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HYDROPOWER AND PUMPED HYDROPOWER STORAGE IN THE EUROPEAN UNION

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

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Contents

Abstract

New developments in the renewable and clean energy sector came on the back of the energy crisis, brought on by the war in Ukraine, and some of the worst droughts Europe has experienced. 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 design 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 foreign fossil fuels, save energy, and accelerate the rollout of renewables. The energy crisis has highlighted the key role of hydropower in providing grid stability, water&energy storage, multipurpose services and dispatchable generation.

Hydropower provides an important contribution to renewable energy, with multiple benefits associated to water reservoirs. However, dams in freshwater systems can cause environmental damages. Hence sustainable hydropower needs to achieve a good balance between electricity generation, impacts on ecosystems and benefits on society, supporting the achievement of the Green Deal targets and the objectives of renewable energy and water policies. Several sustainable hydropower options exist, whose potential is of high relevance especially in the European Union. Amongst others, these are: modernization of the existing hydropower fleet, hydropower integration and hybridization with other energy technologies (floating photovoltaics, heat extraction from generators, batteries), tapping hidden hydropower in water and wastewater distribution networks, hydropower in existing and non-removable barriers (e.g. water mills), reservoir interconnection and hydrokinetic turbines. Digitalisation is also emerging as a relevant strategy to mitigate impacts along rivers and optimize hydropower generation taking into account weather, technical, market and environmental factors. Multi-purpose reservoirs are needed to face with climate changes, increased water demand and ensure flexible energy and storage, but they come also with costs and challenges. The European hydropower sector plays a leading role at the global scale, holding the largest share of export, high-value inventions and 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).

Foreword on the Clean Energy Technology Observatory

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 hydropower storage, 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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Executive Summary

Hydropower is currently the largest low-carbon and renewable electricity technology, with 1397 GW of global installed capacity and 4408 TWh of electricity generation in 2022. Worldwide, pumped hydropower storage (PHS) currently provides regulation, spinning reserve, and approximately 96% of utility scale energy storage. In the European Union (EU), the hydropower installed capacity in 2022 was 152 GW, and generated 374 TWh (including energy generation from PHS), which is the highest share from renewable energy sources, similar to wind energy. Currently, the EU hosts 46 GW of PHS turbine capacity, which is a quarter of the global installed capacity (45 GW in China). Hydropower technical maturity is well established, with overall power plant's efficiencies generally exceeding 80%, and that can reach up to 90%.

Hydropower is a complex and challenging sector within the Water-Energy-Food-Ecosystem (WEFE) nexus (SWOT in Table 1). Hydropower plants, especially the large ones with water reservoirs, interact with the hydrosphere, the biosphere, the lithosphere, the anthroposphere and the atmosphere. Multipurpose hydropower projects and big dams/reservoirs can have important additional functions for society, often more important than hydropower generation per se: irrigation and drinking water provision, flood and drought risk management, river navigation and recreation. The crosscutting effects of hydropower, and its interactions with the Earth's spheres make hydropower relevant to several policies, with often conflictual targets, multiple impacts and benefits. Hydropower is a renewable and flexible energy source, and it contributes to a resilient energy system thanks to its flexible operation and the storage capacity of reservoirs. This flexibility allows to integrate the volatile energy production from non-dispatchable energy sources (e.g. wind and solar power plants), ensuring grid stability (preventing blackouts) and ancillary services. Therefore, hydropower plays a key role in the long-term decarbonisation scenarios (i.e. the IEA's SDS and NZ2050scenario), contributing to reach the renewable energy targets set in the Renewable Energy Directive (Directive 2009/28/EC) and REPowerEU. On the other hand, hydropower barriers installed in freshwater systems are perceived as a source of impact in the Water Framework Directive (Directive 2000/60/EC), which is aimed at the preservation or recovery of the "good ecological status" of the aquatic environment. New barriers can interrupt river continuity, reservoirs generate impoundment, with consequent hydrological and morphological alterations, and hydropower turbines may cause damages to fish. The cumulative and/or relative environmental impact of small hydropower schemes may be significant.

Therefore, despite the high technical maturity of hydropower, there have been policy developments and several research programmes in the European hydropower sector, often associated to the mitigation of impacts and to its sustainable development. Sustainable hydropower needs to achieve a good balance between clean electricity generation and impacts (and benefits) on the environment and on the society. In the EU, an untapped hydropower energy potential still exists, e.g. of new PHS, 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. Novel methods are under investigation to integrate other energy technologies into hydropower plants, e.g. floating photovoltaics on hydropower reservoirs, hydrogen generation, hybridization with batteries and waste-heat recovery. Ocean (tidal and wave) power plants use turbines adapted from the hydropower sector. Digital solutions, such as forecast modelling, real-time and remote control, that are emerging strategies to support the EU digital and green transitions, can be implemented both for monitoring and enhancing quality of the surrounding environment, for improving the overall efficiency and energy generation and supporting the Operation and Maintenance activities. To gain wide acceptance and to obtain a win-win situation among all stakeholders, the large hydropower infrastructures have to be designed as multi-purpose projects by multidisciplinary teams with a complex system approach.

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 several research projects that have had a great scientific and technical impact worldwide, 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 Asia) and other projects aimed at tapping hidden opportunities (e.g. in water distribution networks, REDAWN). Other projects aim at unifying the voice of hydropower industry (i.e. European Technology & Innovation Platforms –ETIP- Hydropower Europe), 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 unifying the voice of hydropower scientists in Europe.

The EU research projects have generated significant positive impacts. 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. 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 33% of all high-value inventions globally (2018-2020), with Germany, France and Poland 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, as well as a wide range of 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 generation technology. Globally in 2021, approximately 2.36 million people worked directly in the hydropower sector. In 2021 there were 2227 employed people in the manufacturing, 108,494 in the construction and 1169 in the R&D in the EU (hydropower), with Italy and Austria, located at the heart of the Alps, being the most relevant employers.

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. Outside of China, three EU-based supply companies delivered 73.5% of the total orders in terms of power capacity within the period 2013-2017. The global exports within the period 2020-2022 accounted for EUR 2.3 billion, with EU countries holding approx. 50% of this (China accounted for EUR 498 Million of exports in the period 2020-2022). The EU's hydropower sector has a significant presence in Russia, Switzerland, Norway, supplying more than 70% of their imports, and in Canada and Chile, contributing to about 40% of their imports, even after the Russia-Ukraine conflict. The large European hydropower operators continue to invest in many hydropower projects outside of Europe, while manufacturing companies have a huge export potential. There are several large construction companies which have a worldwide activity in hydropower and dam projects. Many European engineering and consultancy companies offer knowledge, expertise, or consulting to hydropower projects in and outside of Europe. This makes the EU a global leader in hydropower technology (including pumped hydro). However, it must be noted that 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 invested value in hydropower (early and later stage investments) per inhabitant is 0.02 EUR/person for the EU (2016-2021), while it is 0.49 and 0.019 for the U.S. and China, respectively. Several EU companies are developing projects outside of the EU. European hydropower manufacturers spend more than 5% of annual turnover on R&I. IRENA's and World Bank's analyses identified hydropower as currently one of the least expensive forms of renewable electricity generation (when looking at the LCOE over the lifespan).

Hydropower can be considered an important sector to maintain a competitive EU in the world, and its benefits for the EU must not only be looked from the installed capacity point of view (some additional benefits are: export capacity, services provided by reservoirs, employment, flexibility). Hydropower catalyses an optimal integration of volatile energy sources (e.g. wind and photovoltaics) into the electric grid, and supports the achievement of the renewable energy targets. The multiple services of hydropower reservoirs in the EU can provide additional benefits and mitigate the effects of climate change. Europe is home to more than half of hydro equipment manufacturers and large operators of hydropower. As global hydropower market expands due to increase in global installed hydropower capacity, European operators and manufacturers are an important source of jobs. The export capacity of EU hydropower companies and their innovative characteristics, associated to a lead position in terms of scientific publications, make the EU hydropower sector a world leader. 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 dialog among stakeholders (e.g. industry, academy, associations, citizens and governmental institutions). The development of hydropower, as well as of all the other renewable energy technologies, must objectively consider benefits and impacts on the short and long-term, in order to mitigate possible conflicts among different 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.

Table 1. CETO SWOT analysis for the competitiveness of the hydropower sector.

Strength	**Weakness**
- Mature technology, high efficiency - High flexibility, ensuring supply during peak demand - Grid stabilizer - Long lifespan - Storage capacity (water and energy) of reservoirs - Multipurpose 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 - The EU is a leader in scientific research, technological innovation, export and market development - 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.	- Environmental and social impacts associated to 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 hydropower capacity expansion - Long construction periods and large investment needs/risks of large power plants - Additional benefits are not all remunerated
Opportunities	**Threats**
- 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 hydropower storage - Modernization of hydropower infrastructure is needed in the EU and can bring additional benefits - Still some potential for increasing pumped hydropower storage (interconnecting existing reservoirs, sea water plants) - 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	- 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 reservoir volumes due to sedimentation - In the EU, need of improved market rules and to remunerate the additional benefits - Loss of knowledge due to low attractivity 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

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 (i.e. by water wheels, see section 2.1). Today, hydropower is the largest renewable energy technology, with 1397 GW of global installed capacity worldwide (see section 2.2).

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

1. Storage/Dam power plants (SPP) 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;
2. Run-of-river (ROR) projects utilising the natural flow of water bodies and with limited storage capacity (if storage capacity is below the mean daily inflow, the reservoir is often considered a ROR);
3. Pumped hydropower storage (PHS) is, beside storage power plants, the main water and energy storage technology for power systems, composed of two water bodies (generally, two reservoirs, or a river as lower reservoir) that are connected by a turbine and pump system. A PHS system pumps water into an upper reservoir in periods of low electricity demand (and low electricity prices) and uses it to produce electricity by releasing water to the lower reservoir through the turbines. The reservoirs of closed-loop PHS stations (also known as pure PHS) are not connected to natural watercourses and do not utilise natural (river) inflows. Mixed PHS stations (also known as pump-back facilities, or open-loop), utilise natural inflows from rivers, creeks and groundwater. Pumped hydro energy storage comprises about 96% of global storage power capacity and 99% of global storage energy volume[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, e.g. water distribution, irrigation and sewage networks.

In terms of size, hydropower stations are distinguished in large-scale and small-scale, with a typical threshold 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. This 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 [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 for PHS), 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 PHS and SPP with higher heads approx. 20-25%), whereas the civil engineering structures represent the major part with 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 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, in this report, to investigate some competitiveness indicators (e.g. import/export, trade). This means that the real amount 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, while 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).
- 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[a]), 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 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% (for PHS motor/generator). Power losses in the waterways between the water intake and the turbine generally account for 5-10% of the gross power, depending on the design, flow rate and length of the waterway. The overall efficiency of hydropower is typically > 80% and can exceed 90% at the optimal operating point, 5-times higher than photovoltaics and 3-times higher than wind energy.

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:

- 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[8].

[a] 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 PHS as reversible pump/turbine.

Figure 1. Sketch of a storage hydropower plant, with focus on the powerhouse. Source: Hydropower Europe[8].

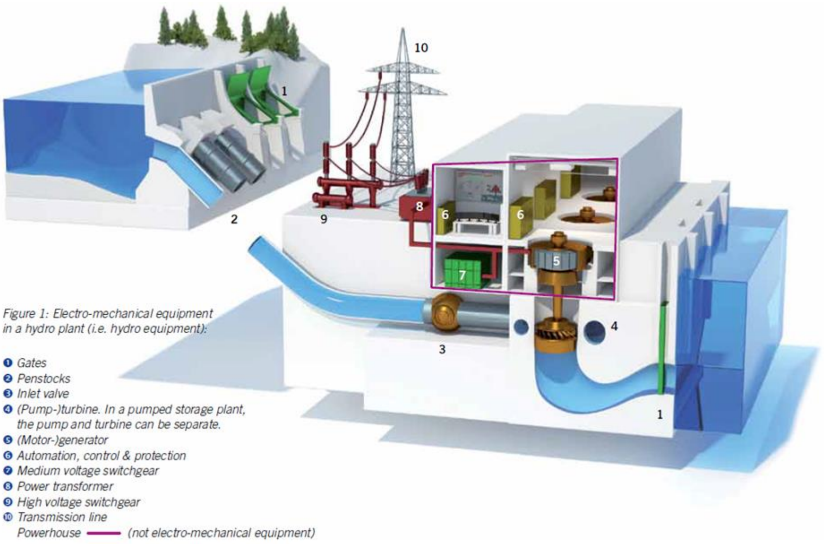
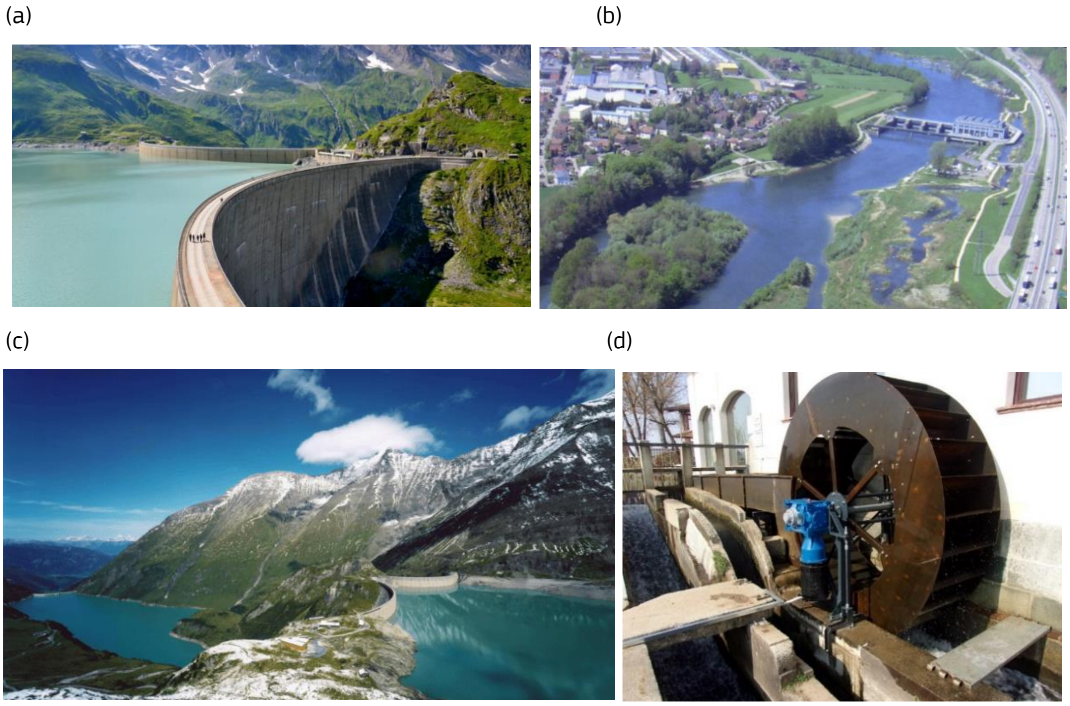


Figure 2. (a) SHP (Mooserboden Dam, Austria, from IEA Hydro report on Annex XIII), (b) ROR plant (Ruppoldingen in Switzerland, with lateral river for fish migration (Courtesy ATEL)), (c) PHS plant with two reservoirs (photo courtesy of Voith Hydro, Limberg II und Kopswerk II, Austria), (d) micro plant with water wheel in a diversion canal (photo 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. The main European Directives dealing with hydropower are the following ones.

- 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)[b]. 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 sites 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. 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 Renewable Energy Directive (RED) (Directive 2009/28/EC) claimed for 20% gross energy consumption of every member state based on renewable energy in 2020, and net zero carbon emissions by 2050. As part of the EU´s Climate and Energy Policy 20/20/20, the increase in hydropower production on the energy market (beside an increase of wind and photovoltaics) will be a consequence of those targets. The energy transition established in REPowerEU, the Green Deal, and the necessity to phase out dependence on Russian supplies, will have a further accelerating effect. Recently, consensus between EU co-legislators has been reached on the RED recast. 42.5% of gross final energy consumption has to be produced from renewables in the EU in 2030.
- 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, which 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). Hydropower currently provides more than 95% of energy storage in the EU. This is also realized by water reservoirs equipped with pumping units. The EU hosts a quarter of the PHS 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.

  To reduce risk from imported flexibility, Art. 22 lit. d) of the Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector, requires that every country has to increase the flexibility of the national system, in particular by means of deploying domestic energy sources, demand response and energy storage, and flexibility procurement mainly based on cross-border-exchange [4]. Hydropower plays a key role in this context, since it is the most flexible renewable energy technology and the sector with the highest water-energy storage capacity.
- To cope with natural hazard of floods, the European Parliament released the Floods Directive (Directive

[b] 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. However, less than 10% of barriers in EU's rivers are for hydropower.

2007/60/EC) in 2007 for managing river systems. Given the severity of floods in Europe (325 major floods in Europe between 1998 and 2004, and more than 200 since 2000), the European Floods Directive addresses the risk analysis and provides operative tasks for the member states. Most of the European river systems are heavily impacted by multiple pressures along the river corridor and/or feature significantly altered conditions in inundation areas. Barriers in rivers can be a source of impact, but the capacity to store water in reservoirs can mitigate floods and droughts. Furthermore, a mission to make water resilient to climate change was recently launched, to design innovative ways to ensure that our 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)[5], 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.

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 [6]. 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 [7]. In a hybrid power plant, PV panels or wind turbines can produce energy when the sun or wind are available, while saving water for hydroelectricity during intermittent times when the sun or wind go down [8]. PV systems can be installed as floating solution on hydropower reservoirs [9], reducing PV land use, optimizing the overall efficiency and reducing evaporation, or on dam's surface[59]. Waste-heat can be extracted from the cooling system of the turbine/generator [10, 11]. Hydropower could also be combined with batteries (for e.g. fast reaction in primary regulation [28]) or with hydrogen-electrolyzers in case less demand in the grid is needed and water cannot be stored [12, 13]. Pumped hydropower is the largest energy storage available worldwide and it allows to better integrate the volatile energy output of wind and solar power plants. Ocean (tidal and wave) energy technologies implement several technologies derived from the hydropower sector [14].

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

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 energy 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 [15]. Kougias et al., (2019)[15] and Oladosu et al., (2021)[16] reviewed the emerging hydropower technologies. Their implementation potential in the existing hydropower facilities was assessed in Quaranta et al., (2021)[28]. The innovative materials are discussed in Quaranta and Davies (2021)[70], while environmentally enhanced turbines are discussed in Quaranta et al. (2021)[116]. Fry et al., (2022)[17], in the EC funded project Hydropower Europe, estimate that between EUR 190 and 324 million are required to be invested by funding schemes in the following topics: flexibility, optimization of operation and maintenance, resilience of electro-mechanical equipment, resilience of infrastructures and operation, environmentally compatible solutions and mitigation of global warming impacts. Furthermore, in order to respond to the increasing needs for flexibility[c] 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[82].

Hydropower is the most established renewable energy technology because of its 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[d]. For example, there were at least 66,000 water wheels operating in France in 1826, and 25,000–30,000 in England in 1850. In Germany 58,000 mills were counted in 1882 and 33,500 water wheels with power outputs ranging from 0.75 to 75 kW were licensed as late as 1925. In Poland, almost 10,500 watermills operated in the late 18th century. For comparison, 55,000 water wheels operated in the United States in 1840, while in Japan water wheels comprised 56% of total power generation[e] 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 [18]. 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 [19].

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-pump/turbines were developed in the early 1940s and spread in PHS installation with heads up to 700 m; nowadays, and are dominating the actual development of PHS. 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[20]). VLH turbines typically work below 500 kW and their total installed capacity in Europe is around 30 MW (MJ2 Technologies, 2023). Water wheels are

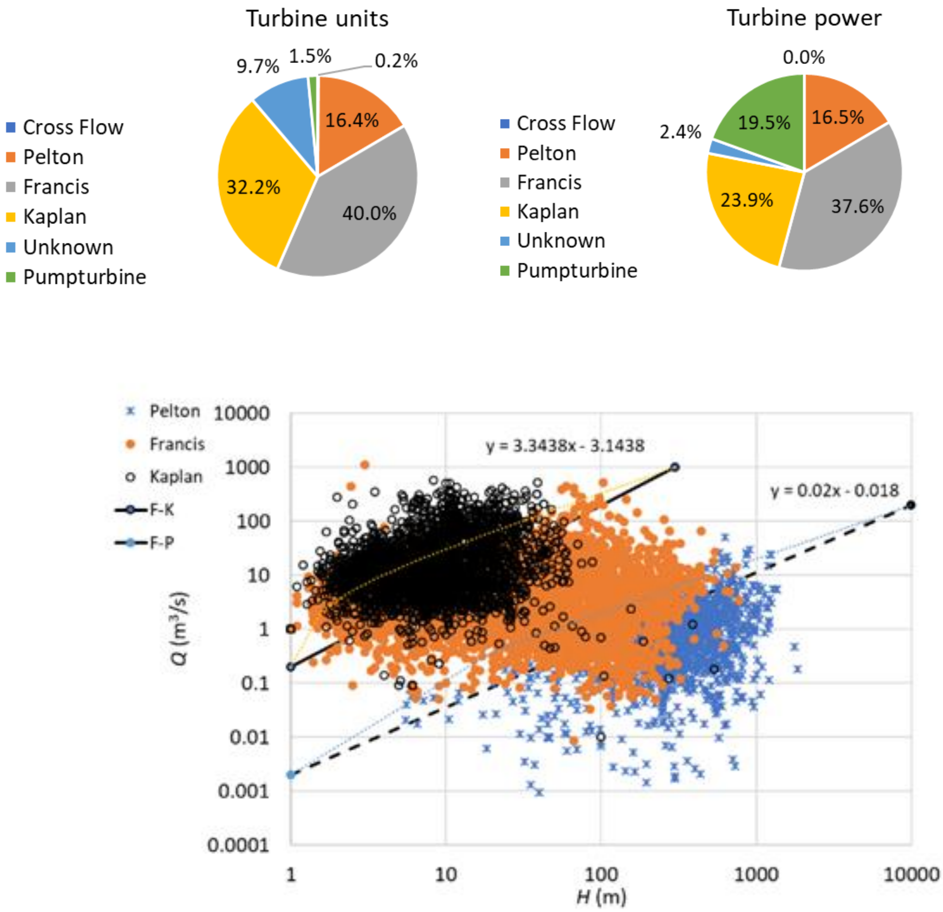
[c] The ability of a system to respond to changes in generation and/or load is called system flexibility.

[d] 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.

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

typically below 30 kW and with average power of 13 kW in the EU (Quaranta et al., 2022b[46]), and it might be possible to assume that their cumulative installed capacity in the EU is below 10 MW (Quaranta, 2023). In the EU, 12 Vortex turbine installations are in operation, with a cumulative power of 78.1 kW (in Austria, Germany and Belgium) [21].

Figure 3. Share of turbine type in the EU according to Voith Hydro database, and their operating range (as in 2020) [28]. Deriaz, Girard were included into the Francis type (Voith Hydro and Quaranta and Muntean (2023)[11]).



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[f] dams exist in the world, storing 8919 billion m^3 at full capacity. More than 6062 large dams are in Europe (including Ukraine and without Turkey). The European hydropower reservoirs store about 440 billion m^3 of water (including Ukraine and without Turkey), 25% of them for multipurpose water use. Amongst the 6062 large dams, 2743 store water for hydropower generation[22]. In the EU there are 4451 large dams according to the ICOLD 2020 register of dams and 33% are for multiple uses. According to ICOLD 2013, in the EU, 47% of single purpose reservoirs are for hydropower, 28% of multiple purpose reservoirs have hydropower as a first use, 18% as second use and 8% as third or fourth use. Overall, 49% of EU reservoirs are powered.

From the AMBER database[23], almost 650,000 barriers were counted in EU's rivers and less than 10% are dams. According to 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 5% of

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

barriers seem to be exploited for hydropower. 90% of power plants are below 10 MW of installed power, but contribute to a cumulative installed capacity of 10%.

In the years 1996–2019, a total of 342 barriers were dismantled in Europe, approximately 95% of which are so-called low barriers: 54.7% are up to 2.5 m high, 40.6% are 2.5–7.5 m high, 2.3% are barriers 7.5–15 m high, and 2.0% are higher than 15 m[24].

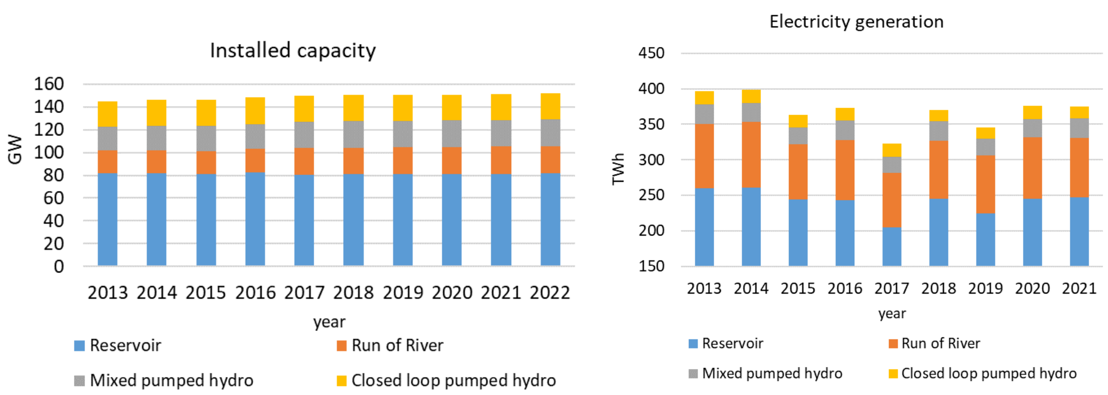
2.2.2 Installed capacity and generation

In 2022, the global installed power of grid-connected hydropower reached 1397 GW, including 175 GW of pumped hydropower storage (PHS), with an annual generation of 4408 TWh [25]. Hydropower also provides 1.8 GW of off-grid hydropower electrification services, mainly in Africa, South America and Asia [26].

According to Xu et al., (2015)[27], Europe has a hydropower technical potential 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[15] and by refurbishing existing plants [28] (section 2.3).

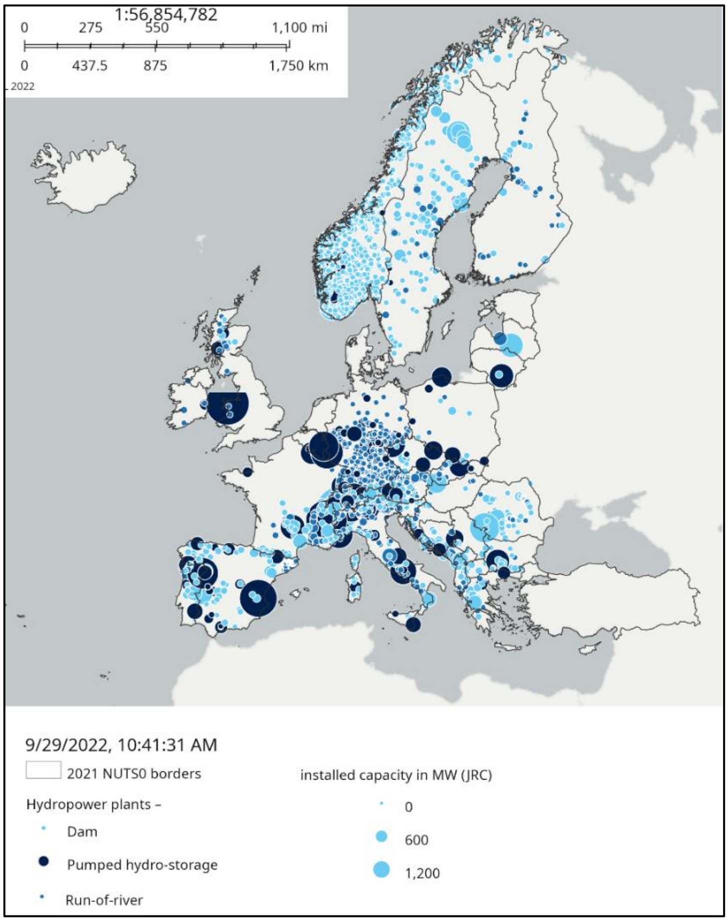
According to Eurostat, in 2021, the hydropower installed capacity was approximately 152 GW in the EU, mostly located in alpine environments (Figure 4 and Figure 5). With respect to 2011, this corresponds to + 6 GW of installed capacity. Out of that, 105.7 GW comprises "traditional" or "pure" hydropower stations, meaning hydroelectric facilities that solely serve electricity generation (including multipurpose services). Another 22.7 GW refers to closed-loop pumped hydropower storage. The remaining 23.3 GW is mixed hydropower, meaning typical PHS facilities connected to rivers [29, 30]. In the last decade, the annual energy generation from hydropower in the EU has oscillated between 322 and 398 TWh/y depending on the hydrological conditions with the average value being 363 TWh/y. This is, on average, 12.5% of EU's total net electricity production and represents one-third of the annual renewable electricity generation. The annual generation was 375 TWh in 2021 including energy from PHS. Pure hydropower plants generated 330.8 TWh and renewable hydropower 348 TWh[9]. For more details on the EU hydropower fleet composition, see Table 2. In Table 2 the installed pumping capacity is, on average in the EU, 90% of the turbine capacity, according to the JRC hydropower database. 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.

Figure 4. Installed capacity and electricity generation in the EU.



[9] Pure hydropower includes ROR and SPP. 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).

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 mini-hydropower plants.



According to IHA (2023)[25], 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) are 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 dam 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 600 Million EUR. Financing included contributions from the European Investment Bank (150 Million EUR) and KfW IPEX-Bank (90 Million EUR). In Ireland, the Silvermines hydropower plant will receive 4.3 Million EUR 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 Storage Plant. Gouvães was inaugurated in July 2022 and is an 880 MW pump storage plant. Finally, Alto Tâmega with a cost of circa 1.5 Billion EUR, will have a storage capacity of 20 GWh and is expected to eliminate 1.2 Million tonnes of CO_2 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. Czech Republic and Slovakia are focusing mainly on upgrading facilities. In Italy, an agreement was contracted to fix technological advancements at 33 hydropower plants in the country. In Portugal, the 880 MW Gouvaes pumped storage plant is planned to increase the size and form part of the Tamega Hydroelectric Complex ongoing structure [31].

The installed hydropower per inhabitant is 0.35 kW/person in the EU, 0.33 kW/person in the U.S. and 0.28

kW/person in China, demonstrating that the EU is a strategic user of hydropower. The EU is also leader in the small hydro sector (Wagner et al., 2019)[32] and in R&D (Manzano-Agugliaro et al., 2017)[33].

Table 2. Installed turbine power (in GW) at the EU level, categorized depending on hydropower plant type (RoR, SPP, PHS) and installed power class *P* (MW), combining data of the JRC hydropower database [28], Voith Database and UNIDO database (year 2019).

P (MW)	RoR	SPP	PHS (turbine mode)	Total (GW)
P>10	26	69	44	140
1<*P*≤10	7.2	4.4	0.0	12
P≤1	3.2	0.0	0.0	3
Total	37	74	44	155

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%. 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 low. Storage power plants are usually fitted with relatively high capacity that cannot run at full power throughout the year using only natural inflows. Storage 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). Storage 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%.

2.2.3 Pumped-hydropower storage power plants

The approximately 270 PHS stations worldwide have a total turbine power capacity of 175 GW, representing over 90% of the global grid-scale electricity storage capacity[34]. 160 PHS stations operate in Europe with an overall turbine capacity of 55 GW, and 140 stations with turbine capacity of 45 GW in the EU (the installed pumping capacity is 39 GW in the EU). The productiveness index, considering closed and open-loop stations, (average monthly PHS consumption [GWh] /average monthly PHS production [GWh]) ranges from 54.8% to 86.8%, with an average EU value equal to 73.9%. PHS stations in most of the countries operate with an average productiveness index of approximately 70-75%. The extreme values refer to Norway (outside of the EU) and Greece. In Norway, PHS plants are operated throughout the day in certain months, followed by periods of low utilization, and this strategy leads to low productiveness index. Greece hosts pump-back stations and their low utilization results in their main operation with river flow, that increases the productiveness index [29].
Averaging the values of 2019, 2020 and 2021 from Eurostat statistics, PHS produced 42.3 TWh. In 2021 the absorbed energy was 37.4 TWh/y. The ratio electricity absorbed/electricity provided was of 88% in 2021 in PHS. Table 4 lists the installed power capacity of large PHS (over 1000 MW) systems by country[35], while Figure 6 depicts the global distribution of PHS systems.

Table 3. Installed turbine power P, installed turbine power of PHS P_{PHS}, energy generation E (including energy generation from PHS), and capacity factor per member state, for the year 2021 (based on 2021 Eurostat data).

Acronym	Country	P (including PHS) (GW)	P P_{PHS} (GW)	E in 2021 (TWh)	Average E 2018-2021 (TWh)	Overall CF in 2021 (including PHS generation)	Adsorbed pumping energy in 2021 (TWh)	share of total electricity generation
AT	Austria	14.7	5.8	42.5	43.3	33%	5.5	60.1%
BE	Belgium	1.4	1.3	1.3	1.3	11%	1.2	1.4%
BG	Bulgaria	3.4	1.0	5.1	4.3	17%	0.4	10.7%
HR	Croatia	2.2	0.3	7.2	6.7	38%	0.1	47.5%
CY	Cyprus	0.0	0.0	0.0	0.0	-	0.0	0.0%
CZ	Czechia	2.3	1.2	3.6	3.2	18%	1.6	4.3%
DK	Denmark	0.007	0.0	0.016	0.016	26%	0.0	0.0%
EE	Estonia	0.006	0.0	0.023	0.022	44%	0.0	0.3%
FI	Finland	3.2	0.0	15.8	14.3	57%	0.0	22.0%
FR	France	26.3	7.1	64.0	65.8	28%	5.9	11.5%
DE	Germany	10.8	6.5	25.0	24.9	26%	8.2	4.3%
EL	Greece	3.4	0.7	6.0	4.8	20%	0.1	10.9%
HU	Hungary	0.1	0.0	0.2	0.2	40%	0.0	0.6%
IE	Ireland	0.5	0.3	1.0	1.1	22%	0.5	3.2%
IT	Italy	22.7	7.2	47.5	48.9	24%	2.9	16.5%
LV	Latvia	1.6	0.0	2.7	2.5	19%	0.0	46.3%
LT	Lithuania	0.9	0.8	1.1	1.0	14%	1.0	22.4%
LU	Luxembourg	1.3	1.3	1.1	1.1	9%	1.4	49.1%
MT	Malta	-	-	-	-		0.0	0.0%
NL	Netherlands	0.037	0.0	0.1	0.1	27%	0.0	0.1%
PL	Poland	2.4	1.8	3.1	2.8	15%	1.1	1.7%
PT	Portugal	7.3	2.8	13.5	12.7	21%	2.0	26.4%
RO	Romania	6.7	0.4	17.7	16.9	30%	0.4	29.8%
SK	Slovakia	2.5	0.9	4.6	4.5	21%	0.4	15.2%
SI	Slovenia	1.4	0.2	5.0	4.9	42%	0.4	31.5%
ES	Spain	20.1	6.4	32.8	32.6	19%	4.3	12.0%
SE	Sweden	16.4	0.1	73.9	68.5	51%	0.1	43.0%
EU	European Union	151.7	46.1*	375	366	28%	37.4	12.9%[1]

[1]= ratio of the totals (the average of the MS ratio values is 17.4%).

Figure 6. Distribution of PHS plants (source: PHS forum of the International Hydropower Association[36]). Blue = operating, Orange = under construction or planned.

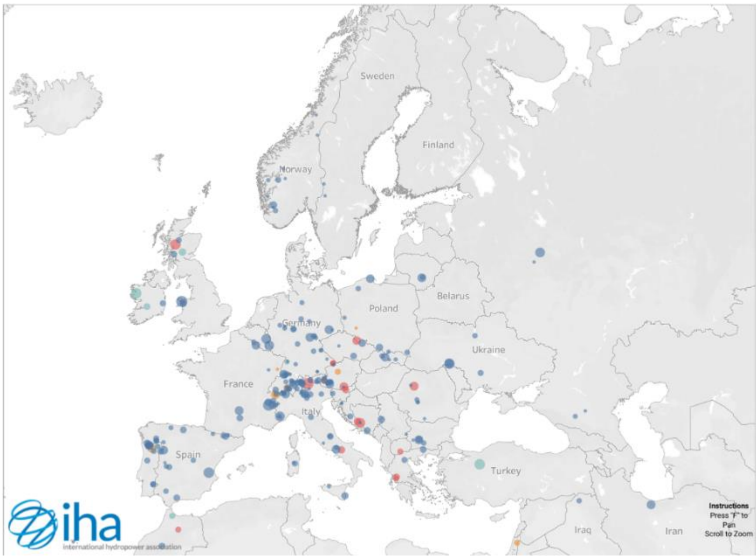


Table 4. Installed power capacity of large PHS (over 1000 MW) systems by country.

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

2.2.4 Energy storage

Hydropower reservoirs and PHS are currently the only well-established long-term (e.g. days, weeks) energy storage technologies, and large water reservoirs can also provide seasonal energy&water storage. However, a clear assessment of energy storage is not present in the literature due to the lack of data (in particular stored water volume, dam height and head). From the JRC hydropower database, it is possible to estimate that the available theoretical potential of energy storage is 35 TWh[h] in the EU's hydropower reservoirs with known data: the energy generation is 92 TWh per year and the installed capacity is 86 GW from these power plants (considering EU's hydropower plants with known reservoir volume and head). Therefore, considering that the overall EU's installed power of reservoir-type hydropower plants is 127 GW (including 45 GW of PHS), the available theoretical potential of energy storage can be extrapolated to 51 TWh based on the installed power (energy storage in PHS reservoirs counts for 9.6 TWh). Using instead the ICOLD2013 database, the theoretical energy storage potential can be estimated in 28 TWh; the cumulative power of the ICOLD's hydropower plants considered in this analysis is 81 GW, and, therefore, extrapolating the value to the 127 GW of current installed capacity in reservoir-type HPP, we obtain 44 TWh of available theoretical energy storage. The value of 44 TWh is reasonably in agreement with the 51 TWh, and it is slightly lower because the height of the dam is used instead of the head difference, thus underestimating the value. Results reported in Graabak et al., (2017)[37] show that in the EU the energy stored in water reservoirs is approx. 90 TWh. By considering that 50% of EU reservoirs are powered (hydropower should not be necessarily the primary use), the theoretical potential of energy storage in hydropower reservoirs would be 45 TWh, in line with the 51 TWh estimated above.

The abovementioned values 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, 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. The technical storage capacity of PHS reservoirs can be estimated with the data available in the IHA database at 1215 GWh (259 GWh closed loop and 957 from open loop). This is significantly lower than the 9.6 TWh of available theoretical potential (calculated as described above), as the latter value considers real operation limitations, the real usable volume (approx. 50% of the design one), head variation and efficiency.

When considering the Europe as a whole, it is estimated that European water (not only hydropower) reservoirs provide a theoretical storage capacity of 220 TWh[38]. Norway has the largest (85 TWh) storage capacity in Europe, more than any EU member states, e.g. Austria (3.2 TWh in water reservoirs), France (9.8 TWh), Germany (0.3 TWh), Greece (2.4 TWh), Italy (7.9 TWh), Portugal (2.6 TWh), Spain (18.4 TWh), Sweden (34 TWh) and Finland (5 TWh). Switzerland hosts 8.4 TWh (Graabak et al., 2017)[37]. Norwegian hydropower acts like a battery for balancing variable renewables in neighbouring countries[37], with more than 1000 reservoirs.

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 1397 GW in 2022[25] to about 1560 GW in 2030 up to 1800 GW in 2050 according to the POLES-JRC model (see Annex 4). POLES'JRC's 2030 figures are well aligned with IEA and IRENA's projections[103] while these organisations have more bullish projections in 2050, reaching 2500 GW of global hydropower installed capacity.

In the EU, the outlook for the expansion of hydropower is less bright, due to several barriers that are extensively discussed throughout the report. The main priorities for hydropower in the EU are defined in the EU Clean Energy Transition Partnership[39], and are flexibility, storage, digitalisation, services of hydropower, sustainable solutions and sediment handling. Some projects are anyway in the pipeline (Figure 9). 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 [40]; 3) new hydropower plants face high

[h] calculated by *head* x *stored volume* x *coef.*, thus assuming: *head* >> dam height and constant while the reservoir empties, and the full design volume (*coef.* is the conversion factor to obtain TWh).

investment costs and/or long construction times that expose them to risk and to complex financing process; 4) remuneration of hydropower plants especially in the long-term is challenged by the expected reduction of electricity prices. Ad-hoc policy interventions 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.

2.3.2 POTEnCIA's CETO Climate Neutrality Scenario

According to POTEnCIA's CETO Climate Neutrality Scenario, hydropower installed capacity in the EU is assumed to remain broadly stable in the future (see Figure 7). Despite that, hydro electricity generation is projected to increase to almost 430 TWh/y in 2030, which marks an increase of about 50 TWh/y compared to 2020 levels. This is mainly driven by a higher utilization of pumped storage hydro, which provides part of the increasing need for flexibility to integrate large volumes of variable renewable energy generation, needed to fulfil the 2030 target of the Renewable Energy Directive. After 2035, hydro electricity generation is assumed to slightly reduce again, while remaining higher than 2020 levels, due to the growing competition with other electricity storage technologies and flexible load from consumers willing to provide demand-response (e.g. smart charging from electric vehicles or flexible hydrogen generation from electrolyzers).

In the example provided in Figure 8, the hourly generation pattern of hydro pumping changes towards 2050, which is a consequence of the change of the residual load hourly pattern by 2050. The residual load is the inflexible load that is left after subtracting inflexible electricity generation from must run units and units that produce with close to zero marginal costs (e.g. wind or solar). By 2020, the residual load is mainly driven by inflexible hourly demand (i.e. inelastic demand), whereas towards 2050 is more and more driven by variable renewable generation, which lead to hours of negative residual load. In the example, by 2050 wind and solar generation combined is highest in the middle of the day, and it is in these hours were hydro pumping loads energy, and the existence of a large fleet of flexible electrolyzers can provide flexible load to the energy system, reducing the need for flexibility from hydro pumping units. Flexible load in this context is the same as demand response. Electrolyzers are the ones behind the vast majority of demand response in the scenarios, but there are other technologies (smart charging of EVs, flexible heat generation) that also provide flexible demand. Inflexible load is load modelled with exogenous time series. Flexible load is load that can be allocated with some degree of freedom (Source: POTEnCIA CETO Climate Neutrality Scenario (see Annex 4)).

Figure 7. Hydropower installed capacity and electricity generation by type of plant in the EU, 2025-2050. Source: POTEnCIA CETO Climate Neutrality Scenario (see Annex 4).

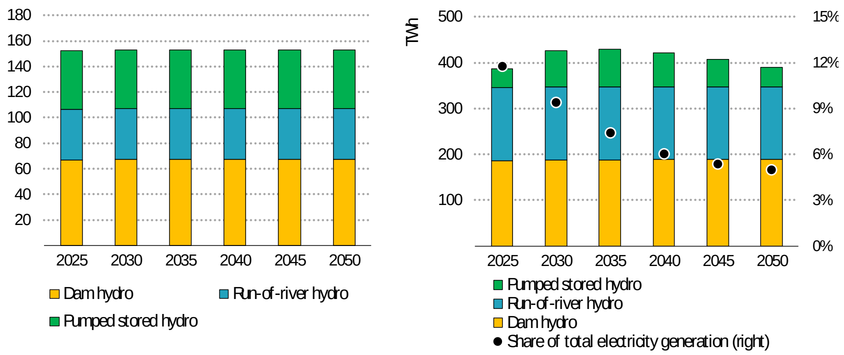
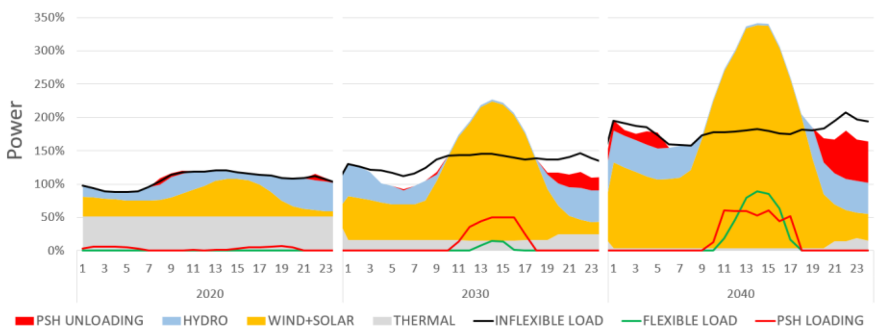


Figure 8. Hourly power generation (stacked area) and load (unstacked lines) relative to 2020's hourly average load aggregated by type, in a summer day in a South European country. PHS unloading = generation.



Tarvydas (2022) [41] has more optimistic assumption that POTEnCIA regarding the future uptake of hydropower in Europe, projecting an increase of hydropower generation up to about 420 TWh/y in 2050, thus an increase of about 60 TWh/y with respect to the average annual generation recorded in the last 10 years. Table 5 lists the PHS under construction and planning in Europe and Table 6 lists the big dams under construction, according to the World Atlas of Hydropower & Dams 2022[42].

Figure 9. Hydropower project pipeline in Europe, 2022-2037[43].

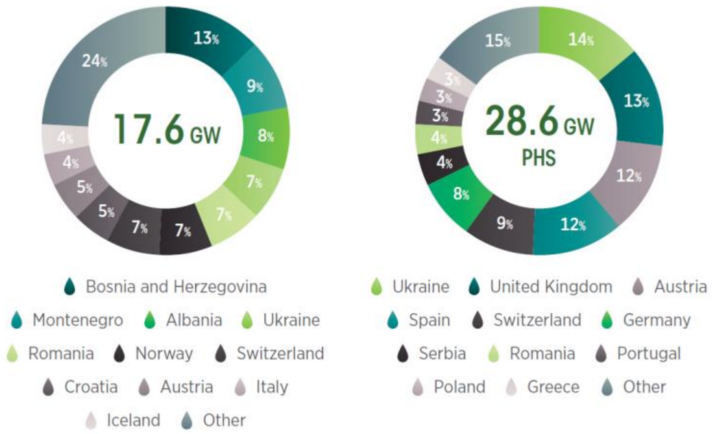


Table 5. PHS under construction/planning/almost ready (in 2022). Empty cell = unavailable data

Member state	Turbine MW	Pump MW	MWh/day storage capacity	GWh/y annual generation
AT	45	45		
AT	480	480		850
AT	170	170	8500	460
AT	170	190		216
AT	170	150		
AT	1015	400		785
DE	18	16		
DE	300	300		
EE	506	509	6000	1100
EE	225	225		
EL	220	234	2250	264
EL	460	496	2250	552
ES	200	220	3500	
ES	570			
IE	360	360		650
LT	110	77		
PL	750	804		1275
PT	880	880	20000	1468
SL	400			777

Table 6. Big dams (>60 m high) under construction/planning/almost ready (2022). H = hydropower, S = water supply, I = Irrigation, reg = regulation, div = diversion.

Member state	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

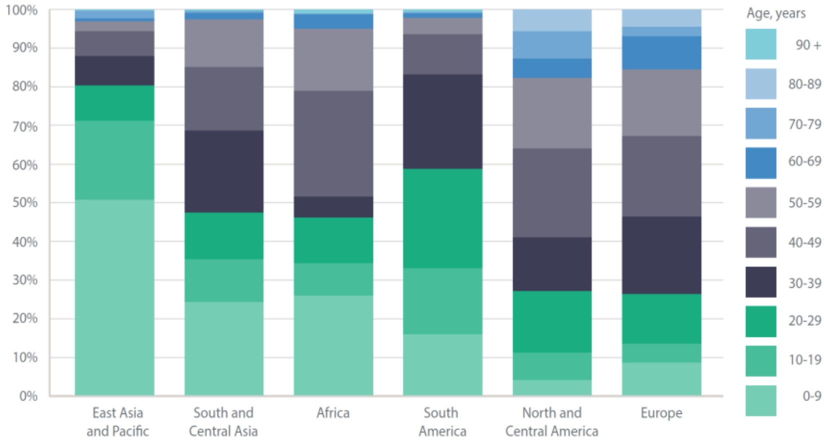
2.3.3 Sustainable hydropower and PHS potential

Considering hydraulic, technical and environmental perspectives, it is possible to estimate the untapped potential of sustainable hydropower, focusing on the optimization and exploitation of the existing fleet and of the existing water facilities and 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, Figure 10). Quaranta et al., (2021) estimated that the annual electricity generation from the existing hydropower fleet could be increased by approximately 8% (~30 TWh/y)[i], implementing hydropower digitalisation, modern electro-mechanical equipment and by optimizing the waterways. 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. Modernization should also aim at improving resilience to climate changes and to optimize hydropower operation to better deal with future energy needs, market requests and new hydrological time series (more floods and droughts). On one hand, hydropower generation depends on water availability, and may suffer of water shortage in long dry periods. On the other hand, optimal management of hydropower reservoirs, along with a better inflow and weather forecast, can help in mitigating droughts and can act as flood control system. Gøtske and Victoria (2021)[44] estimated that the annual inflow for high (mid)-emission scenarios is going to decrease by 31% (20%) in Southern countries and to increase by 21% (14%) in Northern countries, and more frequent and prolonged droughts in Mediterranean countries are expected. The median decrease of generation of ROR (run of river) hydropower will be −3% in the future, focusing on the Italian Alps. For further details see the 2022 CETO report. Farinotti et al., (2016)[56] suggested that the deglacierizing catchments could make an important contribution in increasing the production in the future (by 2050) if the existing hydropower fleet in such catchments were upgraded by increasing the storage volume (for SPP) or production capacity (for ROR and SPP). New development should also aim at increase storage capacity of existing reservoirs, due to sedimentation; the

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

average annual sediment inflow into European reservoir is 0.7% of the reservoir volume, but most of such volume is not filled with sediments thanks to prevention and mitigation solutions (e.g. flushing, dredging) [45].

Figure 10. Age of hydropower plants in different geographic contexts (IHA, 2023).



Developing hydropower in existing infrastructures, e.g. in water distribution networks (aqueducts), in existing low head barriers (e.g. water wheels in water mills) and in wastewater treatment plants has been the aim of numerous research and deployment activities. This is due to the lower impacts compared to conventional reservoir hydropower in freshwater systems, and the untapped potential in the EU [46, 47] (Punys et al., 2019; Quaranta et al., 2022). 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. The technical potential associated to these technologies 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 (Quaranta and Muntean, 2023)[11].

The EU long-term projections and potential estimation for PHS 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 2443 MW of rated power were commissioned in the OECD Europe[j]. 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 building and commissioning. Some projections foresee deployment rates of 4 GW of new PHS until 2030 in the EU (in Switzerland, about 4 GW are ready for approval, pers. comm. Anton Schleiss), and an increase in PHS capacity up to 70-75 GW in 2050 [48]. However, other sources (e.g. POTEnCIA forecast, JRC, Annex 4) foresee a rather stable installed power.

When just looking at the feasible technical potential, Stocks et al., (2021)[49] estimated that the additional potential associated to closed loop PHS in Europe is 260 TWh, among which 19 TWh are the cheapest sites and 67 TWh refer to the most expensive sites. The assessments of Stocks et al. and Hunt et al. did not consider restrictions on population, land use, biodiversity, transmission, etc., so they present the existing potential and not its viability. One of the most limiting factors in the potential use of large-scale PHS is that not many locations could offer economically viable deployment, thus other sources pointed out that the PHS capacity in the EU will not increase due to environmental and geographic constraints[50]. Therefore, a real technical opportunity for PHS expansion is first of all expanding the operating range. By introducing smart sensors, variable speed turbines with increased efficiency and system optimization to new or existing PHS, the overall PHS utilization will increase. Countries with redundant PHS potential could look for increasing their potential market share by selling their services to neighboring countries. Opening cross-border markets for balancing capacities could also serve as an important incentive to increase the use of the existing PHS capacity[29]. Reservoir interconnection, virtual energy storage gains resulting from the spatio-temporal coordination of hydropower over Europe and the

[j] 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

upgrading of existing PHS are opportunities for pumped hydropower and to balance generation variability [51, 52]. The theoretical potential achievable by interconnecting reservoirs within 20 km distance is +4 TWh in the EU and +29 TWh in Europe (Gimeno-Gutiérrez and Lacal-Arántegui, 2017). When a maximum distance of 5 km is considered, the energy storage potential reduces to 141 GWh in the EU. Spatial coordination can virtually increase energy storage by 140 TWh in Europe (Wörman et al., 2020). Underwater PHS, low-head energy storage [53] and underground PHS using abandoned mines[k] are under investigation. 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 PHS from small lakes and reservoirs was estimated to be about 33 GWh, which is approx. 33% of the current national energy storage capacity of PHS [54]. Existing reservoirs can be paired to new reservoirs at higher altitudes.

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, pumped storage 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 the summer to generate electricity during the winter [55]. In Southern European countries, new reservoirs are urgently needed to mitigate the already visible effects of climate change (floods, droughts and fire, and to compensate hydrological changes due to glacier retreat [56]).

Table 7 summarizes the hidden potential in the EU (or Europe) assessed in scientific studies[l].

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 [57] can ensure energy storage for several hours, whilst hydropower can store and release energy for days and weeks, including seasonal transfer, and can be integrated together [58]. Reservoirs can host floating PV, or PV could be installed on dam surfaces [59]. Methane capture processes are under investigation, but R&D is further needed to improve cost-effectiveness (this measure is especially relevant for tropical reservoirs)[11].
Figure 11 shows the potential for additional energy generation (from hydropower) in the EU, with focus on modernization and hidden hydropower in WDN, WWTPs and water mills. For further details refer to Dorati et al. (2023).

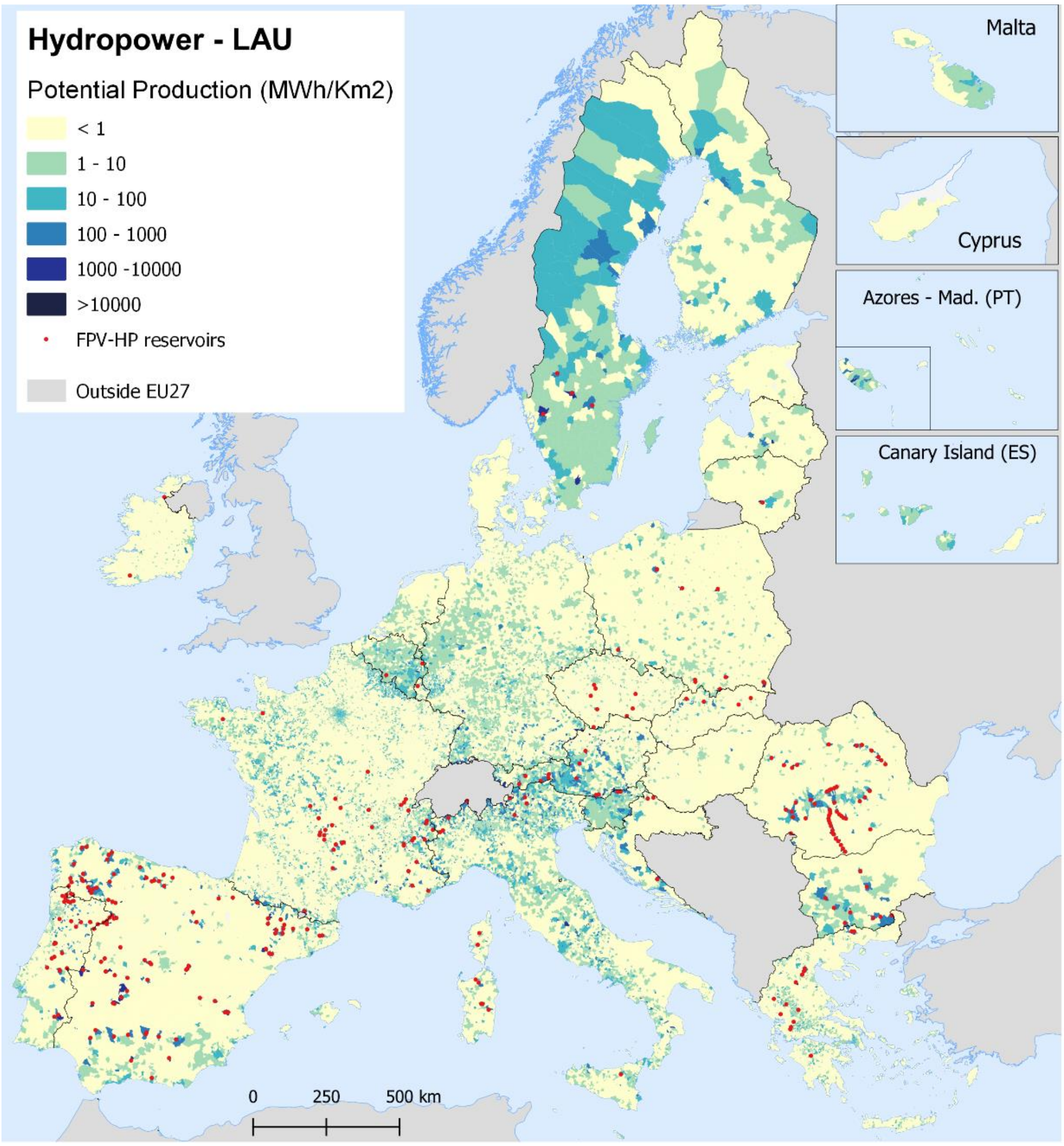
[k] https://www.atlantis-project.eu/

[l] 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, e.g. those reporting the dam characteristics, in order to increase the knowledge of the European hydropower fleet.

Table 7. Potential of different hydropower strategy (in the EU when not specified).

Hydropower tapping opportunity	Generation potential	Comment
Closed-loop pumped hydropower storage (PHS)	260 TWh (19 TWh the cheapest sites)	Stocks et al., (2021)[49], Europe
Open-loop (or, mixed) seasonal PHS	105 TWh (10 TWh the cheapest sites)	Hunt et al., (2020)[60], Europe
Spatio-temporal coordination of reservoirs	140 TWh	Wörman et al., (2022)[51], interconnection between 1200 km and 3000 km, Europe
Hydropower plant modernization	40-50 TWh/y	Quaranta et al., (2021)[28], Quaranta and Muntean (2023)[11]
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), as technically feasible potential.	Gimeno-Gutierrez and Lacal-Arantegu (2015)[52]
Powering of Non-Powered Dams (NPDs)	1.75 GW	Garrett et al., (2021)[61], Europe
Existing historic barriers not mill-related	5.2 TWh/y	EU+UK, Punys et al., (2019)
Hydro in 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)[11]
Water wheels in existing mills	1.6 TWh/y	Quaranta et al., (2022)[46]
Rainfall on building roofs	0.5 TWh/y	Quaranta et al., (2022)[62]
Hydrokinetic turbines in rivers	0.17-1.2 TWh/y	Quaranta et al., (2022)[46]
Pressurized conduits for irrigation and industrial flows	<0.1 TWh/y	EU+UK, Mitrovic et al., (2021)[63]
Floating PV (evaporation reduction)	<0.1 TWh/y	Quaranta et al., (2021)[28], 10% of reservoir surface coverage
Sea water PHS	t.b.d.	Kougias et al., (2019)[15]
PHS in mines, underground PHS and low-head PHS	t.b.d.	Menendez et al., (2017)[64], Hoffstaedt et al. (2022)
Floating PV (FPV) on hydropower reservoirs	139 TWh/y	Kakoulaki et al., (2022)[65], 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.
Floating PV on hydropower reservoirs	729 GWp	Lee et al., (2020)[9], Europe, 14% of reservoir surface coverage

Figure 11 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 Dorati et al. (2023)[66].



2.4 Technology Cost – Present and Potential Future Trends

Hydropower is financially competitive with other electricity technologies, achieving some of the lowest values of electricity generation costs. IRENA and World Bank analysis identified hydropower as currently one of the most economical forms of renewable electricity generation [67]. One of the main advantages of hydropower stations is that the low operation cost is generally very stable since it does not depend on fuel cost. Moreover, hydropower stations have a long service life (typically assumed 40-50 years), with the civil works even exceeding 80-100 years (in Europe the average age of the hydropower fleet is almost 45 years, hence hydropower refurbishment is of strategic relevance [28]). However, hydropower is capital intensive, requiring large upfront investments. Licensing and construction periods can be long and complicated especially in large-scale projects (several years and in certain cases even exceeding 10 years).

Table 8 depicts the approximated share (in %) of civil, mechanical, and electrical components in the total capital cost of different hydropower plants.

Table 8. 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. Electrical: generator, transformer, cabling, grid connection. Source: IRENA, 2022.

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

In 2022, the global weighted-average 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) [67]. 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 [67].

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 storage 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[22].

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. Despite registering low LCOE levels in 2008 and high in 2010, the overall trend is fairly constant [68]. 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 storage hydropower including pumped hydropower storage 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[m]. The cost per kW of run-of-river power plants is investigated in detail in [n, 69]. Micro-hydropower projects have a typical 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.

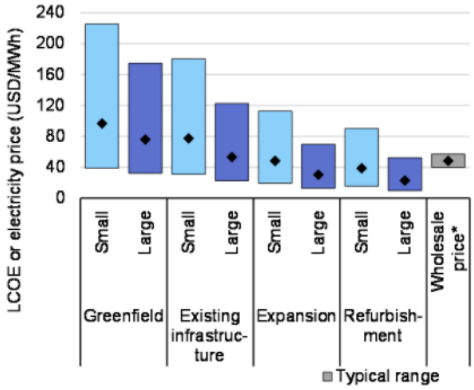
Annual operation and maintenance (O&M) costs are often quoted as a percentage of the investment cost per kW per year, with typical values ranging from 1% to 4%. Operation and salaries take the largest slices of the O&M budget. Maintenance varies from 20% to 61% of total O&M costs, while salaries vary from 13% to 74%[67]. The International Energy Agency (IEA) assumes O&M costs of 2.2% for large hydropower projects and from

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

[n] 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.

2.2% to 3% for smaller projects, with a global average of around 2.5% (IEA, 2021[67]). 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[o]. Materials are estimated to account for around 4% [67].

Figure 12. LCOE costs and wholesale price of hydropower in the European Union[22].



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 developed (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 storage and pumped hydropower storage power plants. Nevertheless, this potential saving will be compensated by the higher costs of environmental mitigation measures, and the expected increase of the investment costs could be better faced if adequate remuneration will be paid for the multiple services and benefits. For example, pumping operation of PHS helps to balance excess supply and avoid curtailment; however, grid operators do not currently remunerate this service apart from lower prices, and this service will become increasingly important to avoid renewable curtailment. Current power market conditions show that the revenues attained from the price differential (arbitrage) along with the declining revenues from the provision of the ancillary services are not enough to cover the fixed investment and administrative costs of these units. Several sites have been placed on indefinite hold due to a perceived lack of profitability, including Lago Bianco 1000 MW and Grimsel III 600 MW in Switzerland, Atdorf 1400 MW and Waldeck II plus 300 MW in Germany (IHA, 2022, Voith 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 [103].

[o] 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 owned by the same operator is today exploited systematically in a coordinated way in order to maximize generation and benefits in view of market demand.

2.5 Public R&I funding

Despite hydropower technological maturity, research efforts are still ongoing to develop new concepts and technologies [15], novel materials [70] and innovative projects [71]. 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 investment trend [EUR Million]. Source: JRC based on IEA data, CIndECS2022.

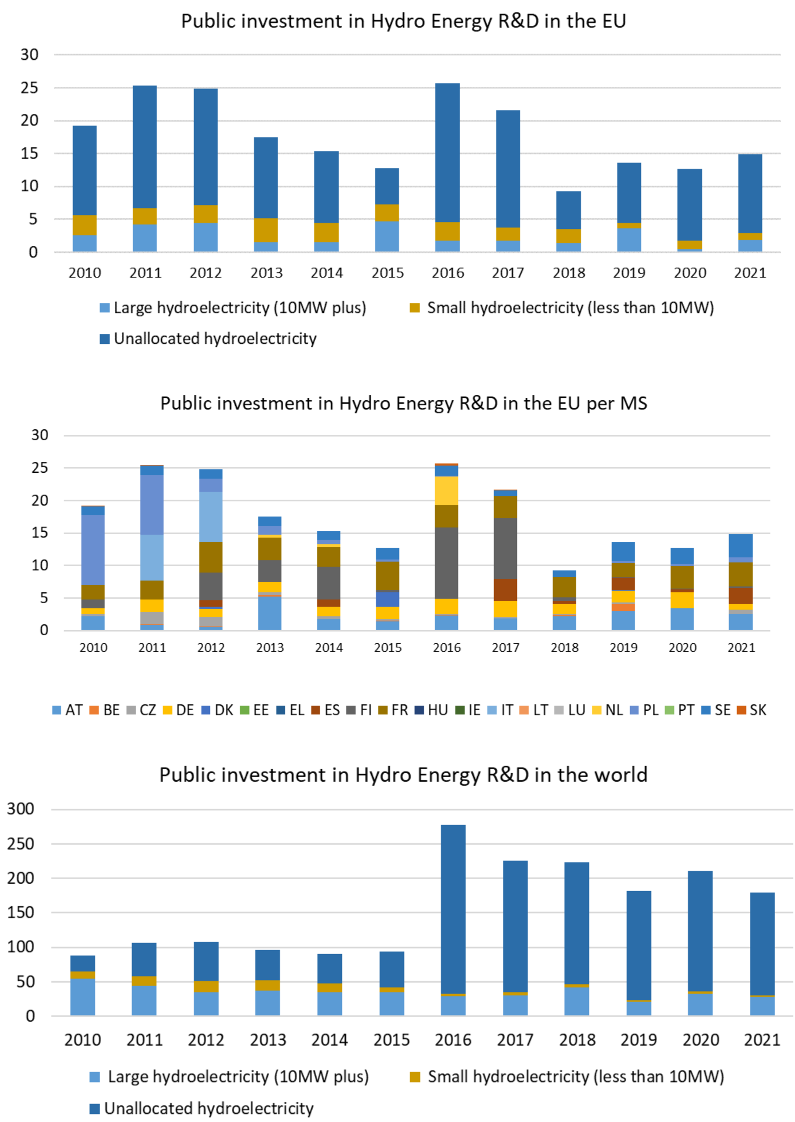
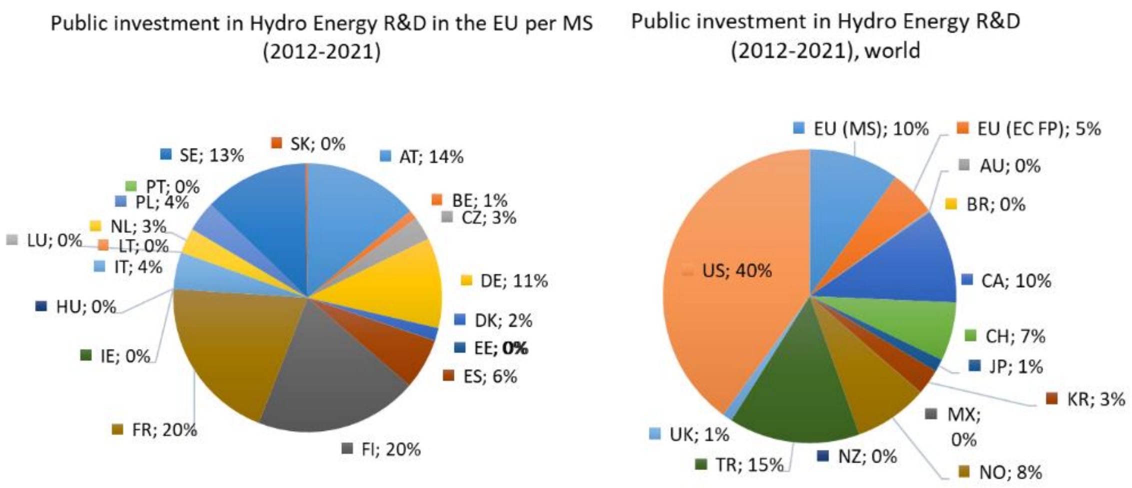


Figure 14. Public R&D investments in hydropower for the EU member states over the period 2012-2021. Source: ClndECS2022. For the non-EU acronyms, see the Nomenclature list.



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[p]). According to the Water Power Technologies Office Budget | Department of Energy[72], 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.

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. Three countries host almost 90% of investments (U.S., China. UK). The EU hosts 4% of investments, mostly in countries connected to the Alps such as France, Germany, Italy and Austria. The U.S. (1st) and France

[p] 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.

(5rd) rely on a relatively strong base of venture capital companies[q] (Figure 15 and Table 9). The trend over time is depicted in Figure 16.

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

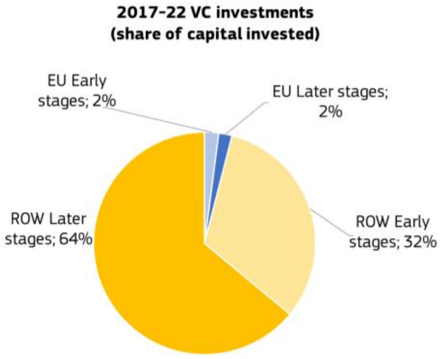
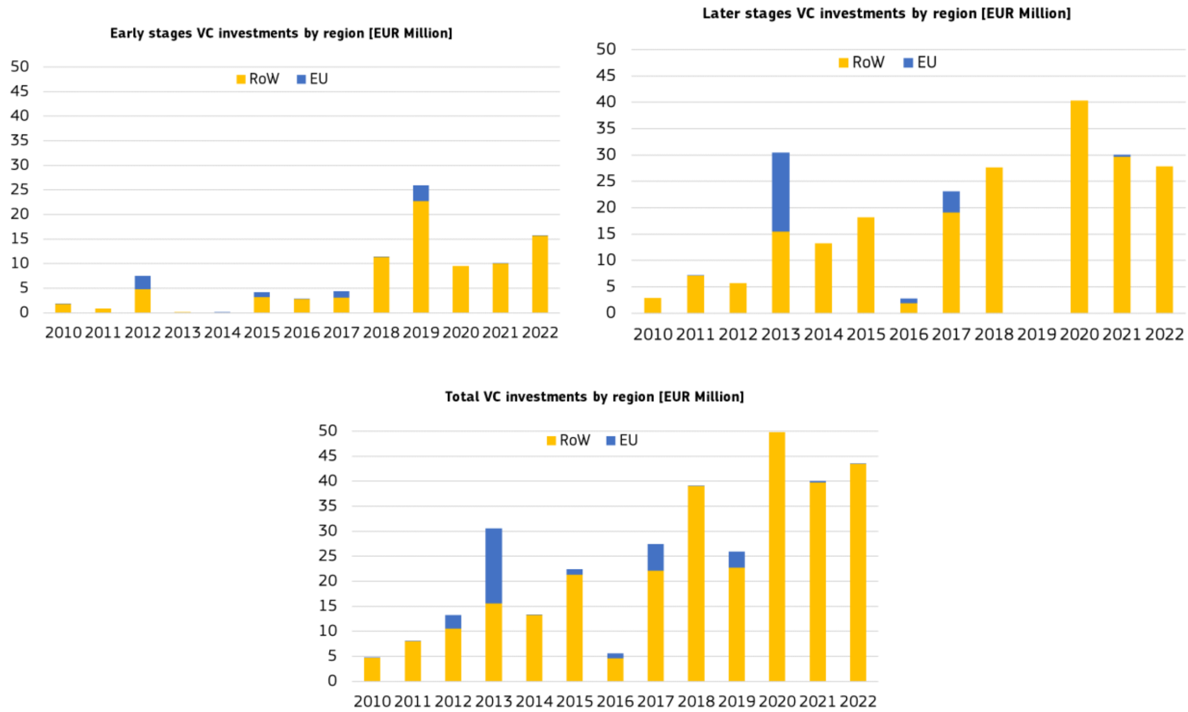


Figure 16. Trend of early and later stage investments. JRC based on Pitchbook.



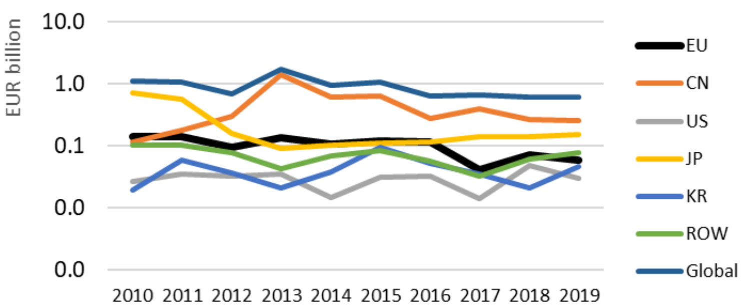
Considering the R&D investments, Figure 17 shows that China is leading the sector and the global trend follows the Chinese one. In the EU, Germany, France, Italy and Sweden are the member states with the largest contribution. The lead companies are Voith Patent GMBH (DE), GE Renewable Technologies (FR), 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).

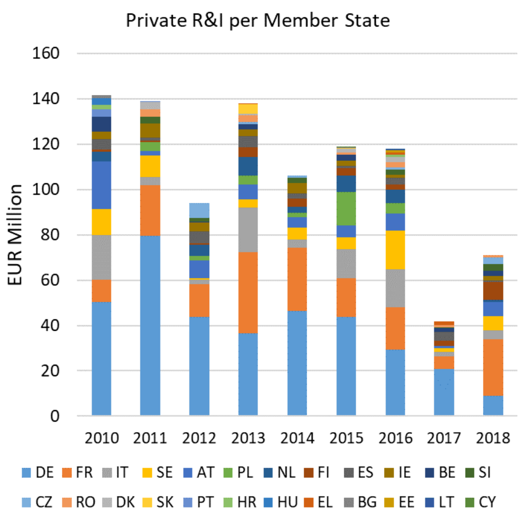
[q] Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. Venture Capital companies are companies that have been at some point part of the portfolio of a VC investment firm (or that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

Table 9. Capital Invested Venture Capital (EUR).

Country	Region	2017-22	2011-16
United States	ROW	161,870,000	40,160,000
China	ROW	27,320,000	12,580,000
United Kingdom	ROW	18,480,000	18,220,000
Canada	ROW	13,470,000	780,000
France	EU	5,330,000	1,110,000
Belgium	EU	3,520,000	90,000
India	ROW	1,190,000	0
Chile	ROW	160,000	0
Norway	ROW	140,000	520,000
Germany	EU	90,000	2,730,000
Italy	EU	60,000	0
Austria	EU	20,000	15,000,000
Iceland	ROW	0	0
New Zealand	ROW	0	890,000
Sweden	EU	0	10,000
Switzerland	ROW	0	0
Israel	ROW	0	0
Spain	EU	0	1,000,000

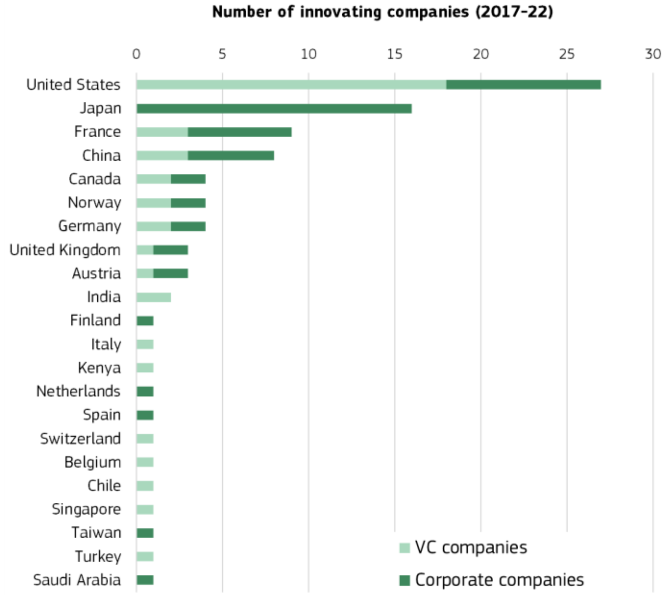
Figure 17. R&D investments.

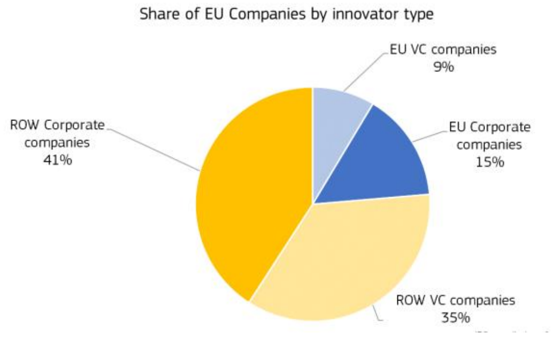




Based on R&D investments, innovative companies can be identified, and Figure 18 shows this data (see Annex 2 for details).

Figure 18. Innovative companies.





2.7 Patenting trends

The present patent analysis was based on data available from the European Patent Office EPO PATSTAT 2021b (autumn), using the CPC (Coordinated Patent Classification) code Y02B 10/50 (Hydropower) and Y02E 10/20. Details of the analysis are described in dedicated JRC publications [73, 74] and in Annex 3. The number of patents for the EU and other major countries are provided in Figure 19, 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 2011-2020, 442 patents were registered by companies in the EU, 18 from government no-profit, 42 from universities, while 80 are individual. Within the EU, Germany is leading in patenting (195), followed by France (105), Poland (53), Italy (47), Sweden (26) and Austria (23). The EU is the lead region in terms of high-value inventions i.e. applicants of the EU tend to extend patent families to more than one patent office, although this trend is decreasing over the years (Figure 19 and Figure 20), probably because it takes time to extend patent protection to other offices. The EU holds 33% of all high-value inventions globally (2018-2020). Germany, France and Finland are the main contributors (Table 10).

Table 10. Number of inventions and share of high-value inventions and international activity (2018-2020). Percentages on the total are also calculated.

Country	Total number	High-value	International	High-value	International
ROW	158	39	27	24%	17%
JP	161	27	16	17%	10%
KR	149	7	9	5%	6%
CN	1512	34	9	2%	1%
US	47	19	6	40%	12%
EU	152	62	26	41%	17%
	EU share	33%	27%		

Figure 19. Patent activity for different owner categories.

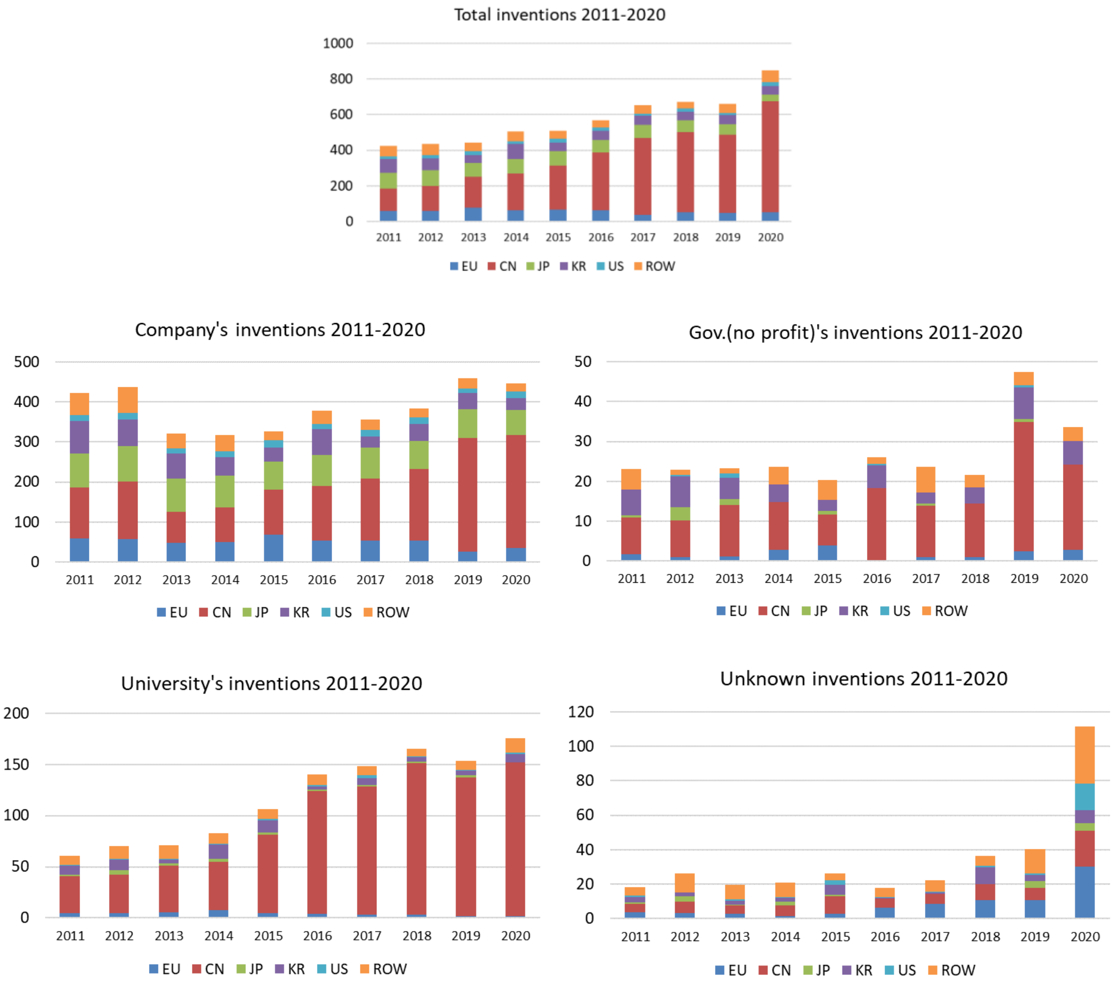


Figure 20. Number of high-value inventions (left) and Top 10 countries (right), Source: JRC based on EPO Patstat.

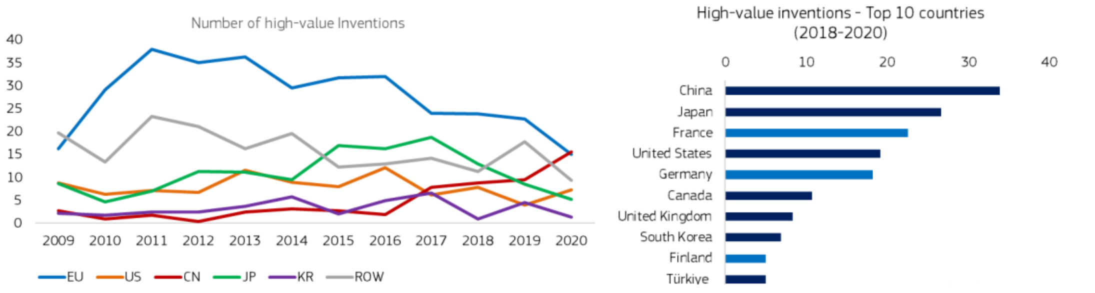
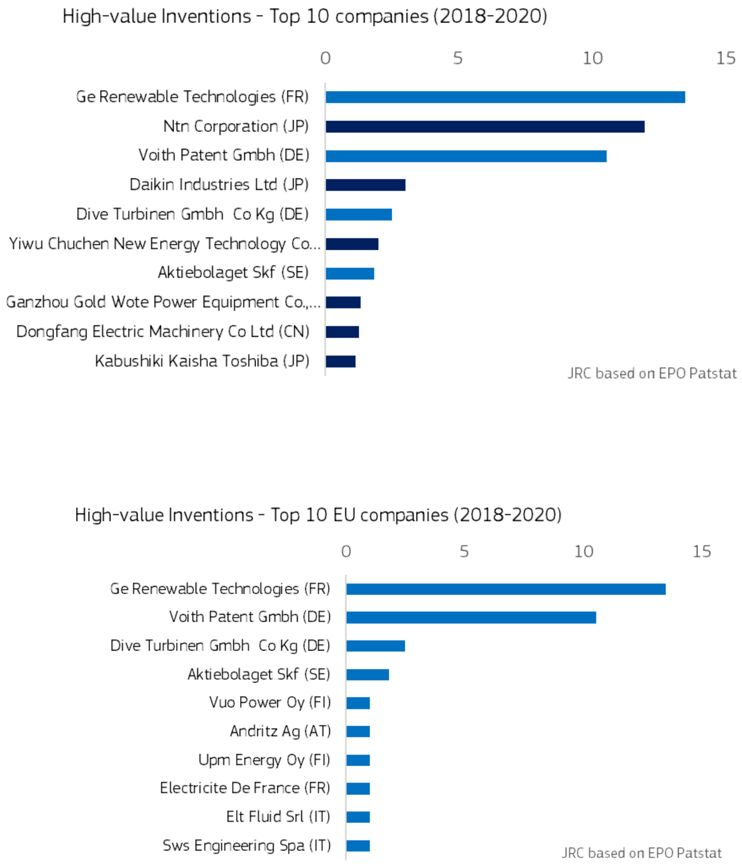


Figure 21 shows the top-10 companies with high-value invention patenting. Four companies from the EU are in this top-10: GE Renewable Technologies (EU branch), Voith Hydro, Dive Turbinen, Aktiebolaget Skf, with Voith and GE within the top-3, sharing together 49% of high-value inventions from the top-10 leader companies worldwide.

R&D expenditures by the subsidiaries of the largest corporate R&D investors, based on patenting activity, are depicted in Figure 17. 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 21. Top patenting companies Source: JRC based on EPO Patstat.



2.8 Scientific publication trends

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)[75] observed a rapid growth rate of publications related to hydropower, highlighting the increasing demand for hydropower-related research (Figure 22). 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 [75]. The main hydropower topics researched by EU's institutions are described in Manzano-Agugliaro et al., (2017)[33] (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) [76]. The same countries, including Italy, appears 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. [77].

According to Figure 22 and Figure 23, EU's institutions are leading the publication trend, together with China, and this reflects the leading position of the EU in high-value inventions (that, generally speaking, may be objetc of scientific publications). 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), "reservoir" ("hydropower" and "reservoir" have to be found 3 keywords apart or less), penstock, turbine, draft tube, fish passage, hydropeaking and sediment (including sedimentation and turbine erosion), as proxy on civil structures, electro-mechanical equipment and environmental operation. The keyword "hydropower", or "hydroelectric" or "hydro electric" must also be present in the text, but with no proximity requirements. Table 7 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. However, although Chinese hydropower dam developers dominate the global dam industry nowadays [78], the Chinese bibliometric indicator (number of scientific papers between 2010 and 2021) is 189 for the keyword dam, thus below the EU (350) and the U.S. (453).

Table 11 lists the top-10 authors, based on number of peer-reviewed publications from 2020 to 2023, according to Scopus ("hydropower" or "hydroelectric" in the keywords or title or abstract). Only one author, the first author of this report, is 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 22. Number of scientific papers published in peer-reviewed journals for the EU and other states.

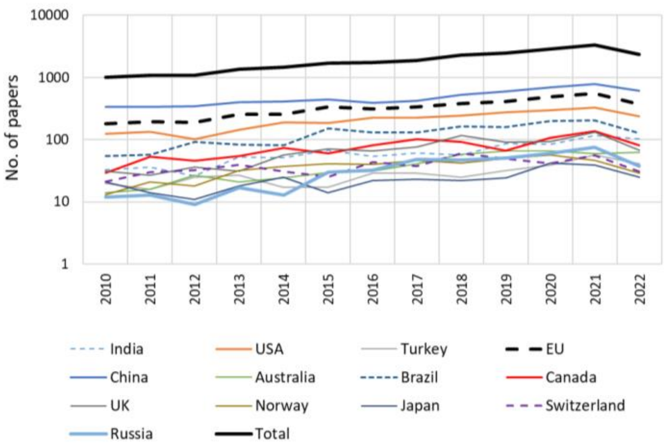


Figure 23. Number of scientific papers published in peer-reviewed journals for EU member states.

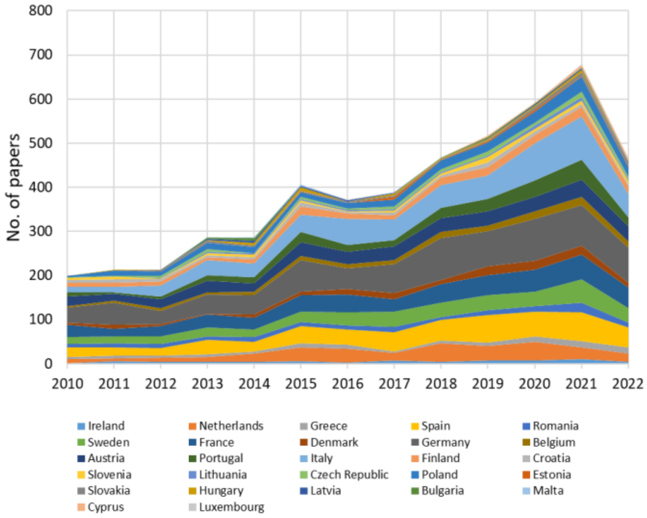


Table 11. List of authors and number of papers 2020-2023.

Author	N° of papers
Cheng, C	85
Liu, P	42
Chen, D	39
Liao, S	36
Ming, B	32
Zhou, J	31
Singh, B	31
Liu, B	29
Shen, J	28
Quaranta, E	27
Kotnala, R.K.	27
Shah, J	27

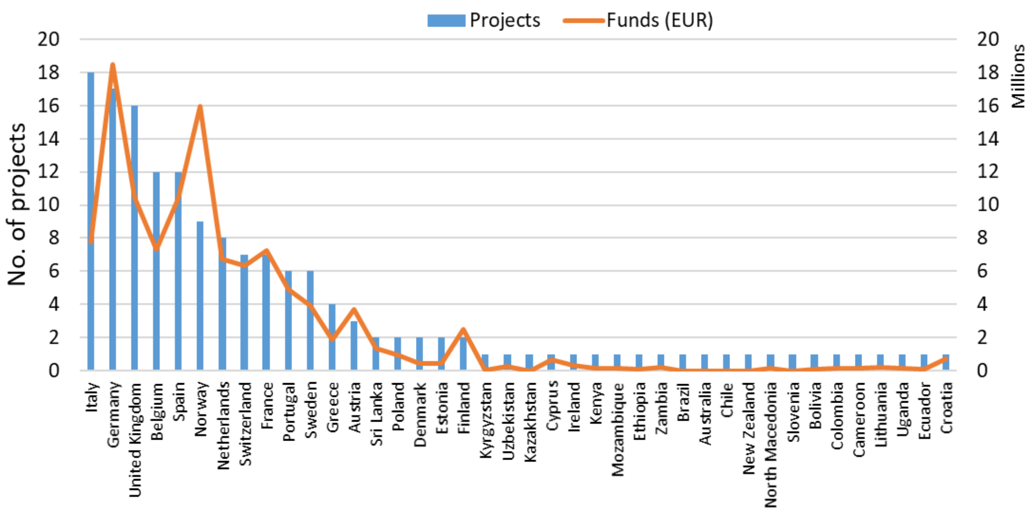
2.9 Assessment of R&I project developments

The European Union has funded several projects in the field of hydropower. From 2015 to 2022, 41 projects have been funded, with a peak in 2018 (10 projects). Figure 24 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.

Table 12 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 (the successor of Hydropower Europe, ETIP Hydropower Europe, started in 2022). PEN@Hydropower is a network to establish 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[r] (see also Quaranta et al., 2022, typically associated to low head hydropower), hydropower digitalisation[s] (typically associated to flexibility, Quaranta et al., 2021, Kougias et al., 2019, Quaranta et al., 2023[82]), pumped storage hydropwoer[t] and sustainable refurbishment[u, v] (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[w]. 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[x] 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 Author 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 24. Received funds and number of projects by country (Interreg projects not included), 2015-2022.



[r] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d3-03-11
[s] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d3-03-08
[t] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2024-d3-01-16
[u] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2023-d3-02-09
[v] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2024-d3-01-07
[w] https://www.ieahydro.org/work-programme/
[x] https://www.eera-hydropower.eu/

Table 12. List of Horizon projects (2015-2022) and number of member states.

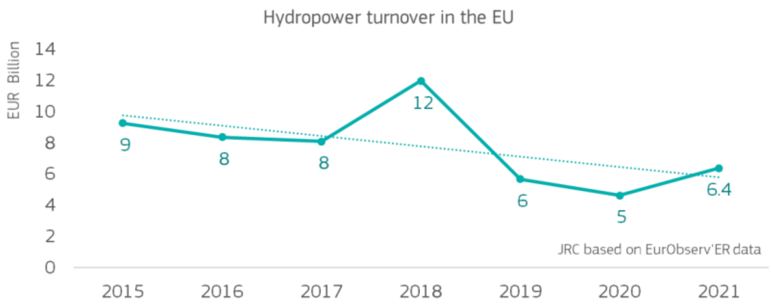
Year	Title	Total cost of the project (EUR).	Project acronym	Countries
2023	intelligent Asset Management Platform for Hydropower operation and maintenance	4100000	iAMP-Hydro	7
2021	Hydropower For You - Sustainable small-scale hydropower in Central Asia	11488428	Hydro4U	12
2020	Modeling Energy for Sustainable 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

3 Value change Analysis

3.1 Turnover

The annual turnover of hydropower electricity generation in the EU is depicted in Figure 25 [79]. Leading Member States in terms of turnover were Austria (EUR 2.85 billion in 2018), Italy (EUR 2.25 billion), France (EUR 1.55 billion), Spain (EUR 1.18 billion) and Germany (EUR 1.06 billion). European hydropower manufacturers spend more than 5% of annual turnover on R&D, which is more than twice the European industry average[77]. In 2021, the turnover was 6.4 billion EUR, led by France (2.2 billion EUR), Italy (0.91 billion EUR), Germany (0.72 billion EUR) and Austria (0.81 billion EUR). The greatest one was approximately EUR 12 billion in 2018. Turnover is decreasing, and this may for example be due to the increase of energy mix and lower prices of hydropower energy.

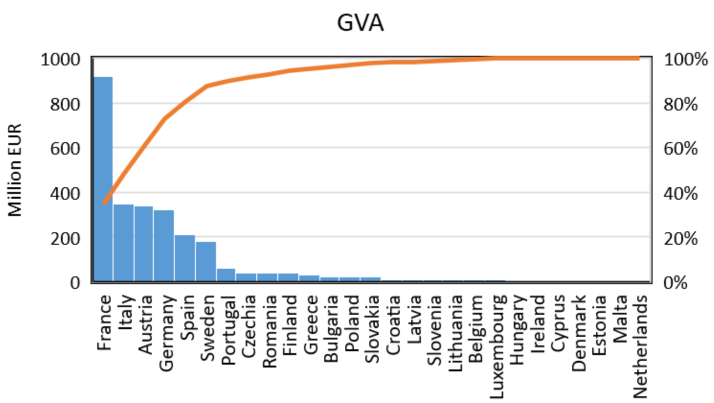
Figure 25. Turnover in the EU.



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 26). Estimate is based on the recorded money flows into 1) new installations; 2) O&M of existing capacity; 3) production (section 3.6, 719 EUR Million in 2021) and trade of equipment (section 4.2, 210 EUR Million in 2021); 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 in 2021 is depicted in Figure 26: the EU's GVA was 2.72 billion EUR in 2021 and 1.95 billion EUR in 2020.

Figure 26. Gross Value Added (GVA) for each EU member state in 2021.



However, 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). 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 (see the discussion above) 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[y] evolution (Diversified Supply or Reference Scenario, respectively) [80].

In the whole of Europe, the annual value creation[z] is approx. 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 multipurpose functions of hydropower represent an additional annual economic value of EUR 10 billion to 20 billion, even when neglecting the potential value of avoided damages from flood events, which may be substantial. These benefits can be expected to increase in the future, for instance due to an increased need for water management and flood control. No more recent economic data was found in the literature. During the past 30yrs 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%[81].

3.3 Environmental, social and economic sustainability

Large hydropower plants are complex systems, and they interact with the hydrosphere, the biosphere, the lithosphere, the anthroposphere and the atmosphere, with impacts and benefits. The same complexity is also entailed by water reservoirs for other uses[82]. 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). Benefits and impacts are summarized in Figure 27, while Table 14 summarizes the sustainability indicators of hydropower.

The studies of Alsaleh and Abdul-Rahim (2021)[31] analysed the interaction between hydropower and 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 through small hydropower. The same authors showed that carbon dioxide releases in EU+UK can be efficiently lessened through expanding hydropower. Boosting the production of hydropower energy by 1% will lessen the carbon dioxide by 0.809%, while a rise in economic growth by 1% leads to an increase in carbon dioxide releases by 0.113% [83]. On the other hand, growth in hydropower production lessens the water quality, although the highest influence on water quality was estimated to be brought by the increase in population density and economic growth [105]. 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 [84], where large projects may generate conflicts, corruption and poverty gaps [85]. Therefore, public sector involvement is critical for hydropower expansion 103. Stakeholders and society, including disadvantaged groups, should be better represented in decisions.

In order to consider the transversal impacts and benefits of hydropower, the International Hydropower Association (IHA) has supported the development of the Hydropower Sustainability Standard, which is governed

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[y] 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.

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

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: Biodiversity and Invasive Species, Indigenous Peoples, Cultural Heritage and more. 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 13 in 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[86].

Table 13. 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

Figure 27. Benefits and impacts of hydropower (figure from Branche, 2017) [87].

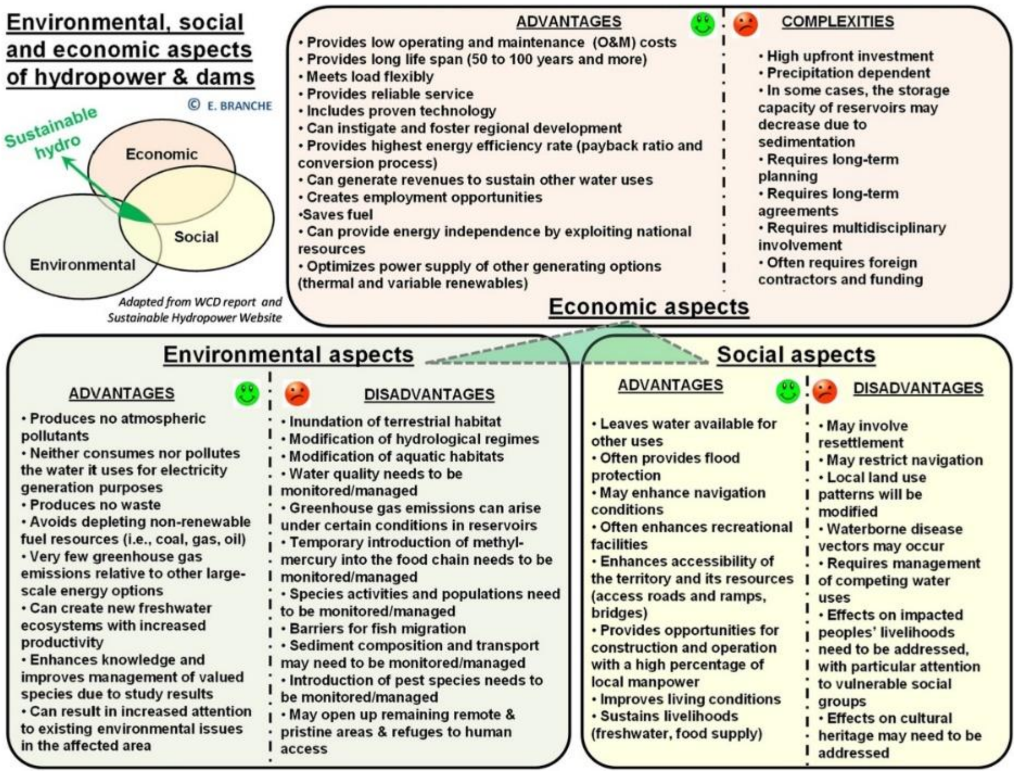


Table 14. Summary table.

Parameter/Indicator	***Input***
Environmental	
LCA standards, PEFCR or best practice, LCI databases	*Y, see* [88, 108, 109, 110]
GHG emissions	*The IPCC states that hydropower has a median greenhouse gas (GHG) emission intensity of 24 gCO_2-eq/kWh (grams of carbon dioxide equivalent per kilowatt-hour of electricity generated allocated over its life-cycle). By comparison, the median figure for gas is 490 gCO_2-eq/kWh. It also depends on the geographic context, e.g. alpine or non-alpine area. Hydropower helps in reducing CO_2 emissions[89]. Additional considerations can be drawn from Gemechu and Kumar (2022)[90], who reviewed the gCO2eq/kWh associated to several 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, this impact is 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, the impact is apparently not dependent on the installed power.*
Energy balance	*EROI = 60-100* [91]*, the highest one amongst energy sources. 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	*Yes, 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 and* Figure 27.
Water use	*The average flow rate discharged by European hydropower plants is 5,045 m^3/MWh (elaborating data of hydropower database, Quaranta et al., 2021*[28]*). Water is used for energy generation and released downstream in ROR plants, while the natural hydrological regime is significantly altered, and evaporation losses can be relevant, in reservoirs and storage-type plants (SPP). The water footprint of hydropower in EU during construction phase is 3.6 m^3/GWh, which is 90-fold less than the solar one (in 2019, but now PV technology is improved and this difference may be slightly attenuated) and similar to the wind one* [92]*. The water footprint for operation (excluding the turbined flow) is almost zero for ROR and 32 m^3/MWh for SPP (evaporation mainly), more than 1-order of magnitude higher than that for PV. Globally, around 507 GW of hydropower competes with irrigation. While hydropower reservoirs might support irrigation, there are well-known cases where it reduces water availability for irrigated food production, e.g. in Portugal* [93]*.*
Air quality	*No pollutant emission, but methane emissions might occur from some reservoirs due to organic matter decomposition* [94]*.*
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 2013 database, the density value for reservoir hydropower plants ranges from 0.48 W/m^2 (5° percentile) to 8000 W/m^2 (95° percentile) (31 W/m^2 is the 50° percentile) 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 5.94 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)*[95]*. 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)* [95] *(infrastructure ratio =1 is the optimal/ideal value).*
Soil health	*Alteration of sediment transport, possible landslides in big projects, but also improved maintenance and additional monitoring of the environment.*
Hazardous materials	*See section 4.3. No critical materials are commonly used.*
Economic	

Parameter/Indicator	***Input***
LCC standards or best practices	*Zakery and Syri (2015)[96] found that the annualized life cycle cost (LCC) for PHS ranged between 200 and 270 €/kW/y, half the LCC of batteries. Donnelly et al., (2010)[97] 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 [98]*
Cost of energy	*See section 2.4.*
Critical raw materials	*No, see section 4.3.*
Resource efficiency and recycling	*The lifespan of civil structures is typically 80 years, after that a retrofitting activity is required. Dams are 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 (supporting irrigation, security, fishing, leisure).*
Industry viability and expansion potential	*See section 2.3*
Trade impacts	*Yes, the hydropower sector involves industry, environment and high financial investments. See section 4.2.*
Market demand	*See section 3.*
Technology lock-in/innovation lock-out	*See section 2.1. Several R&D activities are ongoing, although the main technology is well established. Local materials can be used for the construction.*
Tech-specific permitting requirements	*Several permitting procedures for land and water use [99].*
Sustainability certification schemes	*Yes, e.g. the tool developed by IHA*
Social	
S-LCA standard or best practice	*Yes, see the text.*
Health	*No direct emissions.*
Public acceptance	*It depends. Big projects may require reallocation of people and depletion of water resources. 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	*Yes, especially when hydropower is linked to the industrial heritage and cultural heritage (e.g. water mills) [100, 101].*
Employment and conditions	*For employment data see section 3.5.*
Contribution to GDP	*See section 3.*
Rural development impact	*Yes, especially in case of rural areas that host water mills and hydraulic infrastructures. 80% of the EU's installed capacity is in rural areas [66].*
Industrial transition impact	*Yes, 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 PHS in larger quantities with respect to batteries. For example, the stored energy in the Blåsjø PHS reservoir, the Norways's largest reservoir (8 TWh), is equivalent to more than 40,000 times the Hornsdale battery park in Australia. In the EU, the largest reservoir for hydropower purpose hosts 3.12 TWh; it is in Spain and is PHS with turbine and pump installed capacity of 851 and 1184 MW, respectively (JRC hydropower database).*
Food security	*In the EU, 73 large reservoirs host hydropower and irrigation as first and second use (and no other uses), and 23 large reservoirs host irrigation and hydropower as first and second use, respectively (and no other use), from ICOLD2013 database.*
Responsible material sourcing	*No.*

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

As a low-carbon energy technology with no direct emissions, hydropower contributes to energy targets and climate change mitigation. Its advantages include the reliability of supply, extremely high efficiency and flexibility [102]. 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. Because of this, although its share of total generation remained stable over the last decade due to the growth of wind, solar PV and green hydrogen, hydropower flexibility is critical for integrating rising levels of volatile energy sources into electric systems [103]. Multi-purpose reservoirs can provide additional benefits and water provision for several other uses, more than hydropower generation. According to Hydropower Europe project, hydropower has the best climate indicators, the best performance for storage and flexibility, it is a driver for regional economies and PHS could comply with the objectives of the Taxonomy: climate change mitigation and adaption, protection of water resources, transition to circular economy and pollution prevention.

On the other hand, 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) [104]. Only 40% of surface water bodies surveyed by the European Environmental Agency was found to be in a good ecological state, despite EU's laws and biodiversity protocols [105]. Hydropower partly contributes to this, as 5% of barriers are for hydropower (AMBER database). Furthermore, out of the 4100 big dams listed in the ICOLD2013 database, only 1312 dams are for single-purpose hydropower, and 351 multi-purpose ones host hydropower as a first use; 337 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 note that the effects of a hydropower plant are site and waterbody specific and should not be related to the size of a project a priori. Furthermore, benefits and impacts depend on the climatic and geographic context, as well as on the type of hydropower plant and implemented technology. For example, the study of Mahmud et al., (2019)[106, 108] found that the overall LCA[aa] (Life Cycle Assessment) of hydropower plants (kg CO_2eq/kWh) in Europe is lower than outside of Europe (see also [107]), and, overall, hydropower plants in non-alpine regions are responsible for carbon emission with a higher rate than those in alpine ones (Mahmud et al., 2019), due to higher rate of methane biogenic emissions from non-alpine power plants, that typically include larger reservoirs. In Mahmud et al., (2019), it was found that a higher rate of nitrous oxide is emitted by an alpine plant due to more combustion of fossil fuels during the manufacturing, and more combustion of solid waste at the end-of-life waste management because of the more difficult transport and connection with disposal facilities. The construction phase was responsible for most impacts in alpine areas in Europe, whereas the transmission line is the most impactful for non-alpine areas [108]. ROR are not associated to large impoundments and methane emissions from the reservoir [109], but ROR ecosystem services are smaller than those provided by storage hydropower plants ($ 37 Million with respect to $ 410 Million in the case study described in [88]). However, this example is site-specific and any kind of generalization would be misleading and should be avoided.

When speaking about PHS, a comparison with batteries is worthwhile. Batteries do not have to be expensive centralised installations with capacities in the order of magnitude of several GWh. The capacity can be broken down into smaller units and distributed across a number of sites, and have a very fast response. However, batteries have particular requirements 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 PHS hold large volumes and can provide long-term storage, with a lifespan of up to 100 years (below 20 years for batteries). PHS are less impacting than batteries, except for natural land transformation, in a LCA analysis performed in[110]. However, batteries would need of an enormous area to be comparable with a PHS, and would not provide additional

[aa] 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.

benefits besides energy storage and flexibility. Hence batteries and PHS should be seen as complementary technologies rather than as substitutes.

3.3.1 Challenges associated to multiple-use reservoirs

Multipurpose reservoirs can have important additional functions for society, often more important than hydropower generation per se: irrigation and drinking water provision, flood and drought risk management, river navigation and recreation, fire-fighting, fishing, leisure. Therefore, multiple-use (or, multipurpose) reservoir's operation, management and construction will play a key role. These multiple services will have to provide civil society with greater resilience towards climate change impacts. However, some challenges exist. A major challenge of multipurpose reservoirs is sharing water, costs and impacts amongst competing users, and to define user priorities. Water uses my often be in conflict each other, e.g. hydropower and irrigation, or flood control and hydropower. These conflicts may be aggravated in regions that in the future will suffer of a decrease in water availability due to climate changes, e.g. the Southern Europe. Another challenge for the hydropower sector, and for multipurpose reservoirs, is to pursue energy, climate and environmental targets at the same time, as well as to deal with reservoir sedimentation. As highlighted in section 1.2, hydropower is a major player in several EU's Directives and programmes, i.e. the Water Framework Directive (WFD), the Flood Directive, the Renewable Energy Directive (and REPowerEU). Therefore, sustainable hydropower needs to achieve a good balance between electricity generation, social benefits and impacts on the ecosystem and biodiversity. The achievement of a trade-off has been the aim of several discussions and studies [111, 112, 113].

To mitigate and 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 [114] (e.g. more fish friendly turbines, racks to avoid fish passage through the turbine, efficient fish passages, better sediment management and hydropeaking mitigation measures, digitalisation[115,116]). 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 [117]. It is necessary to identify all stakeholders and engage them in the early stages to participate on a voluntary basis to the dialogue. The involvement of local citizens is important, also for small hydropower plants. 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) have agreed in 2012 to cooperate and launched a program to work on a SHARE concept framework for multi-purpose hydropower reservoirs in order to achieve a higher sustainability. The purpose is to maximise the benefits of the multi-purpose use of hydropower reservoirs by considering the principles of 1) Shared resource, 2) Shared rights and risks, 3) Shared costs and benefits 87[, 118]. Local involvement (as opposed to centralized planning) can help facilitate community acceptance [119, bb].

3.3.2 The hydropower sector for women and youth

Several social initiatives are ongoing to empower women and young professionals in the hydropower sector, as highlighted in the UNIDO Small Hydropower report [123], which interviewed 20 women (4 from the EU) and 21 Young Professionals (6 from the EU, including Emanuele Quaranta) active in the small hydropower sector.

Empowering women and girls and closing gender gaps are critical to the achievement of the 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 in hydropower so far is considered between 27 and 32%, depending on the hierarchical level one looks at (heavily decreasing with the leadership level rising). PV looks much better

[bb] 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.

(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 being part of 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 access to opportunities, incomes, assets and skills because of prevailing social norms. Another perception that carries important opportunity 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 new female students is above 30% if one calls it "environmental engineering", while the header of "hydraulic engineering" still attract far below 20% females. Traditional engineering curricula offered less integrative approaches, including less or no classes in ecology, earth system sciences, integrated river basin management.

Despite the challenges, single opportunities for women in hydropower are on the way, but an overall approach for the industry and 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) clearly show that women's participation can lead to improved governance of the sector and renewable energy generation in general. Indications of this can be drawn from the UNIDO study on small hydro, and the World Bank's ESMAP study undertaken by a working consortium of International Hydropower Association (IHA) and GWNET[120] as a global baseline for all hydro – small and large (publication pending[121]). The Women in Hydropower Mentorship Program[122] provides 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.

The perception that things have started moving in the hydropower sector can be supported in some other frames as well. On one side, one can clearly visually recognize more youth and females in all typical conferences and venues of the sector. On the other side, institutional demands cater for better figures: for example, a Cost Action from the EU on sustainable hydropower (CA 21104) clearly shows that the attempt to put women in the leading functions of working structures was rather successful: translating this into Leads of Working Groups or the Vice Chair have been driven as an initiative to reach possible gender parity from the start in September 2022. There certainly is room for improvement because the gender share within the Working Groups is still the typical around 27% share of women. The Global Women's Network for the Energy Transition (GWNET) since its foundation 6 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.

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:

- hydropower is technical and a domain for men
- lack of awareness among sector and company leaders 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 due to emphasis on masculinity and a lack of diverse hiring teams
- lack of role models and mentors for women in, or wanting to enter, the sector.
- limited opportunities for women to network and limited gender-responsive networking opportunities
- lack of awareness among women of the range of job opportunities available in the sector
- difficulty for women to travel to either meeting venues or sites of plants for work
- opportunities irrespective of science/technology/engineering/mathematics (STEM) options
- lower numbers of women with STEM (science, technology, engineering and mathematics) qualifications

- limited opportunities for women to receive training/on-the-job training to gain skills needed to work in the sector
- workplace policies that are not responsive to women's needs and cultures and are discriminatory to women
- poor workplace safety leading to poor retention

It remains with quite some good practice examples from developed or low-developed countries and initiatives to prove the imbalance of gender in the hydro power sector. For this reason, data and facts must be much more intensely and tightly collected and presented, in order to make recommendations and activities more effective to be translated into real change. While UNIDO is looking at small hydro it already delivers quite some substance to a data-based view on the current situation. However, more research and study on gender in the sector should be done urgently, on a global base, but also on a Europe-wide and nation-focused angle.

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
- Make hydropower showcase their attractive workplaces generally, but in special to women
- 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

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)

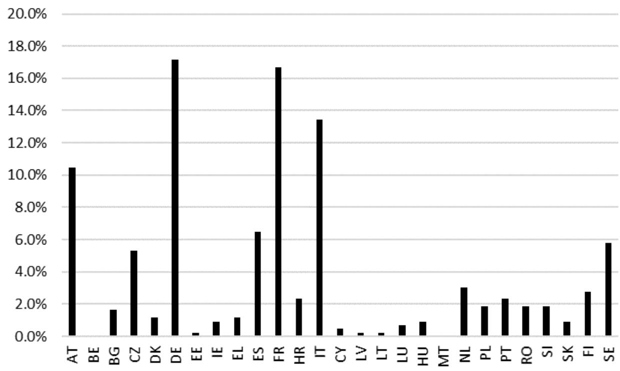
Efforts aimed at employing young people, as well as ensuring their overall well-being, can be hindered by the lack of access to reliable sources of energy. At the same time, the climate emergency and ubiquitous environmental collapse dictate the necessity and urgency to focus not only on developing the energy system, but also on ensuring its sustainability. The development of the renewable energy sector can provide an avenue for achieving the goals of youth employment and development while addressing energy-related challenges. 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 SHP 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[123].

3.4 Role of EU's Companies

A recent JRC research developed a database of EU's companies active in the hydropower sector includes 524 entries (but not including those providing services, e.g. engineering consultancy, hydrological studies) [77]. The large part of EU-based companies are commercial companies (85%). These companies are active in the design, manufacture and supply of hydropower equipment, including automation and control systems. They are also active in consultancy, R&D, and the construction of civil works. A smaller number of companies are national (≈10%) and international (≈5%) organizations active in hydropower.

Figure 28 depicts the share of companies in EU Member States, based on data of 438 EU's companies available in a different database (accessed in 2022) [124]. 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 hydropower companies.

Figure 28. Number of EU-based hydropower companies per Member State [124].



3.5 Employment

The deployment of renewable energy leads to employment in different sectors, with different levels of qualification and duration. We can 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 for sustainability (e.g. in this case, the climate adaptation value chain, which must happen on the side lines of the deployment of the small-scale hydropower system). 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[125].

Globally, IRENA calculated that approximately 2.36 Million people worked directly in the hydropower sector in 2021, the highest in the last monitored decade. Only bioenergy (3.44 Million) and photovoltaics (4.29 Million) exhibit a higher employment level 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 [126].

The numbers associated to the employment vary depending on the source. The number of jobs in Europe as a whole is estimated at 120,000. 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 2021 in the EU there were 2227 employed people in the manufacturing, 108494 in the construction and 1169 in the R&D; alpine countries – i.e. Italy and Austria - were the most relevant employers. According to EurObserv'ER, the number of direct jobs of hydropower ranges between 74,000 and 87,000 [79], while 89,000 was estimated in 2021 by IRENA[126], 7.2% of the direct employment in the renewable energy sector, with almost another 30,000 jobs created in external services of hydropower [77, cc]. A 10% increase of hydropower in the year 2030 would create 27,000 jobs in the EU, mainly outside the hydropower sector itself [80].

3.6 Energy intensity / Labour productivity / Production

Hydropower contributes EUR 25 billion to the EU+UK gross domestic product (GDP), annually (electricity generation and exports), that is roughly EUR 500,000 per FTE (Full Time Equivalent). The main part of this contribution (>90%) derives from hydropower generation. When Norway, Switzerland and Turkey are included, the GDP is EUR 38 billion, which may grow to EUR 75-90 EUR billion by 2030. The multipurpose benefits represent an important additional income that, although very difficult to be quantified, may range between EUR 10 and 20 billion, that are expected to increase in the future due to climate change effects. Direct tax contribution 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 [80]. Turnover in 2021 was 6.4 EUR billion and the GVA was 2.7 EUR billion (new investments, O&M, production and trade).

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 15).

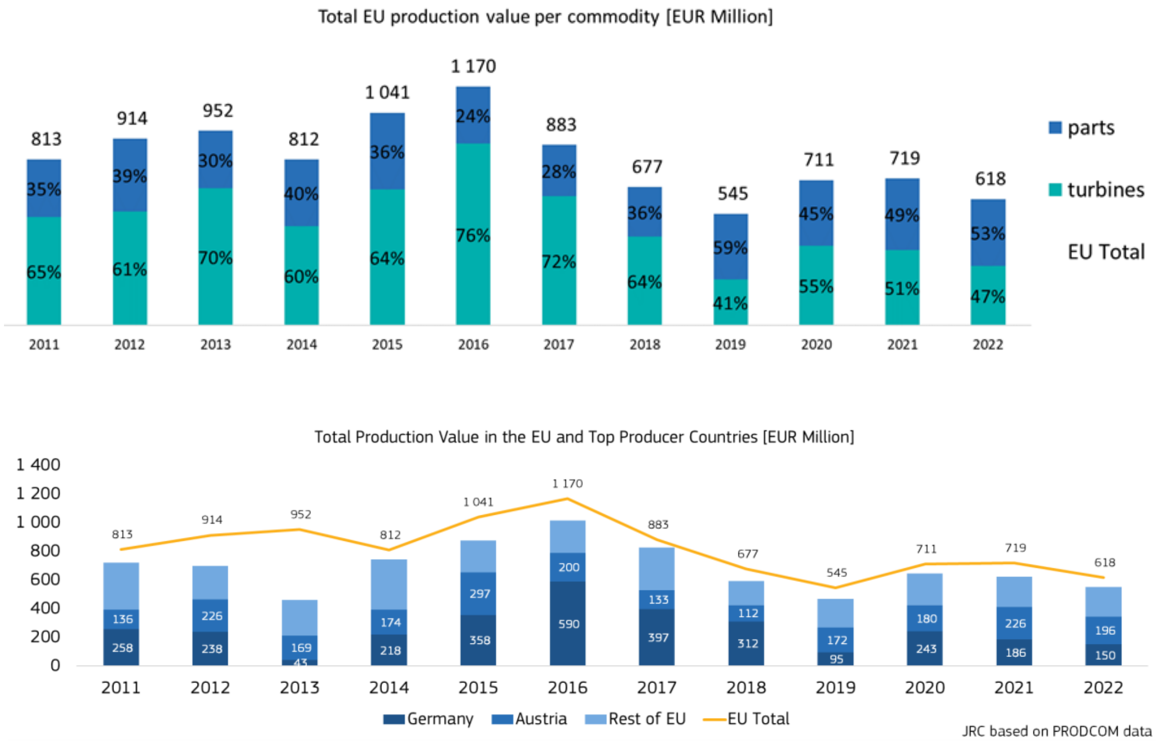
Table 15. Selection of Prodcom codes as a proxy for production of hydropower technologies

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

Figure 29 shows that over the past ten years (2013-2022), the overall production value has decreased with an annual compound growth of -4% and an average value of EUR 813 Million. In 2022, the total value had a 14% drop compared to the previous year, reaching EUR 618 Million. The EU's production was highly focused on turbines until 2018, and afterwards it became more balanced with the production of parts.

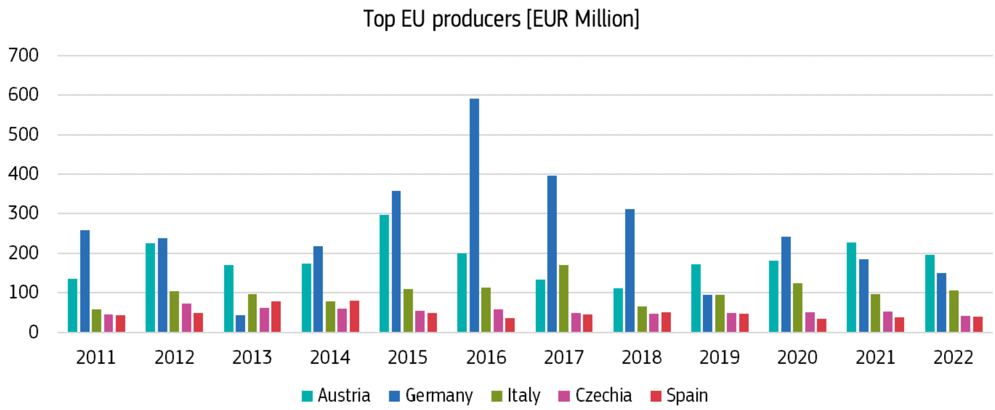
Figure 29. EU production value per commodity [EUR Million]. Source: JRC based on PRODCOM data.

[cc] 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.



Over 2020-2022, Austria, Germany, Italy, Czechia and Spain were the top EU producers, but not all Member states had disclosed data for all the years (Figure 30). Germany and Austria combined hold more than half of the EU production.

Figure 30. Top EU producers among the Member States disclosing data [EUR Million]. Source: JRC based on PRODCOM data.



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 [22].

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.

Outside China, the three EU-based companies delivered 73.5% of the total orders in terms of power capacity (2013-2017). Voith delivered 10.7 GW, Andritz 9.1 GW, and General Electric (European headquarter) 6.6 GW. All Chinese manufacturers combined delivered 15.5% of total capacity outside of China, and the remaining share was almost equally divided between Japanese, Indian, and Norwegian companies [77]. The greatest 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[127] dedicated to hydraulic turbines and their parts (Table 16). The aggregated codes had a trade surplus of almost EUR 230 Million in 2022 (Figure 36).

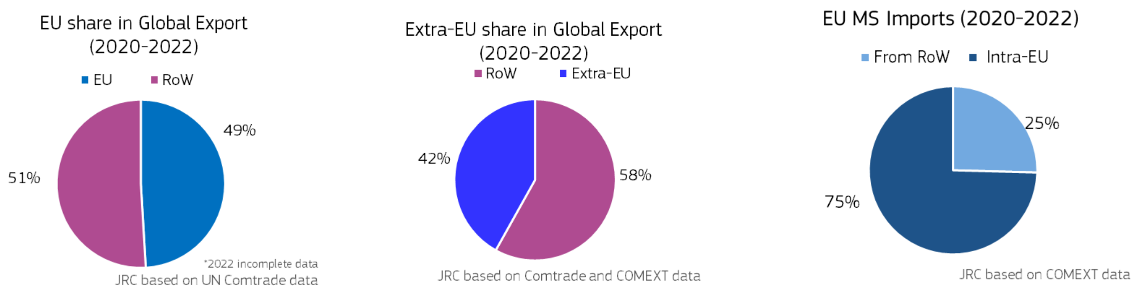
Table 16: Selection of HS codes as a proxy for monitoring trade for hydropower.

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

Despite the relatively low share in the global employment hydropower market (approx. 4%, approx. 100,000 out of 2.36 Million employed), the EU industry holds an important share in global exports[dd]. Total global exports accounted for EUR 2.3 billion over the period 2020-2022. The EU holds 49% of all global exports (EUR 1.12 billion) and 42% if intra-EU trade (EUR 383 Million) is excluded. The major share of global exports by the EU is associated to the big EU hydropower companies. The biggest exporter is China, with 21.7% share, followed by Austria (14%), Germany (8.2%) and Italy (7.3%), which account for about 30% (49% when considering all member states). The remaining exports are mainly generated by Brazil, India, Czechia, Slovenia, United States and France. EU imports accounted for EUR 396 Million from 2020 to 2022, 75% of that was intra-EU trade (295 EUR Million) (Figure 31).

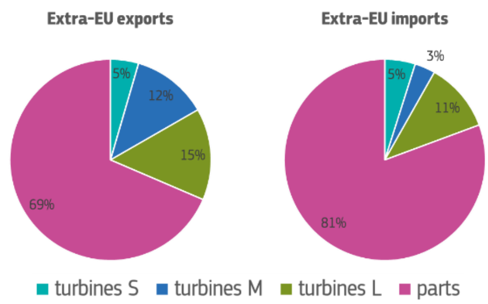
For the future, a wonderful opportunity for EU companies is their export potential associated to innovative equipment and small hydropower (high-value inventions, see section 2.7), as well as assistance in the overall design and operation of hydropower plants.

Figure 31. EU share in global export (left), Extra-EU share in global export (middle) and EU imports (right) (2020-2022).



Over 2020-2022, approximately 75% of the total EU imports came from the Single Market (intra-EU), while extra-EU exports are 42% of the global exports. For the same period, the majority of the extra-EU exports was related to parts (69%) followed by turbines L (15%) and M (12%), while 81% of the extra-EU imports was related to parts (Figure 32).

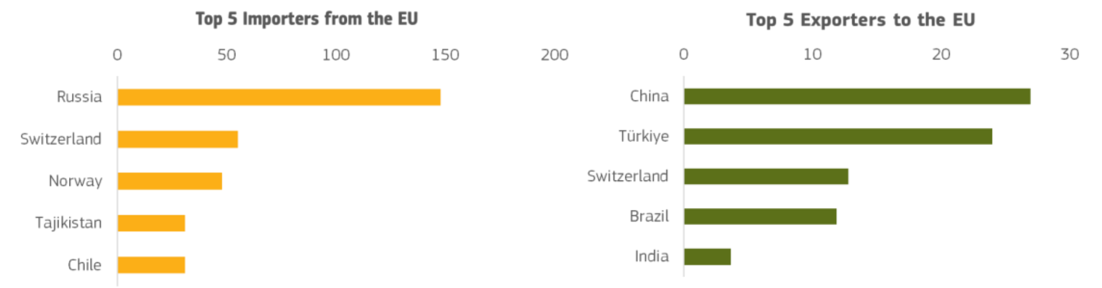
Figure 32. Traded value share of hydropower [2020-2022]. Source: JRC based on COMEXT data.



The EU has a significant presence (in terms of export of equipment) in Russia, Switzerland, Norway, Tajikistan and Chile, supplying EUR 148, 55, 48, 31 and 31 million of their hydropower-related imports, respectively (Figure 33), making the EU the world leader in hydropower technology (included pumped hydro) [128]. 100% of hydropower imports in Ukraine are from the EU. However, as highlighted in Figure 36, exports are decreasing since 2015, as well as the turnover, but the trend seems to be quite constant in the last years.

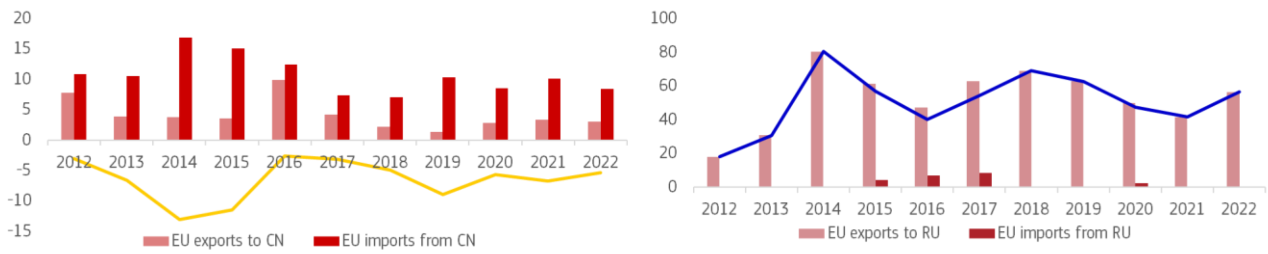
[dd] The main categories of goods associated with hydropower technology are: “hydraulic turbines and water wheels” (28112200) and “parts for hydraulic turbines and water wheels” (28113200).

Figure 33. Top countries importing from (left) and exporting to (right) the EU (2020-2022) [EUR Million]. Source: JRC based on COMEXT data.



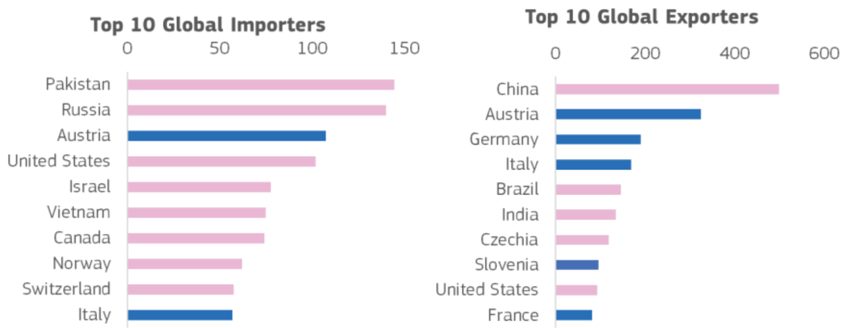
Even though the selected HS codes are subject to licence requirements[ee] for trading with Russia, exports increased by 36% in 2022 compared to the previous year, while imports were something more than EUR 9 Million (Figure 34). Imports from China fluctuate around the value of EUR 10 Million since 2016, while exports to China are stable at EUR 3 Million for the past three years.

Figure 34. EU trade with China (left) and Russia (right) [EUR Million]. Source: JRC based on COMEXT data.



The EU has a strong presence among the top global exporters, while only Austria and Italy are amongst the top importers (Figure 35). Austria features in both ranking list, which is a sign of re-exports.

Figure 35. Top global importers (left) and exporters (right) (2020-2022) [EUR Million]. Source: JRC based on COMEXT and COMTRADE data.



Regarding the growing markets[ff] during 2019-2021[gg], the EU captured the markets in Chile, Norway, Russia and Serbia (Table 17).

[ee] Embargoes and Other Special Controls May 19 2023 - license requirement under § 746.5(a)(1)(ii). Available at https://www.bis.doc.gov/index.php/documents/regulation-docs/420-part-746-embargoes-and-other-special-controls/file

[ff] Calculated as $net\ import\ change = [(import_{2020} - import_{2019}) + (import_{2021} - import_{2020})]/2$

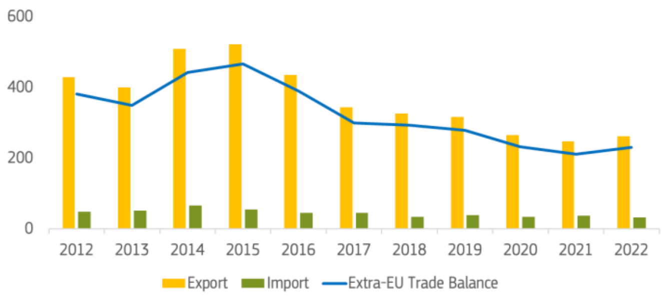
[gg] Latest year data (2022) may be incomplete for Comtrade, because it does not provide estimates for the missing values as Comext.

Table 17. Growing markets based on a 2-year average of net import change. Source: JRC based on COMTRADE data.

Country	Total import (2019-2021) [EUR Million]	% import from the EU
Serbia	29	34%
Japan	34	19%
Chile	43	49%
Norway	63	72%
Laos	82	0%
Ethiopia	145	16%
Pakistan	188	3%
Russia	204	80%

The EU's trade balance has been positive over the period 2012-2022. However, trade surplus has decreased since its peak at EUR 466 Million in 2015 to EUR 210 Million in 2021 and EUR 230 Million in 2022. Austria, Germany and Italy hold the biggest trade surpluses (EUR Million +82, +50, +37, respectively, in 2022), while Sweden, Latvia and Greece the biggest negative balances (EUR Million -1, -1, -3, respectively, in 2022) (Figure 36).

Figure 36. Extra-EU trade for hydraulic turbines and parts [EUR Million]. Source: JRC based on COMEXT data.



4.3 Resources efficiency and dependence in relation to EU competitiveness

Hydropower and pumped hydropower storage are not considered critical sectors. They are of strategic importance to the EU energy system and can contribute to the EU resilience[128].

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 and hydrokinetic turbines[70]. 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)[129].

Hydropower equipment does not contain critical materials such as lithium and cobalt (used in electric vehicles), or neodymium, praseodymium, and dysprosium (used in electric vehicles and wind power plants). Hydropower is the best renewable energy for reducing pressure on mineral resources (Figure 37 and Figure 38). 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 [130]. Figure 37 summarizes these findings and more specific details can be found in the IEA (2023)[131] report, which highlights the wide use of critical material (but not for hydropower) in renewable energy technologies. However, the values calculated on PV reflect the impact of PV energy of years ago, and since that time the performance has improved a lot[132]. 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).

For the hydropower sector, a relevant concern is related to the use of permanent magnets. The emerging variable speed technology generally uses permanent magnets, and some micro-hydropower turbines with low rotational speed (water wheels, Archimedes screws) would be more efficient with permanent magnets. However, the material components of permanent magnets may suffer from shortages in the near future, worsened by the Chinese supply monopoly (the EU plays a significant role only in the assembly stage, where its share is above 50%) [133, 134]. 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 generate large carbon emissions for the construction of the dams and the production of concrete. 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[135]).

Threats and opportunities within the current social, energy, geopolitical and climate situation are discussed in the 2022 release of this report.

Figure 37. Impact indicators from ETIP Hydropower Europe (EU project).

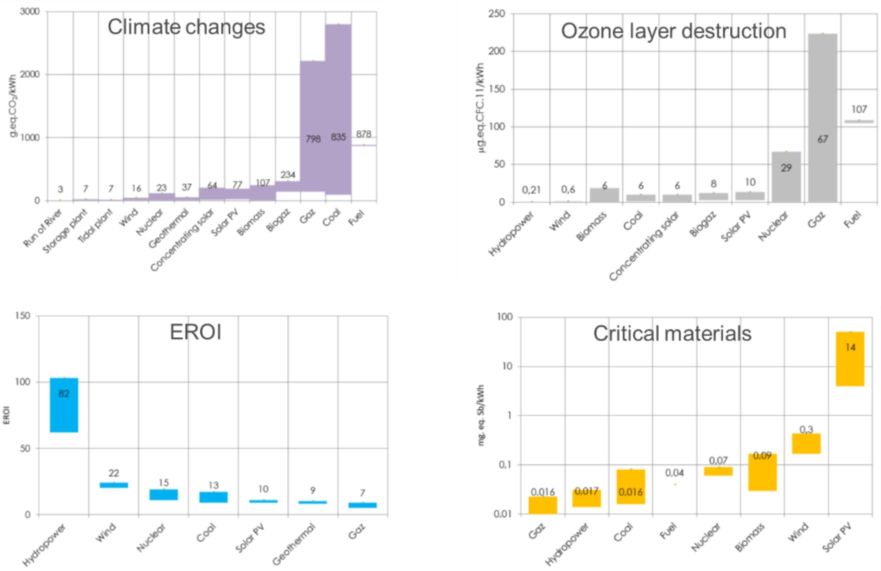
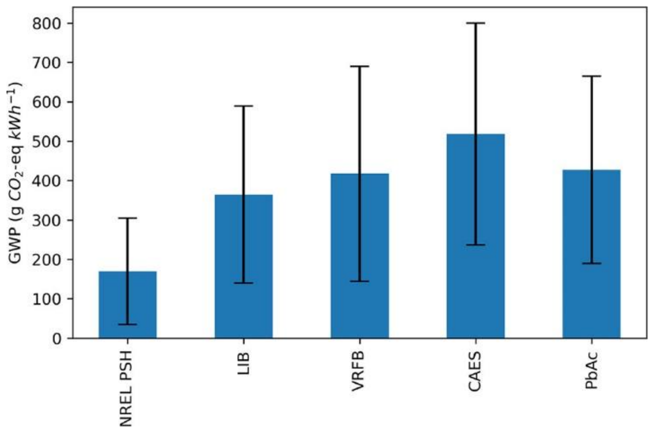


Figure 38. Global warming potential (GWP) of closed-loop PSH (NREL PSH), compared to literature GWP values for lithium-ion battery storage (LIB), vanadium redox flow batteries (VRFB), compressed-air energy storage (CAES), and leadacid battery energy storage (PbAc). The bar heights indicate the mean GWP for each technology, and the error bars indicate the GWP standard deviation[136].



5 Conclusions

Hydropower is the largest renewable energy source to date, with a global installed power capacity of 1397 GW and an annual generation of 4408 TWh in 2022. Hydropower provides, on average, 360 TWh/y in the EU, and a quarter of the global pumped hydropower storage (PHS) installed capacity is in the EU.

The hydropower sector is characterized by several strengths and advantages with respect to the other renewable technologies. The Energy Return on Investment (EROI) is the highest, and traditional hydropower equipment does not use rare and critical materials. Reservoirs provide additional services, 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 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 volatile energy sources (mainly wind and solar power) increases, the flexibility provided by hydropower operation is essential. PHS is a mature technology and, as a result, its technological and manufacturing/market position is considerably more advanced than that of other energy storage technologies (e.g. battery storage, flywheel, thermal and chemical storage). PHS can store water-energy (with daily, monthly and seasonal storage depending on the installed capacity and reservoir's volume) more cost-effectively than any other option, and can put and absorb energy available in seconds. It is the most cost-effective long-term (e.g. seasonal) storage technology.

However, being at the centre of the Water-Energy-Food-Ecosystem nexus, several obstacles and challenges exist. The first major barrier is the effort to simultaneously pursue renewable energy, climate and environmental goals. These are the aims of different European policies and directives, where hydropower exhibits controversial roles. Depending on the context, hydropower can generate several adverse effects on the environment, although 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 would be installed in less favourable sites, increasing costs, especially for the implementation of environmental mitigation measures. Hydropower development is also affected by climate changes (water availability, seasonality, extremes, especially in regions where water availability will decrease), 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 energy market; however, European hydropower operators are not remunerated for all their services. Therefore, another major challenge is putting a value for all benefits, which is necessary to allow discussions and negotiations between different water users and externalities, and to bridge the gap between financial and economic viability. Public sector involvement is critical for hydropower expansion, 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 POTEnCIA's CETO Climate Neutrality Scenario, hydro electricity generation is projected to increase by 50 TWh/y in 2030 compared to 2020 levels. According to the existing scientific assessments (e.g., Quaranta et al., 2021 and 2022) the current hydroelectricity generation could be incremented by 10% by upgrading existing hydropower (partly offsetting climate change effects and limitations imposed by environmental legislation). An additional +3% can be achieved by tapping 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 multipurpose projects, may be required for water management services that could be exploited also for energy storage and generation. In Southern European countries, new reservoirs are urgently needed to mitigate the already visible effects of climate change (floods, droughts and fire, and to compensate hydrological changes due to glacier retreat).

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). 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.

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 concurrence of China. The global exports in 2020-2022 accounted for EUR 2.3 billion with EU countries holding 49% of this. Outside China, the three EU-based companies delivered 73.5% of the total orders in terms of capacity (2013-2017). However, a significant proportion of investment and activity 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 (including the energy crises ahead and the competitiveness of China), the strong competence (scientific and industrial) of EU companies and institutions is key. Dialog and cooperation with some non-EU European countries, which highly rely on hydropower, are strongly encouraged, such as Norway and Switzerland. It is essential to increase public awareness about the benefits of hydropower, as a required catalyst for a safe and independent energy transition, which is key to securing the European Green Deal. European National Energy and Climate Plans should include targets for dispatchable low-carbon energy and storage, and consider regulatory and commercial frameworks to implement the targets. Information availability, dialogue with society, and strategies towards social acceptance of associate benefits in different social, technical, environmental and economic contexts are actions that require immediate consideration. On the other hand, hydropower developers must be aware of the hydropower impacts on the environment, and hydropower operation and construction must consider the complex effects on the environment. 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.

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List of abbreviations and definitions

AU = Australia

BR = Brasil

CA = Canada

CF = capacity factor (-)

CH = Switzerland

EC = European Commission

EROI = Energy Return on Investment

EU = European Union EU27

GDP = Gross Domestic Production

GW = GigaWatt

IEA = International Energy Agency

IHA = International Hydropower Association

IRENA = International Renewable Energy Agency

JP = Japan

JRC = Joint Research Centre

KR = Korea

MS = member state

MX = Mexico

NO = Norway

NZ = New Zealand

O&M = Operation and Maintenance

P = installed power (kW, GW)

PHS = pumped hydropower storage

PV = photovoltaics

R&D = research and development

ROR = run of the river

RoW = Rest of the World

SPP = storage power plant

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

VC Investments:

- Investments are early and later stages investments in VC companies over the considered period.
- VC companies include Pre-Venture companies and Venture Capital companies. Pre-venture companies are companies that have received Angel or Seed funding, or are less than 2 years old and have not received funding. Venture Capital companies are companies that have, at some point, been part of the portfolio of a venture capital firm.
- Investments reflect investments in all active companies over that period irrespectively of their current status (defunct, publicly held, privately held with no VC backing, merged or acquired, no longer actively tracked in the data source).
- Early stages investments include: Grants, Angel & Seed (i.e. Pre-Seed, Accelerator/Incubator, Angel and Seed) and Early stage VC (Series A and B).
- Later stages investments include: Late Stage VC (and undisclosed series), Small M&A and Growth Private Equity. 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.

VC Companies:

- Companies are corporate companies and VC companies.
- VC companies include Pre-Venture companies and Venture Capital companies. Pre-venture companies are companies that have received Angel or Seed funding, or are less than 2 years old and have not received funding. Venture Capital companies are companies that have, at some point, been part of the portfolio of a venture capital firm.
- Corporate companies is a selection of top R&D investors from the EU Industrial R&D investment Scoreboard. They are subsidiaries of Scoreboard companies with a relevant patenting activity over the period.
- The list of companies includes all the identified companies, irrespectively of their founding year, their current operational status or of the fact that they have relevant investments or patenting activities over the current period.
- The count of active VC companies corresponds to the number of active VC companies that have been founded over the period (irrespectively of the investments they have received) or have received investments over the period (irrespectively of the year they have been founded). The count of active corporate companies corresponds to the number of companies with High Value Patents over the current period.

This selection of corporate and VC companies only represent a subset of all market players and innovative companies of the value chain.

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

POTEnCIA Model Overview

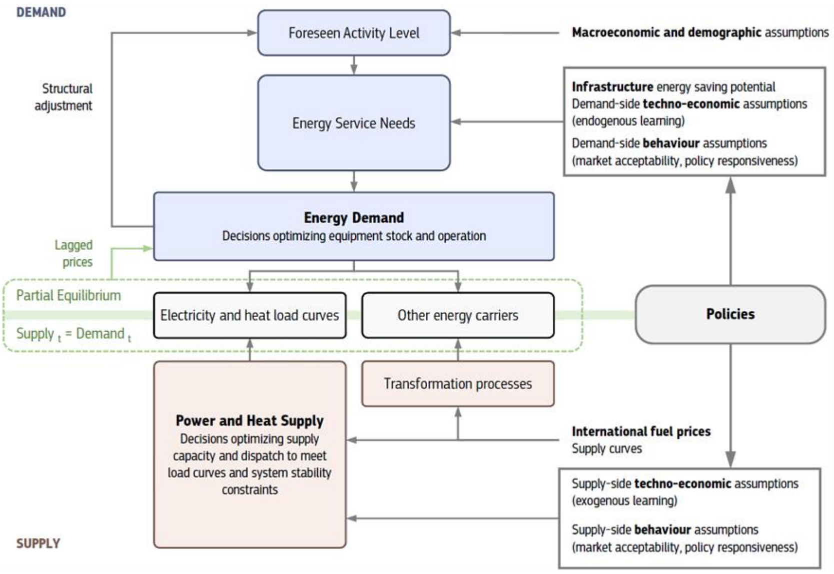
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed 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 A4-1; detailed in the POTEnCIA model description and in the POTEnCIA Central Scenario report) 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. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

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 CO2 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). Developed in parallel to POTEnCIA, an updated release of this database is planned by 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

Figure A4-1. The POTEnCIA model at a glance. Source: Adapted from the POTEnCIA Central scenario report.



POTEnCIA CETO Climate Neutrality Scenario overview

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 EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarized in Table A4-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation 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 deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table A4-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

POLES-JRC Model Overview

POLES-JRC (Prospective Outlook for the Long term Energy System) 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. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand. International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the "*Proposal for a revised energy efficiency Directive*" (COM(2016)0761 final) and "*The Paris Protocol – A blueprint for tackling global climate change beyond 2020*" (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the *EU Long-Term Strategy* (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the *Integrated Assessment Modelling Consortium* (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

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://ec.europa.eu/jrc/en/geco

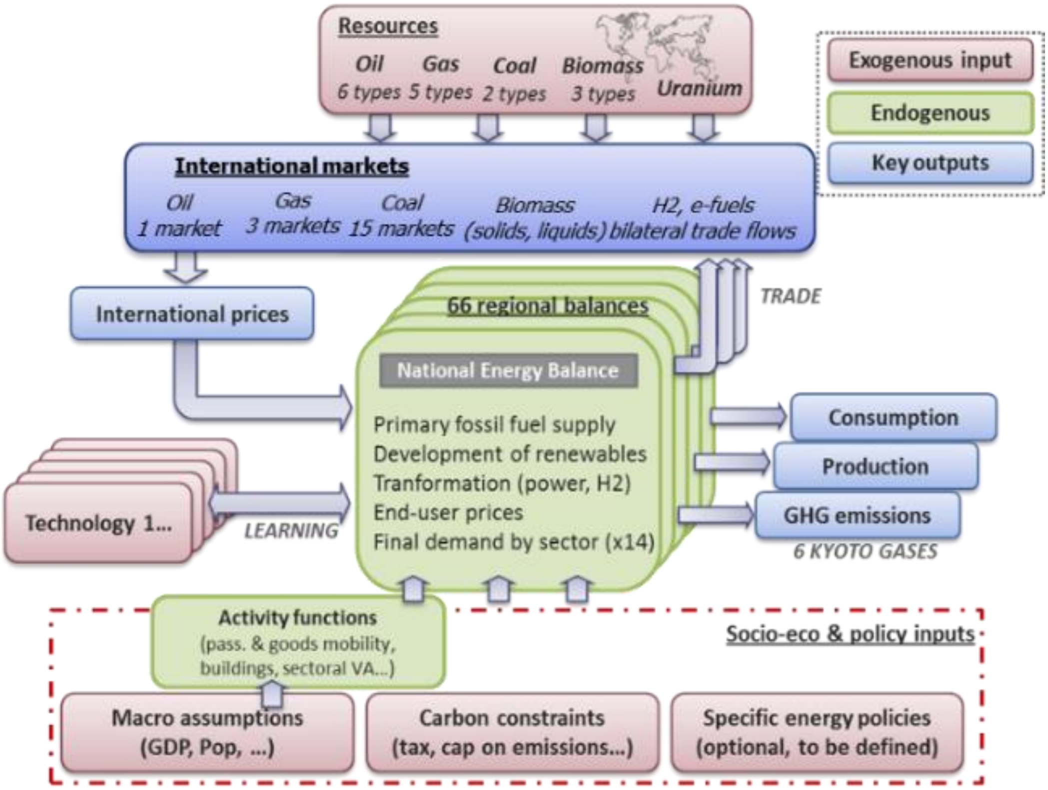
Power system

POLES considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), Concentrated Solar Power (CSP), on-shore and off-shore wind, ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS (carbon capture and storage) power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included.

Figure A4-2. Schematic representation of the POLES-JRC model architecture.



Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to CETO demand side technologies, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

Hydrogen

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

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

Bioenergy

POLES receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[hh]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO2) as well as agriculture (CH4 and N2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

Carbon Capture Utilization and Storage (CCUS)

POLES takes into account CCUS technologies for:

- 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 coal and biomass pyrolysis;

direct air capture (DAC) where the CO2 is stored or used to produce synfuels (gaseous or liquid);

- CO2 storage in geological sites.

Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

https://publications.jrc.ec.europa.eu/repository/handle/JRC113757

https://ec.europa.eu/jrc/en/poles

POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1150 $GtCO_2$, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities).

[hh] Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Laxenburg, Austria. http://www.globiom.org

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