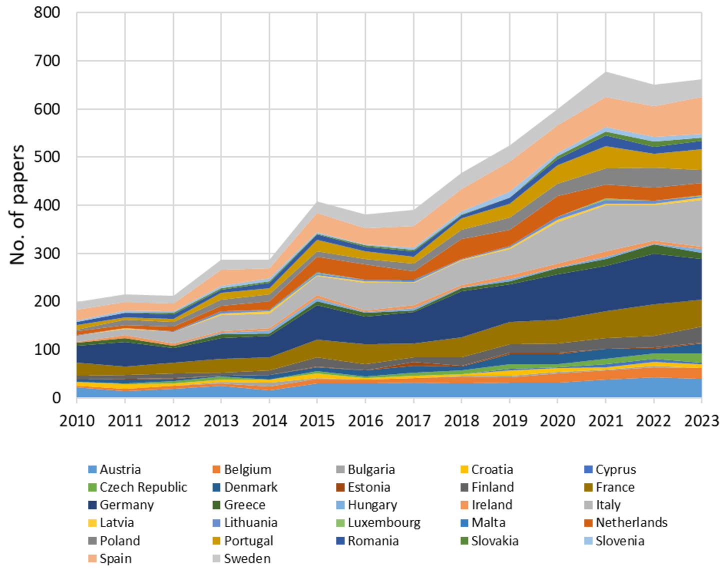
Table 14 lists the first-16 authors, based on number of peer-reviewed publications from 2020 to 2024, according to Scopus ("hydropower" or "hydroelectric" in the keywords or title or abstract). Only two EU authors (including the first author of this report), are in the list. Hydropower research covers 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 are only indicators.

Figure 24. Number of scientific papers published in peer-reviewed journals for the EU and other states.



Source: JRC

Figure 25. Number of scientific papers published in peer-reviewed journals for EU member states.



Source: JRC

Table 13. Highly cited papers on hydropower (top 10% cited normalised per year and field).

	Documents total	Highly cited documents
RoW	9249	14.6%
China	7816	14.7%
EU	5108	16.8%
United States of America	3210	19.8%
United Kingdom	1076	22.8%
India	1069	17.4%
Switzerland	552	21.4%
Japan	374	14.2%
South Korea	228	17.1%

Source: JRC

Table 14. List of main authors and number of papers 2020-2024 (updated at August 2024), under the keyword Hydropower (source: Scopus).

Author	N° of papers
Cheng, C.	100
Liu, P.	56
Chen, D., Liao, S.	44
Zhou, J., Ming, B.	39
Shen, J., Liu, B.	35
Zhang, J., Chen, S.	30
Quaranta, E., Ramos, H.M.	29
Ma, G., Huang, Q.	28
Boes, R.M., Xu, N.	27

Source: Scopus

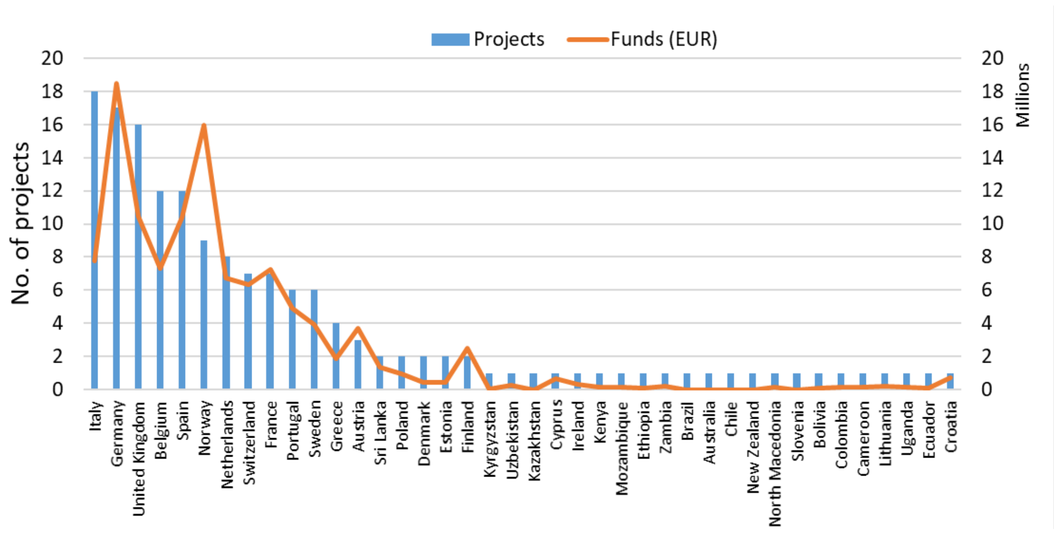
2.9 Assessment of R&I project developments

The European Union has funded several projects in the field of hydropower. From 2015 to 2024, 42 projects have been funded under the Horizon Framework, with a peak in 2018 (10 projects). Figure 26 depicts the received EU contribution for each country, and the total number of projects between 2015 and 2022. 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 equipment. Italy and Germany are amongst the most funded countries, since their territory is suitable both for low head hydropower and for high head plants in the Alpine environment. Different extra-EU countries have been involved, and, in particular: Uzbekistan, Kyrgyzstan, Kenya, Zambia, Mozambique, Ethiopia, Chile, Australia, Brazil, New Zealand, North Macedonia, Colombia, Uganda, Cameroon, Ecuador, Bolivia. Norway and Switzerland are also very active partners.

Table 15 lists some of the Horizon and recent funded projects of the EU, from Cordis database. The three most recurrent topics are hidden and low head hydropower, environmental mitigation and increase of flexibility. It is worth mentioning the research projects Hydropower Europe (now, ETIP Hydropower) and PEN@Hydropower. The former 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. PEN@Hydropower aims at establishing a Pan-European network for a sustainable, digitalised Hydropower contributing to the Clean Energy Transition (CET), made of a united network of researchers, engineers and scholars to facilitate close collaboration among European research groups through projects supporting sustainable hydropower.

Recent Horizon calls deal with hidden hydropower opportunities[dd] (see also Quaranta et al., 2022, typically associated to low head hydropower), hydropower digitalisation[ee] (associated to flexibility, Quaranta et al., 2021, Kougias et al., 2019, Quaranta et al., 2023[106]), pumped-storage hydropower[ff] and sustainable refurbishment[gg, hh] (see also section 2.3). An additional international and comprehensive activity on hydropower, where the JRC and RTD have been involved, is the Hydropower Roadmap of the International Energy Agency, in particular the Annexes Hydropower & Fish and Hidden Hydropower opportunities[ii]. Another similar programme to that of IEA-Hydropower is the one organized by The European Energy Research Alliance (EERA), which expedites a low-carbon energy research platform for 250 organisations and 50,000 researches from 30 countries. The Joint Programme Hydropower[jj] is one of 18 programmes and supports the role for hydropower as an enabler for the renewable energy sector. The main target is the support of current demands and R&D activities in the hydropower sector. The exploratory activity SustHydro, coordinated by the Emanuele Quaranta at the JRC, aimed at identifying sustainable and hidden hydropower opportunities in the EU to support the previous activities and EU's policies (see e.g. Quaranta et al., 2021, Quaranta et al., 2022).

Figure 26. Received funds and number of projects by country (Interreg projects not included), 2015-2022.



Source: JRC

[dd] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d3-03-11
[ee] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d3-03-08
[ff] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2024-d3-01-16
[gg] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2023-d3-02-09
[hh] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2024-d3-01-07
[ii] https://www.ieahydro.org/work-programme/
[jj] https://www.eera-hydropower.eu/

Table 15. List of Horizon projects (2015-2022) and number of partners.

Starting date	Title	Total cost of the project (EUR).	Project acronym	Partners
2024	Revolutionary refurbishment for an efficient and eco-friendly hydropower	3999951	RevHydro	8
2024	new Solutions for Hydropower plants to Enhance operational Range, Performance and improve environmental impAct		SHERPA	7
2024	Innovative storage technology and operations in hydropower		STOR-HY	15
2024	Demonstration of sustainable hydropower refurbishment	7 506 337	REHydro	16
2024	Novel long-term electricity storage technologies for flexible hydropower	4315796	Store2Hydro	8
2023	Digital solutions for improving the sustainability performance and FLEXibility potential of HYDROpower assets	4 038 519	D-HYDROFLEX	7
2023	DIGITAL MAINTENANCE FOR SUSTAINABLE AND FLEXIBLE OPERATION OF HYDROPOWER PLANT	4000000	Di-Hydro	7
2023	intelligent Asset Management Platform for Hydropower operation and maintenance	4100000	iAMP-Hydro	7
2022	Hidden Hydro Oscillating Power for Europe	4854230	H-HOPE	9
2021	Hydropower For You - Sustainable small-scale hydropower in Central Asia	11488428	Hydro4U	12
2020	Modeling Energy for Sustainable Development in Ethiopia	183473	MEND	2
2020	Augmenting grid stability through Low-head Pumped Hydro Energy Utilization & Storage	4996825	ALPHEUS	6
2020	An innovative axial turbine for conversion of hydro-kinetics energy to electricity in rivers and canals	2192125	HyKinetics	2
2019	Predicting changes in species interactions following species loss in hydroelectric reservoir islands	183454	Lost-Biodiv	1
2019	HYdro-POwer-Suite	2397120	HYPOS	5
2020	RIver flow regulation, fish BEhaviour and Status	4048220	RIBES	4
2019	Interoperable solutions for implementing holistic FLEXIbility services in the distribution GRID	8544133	FLEXIGRID	6
2019	A revolutionary HYDRO POWER technology to sustainably exploit super-low-head water steps	3511500	Turbulent	1
2019	Hydropower solutions for developing and emerging countries	2938374	HYPOSO	13
2019	Hydropower Extending Power System Flexibility	18162950	XFLEX HYDRO	7
2019	Waterjade: the global platform to predict water resources	71429	Waterjade	2
2019	A scalable and sustainable grid-scale energy storage system utilising 3rd generation flywheel technology for effective integration of renewable energy.	3465625	Teraloop EES	2
2018	Energy from water in motion: efficient, customisable off-grid hydro-electricity for rural areas with stream access	71429	HYDROGO	2
2018	HYDROPOWER-EUROPE	993571	HYDROPOWER-EUROPE	4
2018	Kinetic Micro Hydro System for electrification of rural areas.	71429	SMART Slowflow	2
2018	A highly scalable grid-scale energy storage system utilising 3rd generation flywheel technology for effective integration of renewable energy.	71429	Teraloop ESS	2
2018	Statistically combine climate models with remote sensing to provide high-resolution snow projections for the near and distant future.	180277	CliRSnow	2
2018	Increasing the value of Hydropower through increased Flexibilty	5716989	HydroFlex	5
2018	An innovative axial turbine for conversion of hydro-kinetics energy to electricity for river applications.	71429	HyKinetics	2
2017	A EUROpean training and research network for environmental FLOW management in river basins	3923989	EUROFLOW	8
2017	Environmentally efficient full profile drilling solution	2811875	ECO-DRILLING	2
2017	Water flow kinetics energy exploitation for mini/micro hydropower plants.	71429	RIVER-POWER	2
2017	Development of a novel wave tidal energy converter (WATEC) to lower renewable electricity generation costs.	71429	WATEC	1
2017	Quantifying ecological effects of small hydropower in Alpine stream ecosystems	180277	SHYDRO-ALP	2
2016	A GLOBAL MOVEMENT FOR ENVIRONMENTAL JUSTICE: The EJAtlas	1910811	EnvJustice	2
2016	Fishfriendly Innovative Technologies for Hydropower	7171550	FIThydro	9

2016	DAFNE: 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.	5420223	DAFNE	11
2016	Adaptive Management of Barriers in European Rivers	6238104	AMBER	10
2016	Knowledge Exchange for Efficient Passage of Fishes in the Southern Hemisphere	135000	KEEPFISH	8
2015	PROFITABLE LOW HEAD HYROPOWER	1512893	Hydrolowhead	2
2015	An online software platform for effectively matching investors with start-ups, focused on boosting the cleantech sector	71429	CAGIX	2
2015	Bringing INnovation to onGOing water management – A better future under climate change	7822423	BINGO	6

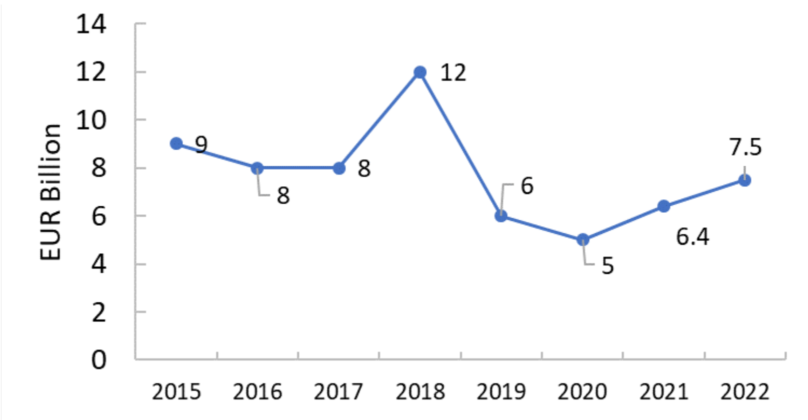
Source: JRC

3 Value chain Analysis

3.1 Turnover

The annual turnover of hydropower electricity generation in the EU is depicted in Figure 27[103]. Leading Member States in terms of turnover in 2021 were Austria (EUR 0.81 Billion), Italy (EUR 0.91 Billion), France (EUR 2.2 Billion), Spain (EUR 0.46 Billion) and Germany (EUR 0.72 Billion). In 2022, leading member states were France (EUR 0.56 Billion), Italy (EUR 0.95 Billion), Austria (EUR 1.1 Billion) and Germany (EUR 1.1 Billion). According to 2021 data, European hydropower manufacturers spend more than 5% of annual turnover on R&D, which is more than twice the European industry average[101]. The greatest turnover was approximately EUR 12 Billion in 2018. Turnover is increasing from 2020. However, the real dimension of turnover could be much higher, going beyond EUR 100 Billion (Prognos, 2024), if including also civil works in addition to the equipment.

Figure 27. Hydropower turnover in the EU, from Eurostat.

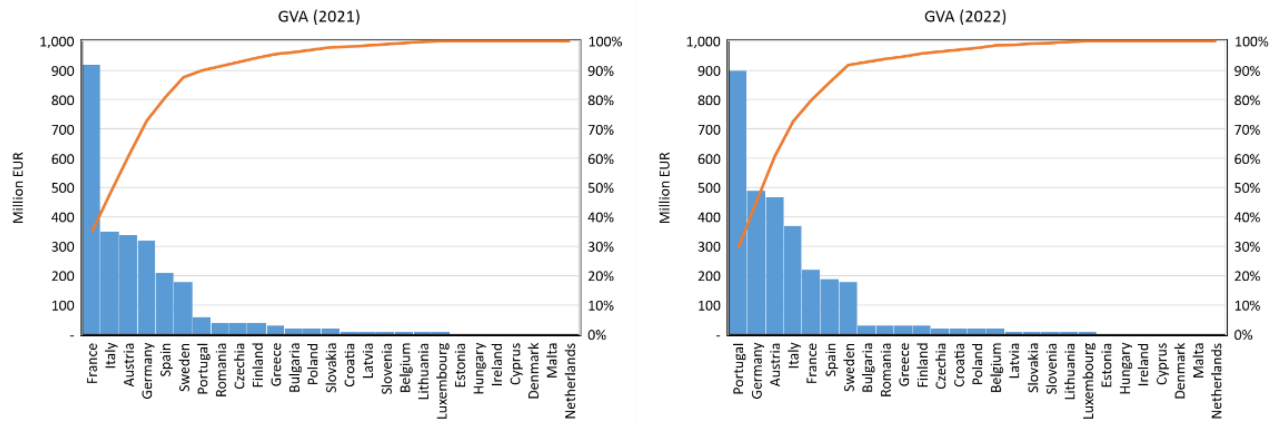


Source: Eurostat

3.2 Gross value added

EurObserv'ER provides an estimate of Gross Value Added (GVA) based on a uniform modelling methodology for all technologies (Figure 28). The estimate is based on the recorded money flows into 1) new installations; 2) O&M of existing capacity; 3) production (section 3.6, EUR 605 Million in 2023) and trade of equipment (section 4.2, extra-EU export of EUR 171 Million in 2023); 4) production and trade of biomass (not relevant for hydro), which are converted to GVA using different technology specific factors – both direct and indirect effect is included, but not induced effect. Gross value added is the total value of output in the sector minus the value of intermediate consumptions and therefore, used as a measure of the contribution to GDP. The GVA of the hydropower sector, according to EurObserv'ER, in 2021 and 2022 is depicted in Figure 28: the EU's GVA was EUR 2.72 Billion in 2021 (EUR 1.95 Billion in 2020) and EUR 3.14 Billion in 2022, with an increasing trend. According to Prognos analysis, the GVA in manufacturing in 2021, 2022, 2023 was EUR 210, 180, 250 Million, in construction and operation it was EUR 22.6, 18.4, 18.7 Billion, and in Research and Development it was EUR 29, 13 and 14 Million, respectively.

Figure 28. Gross Value Added (GVA) for each EU member state in 2021 (left) and 2022 (right), EurObserv'ER's data.



Source: EurObserv'ER

Hydropower contribution to the economy also includes energy generation, ancillary services and multiple services (the latter are mainly associated to the water reservoirs and the hydraulic/civil infrastructures). According to some estimate of 2015, overall, 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. GVA accounts for nearly EUR 2 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[kk] evolution (Diversified Supply or Reference Scenario, respectively) [104].

In the whole of Europe, the annual value creation[ll] was approximately EUR 38 Billion in 2015, which may grow to some EUR 75 Billion to 90 Billion by 2030. 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 multi-purpose 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. Whilst the future impacts on hydropower production are uncertain, the optimal management and operation of hydropower reservoirs for water resources management is among the best ways to mitigate droughts. IHA estimates that through the water storage function of its reservoirs, the hydropower industry prevents US$131.3 Billion in annual GDP losses from drought incidents (IHA, 2024). During the past 30 years a flood year increased, on average, the annual EU hydropower capacity factor by +7% more compared to non-flood years. In years with storms the annual EU hydropower increased by +5.8%, while droughts/heatwaves lowered it by -6.5%[105].

[kk] 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.

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

3.3 Environmental, social and economic sustainability

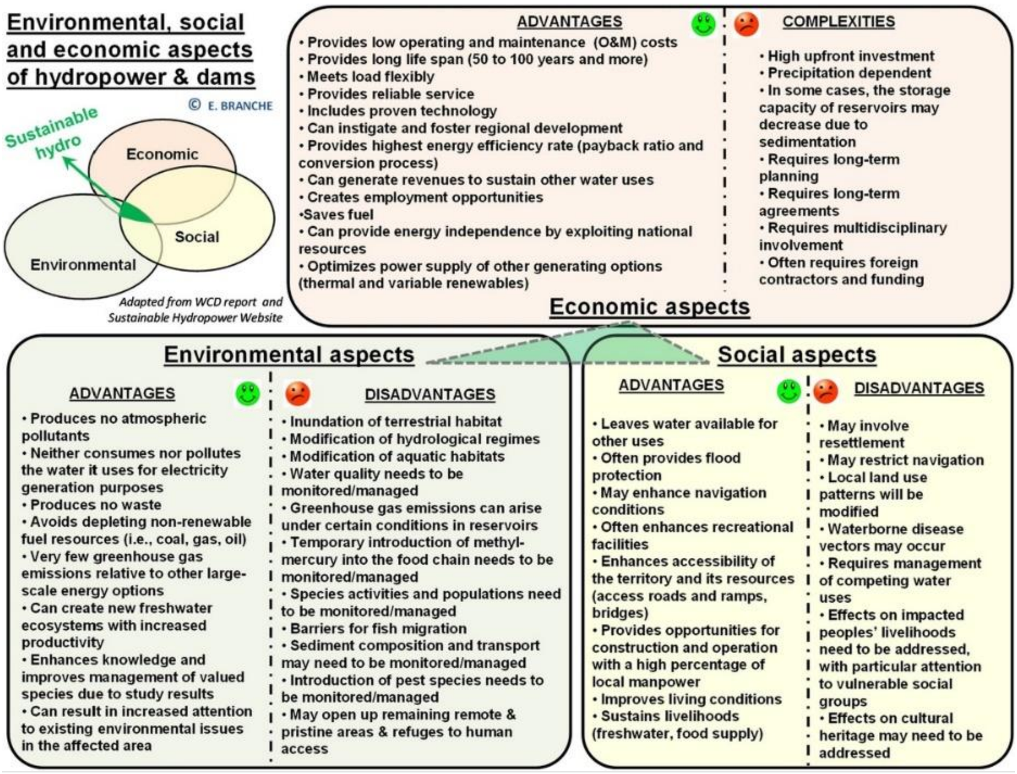
3.3.1 Sustainability indicators and assessment tools

Large hydropower plants, and large reservoirs in general, are complex systems, and they interact with the hydrosphere, the biosphere, the lithosphere, the anthroposphere and the atmosphere, with impacts and benefits[106]. Therefore, sustainable development is a major challenge for hydropower, because sustainable hydropower requires attention to a wide range of economic, social and environmental objectives. Hydropower development, especially the large projects, involves several stakeholders. The complexity of hydropower is well visible in its crosscutting presence in different European Directives, with its benefits and impacts (see Table 1 and section 1.2).

When developed and operated responsibly, hydropower directly supports the achievement of Sustainable Development Goals (SDG) 6, 7, 9 and 13. Hydropower projects can also 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).

Overall benefits and impacts are summarized in Figure 29, while Appendix 1 summarizes the sustainability indicators of hydropower selected for the CETO project.

Figure 29. Benefits and impacts of hydropower.



Source: Branche, 2017 [107]

In order to consider the transversal impacts and benefits of hydropower, the International Hydropower Association (IHA) developed the Hydropower Sustainability Standard, which is governed by a multi-stakeholder Hydropower Sustainability Council. The Hydropower Sustainability Standard is a global certification scheme, outlining sustainability expectations for hydropower projects around the world. The Standard can help make sure that hydropower projects provide net benefits to the local communities and environments they interact with. The Standard covers twelve environmental, social and governance (ESG) topics, including also Biodiversity and Invasive Species, Indigenous

Peoples and Cultural Heritage. The Hydropower Sustainability Council is the multi-stakeholder governance body of the Hydropower Sustainability Certification Scheme. The Council includes representatives of social community and environmental organisations, developed and developing country governments, financial institutions and the hydropower sector in general. The Council consists of seven chambers, each representing a different segment of hydropower stakeholders. Chamber members participate in a democratic process to elect representatives to speak for their stakeholder group on the Governance Committee. The Council ensures multi-stakeholder input and confidence in the content quality, relevance and assurance of the Hydropower Sustainability Certification Scheme. Until now, two projects have received certification (Tajikistan and Canada), five projects are undergoing public consultation (Brazil, Colombia and three in Nepal) and three projects are under assessment (Albania, Indonesia and Malaysia). Historically, over 25 projects have been assessed against the Hydropower Sustainability Tools, and the ones listed in Table 16 are located in Europe. There are also some projects aimed at increasing biodiversity (e.g. by means of afforestation/regeneration/maintenance programs) at hydropower plants in Europe[108].

Table 16. Hydropower projects in Europe which have been assessed against the Hydropower Sustainability Tool.

Country	Project name	Installed power (MW)
Austria*	Kaunertal	1015
Iceland	Kárahnjúkar	690
Norway	Jostedal	288
Albania	Devoll	256
Croatia*	Program Sava	151
Iceland	Blanda	150
Germany*	Walchensee	124
France*	Romanche-Gavet	94
Iceland	Hvammur	82
Sweden*	Semla IV	3.5

** in the EU. Source: IHA*

3.3.2 Additional considerations

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, extremely high efficiency and flexibility [109]. Therefore, hydropower 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 of the grid. Because of this, although its share of the total generation remained almost stable over the last decade due to the growth of wind and solar energy, hydropower flexibility is critical for integrating rising levels of volatile energy sources into electric systems [110]. Multi-purpose reservoirs can provide additional benefits and water provision for several other uses.

On the other hand, water reservoirs and dams/weirs in rivers can be responsible for ecosystem deterioration through diversion and alteration of flow and changes in habitat; barriers (for any purpose) obstruct the natural river flow with ecological, hydrological and morphological consequences. Water 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) [111]. Only 37% of surface water bodies (rivers, lakes and transitional and coastal waters) surveyed by the European Environmental Agency were found to be in a good ecological status, despite EU's laws and biodiversity protocols [112, mm]. Hydropower partly contributes to this, however less than 10% of barriers are for hydropower

[mm] https://www.eea.europa.eu/en/analysis/publications/europes-state-of-water-2024

(AMBER database). Furthermore, out of the 4490 large dams listed in the ICOLD2023 database, 1389 dams are for single-purpose hydropower, and 339 multi-purpose dams host hydropower as a first use; 427 dams host hydropower as second, third or fourth use. 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 notice that the effects of a hydropower plant are site and water body specific, and depend on the climatic and geographic context, as well as on the type of hydropower plant, the size and the implemented technology. For example, the study of Mahmud et al., (2019)[113, 115] found that the overall LCA[nn] (Life Cycle Assessment) of hydropower plants (kg CO2eq/kWh) in Europe is lower than outside of Europe (see also Ueda et al., 2019[114]), 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 wider and shallower reservoirs. Mahmud et al., (2019) also 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 is responsible for most impacts in alpine areas in Europe[115]. Dones et al. (2007) [116] showed that ROR are not associated with large impoundments and thus to methane emissions from the reservoir, and ROR ecosystem services are smaller than those provided by reservoir hydropower plants ($ 37 Million with respect to $ 410 Million in the case study described in [149]). However, each project is site-specific and any kind of generalization would be misleading and should be avoided.

The studies of Alsaleh and Abdul-Rahim (2021)[49] analysed the interaction between hydropower and the environment, human capital, market, innovation ecosystem and economic growth, in the EU+UK from 1990 to 2018. 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. 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% would lessen the carbon dioxide by 0.809%, while a rise in economic growth by 1% would lead to an increase in carbon dioxide releases by 0.113% [117]. On the other hand, growth in hydropower production deteriorates the status of waters, although the highest influence on water quality was estimated to be brought by the increase in population density and economic growth [112]. 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 [118], where large projects may generate conflicts, corruption and poverty gaps [119]. Therefore, public sector involvement is critical for hydropower expansion[110].

When speaking about PSH, 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 on 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 PSH hold large volumes and can provide long-term storage, with a lifespan of the civil works of more than 50 years (for batteries their lifespan is below 20 years). PSH have less impacts on the environment than batteries, except for natural land transformation, in

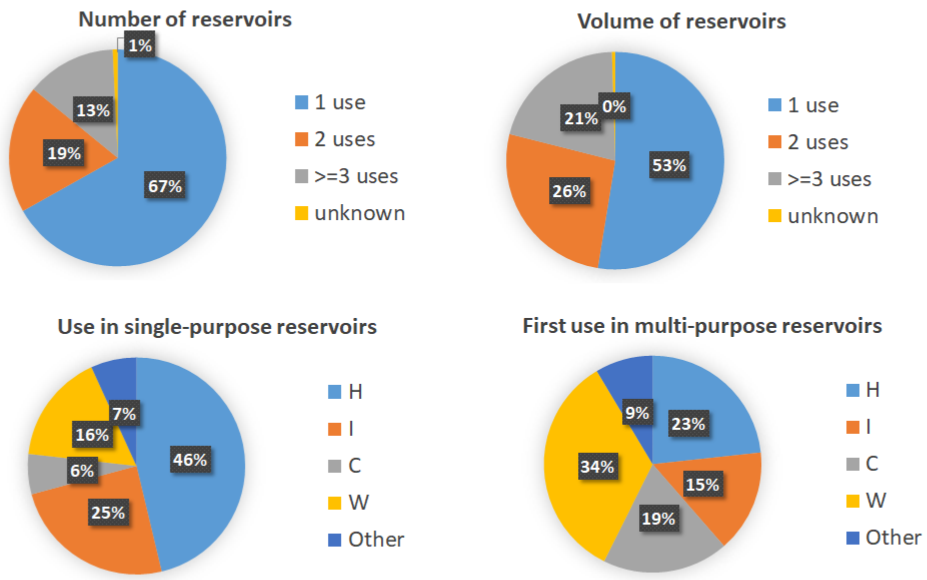
[nn] The Life Cycle assessment (LCA) is a systematic approach to evaluate the effects of a technology/process throughout its lifespan, from raw materials extraction through to processing, transport, operation and end-of-life disposal.

a LCA analysis performed in Immendoerfer et al., (2017)[120]. Several battery parks would be needed to replace one PSH (the largest EU PSH stores 100 times GWh more than the largest EU's battery park) and would not provide additional benefits besides energy storage and flexibility. Batteries could be more suitable for short-term flexibility services (minutes, hours), and this would also reduce hydropeaking effects of hydropower and the deterioration of the electro-mechanical and hydraulic equipment of hydropower plants. The EU Battery impact assessment projects a demand for battery energy storage in the EU between 180-230 GWh in 2025 and 450-730 GWh in 2030, (but assumes a much higher contribution from electric vehicle batteries for a total of 1.5-2.5 TWh, European Commission, 2020b[121]). It is worth noting that smart grids and exchange electricity contracts can reduce the volatility of the consumption.

3.3.3 Challenges associated to multiple-use reservoirs

Multi-purpose reservoirs can have important additional functions for society: hydropower, irrigation and drinking water provision, flood and drought risk management, river navigation and recreation, fire-fighting, fishing, leisure. According to Figure 30, in the EU, 33% of large reservoirs are for multiple use, but they store almost half of the water volume. Among single-use reservoirs, almost 50% are for hydropower, while the most recurrent first use in multi-purpose reservoirs is water supply. These multiple services could provide civil society with greater resilience towards climate change impacts. However, some challenges exist. A major challenge of multi-purpose reservoirs is sharing water, costs and impacts amongst competing users, and to define user priorities. These challenges may be aggravated in regions that in the future may suffer from a decrease in water availability due to climate changes, e.g. the Southern Europe has faced dryer conditions. Another challenge for the hydropower sector, and for multi-purpose reservoirs, is to pursue energy, climate and environmental targets at the same time, as well as to deal with reservoir sedimentation. The achievement of a balance among different targets has been the aim of several discussions and studies [122, 123, 124].

Figure 30. Top: Uses in large water reservoirs (ref: ICOLD, 2023).
Below: use in single-purpose reservoirs (left, number of reservoirs), and first use in multi-purpose reservoirs (right): H (hydropower), I (irrigation), C (flood control), S (water supply), R (recreational), N (navigation), O (other use).



Source: ICOLD

To cope with these challenges, mitigation, environmental-friendly and sustainable solutions have to be implemented, both at the planning/management level and during the construction and O&M stage [125] (e.g. more fish friendly turbines, racks to avoid fish passage through the turbine, efficient fish passages, better sediment management, hydropeaking mitigation measures and digitalisation[126,127]). 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 reservoir and/or hydropower plant location [128]. It is necessary to identify the stakeholders and engage them in the early planning stages. 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, EDF (Electricité de France) and the WWC (World Water Council) 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[107]. By considering the principles of sharing the resource and sharing the costs and benefits with local stakeholders, i.e. local involvement (as opposed to centralized planning), this can help facilitate community acceptance [129, oo].

3.3.4 The hydropower sector for women and youth

Several social initiatives are ongoing to empower women and young professionals in the hydropower sector. Within the EU, the COST Action (CA) CA21104 – “Pan European Network for Sustainable Hydropower”, that was awarded for funding in September 2022 by the EU, has been paying a lot of attention into the youth and women involvement in the hydropower sector, and is also described in this section[pp].

Empowering women and closing gender gaps are critical to realizing sustainable development goals (SDG) and ensuring a good quality of life for all. This is reflected in SDG 5, which aims to achieve gender equality and empower all women and girls. The energy sector can contribute to the achievement of these targets, especially with the energy transition towards low- and zero carbon generation, its multiple innovative opportunities and efficient use of energy. This includes renewables of all types together with sustainable hydropower, that could offer a range of direct and indirect job opportunities for women. Comparing all energy sectors, the share of women working in hydropower is considered to be between 27 and 32% of the total sector, depending on the hierarchical level one looks at (heavily decreasing with the leadership level rising); whereas in the PV sector, this looks higher (40%) than the other renewables, and wind is at 21%. Barriers and gender shares seem to be very similar in comparison with other sectors that are technology- and engineered-driven, also in other renewables.

However, women are still facing several challenges in working in the sector. These barriers are not due to the nature of hydropower, but relate often to the longstanding gender norms and structural barriers, which means in many societies women lag behind men in terms of access to opportunities, incomes, assets and skills because of prevailing social norms. Another perception that carries importance for the sector might be in the low visibility and little attractiveness of hydraulic engineering as compared to the emerging energy generation technologies like wind, solar, biomass and other sub-sectors. Statements from technical universities indicate that the incoming share of

[oo] 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 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.
[pp] Currently 34 countries are represented, 21 of which are ITC countries. Each country can nominate up to two delegates who are responsible for the success of CA21104 within the Management Committee (MC). The structure allows a wide spread of information and input into the CA according to the Memorandum of Understanding (MoU).

new female students is above 30% if one calls it "environmental engineering", while the header of “hydraulic engineering” still attracts far below 20% females.

Despite the challenges, single opportunities for women in hydropower are on the way, but an overall approach for the industry and a valid set of recommendations are greatly missing, whether in developed or in low-developed countries, whether within EU or outside. Best practice examples, collected in the UNIDO report (ICSHP, 2023)[qq, 132], show that women’s participation can lead to improved governance of the sector and renewable energy generation in general. Indications of this can also be drawn from the World Bank’s ESMAP study undertaken by a working consortium of International Hydropower Association (IHA) and GWNET (Global Women’s Network for the Energy Transition) as a global baseline for all hydro – small and large (publication pending)[130]. This report was launched officially by ESMAP in October 2023[131]. The GWNET, since its foundation 7 years ago, has been successful in supporting numerous mentoring programs, determined to foster women in all types of renewables, but also in all sub-sectors active in energy transition – from renewables through storage to clean cooking. Institutions involved in GWNET programs are German and Austrian governmental agencies/ministries or global organizations like OSCE (Organization for Security and Co-operation in Europe), United Nations. There is new initiative through a variety of women’ groups to create a common global network of women – WISH (Women in Sustainable Hydropower) that momentarily brings IHA, NHA (US), GWNET, Women in Hydropower Mentoring, ICOLD, CEATI, and the Dams initiative for women under one umbrella to act commonly and represent all women in hydropower towards more visibility, improving good practices and collaboration.

Since 2017, the Women in Hydropower Mentorship Program[rr] has provided an opportunity for women to connect, generate new friendships and networks, and share experiences in a supportive environment that highlights the powerful contributions women from around the world make in the hydropower industry.

With focus on the CA21104, the overall percentage of women is 30.8%. Given the fact that at technical disciplines the percentage of female members is rather low, the amount of 30% here at CA21104 is a good base to start improvement. CA21104 has started a women’s mentoring and coaching program within the leading positions. The majority of task leaders are young women and are supported by the mentoring and coaching program. As a surplus activity of the Action, a first cohort of 6 tandems has been started as specific a women’s mentoring in spring 2024. This included not only tandems of mentors and mentees working on fostering young and innovative women in research in the Action, but also providing knowledge transfer and training on leadership, self-awareness, self-reflection and self-presentation skills. The goal targets at mentees’ encouragement to step and speak up and get into leading positions, thus being role models that create attraction in other young women to join the hydropower sector, including work in the Action, and at the same time noticeably increase the share of women in the working levels of the Action through its termination in 2026.

As to current insights, clear barriers for women are in standards and norms and perceptions in both low-developed and developed surroundings of hydropower implementation. The pure fact basis available so far shows a steady low representation in the sector of around 27% women’s share, heavily decreasing with the leadership level rising.

Among the main barriers are pre-dominant perceptions on both female and male sides, such as[ss]:

[qq] the UNIDO Small Hydropower report interviewed 20 women (4 from the EU) and 21 Young Professionals (6 from the EU, including Emanuele Quaranta) active in the small hydropower sector.

[rr] https://www.womeninhydropower.org/

[ss] *Most of the information is based on the UNIDO Small Hydropower Report on Gender 2022 or comes from random insights through the GWNET Global Women’s Network on the Energy Transition from their mentoring programs and study participations (www.globalwomennet.org)*

- hydropower is technical and a domain for men
- lack of awareness of the gender gaps in the sector and how to address them
- lack of information of the sector on the job opportunities for women
- gender bias in the hiring process and a lack of diverse hiring teams
- lack of role models and mentors for women in, or wanting to enter, the sector.
- lack of awareness among women of the range of job opportunities available in the sector
- lower numbers of women with STEM (science, technology, engineering and mathematics) qualifications
- workplace policies that are not responsive to women's needs

Recommendations from the momentary analysis, at various levels of action, therefore could be directed at:

- Increased STEM education for girls and young women
- Make hydropower an attractive field for innovative and future-oriented work
- Foster bias trainings in organizations for both, females and males
- Help women grow in the sector by mentoring programs
- Showcase business cases for gender in hydropower

According to UNIDO, young people around the world can play a key role in creating the change required for the transformation of the global energy system, thus contributing to regional and international development aims, including the United Nations Sustainable Development Goals (SDGs), while at the same time finding and creating opportunities for their own professional and personal development. The active participation of youth in small hydropower can play a vital role in achieving a sustainable energy system because young people can bring the creative and forward-oriented thinking that is needed for a rapid energy transition. However, young people continue to face multiple barriers in accessing the required skills as they often do not receive the policy, institutional and financial support that could help them get involved in the hydropower sector[132].

Considering the EU Cost Action CA 21104, the percentage of Young Researchers and Innovators (YRI) is 55.8% of CA 21104 members (below 40 years). COST Actions are more attractive to young researchers than other initiatives. This is certainly also due to the different actions supporting the mobility of YRI and the knowledge and experience exchange between YRI and SR (Senior Researchers). COST is a good opportunity for young researchers to enlarge their professional network and to collaborate already today with the colleagues of tomorrow. One of the actions in that particular direction is the organization of Training Schools (TS) on Sustainable hydropower. Here are all Working Groups (WGs) engaged to contribute to knowledge exchange and teaching of sustainable hydropower topics. CA 21104 supports YRI this by offering additionally Short-Term Scientific Missions (STSM). Another action is the support of conference participation. YRI from Inclusiveness Target Countries (ITC) can apply for a financial support of their conference participation. CA21104 will follow its way to support younger researchers to bring them closer to the field of hydropower in order to solve the tasks of the future, regarding Net-Zero, Green deal or blue economy. All initiatives need skilled and motivated young researchers and CA21104 plays among other organizations an important role to attract the youth.

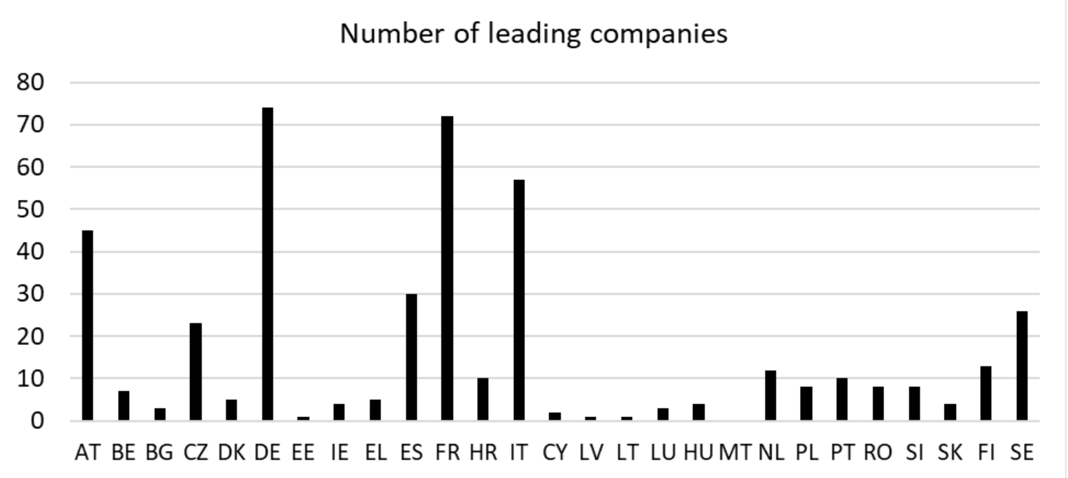
3.4 Role of EU's Companies

The JRC recently developed a database of EU's companies active in the hydropower sector: it includes 524 entries (excluding those providing services, e.g. engineering consultancy, hydrological studies) [101]. The largest part of EU-based companies is made of commercial companies (85%). These companies are active in the design, manufacturing 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 31 depicts the share leading hydropower and dam engineering organisations/companies in EU Member States, based on data of 436 EU's companies available in a different database (accessed in June 2024) [133]. 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 considerable number of them.

Manufacturing capacity of EU companies is of high relevance and their export capacity is great, as EU companies contribute by almost 50% to the global export of hydropower equipment. Many European engineering and consultancy companies offer knowledge, expertise, or consulting to hydropower projects in and outside of Europe. Hydropower does not use critical material, so that manufacturing does not depend on third countries (e.g. China). EU companies also hold several patents and high-value inventions, already discussed in previous chapters.

Figure 31. Leading hydropower and dam engineering organisations/companies per EU's Member State [133].



Source: Hydropower and Dams

3.5 Employment

The deployment of renewable energy generates several employment opportunities in different sectors, with different levels of qualification and duration. It is possible to distinguish between direct, indirect and induced jobs. Direct employment refers to employment generated directly by core activities (implementation value chain). Indirect employment includes jobs in upstream industries that supply and support core activities (e.g., for sustainability, the climate adaptation value chain). Induced employment (generated by productive end uses) encompasses jobs resulting from additional income being spent on goods and services in the broader economy, such as food, clothing, transportation and entertainment (utilisation value chain). Employment can be measured in different ways. Full-time equivalent jobs are equal to one person working full-time over the course of a year. Person-days reflect the amount of work done by one person working full-time for one day.

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. On the basis of existing installations, IRENA estimates that every 1 MW of community-owned hydropower installed generates ten full-time equivalent jobs in every year of its operation. This is significantly more than other generation technologies, including the next-best performer, community-owned solar photovoltaics at around three full-time jobs per 1 MW installed. Together, the feasibility, planning and procurement, manufacturing, installation and connection, operation and maintenance, and decommissioning of a small-scale hydropower plant require more than 17 000 person-days for a pico hydro plant (average 5 kW), around 64 000 person-days for a micro hydro facility (50 kW) and over 160 000 person-days for a mini hydro system (500 kW). The labour requirements vary across the value chain. Operation and maintenance work is needed throughout the lifetime of a system – estimated at around 40 years – and therefore represents a large chunk of the labour required (94%, 87% and 78% of total person-days, respectively, for pico, micro and mini hydro facilities). Installation and connection and manufacturing are the next-largest shares (up to 4%, 11% and 15%, for pico, micro and mini hydro facilities, respectively). Decommissioning is included, but its share is negligible[134].

Globally, IRENA calculated that approximately 2.36 Million people worked directly in the hydropower sector in 2021, the largest number in the last monitored decade. Only bioenergy (3.44 Million) and photovoltaics (4.29 Million) exhibited a higher employment level across clean electricity generation technologies. 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. 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 [135].

The numbers associated to the employment vary depending on the source. According to a study conducted by Prognos AG, Berlin and COWI SE, Kopehagen, commissioned by the European Climate, Infrastructure and Environment Executive Agency (CINEA), in 2023 in the EU there were 3500 employed people in the manufacturing, 98,300 in the construction and 240 in the R&D; alpine countries – i.e. Austria, France, Italy and Germany - were the most relevant employers. According to EurObserv'ER, the number of direct jobs of hydropower ranges between 74,000 and 87,000 [103] in 2019, while 89,000 was estimated in 2021 by IRENA[135], 7.2% of the direct employment in the renewable energy sector, with almost another 30,000 jobs created in external services of hydropower [101, tt]. A 10% increase of hydropower in the year 2030 would create 27,000 jobs in the EU, mainly outside the hydropower sector itself [104]. According to some recent EurObserv'ER's estimates, direct and indirect jobs were 49,000 and 79,000 in 2021 and 2022, respectively. According to the European Renewable Energies Federation (EREF), 4500 SMEs are present in the EU on small hydropower, employing approx. 60,000 people[136].

Focusing specifically on the job figures in the hydropower sector, it is worth noticing the wide range of figures employed in the hydropower sector. Civil, hydraulic, mechanical and electric engineers,

[tt] Employment and turnover figures based on EurObserv'ER include also construction and consulting services, which in the case of hydro represent a bigger share of CAPEX than manufacturing indeed. Data are based on modelling based on CAPEX investments with resulting jobs and turnover effects being assigned to the year of commissioning the project. This is why, in the case of hydro, there are big variations between the years.

hydrologists, are the most typical profiles. Basic knowledge of hydraulic machines (machine type selection, hydraulic design, operating regimes etc.), hydraulic structures as well as a good understanding of electric design and grid stability are also important aspects of an educational background. Hydropower projects must adhere to environmental regulations and mitigate potential ecological impacts. Environmental specialists, often environmental engineers, play a crucial role in conducting impact assessments, designing fish passage systems, biotope restoration and ensuring compliance with environmental standards, especially in view of the concession renewal. Technical skills including welding are also vital: having sufficient simple grinders and welders could become an issue in the future as there are fewer people going into manual jobs and automation processes are difficult and expensive. Other skills necessary for the hydropower sector are those related to project management – contracts, asset management, energy, supervision for installation as well as operations and maintenance (O&M). Skills that will become more important over time include data and digitalisation specialists who can incorporate digitalisation practices into hydropower system design. Electric engineers with a high voltage background are also decreasing over time, so this skill set must be fostered. Additionally, it will be even more important in the future to encourage multidisciplinary approaches, as hydropower is incorporated into the grid and new developments will have multi-purpose use. The collection and analysis of data from sensors and monitoring systems are becoming integral to optimise hydropower plant performance. Data analysts skilled in statistical analysis, machine learning, and programming help extracting insights and improving operational efficiency. Professionals specialising in energy policy and regulations will be instrumental in shaping policies, incentives, and frameworks for hydropower development. They will analyse market trends, assess policy implications, and contribute to the growth of the industry[137].

3.6 Energy intensity / Labour productivity / Production

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 many 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 that are typically hosted in projects worth several EUR hundred Million (or even EUR multi-Billion investments). In monetary terms, such investments represent a 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.

To monitor the trends in hydropower technology development, Prodcom codes for the production of hydraulic turbines and their parts have been selected on Eurostat database (Table 17).

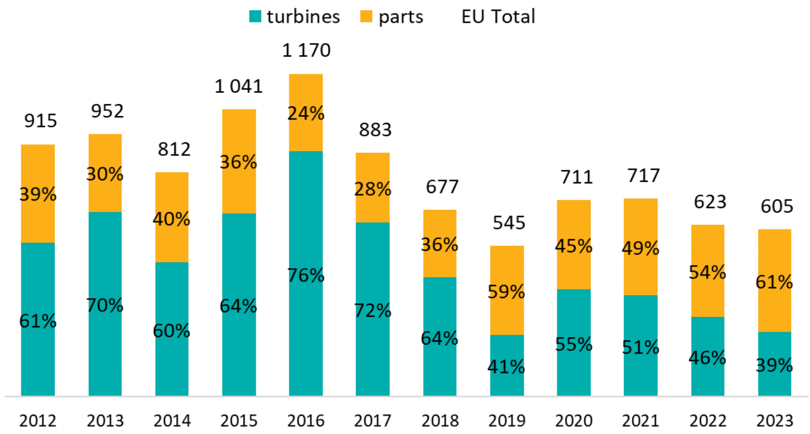
Table 17. Selection of Prodcom codes as a proxy for production of hydropower technologies.

Prodcom code	Description	Alias
28112200	Hydraulic turbines and water wheels	turbines
28113200	Parts for hydraulic turbines and water wheels (including regulators)	parts

Source: Prodcom

In 2023, the EU production value of hydraulic turbines and parts declined slightly at EUR 605 Million, with more than 60% of the EU production being parts (Figure 32). The EU production of parts increased by 11%, while hydraulic turbines decreased by -20%. Germany and Austria were the top EU producers, holding together more than half of the total EU production, followed by Italy and Czechia. According to Prognos, production in the category “manufacturing” was EUR 710, 650 and 840 Million in 2021, 2022 and 2023, respectively, which are In line with the value of Production abovementioned, while EUR 93.4, 73.3 and 75.6 Billion in the “Construction and Operation” and EUR 60, 28 and 29 Million in “Research and Development”.

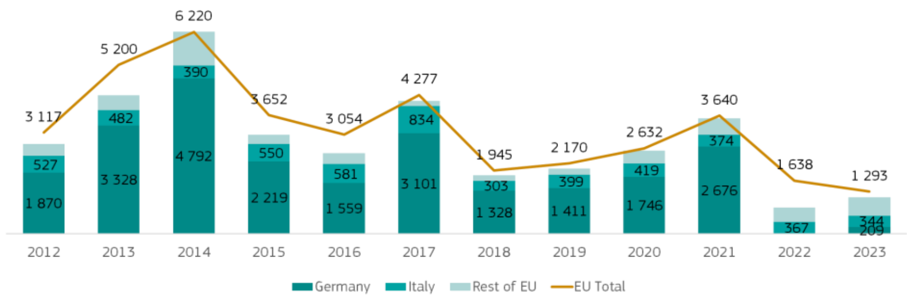
Figure 32. EU production value per commodity [EUR Million].



Source: JRC based on PRODCOM data.

In terms of quantities, the Member States had disclosed data only for the production of turbines (Figure 33). Germany and Italy combined hold more than half of the EU production.

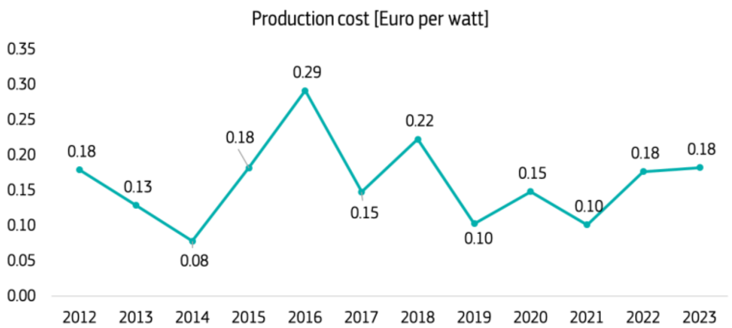
Figure 33. EU production value per commodity [MW]



Source: JRC based on PRODCOM data

The value of EU production cost of hydraulic turbines is relatively stable at 0.18€/W (Figure 34).

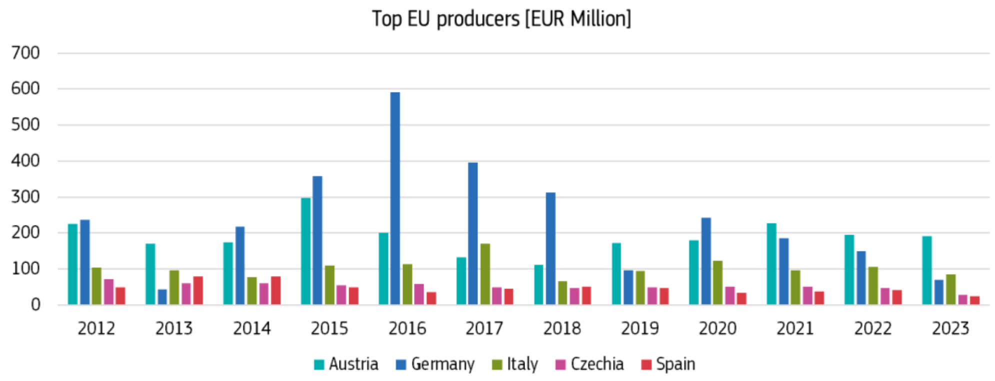
Figure 34. EU production value per quantity of hydraulic turbines [EUR per Watt]



Source: JRC based on PRODCOM data

Over 2012-2023, Austria, Germany, Italy, Czechia and Spain were the top EU producers, but not all Member States had disclosed data for all the years (Figure 35). Germany and Austria combined hold more than half of the EU production. It must be noted that Production values refer exclusively to turbines and associated parts. If all the technologies associated to the hydropower chain were considered (approx. 150 types, e.g. including pipes, penstocks, valves, gates), the European House Ambrosetti found that these numbers would be EUR 27.7 Billion and EUR 43.4 Billion for Italy and Germany, instead of EUR 107 Million and EUR 150 Million in 2022, respectively, for a total EU's Production value of EUR 132.3 Billion from the first ten EU member states, instead of EUR 562 Million in 2022 [138].

Figure 35. Top EU producers among the Member States disclosing data [EUR Million]. Source: JRC based on PRODCOM data.



Source: JRC

Hydropower benefits go well beyond trade of equipment. In 2015, hydropower contributed with EUR 25 Billion to the EU+UK gross domestic product (GDP) (electricity generation and exports), that was roughly EUR 500,000 per FTE (Full Time Equivalent). The main part of this contribution (>90%) derived from hydropower generation. When Norway, Switzerland and Turkey were included, the GDP was EUR 38 Billion, which may grow to EUR 75-90 Billion by 2030. The multi-purpose benefits represent an important additional income that, although very difficult to be quantified, may range between EUR 10 and 20 Billion per year, that are expected to increase in the future if hydropower reservoirs are also used for water management and flood mitigation. The direct tax contribution is estimated at around EUR 2 and 15 Billion, in EU+UK and Europe, respectively, several times higher than the subsides paid to the small hydropower sector [104]. Turnover in 2021 was EUR 6.4 Billion and the GVA was EUR 2.7 Billion (new investments, O&M, production and trade).

4 EU market position and global competitiveness

4.1 Global & EU market leaders: role of EU's companies

European companies are global leaders. 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 (Webuild, Skanska, Strabag, Vinci, Walo, amongst others) act as civil contractors or even as EPCs (Engineering, Procurement and Construction) in the framework of turnkey projects[11].
To support European hydropower, the European Hydropower Alliance was recently founded, and it gathers the following energy utilities: EDF, EDP, Enel, Engie, Fortum, Iberdrola, Statkraft, Uniper, Vattenfall and Verbund. The Alliance is committed to advancing sustainable hydropower's role in achieving the EU Green Deal and Fit for 55 ambitions. The Alliance supports the development of an integrated decarbonized electricity market in Europe by providing affordable, renewable, dispatchable, and secure electricity which ensures the maximum integration of renewable sources of energy.
The Alliance's goal is to ramp-up the visibility of hydropower as:

- A vital source of energy and flexibility contributing to EU security of supply and energy independence.
- A key renewable energy source with development potential contributing to decarbonisation, adaptation to climate change and resilience.
- A sustainable energy source respecting biodiversity.
- A generation technology with multi-purpose non-power related benefits.

In terms of number of sold turbine-units for large-scale stations worldwide, Andritz, Voith and GE held the leading positions in 2013-2017. In 2017 alone, these three EU companies sold 93 units (>10 MW) or 62% of the total number of sold units.

Excluding the delivered capacity in 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 outside of China, and the remaining share was almost equally divided between Japanese, Indian, and Norwegian companies [101]. The large share of EU companies may also be partially due to their leadership in high-value inventions.

In the recent past, the country with the highest increase in hydropower installed capacity was 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 36% of the total capacity orders in China over the analysed period. For further details see section 4.2.

4.2 Trade (Import/export) and trade balance

International trade is monitored using six-digit codes of the Harmonised System (HS) classification[139] dedicated to hydraulic turbines and their parts (Table 18), although these components represent only a small fraction of the total, as discussed for the Production value.

Table 18. Selection of HS codes as a proxy for monitoring trade for hydropower.

HS code	Description	Alias
841011	Hydraulic turbines and water wheels, of a power <= 1.000 kW (excl. hydraulic power engines and motors of heading 8412)	turbines S
841012	Hydraulic turbines and water wheels, of a power > 1.000 kW but <= 10.000 kW (excl. hydraulic power engines and motors of heading 8412)	turbines M
841013	Hydraulic turbines and water wheels, of a power > 10.000 kW (excl. hydraulic power engines and motors of heading 8412)	turbines L
841090	Parts of hydraulic turbines and water wheels incl. regulators	parts

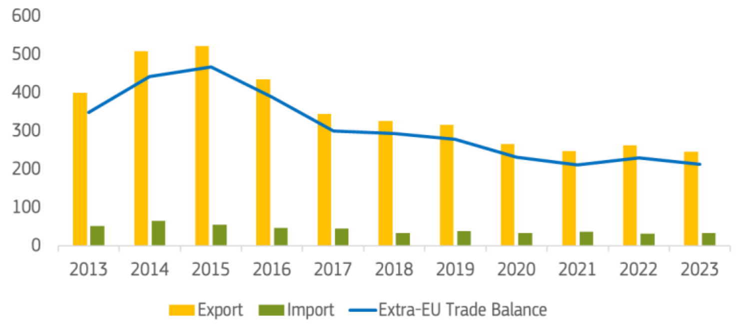
Source: Harmonised System

Global (and EU, aggregating extra-EU and intra-EU) exports were EUR 772 (370), 776 (390), 521 (171) Million in 2021, 2022 and 2023. In 2021-2023, the EU share in global exports decreased to 44% compared to the 2023 study (49% over 2020-2022), Extra-EU exports shrunk by -6% from 2022 to 2023, reaching around EUR 246 Million according to COMEXT (in 2023), while ComTrade estimated EUR 171 Million of total EU export in 2023, lower than COMEXT estimate (Figure 37).

EU imports were EUR 125, 128 and 137 Million, out of which EUR 89, 97 and 105 Million were intra-EU, in 2021, 2022 and 2023, respectively. In 2023, the extra-EU imports of hydraulic turbines and parts increased by 3% compared to 2022, reaching almost EUR 33 Million, but remained well below the intra-EU imports (EUR 105 million). The share of imports (period 2021-2023) coming from the EU (74%) remained similar to the levels of the 2023 (period 2020-2022) study (Figure 37).

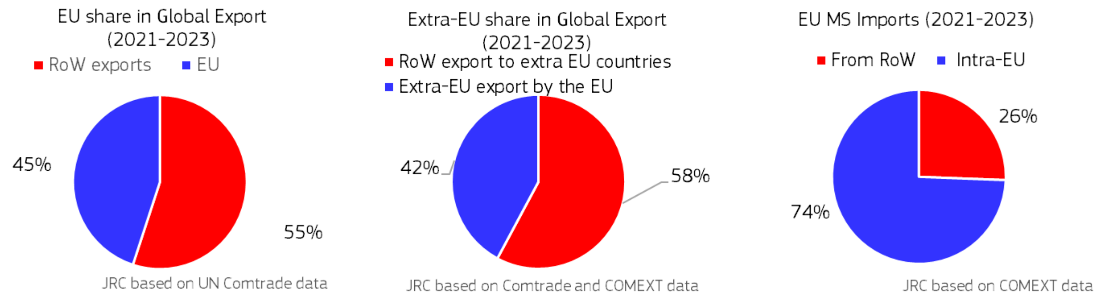
The trade surplus shrunk by -7% at EUR 213 Million (Figure 36). Austria, Germany and Italy remained the Member States with the largest trade surpluses (EUR Million +24, +56, +39, respectively, in 2023), while Greece, Sweden and Luxembourg had the largest trade deficits (EUR Million -1, -2, -1, respectively, in 2023).

Figure 36. Extra-EU trade for hydraulic turbines and parts [EUR Million]



Source: JRC based on COMEXT data

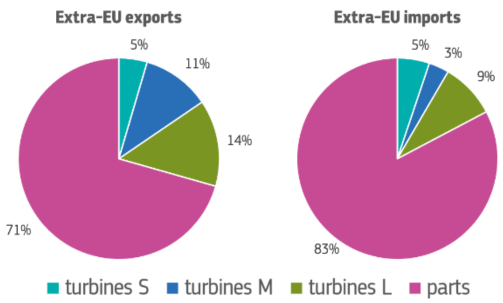
Figure 37. EU share in global export (left), extra-EU share in global export (middle) and EU imports (right) [2021-2023].



Source: JRC based on COMEXT and COMTRADE data

For the same period (2021-2023), the majority of the extra-EU exports was related to parts (71%) followed by turbines L (14%) and M (11%), while 83% of the extra-EU imports was related to parts (Figure 38).

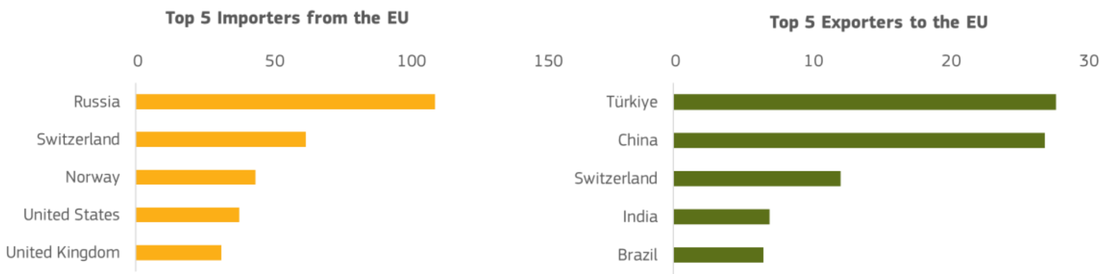
Figure 38. Traded value share of hydropower [2021-2023]



Source: JRC based on COMEXT data

In 2021-2023, Türkiye became the top exporter to the EU, delivering 28% of the extra-EU imports while China's share remained at 27%. Extra-EU exports went mainly to Russia, Switzerland and Norway (Figure 39).

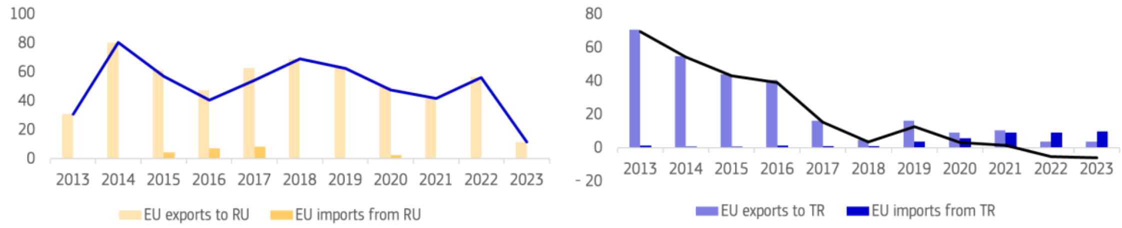
Figure 39. Top countries importing from (left) and exporting to (right) the EU (2021-2023) [EUR Million].



Source: JRC based on COMEXT data

Even though Russia remained the top importer from the EU, EU exports plummeted in 2023 due to export controls[uu] (Figure 40). Imports from Türkiye started increasing after 2019, reaching EUR 10 Million in 2023. Since 2022, the EU trade balance with Türkiye is negative.

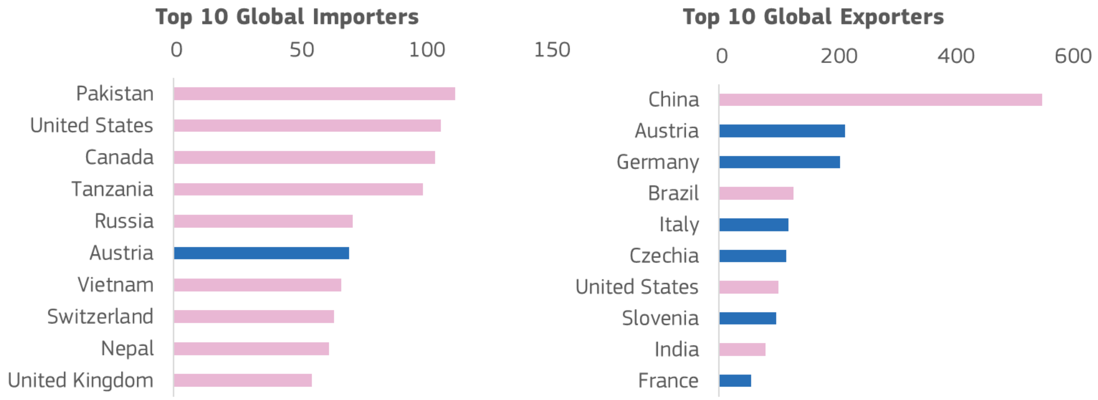
Figure 40. EU trade with Russia (left) and Türkiye (right) [EUR Million].



Source: JRC based on COMEXT data

The EU continued having a strong presence among the top global exporters, while only Austria remained amongst the top importers (Figure 41).

Figure 41. Top global importers (left) and exporters (right) (2021-2023) [EUR Million]

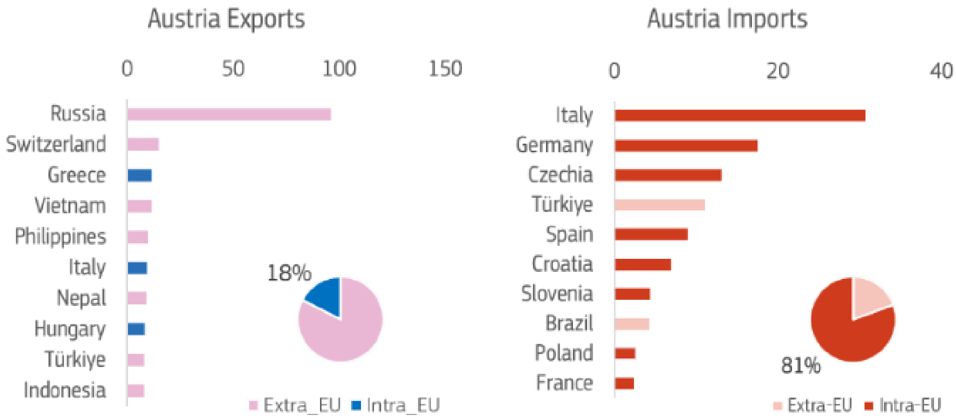


Source: JRC based on COMEXT and COMTRADE data

In 2021-2023, Austria brought 81% of its imports from other Member States, while 52% of its total extra-EU imports were from Türkiye (Figure 42). Only 18% of its exports went to other Member States, sending 42% of its extra-EU exports to Russia.

[uu] Regulation 0833/14, OJ L 229 31.7.2014, p. 1- concerning restrictive measures in view of Russia's actions destabilising the situation in Ukraine. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02014R0833-20240625

Figure 42. Countries Austria exports to (left) and imports from (right) [EUR Million].



Source: JRC based on COMEXT data

Regarding the growing markets[vv] during 2020-2022[ww], Tanzania had the largest net import increase followed by Canada and Nepal. The EU penetrated significantly the markets (EU share >25%) in Japan, the US, Tajikistan and Switzerland (Table 19).

Table 19. Growing markets based on a 2-year average of net import change.

Country	Total import (2020-2022) [EUR Million]	% import from the EU	2-year average of net import change
Tanzania	36	3%	15
Canada	99	24%	6
Nepal	81	7%	5
Uzbekistan	42	11%	5
Tajikistan	53	44%	5
Switzerland	57	97%	3
United Kingdom	37	21%	3
United States	102	29%	1
Ethiopia	64	19%	1
Japan	41	25%	1

Source: JRC based on COMTRADE data

For the future, a great opportunity for EU companies is their export potential associated to innovative equipment and small hydropower (high-value inventions, see section 2.7), as well as assistance in the overall design and operation of hydropower plants.

[vv] Calculated as $net\ import\ change = [(import_{2021} - import_{2020}) + (import_{2022} - import_{2021})]/2$

[ww] Latest year data (2023) may be incomplete for Comtrade, because it does not provide estimates for the missing values as Comext does.

4.3 Resources efficiency and dependence in relation to EU competitiveness

Hydropower and pumped-storage hydropower are of strategic importance to the EU energy system and can contribute to the EU resilience[140].

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 is 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 [94]. It is estimated that the total weight of the electromechanical equipment (runner, distributor, generator, draft tube and casing) amounts to almost 900 ktons in the EU (Quaranta, 2023)[141].

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). Therefore, hydropower is the best renewable energy for reducing pressure on mineral resources (Figure 43 and Figure 44). 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[142]. Figure 43 summarizes these findings and more specific details can be found in the IEA (2023)[143] report, which highlights the wide use of critical material in the other renewable energy technologies. However, the values calculated on PV reflect the impact of PV energy of years ago[xx], and since that time the performance has improved a lot[144].

Variable-speed machines are based on two emerging generator types that use power electronic converters: the doubly fed induction machine and converter-fed synchronous machine (Kougias et al. 2019). Variable-speed permanent magnet generators could be an alternative for very low-head hydropower (water wheels, Archimedes screws). 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 significant role only in the assembly stage, where its share is above 50%) [145, 146]. This should stimulate the development of novel electro-mechanical equipment and the improvement of the lifecycle of such materials (e.g. recycling). Finally, hydropower development may involve substantial excavation and tunnelling, requiring significant amounts of energy to run the appropriate machinery, and concrete to build the dam. Especially for the countries where hydropower is expanding significantly, the construction of large dams can require large amount of concrete, which generates large carbon emissions. Furthermore, concrete depends on sand availability, which is the second most used resource on Earth, after water. Sand is often dredged from rivers, dug up along coastlines and mined. This aspect should be taken into consideration: the International Commission on Large Dams (ICOLD) is looking at this aspect, and it is aiming at reducing the carbon footprint of dam construction, for example by using new construction methods and materials (ICOLD pers. comm., HYDRO2023 conference, and see e.g. Wolfsborg et al., 2023[147]).

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

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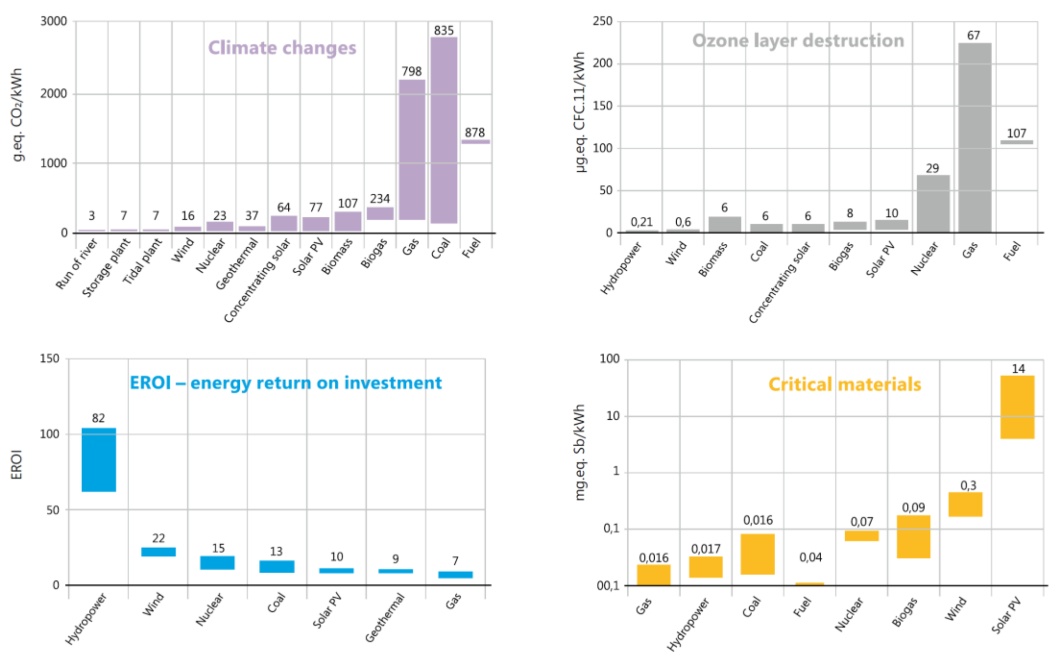
[xx] Furthermore, the critical mineral issue is too complex to be resumed to a single value. Furthermore, the characterization factor used to aggregate the values in Sb.eq also relies on USGS (U.S. Geological Survey) extraction data from the last century, which clearly has some limits. For the mineral impact of the PV value, if it relies on the ecoinvent value, most of the impact here presented is due to indium that is considered as depleted when zinc is extracted from mines (so it is more related to the way some LCI are built than to the use of a really critical material for PV).

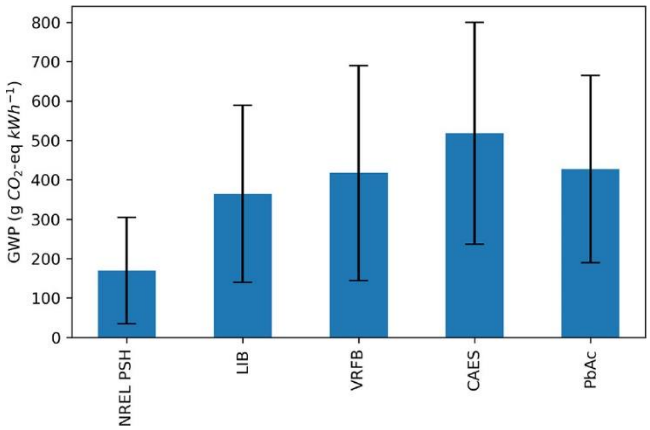
discussed in the 2022 release of this report.

Figure 43. Impact indicators from ETIP Hydropower Europe (EU project), with minimum and maximum values (the bar) and the average value (the numbers). EROI, also sometimes called the energy returned on energy invested (ERoEI) or recovery factor of energy or gain factor of energy and is the ratio of the amount of usable energy (the energy) delivered from a particular energy resource to the amount of energy used to obtain that energy resource.



Source: ETIP Hydropower

Figure 44. Global warming potential (GWP) of closed-loop PSH (NREL PSH), compared to literature GWP values for lithium-ion battery storage (LIB), vanadium redox flow batteries (VRFB), compressed-air energy storage (CAES), and lead-acid battery energy storage (PbAc). The bar heights indicate the mean GWP for each technology, and the error bars indicate the GWP standard deviation[148].



Source: NREL

5 Conclusions

Hydropower is the largest renewable energy source to date, with a global installed power capacity of 1416 GW and an annual generation of 4185 TWh in 2023. Hydropower provided, on average, 360 TWh/y in the EU in the last decade (including approx. 40 TWh/y from PSH, but that also adsorbs an approx. analogous quantity for pumping). A quarter of the global PSH installed turbine capacity is in the EU.

The hydropower sector is characterized by several strengths and advantages with respect to the other renewable and storage technologies. The Energy Return on Investment (EROI) is the highest, and traditional hydropower equipment does not use rare and critical materials. Reservoirs provide additional services in emergency situations, e.g. water and energy storage for irrigation and fire-fighting, flood control and drought mitigation, and navigation, although these uses may sometimes be in conflict one another. Furthermore, capacity factors of hydropower in the EU are generally higher than those of photovoltaics and slightly higher than those of the wind sector. The overall efficiency of a hydropower plant 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, by for example preventing blackouts. As the penetration of variable energy sources (mainly wind and solar power) increases, the flexibility provided by hydropower operation is essential. PSH 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). PSH can store water-energy (with daily, monthly and seasonal storage depending on the installed capacity and reservoir's volume) more cost-effectively (the lowest Levelized Cost of Electricity –LCOE-) than any other option, and can put and absorb energy available in seconds. PSH is the most cost-effective long-term (e.g. seasonal) storage technology.

However, being hydropower plants key examples of the Water-Energy-Food-Ecosystem nexus, several obstacles and challenges exist. The first major barrier is the effort to simultaneously pursue energy, climate and environmental goals, where hydropower exhibits diverse and sometimes controversial roles. Depending on the context, hydropower can generate several adverse effects on the environment, although the estimated less than 30,000 hydropower plants, with respect to the 450,000 barriers in EU's rivers, may suggest that less than 10% of barriers in EU's rivers are for hydropower. 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, although not excluded from being installed in protected areas, would rather be installed in less favourable sites, increasing costs, especially for the implementation of environmental mitigation measures. Hydropower development is also affected by climate change (water scarcity, seasonality, extremes), but, on the other hand, hydropower reservoirs can help to mitigate climate change effects (providing flood control and drought mitigation). An emerging problem is sediment management of reservoirs, and several new technologies and management strategies are under development. Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies and are generally characterised by high investment costs, hence have higher financial risk, requiring specific policy instruments and incentives as well as a longer-term policy perspective and vision. A cost-effective way to ensure secure and affordable energy supplies is a well-functioning and integrated EU's energy market; however, European hydropower operators are not remunerated for all their services (e.g., flexibility). Therefore, another major challenge is defining a value for all the benefits, which is necessary to allow discussions and negotiations between different water users. Public sector involvement is critical for hydropower, 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.

According to the existing scientific assessments (e.g., Quaranta et al., 2021 and 2022) the current hydroelectricity generation could be incremented by 10% by modernising existing hydropower (partly offsetting climate change effects and limitations imposed by environmental legislation). An additional +3% can be achieved by exploiting the hidden potential in existing infrastructures (mills, existing barriers, wastewater treatment plants and water distribution networks), while the contribution of hydrokinetic turbines is limited. 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. New water storage systems, designed as multi-purpose projects, may be required for water management services that could be exploited also for energy storage and generation. In Southern European countries, new reservoirs may be useful to mitigate the already visible effects of climate change (floods, droughts and fire), and in the Alps to store additional water from glacier retreat.

Hydropower exhibits 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 hydropower-PV power plant (e.g. evaporation reduction, increase of PV efficiency). 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. Hydropower technologies can be used, after adaptation and optimization, for tidal and wave power generation.

Hydropower companies within the EU are very competitive and are of strategic relevance, especially considering the current geopolitical situation (e.g. the required independence from Russia and the competitiveness of China). 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 competition of China. The global exports in 2021-2023 accounted for EUR 2.1 Billion with EU countries holding 55% of this, only focusing on turbines, but the overall dimension of the market (pipes, civil works) may be 2-orders of magnitude higher. A significant proportion of investments and activities in the hydropower sector refers to the civil works and associated consultancy services that generally represent two thirds of the construction costs of new large power plants. The data around civil works are difficult to track, making the collection of data and projections challenging.

Therefore, to keep a competitive EU hydropower sector in an increasingly challenging world, the strong competence (scientific and industrial) of EU’s companies and institutions is key. Dialogue 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. 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. Transboundary projects and water reservoirs could be a source of conflicts in some cases (climate changes may aggravate potential conflicts), but could be an opportunity for a profitable cooperation and sharing of the associated benefits. A better communication between stakeholders (e.g. institutions, academy, industry and citizenry) and experts (e.g. engineers, environmental experts, ecologists, ichthyologists, hydrologists, economists and geologists) and a transparent process to find a balance between different policy targets, impacts and benefits, and conflicting interests of multi-purpose reservoirs, are essential.

Appendix 1: Sustainability Indicators

Table 20. Summary table with sustainability indicators.

Parameter/Indicator	*Input*
Environmental	
LCA standards, PEFCR or best practice, LCI databases	Yes [149, 115, 116, 120]
GHG emissions	The IPCC states that hydropower generates 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. Hydropower helps in reducing CO_2 emissions[150]. Additional considerations can be drawn from Gemechu and Kumar (2022)[151], who reviewed the gCO2eq/kWh associated to several hydropower plants (HPPs), from their manufacturing to their dismantling. Below 5 MW, results are quite dispersed because they concern micro/mini hydropower plants. Indeed, the relative impacts of such HPPs are very low when installed in existing structures and in artificial existing canals (and still lower than those of larger HPPs), while relative impacts can be quite high when associated to new barriers in freshwater systems. Their relative impact ranges between almost 0 and 75 gCO2eq/kWh (although most of them range between 0 and 35 gCO2eq/kWh). Above 5 MW, the relative emissions are relatively small and quite constant, generally below 5 gCO2eq/kWh, and may be mainly associated to the reservoir. If European case studies are only used, no correlation between emissions and installed power was found.
Energy balance	EROI = 60-100 [152], the highest one amongst energy technologies. Water reservoirs provide storage capacity and hydropower plants provide flexibility. EROI (Energy return on investment) is a ratio that measures the amount of usable energy delivered from an energy source versus the amount of energy used to get that energy resource
Ecosystem and biodiversity impact	New barriers can generate several impacts. Obsolete and existing barriers are also the cause of river fragmentation, but most of them are not for hydropower use or may not have hydropower as primary use. See the text in this section, section 2.2.1.
Water use	The average flow rate discharged by European reservoir-hydropower plants is 10.5 m^3/kWh (elaborating data of hydropower database, Quaranta et al., 2021[34]). Water is used for energy generation and released downstream in ROR plants, while the natural hydrological regime is altered, and evaporation losses occur, in reservoirs plants (RSHP). 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 [153]. The water footprint for operation (excluding the turbined flow) is almost zero for ROR and 32 m^3/MWh for RSHP (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 [154].
Air quality	No direct pollutant emission during operation, but methane emissions might occur from some reservoirs due to organic matter decomposition [155].
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 may also serve for multiple purposes. Elaborating data of ICOLD 2023 database, the density value for reservoir hydropower is 34 W/m^2 (50° percentile) in single purpose reservoirs, while it is 10 W/m^2 and 2 W/m^2 in multi-purpose reservoirs where hydropower is the first or second (or more) use, respectively, considering the reservoir area as water footprint. 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 approx. 6 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)[156]. 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 infrastructure ratio of biomass power plants is the highest (0.90) [156] (infrastructure ratio =1 is the optimal/ideal value). The energy density value of wind farms is comparable with that of hydropower plants[157].
Soil health	Alteration of sediment transport, possible landslides in big projects, but also improved maintenance and additional monitoring of the environment.
Hazardous materials	See section 4.3. Critical materials are not commonly used.

Economic	
Parameter/Indicator	Input
LCC standards or best practices	Zakery and Syri (2015)[158] found that the annualized life cycle cost (LCC) for PSH ranged between 200 and 270 EUR /kW/y, half the LCC of batteries. Donnelly et al., (2010)[159] 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. For a more comprehensive overview from a hydropower perspective, see [160]
Cost of energy	See section 2.4.
Critical raw materials	No, see section 4.3.
Resource efficiency and recycling	The lifespan of civil structures can reach 80 years if periodic maintenance is carried out, after that a retrofitting activity is required. Dams should be designed to withstand 1000 years floods. Electro-mechanical equipment has a lifespan 20-30 years. 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.
Industry viability and expansion potential	See section 2.3
Trade impacts	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 [161].
Sustainability certification schemes	The tool developed by IHA, see the main text, and overseen by the Hydropower Sustainability Alliance.
Social	
S-LCA standard or best practice	See the text.
Health	No direct emissions.
Public acceptance	Big projects may require reallocation of people and depletion of water resources in the exploited river reach. On the other hand, there is often scarce awareness on the multi-purpose benefits of water reservoirs and hydropower schemes. Several initiatives for youth and women are ongoing in the hydropower sector.
Education opportunities and needs	Especially when hydropower is linked to the industrial heritage and cultural heritage (e.g. water mills) [162, 163].
Employment and conditions	For employment data see section 3.5.
Contribution to GDP	See section 3.
Rural development impact	Especially in case of rural areas that host water mills and hydraulic infrastructures. 80% of the EU's installed capacity is in rural areas[164].
Industrial transition impact	Hydropower can provide flexibility and can be hybridized with other energy technologies (e.g. floating photovoltaics, hydrogen production, heat generation, batteries).
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	Digitalisation 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 hydropower's manufacturing activity 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 PSH in larger quantities with respect to batteries. For example, the stored energy in the Blåsjø PSH reservoir, the Norway's largest reservoir (8 TWh), is equivalent to more than 40,000 times the Hornsdale battery park in Australia. In the EU, the largest reservoir for hydropower purpose hosts 3.12 TWh; it is in Spain and is PSH with turbine and pump installed capacity of 851 and 1184 MW, respectively (JRC hydropower database).
Food security	In the EU, 120 large reservoirs host hydropower and irrigation as first and second use, and 30 large reservoirs host irrigation and hydropower as first and second use, respectively, from ICOLD2023 database.
Responsible material sourcing	No.

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List of abbreviations and definitions

AU = Australia

BR = Brasil

CA = Canada

CAPEX = capital expenditure

CF = capacity factor (-)

CH = Switzerland

EC = European Commission

EROI = Energy Return on Investment

EU = European Union EU27

GDP = Gross Domestic Production

GW = GigaWatt

ICOLD = International Commission on Large Dams

IEA = International Energy Agency

IHA = International Hydropower Association

IRENA = International Renewable Energy Agency

JP = Japan

JRC = Joint Research Centre

KR = Korea

LCOE= Levelized Cost of Electricity

MS = member state

MX = Mexico

NO = Norway

NZ = New Zealand

O&M = Operation and Maintenance

P = installed power (kW, GW)

PSH = pumped-storage hydropower

PV = photovoltaics

R&D = research and development

ROR = run of the river

RoW = Rest of the World

RSHP = reservoir storage hydropower plant

TR = Türkiye

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

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Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	Scientific literature
	Installed capacity & energy production	Eurostat, IHA, IRENA, IEA
	Technology costs	IEA, IRENA, Hydropower Europe, Scientific literature
	Public and private RD&I funding	JRC
	Patenting trends	JRC, scientific papers
	Scientific publication trends	JRC, Scopus
	Assessment of R&I project developments	JRC, CORDIS
Value chain analysis	Turnover	JRC
	Gross Value Added	JRC
	Environmental and socio-economic sustainability	Scientific literature
	EU companies and roles	JRC, Hydropower and Dam website
	Employment	JRC, IRENA, EUROBSERVER
	Energy intensity and labour productivity	JRC
	EU industrial production	JRC
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	JRC, IEA
	EU market share vs third countries share, including EU market leaders and global market leaders	JRC
	EU trade (imports, exports) and trade balance	JRC
	Resource efficiency and dependencies (in relation EU competiveness)	Scientific literature

Annex 2: details on investments

Private Equity refers to capital investments (ownership or interest) made into companies that are not publicly traded. 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.

The early and later stages indicators that aggregate different types of equity investments in a selection of companies and along the different stages of their growth path. We only include pre-venture companies (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (companies that have been part of the portfolio of a venture capital investment firm at some point).

The early stages indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC[yy] investments; it also include public grants. At the time they raise such investments, those companies can usually be considered as start-ups. But while those companies often rely on innovative solutions and business models, such investments aim at financing the companies' operational expenditures and investment needs until they can scale their revenues and cannot be assimilated to R&I funding.

The later stages indicator reflect growth investments for the scale-up of start-ups or larger SMEs. It include Late Stage VC[zz], Small M&A[aaa] and Private Equity Growth/Expansion. Very large early stage deals (outliers) are also re-classified as later-stage deals. Small M&A refers to the acquisition by an operating company of a non-control stake in a pre-venture or VC company. Later stages investments do not include: Buyout Private Equity and Public investments.

The lists of companies include two distinct populations: VC and corporate companies.

Corporate companies is a selection of companies with a relevant patenting activity among the subsidiaries of top R&D investors from the EU Industrial R&D investment Scoreboard.

VC companies are selected based on their activity description (specific keyword selection for each technology and expert inputs) and this selection does not rely on patents. This selection tries to focus on companies that develop and manufacture technological solutions as much as possible. It does not e.g. include operators, project developers, specific applications (...)

Those selections include all identified companies for each technology, irrespectively of their current operational status or of the fact that they have relevant investments or patenting activities over the current period. VC companies may e.g. currently be start-ups, may have been start-ups or larger SMEs that grew into larger private companies, went public or were acquired by larger companies. They may also currently be out of business.

As they focus on two specific populations, those lists only represent subsets of all market players in each value chains. The aim is however to illustrate the dynamics of emerging innovators with growth potential and large corporate innovators (that are responsible for most private R&I investments).

To support that analysis, the count of companies corresponds to the number of active companies over the current period. Active corporate companies have High Value Patents over the current period. Active VC companies either have been founded (irrespectively of received investments) or have received investments (irrespectively of their founding year) over the current period.

[yy] Usually series A and B occurring within 5 years of the company's founding date

[zz] Usually Series B to Series Z+ rounds and/or occurring more than 5 years after the company's founding date, as well as undisclosed series

[aaa] Small M&A refers to the acquisition by an operating company of a non-control stake

Annex 3: details on patents

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.

Annex 4: Models and Scenarios: POTEnCIA and POLES

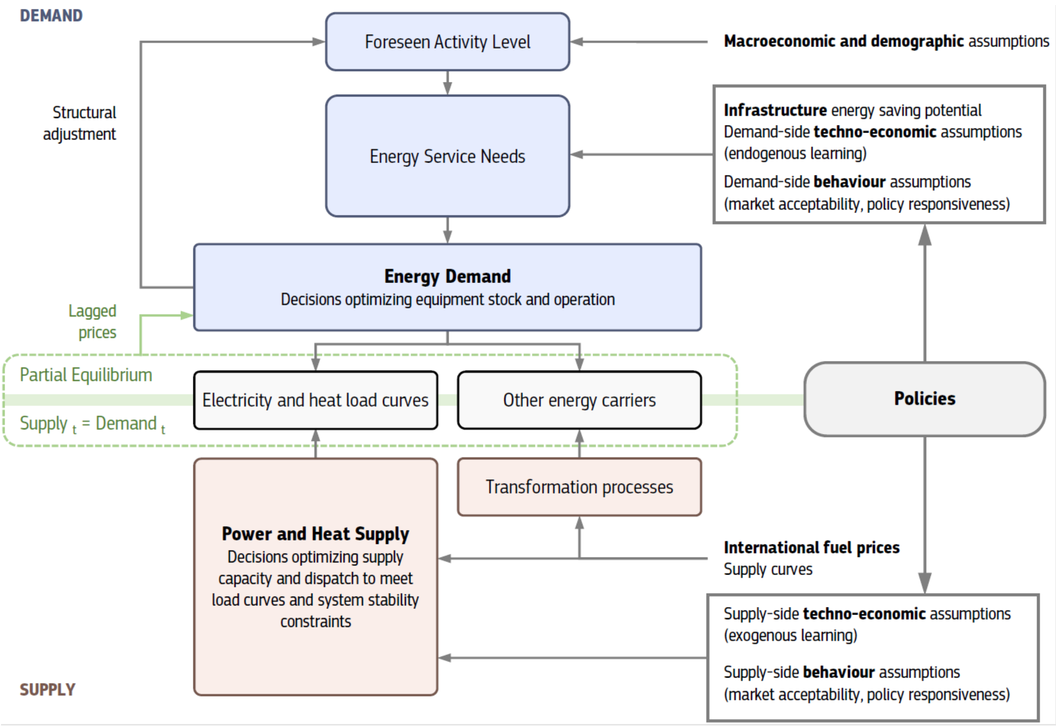
4.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure 45; detailed in Mantzos et al., 2017, 2019 [165,166]) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 45. The POTEnCIA model at a glance.



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; Rózsai et al., 2024[167]).

4.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the POTEnCIA CETO 2024 Scenario will be available in the forthcoming report (Neuwahl et al., 2024[54]).

4.2 POLES-JRC model

4.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System, Figure 46) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

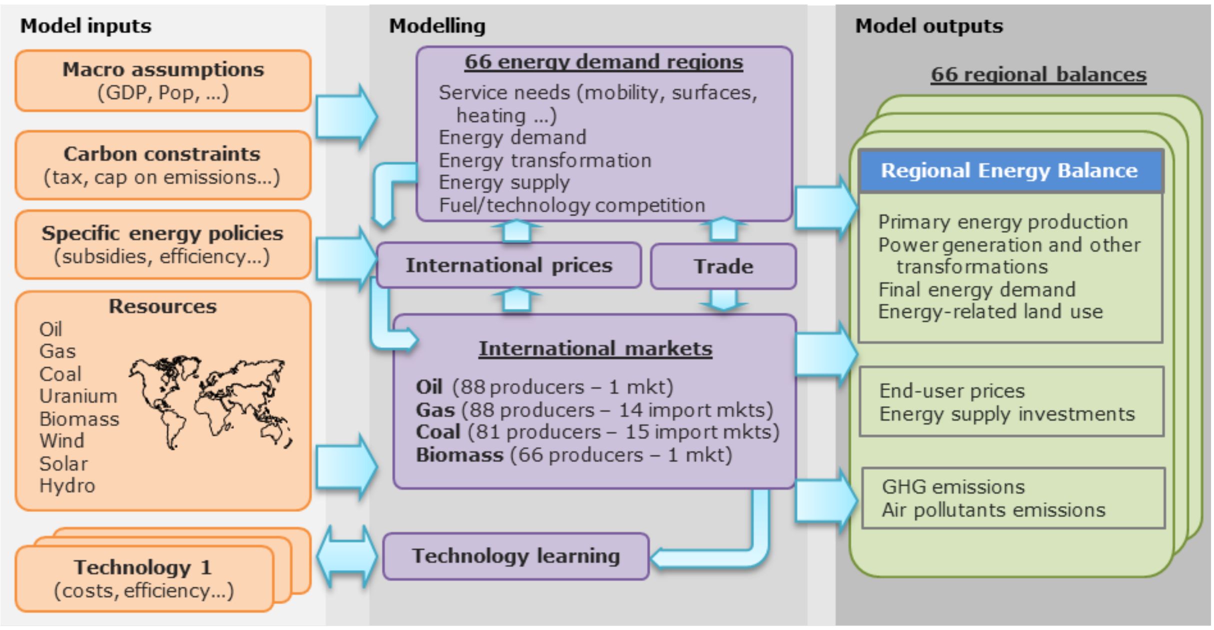
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Després et al., 2018[168]).

Figure 46. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

4.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024[169]). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.

- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synthetic fuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

4.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024[55]).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[bbb]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.
- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the Global CETO 2°C scenario 2024 regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

4.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The Global CETO 2°C scenario 2024 (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.

The POTEnCIA CETO 2024 scenario is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

[bbb] A description of the Global CETO 2°C scenario 2023 can be found in Annex 3 of (Chatzipanagi et al., 2023[170]).

Annex 5: PSH potential

The RE100 Map (re100.anu.edu.au) includes the following data sets:

- Greenfield Atlas based on dry-gully reservoir pairs (two new off-river reservoirs on undeveloped land);
- Bluefield Atlas which uses an existing lake or reservoir to create off-river system;
- Brownfield Atlas which repurposes an existing mining pit, pit lake, or tailings pond to create off-river system;
- Ocean Atlas which pairs dry-gully upper reservoirs with the ocean to create off-river system;
- Seasonal Atlas (open-loop) which pairs very large dry-gully reservoirs with rivers that have large annual water flows (an example of a site like this is the Lake Onslow project that was proposed in New Zealand, but has since been scrapped by the new government: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/low-emissions-economy/nz-battery)
- Turkey's Nest Atlas which uses "ring-dams" for one reservoir, allowing reservoirs to be built around natural depressions or on flat land. Turkey's Nest reservoirs may be paired with dry-gully reservoirs, existing lakes/reservoirs/very large rivers, or mining pits/pit lakes/tailings ponds to create off-river system.
- There are separate datasets for sites outside protected areas and sites with reservoirs that intersect with protected areas.

They have also calculated the non-overlapping storage potential across all of the Atlases for the 27 member states of the European Union (excluding overseas countries and territories), with a summary provided in the tables below. In total, the European Union member states have about 26,000 non-overlapping PHES sites with 2.2 Million Gigawatt-hours of energy storage potential. Some notes about the table:

- "All" checks for the non-overlapping potential for sites that are in both protected and unprotected areas. It is not equal to the sum of protected potential and unprotected potential, because some sites in protected areas may overlap with sites outside protected areas (e.g., one reservoir is in a protected area and one is outside)
- "Totals" checks for non-overlapping potential for sites across all Atlas types. It is not equal to the sum of potential in each Atlas, since sites across the Atlases may overlap (e.g., a dry-gully reservoir that could be paired with another dry-gully reservoir on the Greenfield Atlas, as well as with an existing reservoir on the Bluefield Atlas).

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