



## Strategic Energy Technology Plan

Implementation Working Group on  
Ocean Energy and Hydropower

# Thematic Vision on Ocean Energy and Hydropower

16 July 2026



## **Preface**

The Implementation Working Group (IWG) on Ocean Energy and Hydropower was established by the Steering Group (SG) to support the implementation of the SET Plan in the areas of ocean energy and hydropower technologies.

Within this consolidated IWG, the Ocean Energy subgroup will focus mainly on wave and tidal-stream energy, but also on tidal range, ocean thermal energy conversion (OTEC), sea-water air conditioning (SWAC) and salinity-gradient technologies considering system integration and complementarity, while the Hydropower Generation and Storage subgroup covers all hydropower technologies and energy derived from falling or fast-running water, including pumped hydropower storage, with specific attention to flexibility, long-duration energy storage and essential ancillary services.

Strategic cooperation between the two subgroups will be pursued on cross-cutting issues, including efficient and fish-friendly low-head turbine technologies, environmental monitoring, digital tools and sustainable deployment practices, while preserving the distinct scope and deliverables of each subgroup.

While Hydropower and Ocean Energy address distinct technologies, both Thematic Visions share important overlaps. They face identical deployment barriers, high capital costs, complex permitting, fragmented national research, revenue uncertainty, and skills shortages, and are driven by the same strategic objectives: energy security, climate neutrality, industrial competitiveness, and strategic autonomy.

Both address Europe's pressing needs for system flexibility and long-duration storage, setting GW-scale capacity targets and proposing similar market support mechanisms such as Contracts for Difference and feed-in tariffs.

Cross-cutting priorities, digitalisation and AI, skills development, market design reforms to value flexibility and storage, standardization, environmental innovation, and circular economy, are advanced collaboratively through the IWG's engagement with the five SET Plan Task Forces, ensuring consistency with the nine guiding principles that underpin Europe's energy transition.

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# **Chapter I**

## *Ocean Energy*

## Contents – Chapter I

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## Executive Summary

Ocean energy is a strategic European technology for climate neutrality, competitiveness and energy security. Tidal-stream resources are predictable years in advance, while actual generation depends on device availability and operating conditions. In several European Atlantic systems, wave energy can complement wind and solar production, including through higher winter output, when demand is often higher and solar generation lower. This potential system value makes ocean energy relevant for a power system increasingly dominated by variable renewables.

The Implementation Working Group's vision is a credible pathway from today's demonstration and pre-commercial stage to a bankable European ocean-energy industry. In line with the EU Offshore Renewable Energy Strategy (COM(2023) 668), the policy framework retains an indicative milestone of 100 MW by 2027, at least 1 GW by the end of the decade or the early 2030s, and 40 GW by 2050. The 100 MW milestone is at risk of not being achieved exactly on schedule, although publicly supported projects could bring the sector close to it by 2027 or shortly thereafter if financial close, consenting, construction and grid connection are not delayed. The quantitative deployment milestones refer primarily to emerging electricity-generating technologies, notably tidal-stream and wave energy. Tidal range, OTEC, SWAC and salinity-gradient technologies require technology-specific pathways and indicators.

By the early 2030s, the priority is to convert awarded and publicly supported projects into operational pilot and pre-commercial farms: consolidate tidal stream at TRL 8-9, bring wave energy to pilot-farm operation with multiple full-scale devices in real-sea conditions, and support OTEC, SWAC and salinity-gradient applications where geographically appropriate. Their contribution should be reported through suitable metrics and not mechanically aggregated with wave and tidal-stream GW targets. By 2040, ocean energy should be a recognised commercial offshore renewable option in selected European sea basins, with at least 10 GW installed or under construction as an IWG strategic staging milestone. By 2050, the objective remains 40 GW of installed ocean-energy capacity.

The main drivers are energy security, the 42.5% renewable energy target for 2030, the revised SET Plan and the Net-Zero Industry Act. The main barriers are high capital and operating costs, weak market pull, complex permitting, fragmented national R&I, limited revenue certainty and the absence of dedicated ocean-energy deployment frameworks in several Member States. To address them, the IWG will pursue four country-led activities: a European Ocean Energy Policy and Funding Alignment Forum, a KPI and Evidence Dashboard including policy-readiness indicators, a Market Access and Permitting Taskline, and a Ports, Skills and Supply Chain Readiness Initiative. The 2028-2034 Multiannual Financial Framework should prioritise farm-scale validation and bankability, next-generation devices and digital tools, industrialisation, market uptake, environmental evidence, standards, ports, supply chains and skills.

## 1. Introduction

The SET Plan Implementation Working Group on Ocean Energy and Hydropower operates in a policy context in which Europe must accelerate the deployment of clean, resilient and competitive energy technologies while reinforcing strategic autonomy. The SET Plan is designed to align European and national research and innovation agendas, maintain European industrial leadership in low-carbon technologies, and support the EU's 2030 and 2050 climate and energy targets. Its guiding principles, as articulated under the revised SET Plan governance, include decarbonisation alignment, technological neutrality, research and innovation, circular economy, competitiveness, security and resilience, digitalisation and AI, societal needs, and skills. These nine principles follow the revised SET Plan governance set out in the SET Plan Onboarding Guide (March 2026).

The scope of this Thematic Vision is ocean energy, including wave energy, tidal-stream energy, tidal range, ocean thermal energy conversion (OTEC), sea-water air conditioning (SWAC) and salinity-gradient technologies. The operational focus for 2030 remains on wave and tidal-stream energy, because they are the leading emerging ocean-energy sub-technologies in deployment, innovation and EU market relevance. Tidal-stream energy is more mature, with horizontal-axis turbines already reaching TRL 8-9, while wave energy remains more diverse, with no single dominant design yet established. Quantitative capacity milestones should refer primarily to emerging electricity-generating technologies, notably tidal-stream and wave energy. Tidal range, OTEC, SWAC and salinity-gradient technologies should be addressed through technology-specific pathways and indicators reflecting their different maturity levels, applications and measurement metrics.

The IWG's role in the SET Plan should be to act as the European alignment platform between national authorities, the European Commission, ETIP Ocean, EERA, industry, research organisations, test centres and relevant regional authorities. Its distinctive added value is not to duplicate ETIP Ocean or EERA, but to translate the sector's research, technical and industrial priorities into country-led commitments, coordinated public funding, measurable targets, and coherent policy conditions for deployment. As the Ocean Energy subgroup operates within the joint SET Plan Implementation Working Group on Ocean Energy and Hydropower, strategic cooperation with the hydropower strand will be pursued on cross-cutting issues, including efficient and fish-friendly low-head and hydrokinetic turbine technologies, environmental monitoring, digital tools and sustainable deployment practices, while preserving the distinct scope and deliverables of each subgroup.

The objective of this Thematic Vision is to define a realistic but ambitious pathway for ocean energy to contribute to European climate neutrality, industrial competitiveness and security of supply. It sets targets for 2030, 2040 and 2050, identifies milestones and KPIs, and proposes IWG-led activities that can reduce fragmentation, de-risk technology and support market uptake. Consistent with the SET Plan governance, the sequence is: this Thematic Vision sets the targets and Member State priorities; the updated Strategic Research and Innovation Agenda (SRIA), to be developed under the leadership of ETIP Ocean according to the accelerated timeline communicated by the SET Plan Secretariat, will translate the targets into specific R&I and non-R&I activities; the Implementation and Investment Commitments (IICs), to be collected from Member States, EC and stakeholders, will mobilise resources; together, these three components will form the Common Implementation and Investment Plan (CIIP) for Ocean Energy.

A Vision document is essential because the sector is entering a decisive window. Europe has led ocean-energy innovation for two decades, but current deployment remains far below strategic targets. The challenge is no longer only to demonstrate individual technologies, but to convert Europe's innovation leadership into operational farms, bankable project pipelines and industrial-scale

deployment. This requires closing the policy, market and industrial gap between today's pre-commercial stage, the objective of at least 1 GW by the end of the 2030-2040 decade or the early 2030s, and the EU objective of 40 GW by 2050.

Key recent developments confirm both momentum and risk. In 2024, Europe had a publicly funded planned ocean energy pipeline of around 165 MW across 15 farms, with cumulative tidal stream production reaching 106 GWh. At the same time, the United States allocated USD 141 million in public support to ocean energy in 2024 and USD 591 million over five years, increasing competitive pressure on Europe.

The most relevant policy drivers are the revised Renewable Energy Directive, which raises the EU's 2030 renewable-energy target to at least 42.5% of gross final energy consumption; the EU objective of at least 1 GW of ocean energy by the end of the decade or the early 2030s and 40 GW by 2050; the revised SET Plan; and the Net-Zero Industry Act, which strengthens Europe's manufacturing ecosystem for net-zero technologies and includes offshore renewable technologies within its scope.

The focus areas for the 2028–2034 MFF should be: farm-scale validation and bankability; next-generation devices, subsystems and digital tools; and industrialisation, market uptake and enabling infrastructure. These align with ETIP Ocean's 2024 SRIA, which identifies six challenge areas: design and validation of ocean energy farms; next-generation technologies and subsystems; analysis and modelling tools; integration of enabling technologies; market development; and coordination and sector support actions. The forthcoming 2026 SRIA update will refresh these challenge areas in light of the targets set by this Thematic Vision.

All SET Plan Task Force cross-cutting areas are relevant to ocean energy: Access to Market, Digitalisation, Circularity and Materials Substitution, Skills, and R&I for Societal Needs. Access to Market is central because ocean energy will not move from prototypes to farms without revenue support, bankable project structures and fit-for-purpose permitting. Digitalisation is essential for resource assessment, array optimisation, condition monitoring, predictive O&M and environmental monitoring. Circularity is critical because ocean energy depends on steel, composites, copper, aluminium and, in some generator designs, rare earths and boron. Skills are needed for offshore installation, subsea electrical systems, operations, maintenance, ports, certification and environmental monitoring. Societal Needs are relevant because ocean energy must be designed around coastal communities, islands, fisheries, aquaculture, maritime spatial planning and local acceptance, which is a precondition for local deployments and for sustained national investment in ocean energy.

## 2. Vision and targets

The IWG vision is that ocean energy should become a European industrial technology by 2050, with a staged pathway from demonstration to commercialisation. The core principle is sequencing: technology push must reduce technical risk, market pull must create investable projects, and infrastructure, standards, permitting and skills must scale in parallel.

The IWG should use measurable KPIs to monitor progress. Core technology KPIs should include TRL, availability factor, annual energy production, mean time to failure, mean time to repair, CAPEX and OPEX. Industrial KPIs should include manufacturing readiness level, lead time, local content, jobs, GVA, port readiness, certification status and supply-chain bottlenecks. Environmental and societal KPIs should include LCA, global warming potential, material circularity, environmental footprint, marine biodiversity interactions, technology acceptance (including acceptance of local deployments and of sustained national investment) and cumulative energy produced per unit of public support. ETIP Ocean's SRIA already proposes such KPI families for competitiveness, industry, knowledge, acceptance and investment.

To reduce fragmentation among national and regional R&I programmes, understood here as uncoordinated national calls, public funding of similar work without shared learning, and project results that cannot be compared across Member States, the IWG could explore options to align national and EU R&I efforts more closely, with the specific coordination arrangements to be agreed within the IWG, without prescribing a specific instrument at this stage. Such coordination could map national calls, planned demonstration projects, test sites, national market-pull schemes, environmental evidence and infrastructure investments. It should also identify gaps where no Member State is acting and overlaps where multiple programmes fund similar work without shared learning. This would translate the revised SET Plan's coordination function into practical country-led action.

To translate this Vision into action, the IWG will carry forward four country-led activities that constitute the core of its commitments. They span the full innovation-to-deployment chain and are designed to reduce fragmentation, strengthen the evidence base, improve market access and prepare the industrial base. Their detailed fiches, full sets of key performance indicators and implementation arrangements will be developed in the SRIA and, where appropriate, the CIIP; a first baseline for each is foreseen in 2026 and a consolidated input to the 2028–2034 Multiannual Financial Framework in 2027.

**European Ocean Energy Policy and Funding Alignment Forum:** an annual mechanism, led by the IWG with European Commission support and input from ETIP Ocean, EERA, Ocean Energy Europe and JRC/SETIS, to align national and EU R&I, demonstration and deployment support, connect technology-push and market-pull instruments, and identify gaps and overlaps against the Vision, SRIA and CIIP priorities. The Forum should use these indicators to identify where national frameworks are sufficiently mature to support near-term deployment, where policy gaps remain, and where coordination between national schemes could create a more bankable European project pipeline.

**Ocean Energy KPI and Evidence Dashboard:** a harmonised monitoring framework providing comparable indicators on technology readiness, cost, deployment, environmental performance, industrial capacity and market uptake across wave energy, tidal stream and, where relevant, the less mature technologies. Building on the ETIP Ocean, JRC/CETO and IEA-OES frameworks, it gives the IWG, Member States and the European Commission a single, comparable evidence base for decision-making. The Dashboard should also include policy-readiness indicators, including the number of Member States or SET Plan countries with explicit ocean-energy deployment targets or indicative

capacity ranges, dedicated or accessible revenue-support mechanisms, identified pilot or pre-commercial project pipelines, and fit-for-purpose permitting procedures.

**Ocean Energy Market Access and Permitting Taskline:** support to Member States in designing the revenue-support and permitting frameworks needed to move projects from demonstration to bankable deployment, addressing the sector's two most persistent barriers. It reviews market-access instruments (Contracts for Difference, feed-in tariffs, power purchase agreements, innovation auctions, public guarantees and blended finance), benchmarks permitting procedures, and examines how the system value of ocean energy can be recognised in market design, building on recent IEA-OES analysis to avoid duplication.

**Ports, Skills and Supply Chain Readiness Initiative:** an assessment and preparation of the industrial base required for deployment to 2030 and scale-up to 2040 and 2050, covering ports, manufacturing and assembly capacity, vessels and offshore logistics, the skilled workforce and supply-chain depth, including critical materials and strategic components. Pursued in synergy with offshore wind where appropriate, its principal output is a European Ocean Energy Industrial Readiness Map, with a major progress review by 2030.

## 2.1. Short-term (2030)

The IWG proposes to retain at least 1 GW of installed ocean-energy capacity as a strategic objective for the end of the decade or the early 2030s, consistently with the EU Offshore Renewable Energy Strategy COM(2023) 668. The GW deployment figures set out in this Vision represent the aspiration of the sector and will in any case be subject to revision over time as the technologies mature, deployment evidence accumulates and market conditions evolve. The indicative milestone of 100 MW by 2027 remains part of the policy framework established in COM(2023) 668. However, current deployment evidence indicates that it is at risk of not being achieved exactly on schedule, although current publicly supported projects could bring the sector close to the milestone by 2027 or shortly thereafter, provided that financial close, consenting, construction and grid connection are not delayed. Meeting the early-2030s objective will require the timely conversion of awarded and publicly supported projects into operational farms.

This calls not only for continued R&I support, but also for accelerated financial close, consenting, construction and grid connection. The main implementation risk is the cumulative delay that may arise across these successive project-development stages.

The 2030 technology target is to consolidate tidal stream at TRL 8–9, with repeated multi-device farm operation and validated availability, and to bring wave energy to pilot-farm operation with multiple full-scale devices operating in real-sea conditions. Tidal technologies should converge around bankable design families, while wave energy should retain a portfolio approach until performance data identifies the most competitive concepts for specific wave climates. Other ocean energy technologies (SWAC, OTEC and salinity-gradient technologies) should benefit from continued support where geographically appropriate, to ensure that advanced industrial players can move forward. For OTEC, SWAC and salinity-gradient applications, installed capacity and impact should be reported through technology-specific metrics, such as MWe, MWth, cooling capacity, avoided electricity demand, desalinated water or island-system resilience, and should not be mechanically aggregated with wave and tidal-stream electrical GW targets.

As a proposed IWG policy-readiness milestone, by 2030 at least five European or SET Plan countries with significant ocean-energy resources should have operational deployment frameworks for ocean energy. These frameworks should not be limited to generic references to offshore renewables, but

should include, where appropriate, explicit ocean-energy deployment objectives or indicative capacity ranges, ring-fenced or otherwise clearly accessible revenue-support mechanisms such as CfDs, feed-in tariffs or innovation auctions, access to grants and financial instruments, proportionate permitting procedures, and identified routes to grid connection. Progress against this milestone should be monitored through a dedicated KPI tracking the number of countries with explicit ocean-energy targets or indicative deployment ranges, dedicated or accessible revenue-support schemes, and permitting frameworks suitable for pilot and pre-commercial farms. Where appropriate, these instruments will deliver most value when coordinated at European level, aggregating national schemes into an investable European market rather than a fragmented set of isolated national initiatives.

An additional 2030 policy priority, anticipating the proposed 10 GW milestone for 2040, is the early integration of credible ocean-energy deployment scenarios into grid planning. Member States and ENTSO-E should account for ocean energy in offshore grid planning where these scenarios are material, while ensuring timely local grid connections for pilot and pre-commercial farms. This is necessary because infrastructure lead times may be incompatible with multi-GW deployment during the 2030s.

The 2030 R&I target is to ensure that the updated SRIA, to be developed under the leadership of ETIP Ocean according to the accelerated SET Plan timeline, fully reflects the targets set in this Thematic Vision and reassesses the European R&I needs relevant to the 2028-2034 MFF. As a reference, the ETIP Ocean 2024 SRIA estimated that implementing its priority actions for 2025-2030 would require almost 200 projects and approximately EUR 1.4 billion in total funding, including an estimated private contribution of around 40%. The forthcoming SRIA update should reassess these needs and identify the priorities relevant to the 2028-2034 MFF. Given differences across recent references on LCOE baselines and targets, the forthcoming SRIA update should reconcile the applicable cost-performance benchmarks for tidal stream and wave energy. This should distinguish current observed project evidence, revised OceanSET cost-reduction trajectories and earlier SET Plan benchmark assumptions, while avoiding the use of LCOE alone as the sole indicator of competitiveness.

The 2030 IWG activities should include: an annual Ocean Energy Policy and Funding Alignment Forum; a European ocean energy KPI dashboard; a joint national pipeline review for pilot and pre-commercial farms; a permitting and environmental evidence workstream; and an industrial readiness assessment covering ports, test sites, cables, moorings, foundations, PTOs, O&M capacity and skills. This section has been deliberately streamlined to maintain the appropriate level of detail for a Thematic Vision. A more comprehensive description of the actions, implementation arrangements and related priorities will be developed in the forthcoming SRIA.

## **2.2. Medium-term (2040)**

By 2040, ocean energy should have moved beyond isolated pre-commercial farms and become a commercially recognised offshore renewable option in Europe. The IWG proposes a medium-term strategic milestone of at least 10 GW installed or under construction by 2040, complemented by a separately monitored consented and financed pipeline sufficient to support progress towards the 2050 EU objective. This milestone is not a substitute for the EU's 2050 objective; it is intended as an intermediate bridge to avoid a late and unrealistic acceleration in the 2040s.

By 2040, tidal stream should be commercially deployable in the best European tidal resources, with standardised devices, certified components, established O&M procedures and competitive insurance conditions. Wave energy should have converged towards a smaller number of bankable technology

families, differentiated by resource class: high-energy Atlantic conditions, moderate-energy Atlantic and North Sea conditions, island/off-grid applications, and hybrid/co-located configurations. Other ocean energy technologies (SWAC, OTEC and salinity-gradient technologies) should benefit from continued support where geographically appropriate, to ensure that advanced industrial players can move forward. If a specific technology shows significant progress, it should be assessed against the same staged logic used for tidal stream and wave energy, while retaining technology-specific KPIs.

The 2040 cost target should be market competitiveness on a system-value basis. Ocean energy should be assessed against the avoided costs it may create: lower fossil backup, reduced curtailment, lower storage needs, improved security of supply and better seasonal complementarity. ETIP Ocean's 2025 scenario-based case studies indicate that adding wave energy can reduce fossil dispatch and emissions in Ireland and Portugal, while tidal-stream energy in island systems can reduce both generation-capacity needs and system costs. These model-based results should not be presented as empirically demonstrated system-wide outcomes. A social cost-benefit analysis capturing system, environmental and socio-economic effects alongside generation cost would provide a clearer appraisal framework.

The 2040 industrial target is the emergence of a European ocean energy manufacturing and service base. This should include serial manufacturing of main subsystems, dedicated supply chains for offshore electrical connections and dynamic cables, port facilities adapted to deployment and maintenance, shared logistics with offshore wind where appropriate, and a skilled workforce. The IEA-OES roadmap indicates that large-scale ocean energy growth will require early infrastructure planning, including port upgrades, manufacturing and fabrication space, laydown areas, and public-private partnerships.

The 2040 policy target is that ocean energy should be embedded in maritime spatial planning, offshore grid planning, island energy strategies, renewable auctions, innovation procurement and industrial policy. Member States should treat ocean energy not only as a R&I topic, but also as a strategic industrial option requiring bankable volume signals.

The 2040 IWG activities should include a mid-term revision of the Thematic Vision; a European Ocean Energy Industrial Readiness Map; a ports and supply-chain observatory; a framework for environmental data transferability; and a joint recommendation on ocean energy integration in national energy and climate planning. The detailed activity fiches will be developed in the SRIA and, where appropriate, the CIIP.

### **2.3. Long-term (2050)**

By 2050, the EU objective remains 40 GW of installed ocean-energy capacity. By 2050, ocean energy should be an established component of Europe's offshore renewable system. It should contribute to electricity generation, system balancing, island decarbonisation, offshore hybrid energy hubs, aquaculture and desalination where appropriate. Other ocean energy technologies (SWAC, OTEC and salinity-gradient technologies) should benefit from continued support where geographically appropriate, to ensure that advanced industrial players can move forward. If a specific technology shows significant progress, it should follow the paths of tidal and wave energies according to this thematic vision. Their contribution should be assessed through technology-specific indicators. The value of ocean energy should also be measured through whole-system metrics, including avoided fossil dispatch, balancing requirements, seasonal storage needs, energy security, local industrial value and resilience.

The 2050 competitiveness target is that mature tidal and wave projects should be financeable under mainstream renewable energy investment conditions in high-quality sites, with residual public support limited to system-value remuneration, innovation upgrades, strategic manufacturing and early deployment in emerging sea basins. Bankability should rely on certified performance, long operational histories, standardised components, predictable O&M costs, transferable environmental data and mature insurance products.

The 2050 industrial target is that Europe should remain a global technology, manufacturing and services leader in ocean energy. This requires retaining intellectual property, maintaining European test and certification capabilities, supporting strategic component suppliers, building export channels, and linking ocean energy to broader European strengths in offshore wind, hydropower, marine engineering, shipbuilding, subsea systems, power electronics, digitalisation and environmental monitoring.

The 2050 societal target is that ocean energy should be deployed with high social legitimacy. Projects should be designed with coastal communities, fisheries, aquaculture operators, port authorities, environmental regulators, islands and regional governments. Environmental impacts should be monitored using robust, comparable and transparent data, and adaptive management, with the explicit goal of minimising environmental impact, should be the default approach.

The 2050 IWG activities should include the preservation and transfer of knowledge generated by projects deployed between 2025 and 2040; a periodic strategic review of technology families; a joint European position on international standards and certification; and coordination with global initiatives such as IEA-OES. The detailed scope, implementation arrangements and monitoring framework will be further developed in the SRIA and, where appropriate, in the CIIP.

### 3. Conclusions and next steps

In line with the revised SET Plan governance and the SET Plan Onboarding Guide (March 2026), the Common Implementation and Investment Plan (CIIP) for Ocean Energy will consist of three integrated components: this Thematic Vision (Component 1, defining targets and Member State priorities), the updated Strategic Research and Innovation Agenda (Component 2, defining R&I and non-R&I activities), and the Implementation and Investment Commitments (Component 3, mobilising public and private resources). The actions and timeline below should be read against this tripartite architecture.

Ocean energy is no longer a purely experimental technology field. Tidal stream has reached advanced pre-commercial maturity, wave energy is entering a more credible full-scale demonstration phase, and Europe has a visible project pipeline. Ocean energy is entering the decade in which Europe must decide whether it will remain a research leader or become an industrial leader. The evidence base is now sufficient to justify a coordinated scale-up strategy for wave and tidal stream energy, but not yet sufficient to assume automatic market uptake. The sector needs a combined package: sustained technology push, disciplined market pull, de-risking instruments, accelerated consenting, shared infrastructure, standards and stronger integration into national energy planning. The strategic problem is that deployment is still too slow to meet EU targets, and global competitors are increasing support. The IWG must therefore focus on converting European innovation leadership into industrial deployment.

The first step is to combine technology push and market pull. Grants, stage-gate programmes, test access and R&I projects are necessary but not sufficient. Ocean energy also needs long-term revenue certainty, dedicated auction pots or equivalent mechanisms, guarantees, publicly supported equity and national deployment targets. These instruments deliver most value when coordinated at European level, so that national schemes aggregate into a single, investable European market rather than a fragmented patchwork of small national ones. The IEA-OES policy guidance is clear that market pull is the foundation of commercial deployment, while technology push reduces the total cost of market pull by accelerating learning and cost reduction.

The second step is to use the 2028-2034 MFF as a key industrialisation window for ocean energy, in which EU funding progressively shifts emphasis from research and single-device demonstration towards farm-scale validation, industrial manufacturing, supply-chain build-up and first commercial farms. Funding priorities should include pilot farms, single-device validation, PTO and control systems, moorings, foundations, dynamic cables, digital tools, AI-enabled monitoring, environmental evidence, circular materials, standards, certification and port or test-site upgrades. This list is illustrative rather than exhaustive. The detailed prioritisation should be developed in the SRIA and, where appropriate, in the CIIP.

The third step is to reduce fragmentation. The IWG should lead a structured alignment process among Member States, regions and the Commission to connect national programmes to European priorities, and ensure that funded projects produce comparable performance, environmental and cost data. National R&I programmes, which in several Member States have no predefined budget lines per technology area, are understood here as complementary to EU programmes rather than as duplication to be eliminated. A specific priority within this effort is to establish reliable levelised cost of energy (LCOE) values for ocean energy based on the most recent at-sea installations, so that future cost references rest on operational evidence from recent deployments rather than on earlier benchmark assumptions.

The fourth step is to assign the next SRIA drafting process to ETIP Ocean, which has been recognised by the Commission as the main advisory body for ocean energy. The Ocean Energy Forum Support (OEFS) CSA project will provide technical support to ETIP Ocean and the IWG in this work, alongside EERA, whose Joint Programme on Ocean Energy is part of ETIP Ocean, Ocean Energy Europe, the European test-centre community, national authorities, industry and relevant regional authorities. The IWG should validate the strategic orientation and ensure that the SRIA reflects country-led priorities.

Synergies should be developed with relevant SET Plan Implementation Working Groups, notably Wind Energy (ports, vessels, subsea cables, maritime spatial planning, O&M and hybrid offshore hubs), Energy Systems (predictability, flexibility and market design), Direct Current Technologies (offshore connections), Batteries (hybrid generation-storage systems), Hydrogen (offshore green hydrogen where relevant), Renewable Fuels and Bioenergy (maritime applications), and Sustainable and Efficient Energy Use in Industry (desalination and industrial applications). Strategic cooperation with the hydropower strand will be pursued on cross-cutting issues, including efficient and fish-friendly low-head and hydrokinetic turbine technologies, environmental monitoring, digital tools and sustainable deployment practices, while preserving the distinct scope and deliverables of each subgroup. Engagement with the five cross-cutting Task Forces – Skills, Circularity and Materials Substitution, Digitalisation, Access to Market, and R&I for Societal Needs – will be channelled into the SRIA and the CIIP.

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## **Chapter II**

### *Hydropower generation and storage*

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## Executive Summary

Hydropower is Europe's largest source of stored energy and second-largest renewable electricity source, making it a strategic pillar for energy security, industrial competitiveness, greenhouse-gas reduction, climate resilience, and decarbonisation. As variable renewables expand, hydropower and pumped-storage hydropower (PSH) will become increasingly essential for system flexibility, long-duration storage, adequacy, ancillary services, sector integration, and integrated water management. Building on previous SET Plan activities and the substantial technical, regulatory, and research work already undertaken across Europe, this SET Plan Hydropower IWG vision defines the sector's contribution to a climate-neutral, resilient, and competitive European energy system by 2030, 2040, and 2050.

Hydropower is recognised as critical infrastructure supporting six strategic benefits for Europe: secure and reliable electricity supply, large-scale renewable integration, long-duration energy storage and flexibility, industrial competitiveness and affordable energy, climate adaptation and water resilience, and greenhouse-gas emissions reduction through low-carbon dispatchable generation. Its distinctive capabilities make hydropower a key component of Europe's renewed energy security, competitiveness, and GHG reductions goals. The pathways proposed in this document prioritise refurbishment, uprating, digitalisation, optimisation, and storage-oriented upgrades of existing assets, combined with selective development of pumped-storage, hybrid systems, and conversion projects, as opposed to broad greenfield development policies.

By 2030, hydropower should strengthen its system role through modernisation, hybrid and pumped-storage demonstrations, conversion pilots, and rapid deployment of digital monitoring, forecasting, and AI-based operation. By 2040, it should become a core flexibility and long-duration storage backbone of a highly decarbonised energy system, enabled by digital twins, predictive maintenance, and integrated energy-water planning. By 2050, hydropower and PSH should operate as fully digitalised, cyber-secure, climate-resilient infrastructure integrating generation, storage, water management, climate adaptation, and environmental performance within a climate-neutral European economy.

Key drivers include renewable integration, electrification, climate adaptation, and European energy sovereignty, while key barriers remain ageing assets, high upfront investment costs, permitting complexity, environmental constraints, hydrological variability, insufficient recognition of flexibility services, regulatory fragmentation, and skills shortages. To address these challenges, the IWG identifies three priority R&I areas for 2028–2034: digitalisation and AI-enabled operation; modernisation and storage-oriented upgrading, including pumped-storage conversion, hybridisation, and flexibility valuation; and environmental and climate-resilience solutions such as fish-friendly technologies, sediment management, adaptive flows, and basin-scale water management.

IWG activities support the SRIA through coordination among Member States, consolidation of R&I priorities, gap analysis, demonstration support, cross-SET Plan cooperation, and dedicated activity fiches on flexibility, digitalisation, climate resilience, environmental performance, and storage. KPIs will be further defined within the SRIA framework.

Overall, this vision positions hydropower as a foundational element of Europe's future energy architecture and a tool for achieving the goals outlined in Fit for 55, the Renewable Energy Directive, and the Net-Zero Industry Act. It also recognizes that while Europe needs hydropower to achieve its security, competitiveness, and decarbonization goals, the hydropower sector will need Europe's coordinated support to accelerate its innovation in response to the Union's most pressing challenges.

# 1. Introduction

## 1.1. General introduction to the IWG

Hydropower is one of Europe's main renewable electricity sources and its largest source of stored energy, underpinned by pumped-storage hydropower as a mature large-scale long-duration storage technology. Together, run-of-river, reservoir and pumped-storage hydropower combine flexible low-carbon generation, long-duration storage, multi-purpose water management, system resilience and climate-adaptation services. In the current EU policy environment, hydropower is directly relevant to industrial competitiveness, strategic autonomy, security of supply, climate neutrality and water resilience. Europe requires more dispatchable, domestically anchored clean electricity capacity and long-duration storage to support a secure and affordable decarbonised energy system<sup>1</sup>.

Against this policy and system background, the Implementation Working Group (IWG) on Ocean Energy and Hydropower was established by the Steering Group (SG) to support the implementation of the SET Plan in the areas of ocean energy and hydropower technology. Within this consolidated IWG, the Hydropower Generation and Storage subgroup operates with functional autonomy and covers all hydropower technologies and energy derived from falling or fast-running water, including pumped hydropower storage, with specific attention to flexibility, long-duration energy storage and essential ancillary services. Its role is to translate system needs into common European research, innovation and deployment priorities, reduce fragmentation across national R&I programmes, and support the preparation of the Common Implementation and Investment Plan (CIIP), composed of the Thematic Vision, the Strategic Research and Innovation Agenda (SRIA) and the Implementation and Investment Commitments (IIC)<sup>2</sup>.

Strategic cooperation with the Ocean Energy subgroup will be pursued on cross-cutting issues, including efficient and fish-friendly low-head turbine technologies, environmental monitoring, digital tools and sustainable deployment practices, while preserving the distinct scope and deliverables of each subgroup<sup>3</sup>.

## 1.2. Objective of the Thematic Vision

In 2021, IEA Executive Director Dr Fatih Birol described hydropower as “the forgotten giant of low-carbon electricity”, noting that it produced more low-carbon electricity than any other source worldwide. In 2025, he reiterated that statement, calling for hydropower to receive the policy attention it deserves. This continuous lack of recognition is precisely why coordinated action cross

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<sup>1</sup> Quaranta, E., Georgakaki, A., Letout, S., Mountraki, A., Ince, E., Gea Bermudez, J., & Schmitz, A. (2025). *Hydropower and Pumped Storage Hydropower in the European Union: Status Report on Technology Development, Trends, Value Chains and Markets*. [https://publications.jrc.ec.europa.eu/repository/bitstream/JRC143929/JRC143929\\_01.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC143929/JRC143929_01.pdf)

<sup>2</sup> European Commission. (2025, November 28). *Strategic energy technology (SET) plan governance*, pp. 7–8, 12–15. [https://setis.ec.europa.eu/document/download/68ead1b5-1e50-4142-bf47-f35a0c702cb2\\_en?filename=Strategic%20Energy%20Technology%20%28SET%29%20Plan%20Governance%20%281%29.pdf](https://setis.ec.europa.eu/document/download/68ead1b5-1e50-4142-bf47-f35a0c702cb2_en?filename=Strategic%20Energy%20Technology%20%28SET%29%20Plan%20Governance%20%281%29.pdf)

<sup>3</sup> *Mandate for SET Plan Implementation Working Group on Ocean Energy and Hydropower*. (2026). p. 1.

technology development, asset modernisation, environmental performance, market design, permitting, water management and skills is needed<sup>4</sup>.

Much of the existing hydropower and pumped-storage fleet requires rehabilitation, modernisation, digitalisation, dam-safety investment and climate-resilience upgrades, while new or upgraded projects face long lead times, high upfront capital costs, complex permitting, uncertain revenue frameworks and increasing expectations regarding biodiversity protection and social acceptance<sup>5</sup>.

Therefore, the objective of this Thematic Vision is to define a common strategic direction for hydropower generation and storage in Europe up to 2030, 2040 and 2050 by prioritising refurbishment, uprating and optimisation of existing assets, while enabling targeted new or upgraded infrastructure, including pumped-storage and multi-purpose reservoir projects, where justified by system needs, environmental assessment and regional energy-security value<sup>6</sup>.

### 1.3. Key developments

Several policy, technological and geopolitical developments make a renewed European hydropower vision necessary. The acceleration of clean electricity deployment increases flexibility needs across multiple timeframes, from fast balancing and grid-support services to multi-day and seasonal storage. European Commission information on energy storage refers to studies pointing to more than 200 GW of energy storage capacity needs by 2030 and around 600 GW by 2050, from roughly 89 GW in 2024, mainly in the form of pumped hydro storage<sup>7</sup>.

Hydropower reservoirs and pumped-storage hydropower should therefore be assessed through system-value metrics, including usable storage volume, discharge duration, cycling and ramping capability, adequacy contribution, inertia, frequency and voltage support, black-start capability, congestion relief and avoided renewable curtailment<sup>1</sup>.

At the same time, climate change is reshaping hydrological patterns and reinforcing the need for resilient, flexible and secure energy systems. Hydropower remains one of the most reliable and dependable renewable energy sources, providing stable electricity generation, long-duration storage and essential system flexibility. In parallel, hydropower infrastructure plays a key role in strengthening water resilience through flood and drought mitigation, irrigation support, water supply management and broader climate adaptation measures. Main barriers include ageing infrastructure, insufficient remuneration for hydropower and pumped-storage services, fragmented permitting, high upfront capital costs, uncertain market signals, environmental pressures, public acceptance challenges and shortages of specialised skills<sup>8</sup>.

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<sup>4</sup> International Energy Agency. (2021, June 30). *Hydropower Special Market Report*, foreword. <https://www.iea.org/reports/hydropower-special-market-report>

<sup>5</sup> Fry, J.-J., Morris, M., & Schleiss, A. (2021, December). *Strategic Industry Roadmap*. [https://hydropower-europe.eu/private/Modules/Tools/EUProject/documents/54/HPE\\_SIR\\_D4-8\\_WP4-DIRp-54\\_V5\\_0\\_Final.pdf](https://hydropower-europe.eu/private/Modules/Tools/EUProject/documents/54/HPE_SIR_D4-8_WP4-DIRp-54_V5_0_Final.pdf)

<sup>6</sup> Mišech, A., Schleiss, A., Fry, J.-J., & Mulhaupt, H. (2021, November). *Research and Innovation Agenda*. [https://hydropower-europe.eu/private/Modules/Tools/EUProject/documents/54/HPE\\_SIR\\_D4-8\\_WP4-DIRp-54\\_V5\\_0\\_Final.pdf](https://hydropower-europe.eu/private/Modules/Tools/EUProject/documents/54/HPE_SIR_D4-8_WP4-DIRp-54_V5_0_Final.pdf)

<sup>7</sup> European Commission. (n.d.). *Key facts on energy storage*. Energy. [https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/key-facts-energy-storage\\_en](https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/key-facts-energy-storage_en)

<sup>8</sup> European Commission. (2025, June 4). *European Water Resilience Strategy*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52025DC0280&qid=1750857768458>

## 1.4. Focus areas

For the next Multiannual Financial Framework period 2028–2034, the Hydropower subgroup identifies three R&I focus areas, grounded in hydropower's six strategic benefits for Europe: flexibility and energy transition; strategic autonomy, sovereignty and industrial competitiveness; affordability and market stability; climate neutrality and low-carbon performance; water resilience and socio-economic value; and environmental, biodiversity and climate-risk protection<sup>9</sup>.

First, Europe should prioritise generation and storage performance for grid flexibility and resilience. This includes flexible operation of run-of-river, reservoir and pumped-storage hydropower, balancing and ancillary services from fast response to long-duration storage, and digital tools for forecasting, operation, maintenance, automation and optimisation<sup>6</sup>.

Second, Europe should support strategic modernisation and storage-oriented upgrading of existing assets. This includes refurbishment, uprating, lifetime extension, dam-safety upgrades, operational optimisation, competitive manufacturing, digital services, hybridisation, reservoir interconnection, reversible pump-turbine solutions and structured assessment of technically, environmentally and economically suitable conversion to pumped-storage operation<sup>10</sup>.

Third, Europe should accelerate sustainable technological solutions for biodiversity, water resilience and climate adaptation. This includes fish-friendly turbines, fish migration and protection systems, sediment continuity, adaptive environmental flows, water-quality protection, lifecycle greenhouse-gas assessment, circular construction and refurbishment, biodiversity-compatible operation, flood-risk management, drought resilience, multi-purpose reservoir operation and digital environmental monitoring. Hydropower development and operation should comply with EU water and biodiversity legislation, applying avoidance, mitigation and, where required, compensation measures, while maximising ecological improvement where technically and economically feasible<sup>11 12 13</sup>.

## 1.5. Task Force recommendation reflections

The above focus areas are closely linked to the following SET Plan Task Force recommendations: Digitalisation, Access to Market, Circularity, Societal Needs and Skills. These will be further explained in section 2 of this Thematic Vision and operationalised in depth in the Hydropower SRIA – digitalisation, access to market, circularity, societal needs, skills.

The Hydropower SRIA will further define activities, indicators, funding needs and enabling framework conditions for manufacturing and market uptake<sup>14</sup>.

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<sup>9</sup> ETIP HYDROPOWER and EERA. (2025). *Hydropower for a Resilient, Secure and Competitive Europe*, pp. 1-2. [https://etip-hydropower.eu/assets/Hydro%20position%20paper\\_full.pdf](https://etip-hydropower.eu/assets/Hydro%20position%20paper_full.pdf)

<sup>10</sup> Quaranta, E., Aggidis, G., Boes, R. M., Cornoglio, C., De Michele, C., Ritesh Patro, E., Georgievskaia, E., Harby, A., Kougias, I., Muntean, S., Pérez-Díaz, J., Romero-Gomez, P., Rosa-Clot, M., Schleiss, A. J., Vagnoni, E., Wirth, M., & Pistocchi, A. (2021). *Assessing the energy potential of modernizing the European Hydropower Fleet*. *Energy Conversion and Management*, 246. <https://doi.org/10.1016/j.enconman.2021.114655>

<sup>11</sup> European Union. (2000). *Directive 2000/60 (Water framework directive)*. <https://eur-lex.europa.eu/eli/dir/2000/60/oj>

<sup>12</sup> European Commission: Directorate-General for Environment. (2021). *EU biodiversity strategy for 2030: Bringing nature back into our lives*. Publications Office of the European Union. <https://data.europa.eu/doi/10.2779/677548>

<sup>13</sup> European Union. (2024, June 24). *Regulation (EU) 2024/1991 on nature restoration and amending Regulation (EU) 2022/869*. <http://data.europa.eu/eli/reg/2024/1991/oj>

<sup>14</sup> *Mandate for SET Plan Implementation Working Group on Ocean Energy and Hydropower*. (2026).

## 2. Vision and targets

The targets set out in this section, albeit primarily qualitative in nature, have been developed in line with the nine SET Guiding Principles and are intended to facilitate the development of the subsequent SRIA and IIC by defining the main directions of progress expected by 2030, 2040 and 2050. They build on the three R&I focus areas identified in Section 1 — generation and storage performance for grid flexibility and resilience; strategic modernisation and storage-oriented upgrading of existing assets; and sustainable technological solutions for biodiversity, water resilience and climate adaptation — and reflect the relevant SET Plan Task Force recommendations. Digitalisation is addressed through advanced monitoring, forecasting, automation and AI-supported operation; Access to Market through the recognition and remuneration of flexibility, long-duration storage, adequacy and ancillary services; Circularity through refurbishment, low-carbon construction, sediment management and extended use of existing infrastructure; Societal Needs through water resilience, biodiversity, public acceptance and multi-purpose reservoir functions; and Skills through the renewal of specialised engineering, hydrology, dam-safety, electromechanical, environmental and digital expertise<sup>15 16 17</sup>.

The figures presented below provide an indicative upper-bound scenario for the future evolution of hydropower energy production, installed generation capacity, pumped-storage capacity, and reservoir-based storage capacity in Europe. They illustrate the scale of development that may be required for hydropower to strengthen its role in supporting Europe's energy transition, decarbonisation, energy security, and system flexibility objectives. As such, they provide an important reference for understanding expected sectoral demands and for framing the proposed objectives, targets, and milestones presented in the following sections.

The scenario reflects a value-driven development pathway in which hydropower expands its contribution to flexibility, long-duration storage, adequacy provision, and operational optimisation. It prioritises refurbishment, upgrading, digitalisation, conversion, and optimisation of existing infrastructure, while enabling targeted new pumped-storage and multi-purpose reservoir projects, where justified by system and regional energy-security needs. The projections are aligned with European decarbonisation pathways and assume compliance with EU water and biodiversity legislation<sup>1</sup>.

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<sup>15</sup> European Commission. (2025, November 28). *Strategic energy technology (SET) plan governance*, pp. 6-7, 12–15. [https://setis.ec.europa.eu/document/download/68ead1b5-1e50-4142-bf47-f35a0c702cb2\\_en?filename=Strategic%20Energy%20Technology%20%28SET%29%20Plan%20Governance%20%281%29.pdf](https://setis.ec.europa.eu/document/download/68ead1b5-1e50-4142-bf47-f35a0c702cb2_en?filename=Strategic%20Energy%20Technology%20%28SET%29%20Plan%20Governance%20%281%29.pdf)

<sup>16</sup> European Union Agency for the Cooperation of Energy Regulators. (2025, July 25). *Type and format of data and the methodology for TSOs' and DSOs' flexibility needs analysis*. <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-flexibility-needs-assessment-methodology-2025.pdf>

<sup>17</sup> European Union Agency for the Cooperation of Energy Regulators. (2026, March 19). *Recommendation No. 01/2026 on NRAs' reporting on barriers for non-fossil flexibility*. <https://www.acer.europa.eu/sites/default/files/documents/Recommendations/ACER-Recommendation-01-2026-NRAs-reporting-barriers-to-flexibility.pdf>

|                                | EU27               |      |                         |                   | EU27 +<br>Norway & Switzerland |       |       |       |
|--------------------------------|--------------------|------|-------------------------|-------------------|--------------------------------|-------|-------|-------|
|                                | Today              | 2030 | 2040                    | 2050              | Today                          | 2030  | 2040  | 2050  |
| Energy production [TWh]        | 36018              | 373* | 400 (target prediction) | 427 <sup>18</sup> | 536*                           | 553*  | 589*  | 624*  |
| Power generation [GW]          | 15218              | 158* | 169*                    | 180*              | 203*                           | 210*  | 226*  | 242*  |
| Pump Storage Capacity [GW]     | 461 <sup>19</sup>  | 60*  | 80*                     | 120 <sup>20</sup> | 51*                            | 69*   | 93*   | 137*  |
| Storage Energy Potential [TWh] | 83.6 <sup>21</sup> |      |                         |                   | 17921                          | 18221 | 19321 | 20421 |

\* These quantitative figures are estimates which have been derived through interpolation and/or extrapolation of available data from the cited sources, courtesy of ETIP Hydropower. They are provided for analytical and illustrative purposes only and do not constitute official projections, policy commitments, or binding targets. Actual developments may differ substantially from these indicative estimates.

The potential contribution shown above includes rehabilitation and uprating of existing hydropower assets, development using existing infrastructure, and targeted new mainly multi-purpose hydropower schemes. Literature estimates that modernising the European hydropower fleet through powerhouse-equipment rehabilitation alone could increase present generation by around 8.4% in the European Union and 9.4% in Europe as a whole, with further potential from limited infrastructure uprating and reservoir interconnection. These figures should be treated as evidence of development potential to be further assessed in the SRIA and CIIP process, not as automatic deployment assumptions<sup>1 10 19</sup>.

The flexibility and storage requirements of the European power system are expected to grow rapidly as variable renewable energy sources become dominant. ENTSO-E indicates that, by 2033, daily flexibility needs could increase around threefold, weekly needs around twofold and seasonal needs around 1.6 times. Hydropower reservoirs and pumped-storage hydropower should therefore be assessed through system-value metrics such as usable storage volume, discharge duration, ramping

<sup>18</sup> Quaranta, E. (2023). The future of sustainable hydropower in the EU: challenges, projections and opportunities. *International Journal on Hydropower and Dams*, 30(5), 45–51. [https://www.researchgate.net/publication/374865867\\_The\\_future\\_of\\_sustainable\\_hydropower\\_in\\_the\\_EU\\_challenge\\_s\\_projections\\_and\\_opportunities](https://www.researchgate.net/publication/374865867_The_future_of_sustainable_hydropower_in_the_EU_challenge_s_projections_and_opportunities)

<sup>19</sup> Quaranta, E., Georgakaki, A., Letout, S., Mountraki, A., Ince, E., & Gea Bermudez, J. (2024). *Clean Energy Technology Observatory, Hydropower and pumped-storage hydropower in the European Union: Status report on technology development, trends, value chains and markets: 2024*, Publications Office of the European Union. <https://data.europa.eu/doi/10.2760/8354439>

<sup>20</sup> International Hydropower Association (IHA) & Eurelectric. (2025, September). *The Paris Pledge: Committing to Pumped Storage to Secure Europe's Clean Energy Future*. <https://indd.adobe.com/view/385c4753-2b01-4a7f-8ab7-e2ae22ac0a99>

<sup>21</sup> Graabak, I., Jaehnert, S., Korpås, M., & Mo, B. (2017). *Norway as a Battery for the Future European Power System—Impacts on the Hydropower System*. *Energies*, 10(12), 2054. <https://doi.org/10.3390/en10122054>

capability, multi-day and seasonal contribution, and ancillary services, rather than only annual generation or installed capacity<sup>22 23</sup>.

|                              | Today | 2030              | 2050   |
|------------------------------|-------|-------------------|--------|
| Flexibility needs [TWh/year] | 31020 | 456 <sup>24</sup> | 200020 |
| Storage capacity needs [GW]  |       | 20024             | 60024  |

These values illustrate the growing gap between flexibility demand and short-duration storage solutions, underlining the strategic relevance of hydropower reservoirs and pumped-storage hydropower in the period to 2050. The innovation and technology-deployment targets below are therefore derived from the priority areas identified in Section 1 and from the position paper *Hydropower for a Resilient, Secure, and Competitive Europe*, while remaining framed as qualitative targets to support future European R&I calls and ensure continuity between policy objectives, system needs and technology-development priorities<sup>9</sup>.

The following targets and milestones are based on recommendations for research and innovation<sup>2</sup> are structured around key strategic priorities such as **grid flexibility, water resilience, environmental protection, industrial innovation, and market design**, ensuring alignment with EU objectives on climate neutrality, energy security, and economic sovereignty. By covering different technology readiness levels, they create a pathway from early-stage research to large-scale deployment and system integration. Ultimately, the ten recommendations aim to position hydropower as a **flexibility backbone and long-duration storage solution** in a decarbonised European energy system, while ensuring that its development remains sustainable, innovative, and socially accepted. The headlines for each of the R&I actions are the following:

1. Adaption of hydropower operation to climate change
2. Conversion of existing infrastructures to pumped storage
3. Regional Grid Flexibility and Resilience through Hydropower
4. Water Quality under Climate Change – Hydropower Reservoir Management
5. Adaptive Environmental Flow Management for Biodiversity and Sustainable Hydropower
6. Development of innovative manufacturing, construction methods, and design tools
7. Valuing Hydropower’s Flexibility: Development and Application of a Business Model for Flexibility in a Decarbonized Energy System

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<sup>22</sup> ENTSO-E. (2024, December). *System Flexibility Needs for the Energy Transition*. ENTSO-E. <https://www.entsoe.eu/publications/reports/system-flexibility-needs-for-energy-transition/>

<sup>23</sup> European Union Agency for the Cooperation of Energy Regulators. (2025, July 25), pp. 4–6. *Type and format of data and the methodology for TSOs’ and DSOs’ flexibility needs analysis*. <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-flexibility-needs-assessment-methodology-2025.pdf>

<sup>24</sup> EASE. (2022, June). *Energy Storage Targets 2030 and 2050: Ensuring Europe’s Energy Security in a Renewable Energy System*. <https://energystorageeurope.eu/wp-content/uploads/2022/06/Energy-Storage-Targets-2030-and-2050-Full-Report.pdf>

8. Innovative Solutions for Fish Protection and Monitoring in Hydropower Systems
9. High Dynamics Flexibility for Hydropower: Advanced Control, Simulation, and Operational Optimization
10. Bridging the GHG Knowledge Gap in Hydropower – Emissions Accounting & Mitigation

In the following targets and milestones, the numbers correspond to the R&I actions above.

## **2.1. Short-term (2030)**

### **2.1.1. Strategic Objective (2030)**

By 2030, hydropower and pumped-storage hydropower shall consolidate their role as cornerstones of the European power system, maintain global leadership in sustainable hydropower technology, enabling the large-scale integration of variable renewable energy sources through flexibility, long-duration storage, adequacy contribution and ancillary services, while improving environmental performance and accelerating innovation uptake across existing and new strategic assets.

### **2.1.2. Targets**

By 2030, the IWG Hydropower aims to promote the following innovation and technology deployment targets:

1. Deployment of digital decision-support systems for climate-resilient reservoir management
2. Implementation of new technology in demonstration projects for retrofitted pumped storage capacity
3. Rollout of small-scale hydropower flexibility solutions in 10+ countries
4. Implementation of sediment management digital twins in major basins
5. Adoption of harmonised environmental flow frameworks across the EU
6. Integration of digital design, innovative manufacturing, and modular construction methods in hydropower projects
7. Establishment of an EU framework for valuing hydropower flexibility in markets
8. Deployment of AI-based fish monitoring systems at scale (TRL 4-6)
9. Introduction of advanced operational control systems for high-dynamic flexibility (TRL 4-5)
10. Development and adoption of a standardised GHG accounting methodology

### **2.1.3. Milestones**

Progress towards the 2030 targets will be demonstrated through:

1. Validation of climate-risk models and decision-support tools (TRL 4-5)
2. Implementation of first commercial pumped storage retrofit projects (TRL 7-8)
3. Demonstration of standardised modular solutions for regional grid applications
4. Pilot implementation of “sediment-smart” reservoir management systems

5. Deployment of operational E-flow decision-support tools
6. Demonstration of low-carbon and modular construction techniques
7. Integration of flexibility valuation into EU energy market reform discussions
8. Demonstration of a fully based AI-based fish monitoring systems in a hydropower system
9. Demonstration of AI-supported fast-response hydropower operations
10. Initial integration of GHG accounting into regulatory reporting frameworks

## **2.2. Medium-term (2040)**

### **2.2.1. Strategic Objective (2040)**

By 2040, hydropower and pumped-storage hydropower shall operate as a fully integrated flexibility, long-duration storage and system-adequacy backbone of a fossil free-dominant European energy system, contributing simultaneously to energy security, water resilience, climate adaptation and European industrial competitiveness.

### **2.2.2. Targets**

By 2040, the IWG Hydropower aims to promote the following innovation and technology deployment targets:

1. Fully integrated digital water-energy management systems across Europe
2. Fully commercially availability of retrofit technology for the conversion of hydropower plants to pumped storage plants
3. Hydropower established as a core provider of flexibility in regional and national grids
4. Sediment-neutral operation implemented across major reservoir systems, and developments of sediment resistant equipment (TRL 6-8)
5. Measurable biodiversity recovery through adaptive environmental flow regimes
6. Significant reduction in hydropower construction time and lifecycle emissions
7. Full recognition and compensation of hydropower flexibility in electricity markets
8. Standardisation of fish-safe turbine and monitoring technologies
9. Fleet-wide deployment of high-dynamic operational capabilities
10. Full implementation of asset-level GHG monitoring and mitigation strategies

### **2.2.3. Milestones**

Progress towards the 2040 targets will include:

1. Operation of cross-border real-time water-energy optimisation platforms
2. Widespread deployment of standardised PSH retrofit technologies
3. Full integration of hydropower in smart distribution grids

4. Restoration of sediment continuity at river-basin scale and demonstration projects for innovative sediment resistant technologies
5. Large-scale implementation of adaptive E-flow regimes
6. Industrial-scale rollout of modular and automated manufacturing and construction systems
7. Operation of mature multi-market frameworks (energy, capacity, ancillary services)
8. Achievement of near-zero fish mortality for sensitive species
9. Full deployment of predictive maintenance systems across hydropower plants
10. Large-scale application of emissions mitigation and reporting practices

## **2.3. Long-term (2050)**

### **2.3.1. Strategic Objective (2050)**

By 2050, hydropower and pumped-storage hydropower shall be key enablers of a climate-neutral, resilient, secure and competitive European energy system, delivering sustainable flexibility, long-duration storage, adequacy and system-restoration services while generating high socio-economic and environmental value and European hydropower industry is the leading exporter of integrated sustainable hydropower system solutions worldwide.

### **2.3.2. Targets**

By 2050, the IWG Hydropower aims to achieve promote the following innovation and technology deployment targets:

1. Deployment of real-time water-energy management systems
2. European technology of retrofit technology for the conversion of hydropower plants to pumped storage plants is dominating the market world wide
3. Fully decentralised and resilient electricity system supported by hydropower
4. Net-zero sediment loss across all reservoir systems
5. Achievement of nature-positive hydropower with net biodiversity gain
6. Fully circular and net-zero construction and manufacturing lifecycle
7. Fully optimised electricity markets monetising flexibility at all timescales
8. Full restoration of ecological continuity in European rivers
9. Hydropower fleet fully optimised for real-time grid balancing
10. Net-zero lifecycle GHG emissions across the hydropower sector

### **2.3.3. Milestones**

Progress towards the 2050 targets will be marked by:

1. Deployment of optimising reservoir systems managing climate extremes
2. European manufacturers are the preferred technology providers worldwide

3. Operation of autonomous regional balancing and flexibility systems
4. Implementation of self-sustaining sediment management processes and commercially availability of sediment resistant technologies
5. Demonstration of basin-scale net biodiversity gains
6. Full automation of low-carbon hydropower construction ecosystems
7. Implementation of fully integrated and efficient flexibility markets
8. Deployment of autonomous biodiversity monitoring networks where European technology is the preferred providers worldwide
9. System-wide AI-driven optimisation of hydropower operations where European technology is the preferred providers worldwide
10. Global adoption of transparent, standardised hydropower GHG accounting frameworks

## **2.4. IWG Contribution**

Beyond 2050, the IWG Hydropower will continue to monitor technological performance, assess emerging system needs, and provide strategic input to EU energy, water and climate policies, maintaining alignment with the reference framework defined in this document and supporting the achievement of relevant Sustainable Development Goals (SDGs).

### 3. Conclusions and next steps

The thematic vision developed by the IWG Hydropower confirms that hydropower and pumped-storage hydropower are not peripheral technologies, but core enabling infrastructures for the European energy transition.

The milestones for 2030, 2040 and 2050 established in this document position hydropower as a strategic flexibility, storage, and water-resilience asset that supports European industrial competitiveness, security of supply and climate neutrality simultaneously. By 2030, priorities focus on accelerating digitalisation, AI-enabled operations, climate-resilient reservoir management, early deployment of hybrid and pumped-storage conversion solutions, improved environmental performance, and the development of methodologies to value flexibility across multiple time scales, supported by large-scale refurbishment and demonstration projects. By 2040, these capabilities are expected to be mainstreamed through broader deployment of digital twins, enhanced planning, mature storage and hybrid solutions, and regulatory and market conditions that place emphasis on flexibility and storage services. By 2050, hydropower is envisioned as a fully digitalized, circular, and nature-compatible infrastructure system, embedded in EU energy, water and climate policy frameworks and supporting the global competitiveness of the European hydropower industry.

The implementation pathway outlined in this vision requires a coordinated European research, development, and innovation framework capable of linking technology deployment, environmental performance, digitalisation, market design and basin-scale water management. The future SRIA must therefore move beyond technology-specific objectives and establish concrete implementation pathways connected to the milestones defined under the SET Plan.

To ensure continuity between the thematic vision and implementation activities, the IWG Hydropower proposes that the drafting of the SRIA be coordinated jointly by the following stakeholder organisations and initiatives:

- SET Plan IWG Ocean Energy and Hydropower, compiled of the Ocean and Hydropower subgroups, will ensure alignment with SET Plan implementation priorities and coordination with Member States
- ETIP Hydropower will act as the principal coordination platform for industrial, technical and priorities on a system level
- SET Plan task forces on circularity and materials substitution, R&S for societal needs, digitalization, and access to market, will help with suggestions regarding the stated milestones and how they can be achieved within the specified timeframes
- EERA Joint Programme Hydropower, will lead the research, scientific and skills contributions
- Hydropower Europe Forum, will ensure continuity with the strategic recommendations and stakeholder consultations developed between 2018 and 2022

Achieving the defined milestones will further require structured cooperation with several other SET Plan working groups. In particular, the Hydropower subgroup identifies the following priority collaborations:

- IWG on Batteries – Since both technologies provide complementary flexibility and storage services for a renewable-dominant energy system, collaboration with the Batteries IWG is

relevant for understanding hybrid storage concepts, ancillary services, and digital optimisation.

- IWG on Sustainable and Efficient Energy Use in Industry – Cooperation with the working group on sustainable and efficient energy use in industry is important due to the role of hydropower in supporting industrial competitiveness through reliable and dispatchable green electricity supply. Synergies include industrial electrification, flexibility services, circularity and decarbonising industrial processes.
- IWG on Energy Systems – The IWG on Ocean Energy and Hydropower has strong synergies with the Energy Systems group, particularly regarding resilient energy infrastructure, integrated regional energy systems, smart flexibility services, and sector integration.

In conclusion, the successful implementation of the hydropower thematic vision depends not only on technological innovation, but also on the ability of the IWG Hydropower to operate as a coordination platform between energy, water, digital, industrial and environmental policy domains. The SRIA should therefore be developed as a multi-sectoral implementation instrument capable of translating the SET Plan objectives into coordinated European demonstration, deployment and investment steps over the next couple of decades.

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## Annexes

### Annex 1 – Hydropower in Europe area

Hydropower has a long tradition in Europe, contributing significantly during the first half of the last century to the welfare and industrial development of most countries across the European area. Today hydropower has become a key enabler of Europe's clean energy transition, offering its unique ability to deliver dispatchable zero-carbon power, long-term storage, grid resilience, water-security co-benefits, and industrial competitiveness. Its dispatchable nature is crucial for integrating variable renewables and stabilizing the grid, while modern technologies enable nature-positive operation. Today, almost 650 TWh are generated in an average hydrological year, which equates to about 65% of the economically feasible hydropower potential within the European Area including Türkiye<sup>25</sup> (Figure 1).

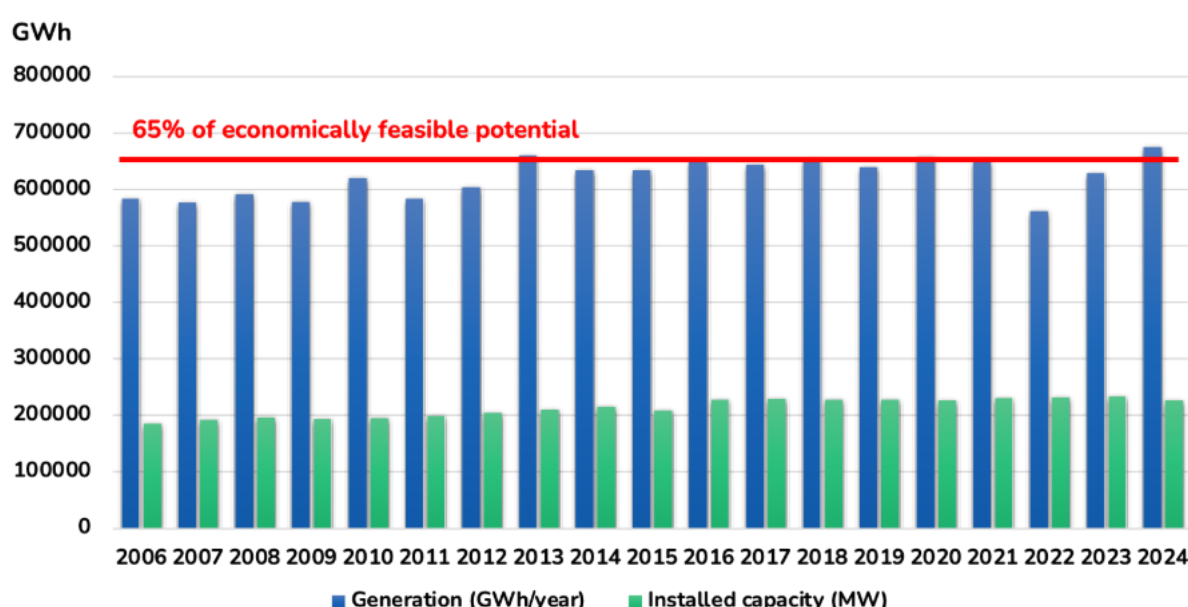


Figure 1: Evolution of yearly production and installed capacity of hydropower in Europe Aea since 2005<sup>25</sup>.

Since a few years, the yearly production of hydropower stabilizes near 650 TWh and the total installed capacity near 230 GW. It should be noted, however, that the yearly hydropower production is also influenced by the hydrological situation each year as for example can be seen by the very dry year 2022.

In the European Union (EU), the hydropower installed capacity in 2023 was 152 GW and generated capacity was approx. 300 TWh (pumped storage powerplants adsorbed 43 GWh and generated 42 TWh in 2022), which is the second highest share in electricity production from renewable energy

<sup>25</sup> World Atlas of Hydropower & Dams 2025. Hydropower & Dams International. (2025). <https://www.hydropower-dams.com/product/2025-world-atlas/>

sources, after wind energy. In the EU hydropower contributes with 16% to the total electricity production whereas in the European region with more than 20%<sup>26</sup>.

The current situation for hydropower usage and untapped potential in countries within the European Area is shown in Figure 2. It can be noted that many countries still have considerable potential for development regarding hydropower generation. The countries highlighted with a “sun star” in Figure 2 have developed less than 50% of the economically feasible potential, should the market conditions demand for it. For 10 countries the share of hydro in the overall electricity generation in 2024 is between 20% and 50%, and for 8 countries more than 50%. This demonstrates that in almost half of the countries in the European region, hydropower represents a significant share of electricity generation, which is important for the success of a safe energy transition to renewable sources.

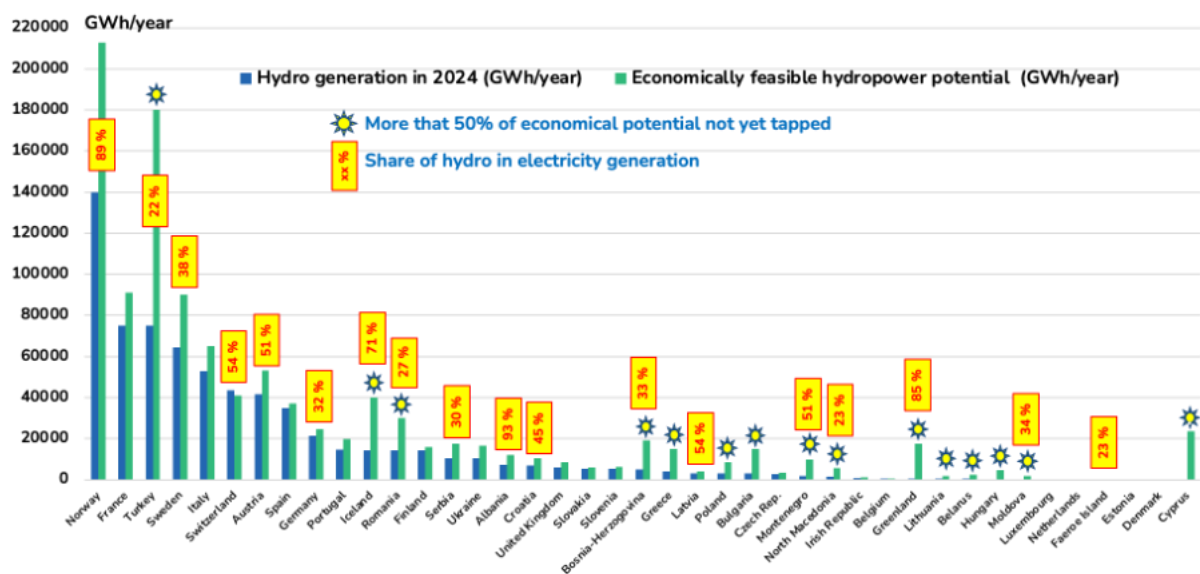


Figure 2: Generation and extension potential of hydropower in countries in the European Area<sup>25</sup>.

Countries having developed less than 50% of their economical feasible potential (assuming market conditions have demand for it) are highlighted. The share of hydro in the electricity generation is indicated for the countries with a share more than 20%.

Due to massive development of solar-PV (infra-day flexibility) and wind power (weekly flexibility) hydropower contributes to more than 30% of the flexibility services, ensuring that during “Dunkelflaute” events, as experienced in November 2024, the grid can be stabilized avoiding catastrophic blackouts. The trend of required flexibility services is strongly increasing in EU as shown in Table 1. Thus, storage and pumped storage hydropower will be most vital in Europe to safely overcome severe and critical winters with “Dunkelflaute” also in case of potential gas supply problems. Today, European Hydropower reservoirs hold hundreds of TWh of stored energy and

<sup>26</sup> Eurostat. (2025, December 16). *Renewable energy statistics*. Eurostat. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable\\_energy\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics)

pumped storage totalizes ~46 GW of flexible power capacity<sup>27</sup>. Multiple prospective analyses indicate the need to at least double to quadruple this storage capacity by 2050, aligned with the 2025 PSH Paris Pledge<sup>20</sup>.

| Electric Power Capacity in EU (GW) | 2000 (GW) | 2012 (GW) | 2022 (GW) | 2025 (GW) |
|------------------------------------|-----------|-----------|-----------|-----------|
| HYDRO                              | 135       | 145       | 153       | 150       |
| SOLAR PV                           | ≈ 0       | 71        | 206       | 345       |
| WIND                               | 12        | 97        | 204       | 230       |
| GAS + COAL + OIL                   | 340       | 425       | 380       | 315       |
| NUCLEAR                            | 125       | 113       | 100       | 96        |
| Other ...                          | ...       | ...       | ...       | ...       |
| TOTAL                              | 605       | 845       | 1 055     | 1 150     |

Table 1: Evolution of EU electricity generation mix from 2000 to 2025 (Eurostat data).

Regarding **construction activity in hydropower**, relatively little investment has been undertaken over the last 15 years, as can be seen in Figure 3 which shows the installed capacity under construction. In 2012, a quite significant increase in the construction of new power plants reaching almost 10'000 MW can be seen. This may be attributed to the Fukushima catastrophe leading many countries to redefine their energy strategy towards renewable sources such as hydropower alongside the planned phasing out of nuclear energy. Since 2015, however, construction activity has been decreasing to some 1600 MW in 2022 but increasing again above 2000 MW since 2023.

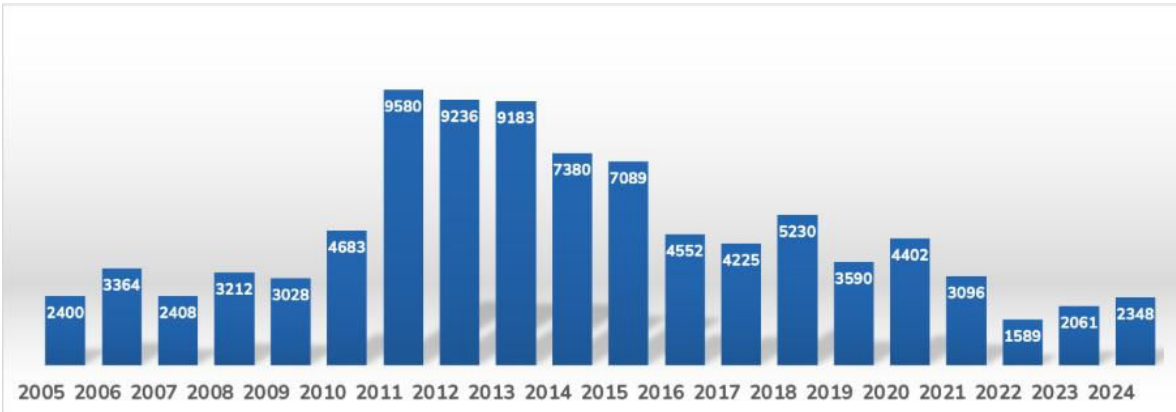


Figure 3: Installed capacity in MW under construction since 2005 (according to Hydropower & Dams World Atlas 2025 without Türkiye)<sup>25</sup>.

This low and decreasing investment level between 2016 and 2022 can be attributed to the fact that electricity prices on the European spot market since a decade were very low due to the following reasons:

<sup>27</sup> Quaranta, E., Boes, R. M., Hunt, J. D., Szabò, S., Tattini, J., & Pistocchi, A. (2024). Considerations on the existing capacity and future potential for energy storage in the European Union's hydropower reservoirs and pumped-storage hydropower. *Journal of Energy Storage*, 104. <https://doi.org/10.1016/j.est.2024.114431>

- Production capacity in Europe was too high (especially via conventional thermal generators using coal).
- The cost of CO<sub>2</sub> certificates was very low.
- The market was distorted due to the high subsidies provided for renewable energy sources such as solar and wind.

Thus, under such market conditions hydropower generation was strongly penalized. However, the energy crisis since 2022 reveals the important and vital role of hydropower – storage and pumped-storage – to help ensure a safe supply of electricity in the coming winters in Europe. Due to the energy crisis, the attractiveness of the extension and upgrading of existing and ageing hydropower plants, with the purpose of making them more flexible through the refurbishment of equipment and increasing storage where possible, together with the construction of new pumped-storage power plants, has increased again strongly in countries with high storage potential. This is underlined by an increase of the construction activity above 2300 MW in 2024 (Figure 3). Furthermore, a kind of renaissance of hydropower can be seen in many countries. In 2025 between 11,000 MW to 16,000 MW of new installed capacity were under planning (without Türkiye) revealing that a significant amount of untapped hydropower potential still exists in Europe.

Additionally, regulatory uncertainty related to the renewal of hydropower concessions is hindering investment and delaying the development of hydropower projects in some European countries.

