



## D13.2 – Policy and Regulation Analysis

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## EXECUTIVE SUMMARY

As the second largest renewable electricity source in the European Union, hydropower is a key energy source in the energy transition. According to Eurostat, it accounted in 2022 for 29.9% of the EU's renewable electricity production and provided 12.3% of the EU's electricity.

Hydropower is also one of the oldest sources of electricity generation, with the first hydroelectric plants of Europe being built at the end of the XIX century. The average age of hydropower plants in Europe today is around 50 years and most of the existing plants are in need for modernisation measures. This offers an excellent opportunity for the introduction of innovative digital solutions and the installation of modern digital technologies into aging hydroelectric plants. Nevertheless, this digitalisation process comes not without challenges as significant investments will be required and as hydropower projects operate within a complex regulatory landscape.

This report analyses the legislative provisions and the policies affecting the hydropower sector of selected countries with the goal to estimate the existing potential and opportunities and to detect challenges and barriers for the exploitation of the digitalisation solutions developed by the iAMP-Hydro project.

The report covers 7 EU Member States (Cyprus, Germany, Greece, Ireland, Norway, Romania, Spain), 3 non-EU countries (Ethiopia, Kyrgyzstan and Columbia), as well as the European Union as a region, by providing figures and statistics on hydropower in each selected country, the role of hydropower in the national energy transitions, and a review of EU and national legislative provisions and policies impacting the hydropower sector. EU-level recommendations are also provided in order to encourage the overcoming of challenges related to the modernisation of the European hydropower fleet and to ensure that the sector fully reap the benefits deriving from the digitalisation process.

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## List of Acronyms

Acronym	Explanation
<b>EU</b>	European Union
<b>GW</b>	Gigawatt
<b>GWh</b>	Gigawatt-hour
<b>HPP</b>	Hydropower plant
<b>iAMP</b>	Intelligent Asset Management Platform
<b>MW</b>	Megawatt
<b>NECP</b>	National Energy and Climate Plan (NECP)
<b>O&amp;M</b>	Operations and maintenance
<b>PSH</b>	Pumped storage hydropower
<b>RES</b>	Renewable energy sources

<b>SHPP</b>	Small hydropower plant
<b>TWh</b>	Terawatt-hour

# 1 Introduction

## 1.1 About iAMP-Hydro

iAMP-Hydro will improve the digital operation of existing hydropower plants through the development of six expected results (R) which will collectively form a novel intelligent Asset Management Platform – in short: the iAMP (being result R5) – encompassing secure open and transparent data sharing protocols (R4) and three novel digital solutions (R1 – R3):

- R1. Condition monitoring and predictive maintenance modelling;
- R2. Ecological status monitoring and water management;
- R3. Improved weather and flow forecasting;
- R4. Secure open and transparent data sharing protocols;
- R5. The intelligent Asset Management Platform.

The full package of digital solutions will be validated at a diverse set of five real-world existing hydropower plants producing evidence for policy making to support the green and digital transition of hydropower (R6).

The existing plants include differing power capacities, electro-mechanical equipment type, water end-use, flow and head regimes, climatic conditions, and environmental sensitivities (biodiversity).

The iAMP-Hydro project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No. 101122167. Additional information and results of the project are available and continuously updated on the project website at [www.iamp-hydro.eu](http://www.iamp-hydro.eu)

## 1.2 About D13.2 – Policy and Regulation Analysis and aim of this work

The present deliverable, titled “D13.2 – Policy and Regulation Analysis” presents the outcome of *Task 13.4 – Policy and Regulation Analysis* of the iAMP-Hydro project.

This work analyses the regulatory and framework conditions affecting the hydropower sector of selected countries with the goal to estimate the existing potential and opportunities and to detect challenges and barriers for the exploitation of the digitalisation solutions developed by the iAMP-Hydro project.

The report covers all the countries where iAMP-Hydro project partners are based (Cyprus, Germany, Greece, Ireland, Norway, Romania, Spain), plus one selected country from Central Asia (Kyrgyzstan), one selected country from South America (Colombia) and one selected country from Africa (Ethiopia). Additionally, the European Union as a region is covered by the report through a dedicated chapter.

The selection of countries is based on common agreement among the consortium partners and is based on additional considerations, such as the amount of electricity generated through hydropower in the country, the availability of public information on energy data in the country and the recent introduction of schemes and incentives favourable to further development of hydropower (i.e. feed-in-tariffs).

### Structure of the report

Following this short introduction on the iAMP-Hydro project and on the aim of this work, the report provides preliminary information about hydropower, how it works and its benefits for the energy system. It then follows with an analysis of hydropower in the European Union, including its share in the electricity mix, its role in the energy transition and a review of EU legislative provisions and policies impacting the hydropower sector.

The following chapters cover individual countries. For each of them the report offers an overview of the country’s energy and electricity sector, including a review of legislations and policies on energy and digitalisation, data on hydropower in the country, challenges and potential for the digitalisation of the hydropower sector in the country, and best practice examples whenever available.

Finally, some concluding remarks and recommendations at EU-level are presented at the end of the report.

## 2 About hydropower

Hydropower, also known as hydroelectric energy or hydroelectric power, is a renewable energy technology that harnesses the power of water in motion (i.e. rivers, streams or waterfalls) to generate electricity. It works by capturing the kinetic energy of flowing water and converting it into mechanical energy, which then powers a generator to produce electricity.

Water power is one of the earliest forms of renewable energy, dating back to more than 2,000 ago when the ancient Greeks used it to run wheels for grinding grain. Today it is among the most cost-effective means of generating electricity.

### 2.1 How does hydropower work?

The fundamental principle of hydropower revolves around harnessing the gravitational potential energy inherent in water's height, converting it successively into motion, which is kinetic energy, then into mechanical energy, and ultimately into electrical energy. This retrieved energy is the final product, used to power our devices and technologies<sup>1</sup>. The process works according to the following steps:

- Water at a higher elevation holds significant gravitational potential energy due to its position above the Earth's surface. As the water flows downhill, this potential energy is transformed into kinetic energy as the water accelerates.
- To capture and control this energy, dams or diversion structures are constructed to regulate the water flow. By managing the flow, the stored potential energy can be released in a controlled manner.
- This controlled release of water is directed through a penstock, a specially designed channel that funnels the water towards a turbine. The kinetic energy of the flowing water is then converted into rotational motion, causing the turbine blades to spin. This motion is transferred to a generator, where the process of electromagnetic induction transforms the mechanical energy into electrical energy.

The generated electricity is then transmitted to end consumers through power lines. Remarkably, this entire process operates with an efficiency of 85-90%, meaning that only a minimal amount of energy is lost during this process<sup>2</sup>.

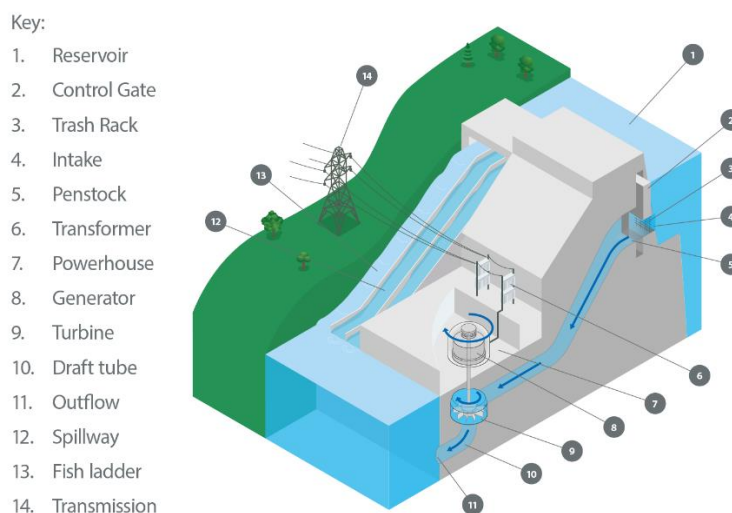


Figure 1 Hydropower plants with main components. Source: International Hydropower Association: <https://www.hydropower.org/iha/discover-types-of-hydropower>

<sup>1</sup> Eurelectric, "What is hydropower?", 2024 (<https://www.eurelectric.org/in-detail/hydropower/>).

<sup>2</sup> *Ibidem*.

## 2.2 Types of hydropower plants

Hydropower plants can be categorised into several types based on their design and operation:

- **Impoundment:** this is the most common type, where a dam stores river water in a reservoir. Water released from the reservoir flows through turbines, generating electricity.
- **Diversion (Run-of-River):** these plants channel a portion of river water through a canal or penstock without the need for a large reservoir. They rely on the natural flow and elevation drop of the river to generate power.
- **Pumped storage:** this type acts like a giant battery. It pumps water from a lower reservoir to an upper reservoir during low electricity demand periods. When demand is high, the stored water is released back to the lower reservoir, generating electricity as it flows through turbines.
- **Offshore hydropower:** a less established but growing group of technologies that use tidal currents or wave power to generate electricity from seawater.

Additionally, hydropower facilities range in size from large power plants (generally with a capacity of more than 30MW), which supply many consumers with electricity, to small (generally with a capacity between 100 kilowatts and 10 MW), and even 'micro' plants, which can produce enough electricity for a single home and are often operated by individuals for their own energy needs or to sell power to utilities<sup>3</sup>.

## 2.3 Benefits of hydropower:

Hydropower offers numerous benefits as a renewable energy source, contributing to energy production, environmental goals, and economic development. The list below provides an overview of the main benefits of hydropower<sup>4</sup>:

- **Renewable and clean:** hydropower relies on the water cycle, making it a renewable and clean source of energy, virtually limitless as long as precipitation and river flow continue. Additionally, it does not release pollutants in the air and the hydroelectric lifecycle produces very small amounts of greenhouse gas. Additionally, when measured in terms of the energy payback ratio (which compares energy generated to the energy expended in the construction, operation, maintenance, and decommissioning of the power plant) hydropower outperforms all other renewable electricity generation technologies<sup>5</sup>.
- **Reliable and flexible:** reservoir-based hydropower plants can store water, allowing them to quickly adjust output to match energy demand, making them highly flexible for balancing the grid, especially when integrated with intermittent renewables like wind and solar.
- **Cost-effective:** once a hydropower plant is built, it has low operating and maintenance costs. The long lifespan of these plants, often 50-100 years, ensures a stable and affordable energy supply. The cost-effectiveness of hydropower has been validated by both the World Bank and the International Renewable Energy Agency, recognising it as one of the most competitive generation technologies in terms of levelised costs of electricity<sup>6</sup>.
- **Supports other renewables:** hydropower can complement other renewable energy sources like wind and solar by providing storage and balancing services. Pumped storage hydropower, for example, stores energy for use when demand is high.

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<sup>3</sup> US Department of Energy, „Types of Hydropower Plants“ (<https://www.energy.gov/eere/water/types-hydropower-plants#sizes>).

<sup>4</sup> US Department of Energy, “Benefits of Hydropower” (<https://www.energy.gov/eere/water/benefits-hydropower>) and US Geological Survey, “Hydroelectric Power: Advantages of Production and Usage (<https://www.usgs.gov/special-topics/water-science-school/science/hydroelectric-power-advantages-production-and-usage>).

<sup>5</sup> Eurelectric, “What is hydropower?”, 2024 (<https://www.eurelectric.org/in-detail/hydropower/>).

<sup>6</sup> *Ibidem*.

- **Energy independence:** by utilising domestic water resources, hydropower helps reduce a country's dependence on imported energy, enhancing energy security. It provides a reliable and local source of energy, particularly in regions with abundant water resources.
- **Environmental and social benefits:** the infrastructure of hydropower plants, including dams and reservoirs, can also support irrigation, water supply, flood control, and recreational opportunities (i.e. fishing, boating, and swimming). Namely, in terms of adaptation to climate change, hydropower plants help manage flood events and strategically release water during droughts to safeguard ecosystems and agriculture, while also supporting navigation in large rivers. Additionally, they are essential for maintaining a dependable water supply for various uses, including drinking water, irrigation, industrial processes, and firefighting.
- **Economic benefits:** hydropower projects create jobs and boost local economies (i.e. through taxes and concession fees), particularly in rural areas. The industry supports a wide range of employment opportunities, from construction to environmental science.
- **Proven and mature technology:** hydropower is a well-established and widely used technology with a long history of successful implementation, making it a low-risk option for reliable power generation.

These benefits make hydropower a critical component of many countries' renewable energy strategies and a key player in the global transition to cleaner, more sustainable energy systems.

## 2.4 Common criticisms towards hydropower

Hydropower, despite its benefits as a renewable energy source, often faces several criticisms. One of the primary concerns is the environmental impact, particularly the disruption of local ecosystems. The construction of dams can significantly alter natural waterways, affecting fish migration patterns and aquatic habitats. This could lead to a decline in fish populations and biodiversity, but today the construction and operation of hydropower plants in Europe must comply with strict environmental standards and legislative provisions (i.e. the EU Water Framework Directive and other key legislations – see chapter 3.1 for a comprehensive overview). Additionally, to address these issues, implementing fish ladders and bypass systems can help maintain fish populations and support biodiversity, while regular environmental monitoring and adaptive management practices can ensure that the ecological impacts are minimised over time.

Another major criticism is that hydropower's reliance on water flow makes it vulnerable to climate change, particularly in regions prone to droughts. Changes in precipitation patterns and water availability can affect the reliability and efficiency of hydropower plants. Nevertheless, developing adaptive management strategies that consider future climate scenarios can enhance the resilience of hydropower systems and integrating other renewable energy sources, such as solar and wind, can also provide a more balanced and reliable energy mix. Additionally, hydropower plants also help manage flood events and strategically release water during droughts.

Furthermore, the initial cost and long construction periods of hydropower projects are often criticised. On the one hand, these projects require significant investment and can take many years to complete. On the other hand, hydropower plants have very low operating and maintenance costs (hydropower is considered one of the most competitive generation technologies in terms of levelised costs of electricity<sup>7</sup>), and a very long lifespan (often 50-100 years). Streamlining regulatory processes and improving project management can also help reduce construction times and costs.

Overall, while hydropower has its challenges, addressing these criticisms through thoughtful planning, and adaptive management can help maximise its benefits as a sustainable energy source.

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<sup>7</sup> *Ibidem.*

### 3 Hydropower in the European Union

Hydropower is the main source of renewable electricity generation in Europe, accounting for 41.6% of all electricity generated by RES in 2022 (corresponding to 594.824 GWh and to 14.8% of total electricity generation in the region)<sup>8</sup>. However, the yearly hydropower production is influenced by the hydrological situation each year, and in 2022 the worst drought in 500 years led to a 19% decline in regional output<sup>9</sup>. Today, almost 650 TWh are generated in Europe in an average hydrological year, which equates to about 65% of the economically feasible hydropower potential within Europe (including Turkey)<sup>10</sup>. The capacity of pure generation hydropower plants in the EU27 is 106 GW, complemented by a capacity of 46 GW from pumped storage plants<sup>11</sup>.

Hydropower plants in Europe serve as the renewable energy source for baseload electricity, load following and grid support.

There are currently more than 21.300 existing hydropower plants in Europe, with more than 8.700 additional plants planned or under construction. Over 90% of all the existing and planned hydropower plants in Europe are small plants, meaning that each plant generates at most 10 MW of electricity<sup>12</sup>.

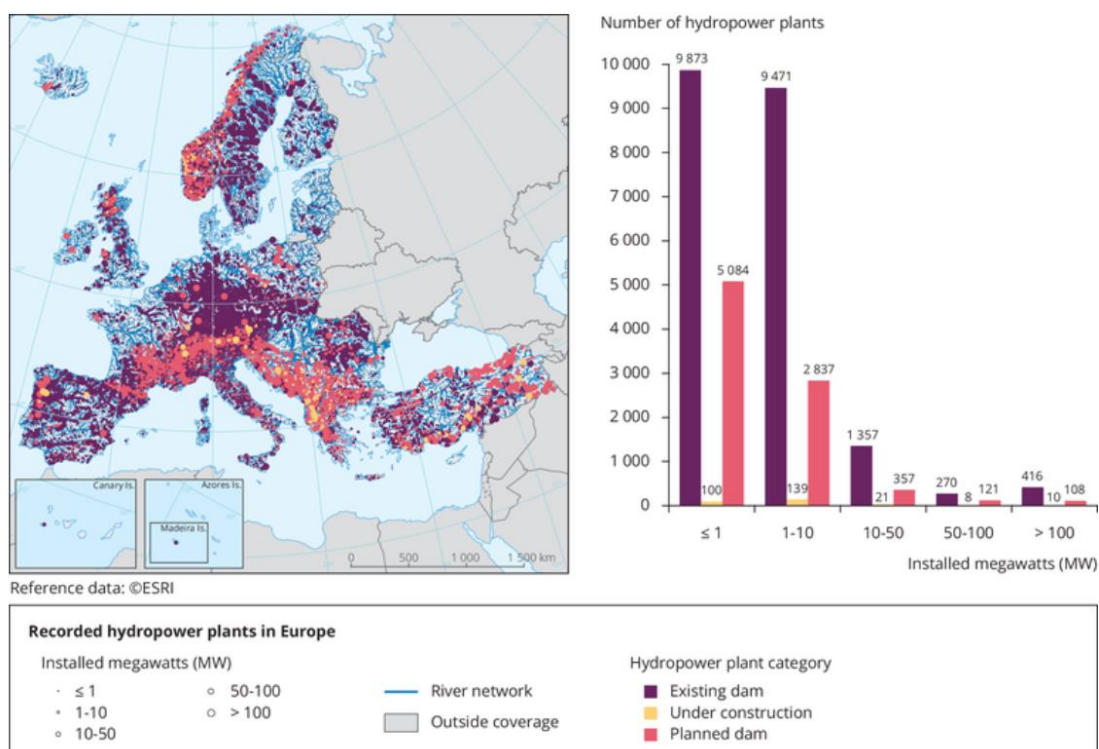


Figure 2 Recorded hydropower plants in Europe (existing, under construction and planned hydropower plants by size categories). Source: EEA, 2021 (<https://www.eea.europa.eu/en/analysis/maps-and-charts/recorded-hydropower-plants-in-europe#references-and-footnotes>).

Installed hydropower capacity varies significantly throughout the continent, depending on the geographical region, water resources and national energy policies.

<sup>8</sup> International Energy Agency, "Europe" (<https://www.iea.org/regions/europe/electricity>).

<sup>9</sup> REN21, 2023, "Renewables 2023 Global Status Report" ([https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023\\_Energy-Supply-Module.pdf](https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023_Energy-Supply-Module.pdf)).

<sup>10</sup> ETIP Hydropower, "About Hydropower in Europe" (<https://etip-hydropower.eu/about-hydropower-in-europe/#inEurope>).

<sup>11</sup> VGBE, "Hydropower in Europe: Facts and Figures", 2023 (<https://www.vgbe.energy/wp-content/uploads/2023/04/Hydropower-in-Europe-Facts-and-Figures-2023-Final.pdf>).

<sup>12</sup> WWF, "Hydropower" ([https://www.wwf.eu/what\\_we\\_do/water/hydropower/](https://www.wwf.eu/what_we_do/water/hydropower/)).

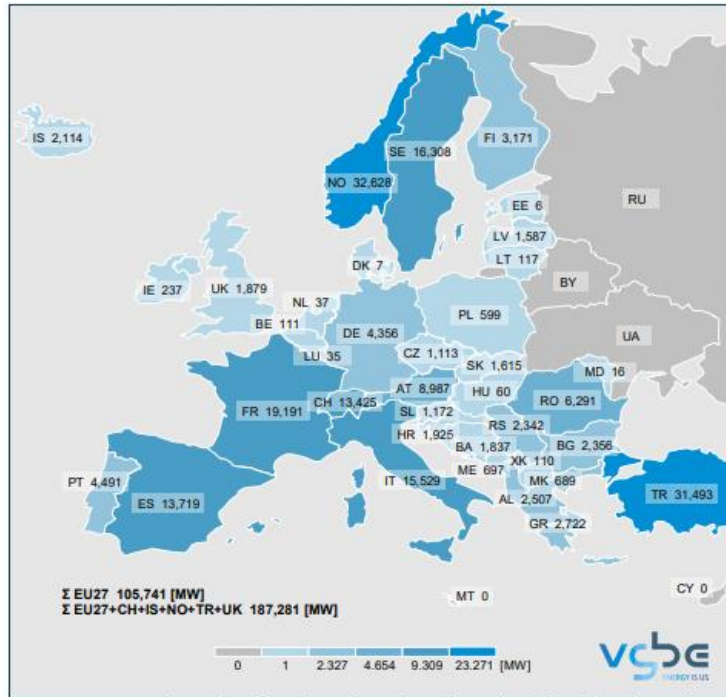


Figure 3 Installed capacity of hydropower plants (excluding pumped storage hydropower plants) in Europe in 2021 (source: VGBE, “Hydropower in Europe: Facts and Figures”, 2023 (<https://www.vgbe.energy/wp-content/uploads/2023/04/Hydropower-in-Europe-Facts-and-Figures-2023-Final.pdf>)).

According to the 2022 edition of the Hydropower & Dams World Atlas, 65% of the economically feasible hydropower potential within Europe including Turkey has already been exploited (see figure below), and in many countries a significant amount of untapped hydropower potential still exists. However, in view of environmental and socio-economical constraints, the partial use of this remaining potential is extremely challenging and can be reached only through innovative and sustainable solutions for new hydropower plants.

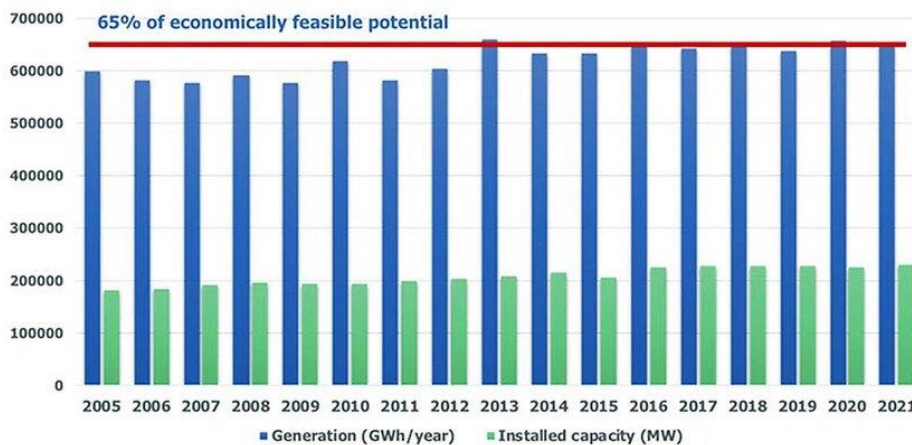


Figure 4 Evolution of yearly production and installed capacity of hydropower in Europe (including Turkey) since 2005. Source: Hydropower & Dams World Atlas 2022.

Therefore, the untapped potential in the EU mainly refers to new PSH, modernisation of the existing hydro stations, digitalisation of the operation and small hydropower development in existing infrastructures (“hidden hydropower”)<sup>13</sup>. Hydropower installed capacity in the EU is assumed to

<sup>13</sup> European Commission’s Joint Research Centre, “Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, 2024 (<https://data.europa.eu/doi/10.2760/8354439, JRC139225>)).

remain almost stable in the future, but still growing by 3 GW of new pumped storage hydro in 2050 (see figure below). Generation is expected to increase by 2030, but projected to slightly decrease after 2025, due to the growing competition with other electricity storage technologies and more flexible load from consumers willing to provide demand-response<sup>14</sup>.

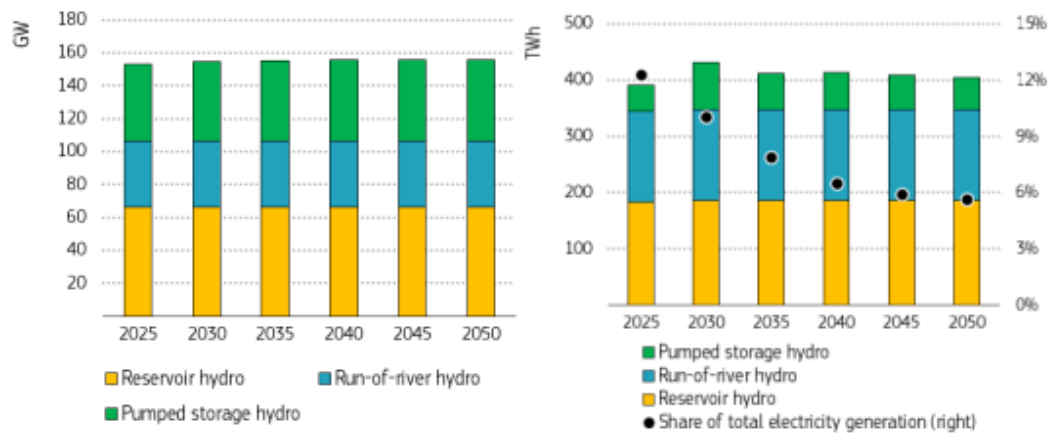


Figure 5 Hydropower installed capacity and electricity generation in the EU, 2025-2050. Source: European Commission's Joint Research Centre, "Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, 2024 (<https://data.europa.eu/doi/10.2760/8354439,JRC139225>).

In the EU, further development of hydropower potential will in fact primarily focus on optimising and retrofitting existing infrastructure. Modernising the aging European hydropower fleet (with an average age of nearly 45 years) presents an opportunity to enhance efficiency, production, flexibility, sustainability, and resilience to climate change. Hydropower is in fact significantly affected by climate change, as it relies on water availability and may suffer during prolonged dry periods. However, optimal reservoir management and improved inflow and weather forecasting can help mitigate droughts and serve as a flood control system.

By implementing advanced technologies, digitalisation tools, modern electro-mechanical equipment, and optimizing waterways, annual electricity generation from the existing fleet could increase by approximately 10% (corresponding to ca. 40 TWh/year)<sup>15</sup>.

In order to thrive, sustainable hydropower must strike a balance between electricity generation, social benefits, and impacts on ecosystems and biodiversity. The key challenges for further hydropower development in Europe include:

- **Regulatory hurdles:** stringent environmental, climate, and wildlife standards create administrative challenges.
- **Site limitations:** most suitable locations have already been utilised or are in environmentally protected areas.
- **High costs and risks:** new large greenfield projects face high investment costs and long construction times, leading to financial risks and complex financing processes.
- **Economic viability:** long-term remuneration is challenged by expected reductions in electricity prices due to the increased penetration of renewable energy. Policy interventions and robust implementation of Electricity Market Design (EMD) reforms are needed to address these barriers and fully exploit hydropower potential, which is crucial for achieving the EU's carbon neutrality goals<sup>16</sup>.

<sup>14</sup> *Ibidem*.

<sup>15</sup> *Ibidem*.

<sup>16</sup> *Ibidem*.

### 3.1 Policy context for hydropower in the EU

Due to its crosscutting relevance, the hydropower sector is affected by several EU Directives, related to the environment, energy and climate:

- **Environment**

Environmental sustainability is a critical consideration, and the Water Framework Directive (WFD) has a major impact on hydropower operations. It requires that hydropower plants meet strict ecological standards to protect water resources and biodiversity. Hydropower projects must also comply with the Environmental Impact Assessment (EIA) Directive, which mandates thorough assessments of any potential environmental effects before new plants can be built or existing ones expanded.

Other legislation, like the Habitats and Birds Directives, also shapes hydropower by protecting wildlife and ecosystems. These directives ensure that hydropower development respects biodiversity, particularly in sensitive areas such as Natura 2000 sites. Projects affecting Natura 2000 sites or water bodies must undergo detailed assessments and may be authorised if compensatory measures are implemented.

Compliance with the Do No Significant Harm (DNSH) criteria is necessary for EU co-financing under the Recovery and Resilience Facility (RRF).

The EU Biodiversity Strategy and Nature Restoration Law aim to restore freshwater ecosystems, including rivers, floodplains, and wetlands<sup>17</sup>.

- **Renewable Energy**

The Renewable Energy Directive (RED) promotes the transition to renewable energy, targeting 42.5% of gross final energy consumption from renewables by 2030. Hydropower is included, with a view to ensuring that a potential adverse impact on the water bodies concerned is justified and that all relevant mitigation measures are implemented.

Additionally, the European Commission recognises hydropower as a clean technology under the Net Zero Industry Act (NZIA)<sup>18</sup>.

- **Storage and Flexibility**

The Electricity Market Design supports the integration of renewable energy into the EU's electricity markets. Hydropower is the most flexible renewable energy technology, and it is highly dispatchable. Its flexibility in energy production helps stabilise the grid, especially as more intermittent renewables like wind and solar come online.

Additionally, hydropower is crucial for energy storage, providing over 95% of energy storage in the EU.

Recent reforms in the electricity market design aim to incentivise longer-term energy contracts and to encourage the use of long-term instruments like power purchase agreements and capacity remuneration mechanisms, although two-way contracts will not be available for reservoir hydropower and PSH, so that they remain fully exposed to market signals<sup>19</sup> (while long-term pricing is essential for financing large infrastructure projects).

- **Energy Efficiency**

Energy efficiency is also a key concern, addressed by the Energy Efficiency Directive. Hydropower plants are encouraged to adopt modern technologies that reduce energy losses and improve output. The EU also provides financial support for hydropower projects through the State Aid Guidelines for Energy and Environment, which help fund the modernisation and expansion of hydropower infrastructure.

- **Floods**

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<sup>17</sup> European Commission's Joint Research Centre, "Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, 2024 (<https://data.europa.eu/doi/10.2760/8354439, JRC139225>).

<sup>18</sup> *Ibidem*.

<sup>19</sup> *Ibidem*.

The Floods Directive aims to reduce and manage flood risks to human health, the environment, cultural heritage, and economic activity. It requires EU countries to assess flood-prone areas, map flood risks, and implement coordinated measures. Hydropower can help mitigate floods and droughts through water storage in reservoirs<sup>20</sup>.

- **Innovation and Digitalisation**

With increasing digitalisation in hydropower, the Cybersecurity and Network Information Security (NIS2) Directive ensures that hydropower plants adopt robust cybersecurity measures to protect against potential threats.

Lastly, the EU's Horizon Europe research programme supports innovation in renewable energy technologies, including hydropower. It funds projects focused on improving hydropower efficiency, reducing environmental impacts, and integrating digital solutions into energy systems.

Balancing the friction among climate, energy and environmental law while improving the ecological sustainability of hydropower production remains a challenge to be addressed by the sector.

### 3.2 Why is hydropower important for the EU?

As the first largest source of renewable energy in the EU, hydropower plays a crucial role in ensuring the security and stability of the electricity grid. Through its reservoir systems and run-of-river plants, hydropower offers flexible renewable energy solutions that cater to both short-term and long-term electricity needs.

Despite advancements in other climate-friendly energy storage technologies, pumped storage hydropower still accounts for over 90% of the EU's available storage capacity. This well-established technology is capable of meeting storage demands across various timescales, from minutes to entire seasons. The Renewable Energy Directive's binding target of 42.5% renewable energy requires the addition of more than 1,000 GW of new wind and solar photovoltaic (PV) capacity in the EU—equivalent to the current total capacity from all sources, including fossil, nuclear, and renewable energy—within the next five years. As the power sector pushes to meet these ambitious targets, the need for flexible generation and storage capacities will become increasingly vital. Hydropower holds significant potential in supporting the integration of variable renewable energy, preventing curtailment during times of excess power generation, and ensuring a reliable supply during shortages<sup>21</sup>.

Europe has established itself as a global leader in hydropower technology. By leveraging a transparent and sustainable value chain, hydropower offers substantial autonomy and reduces dependence on critical raw materials, fossil fuels, skilled labour, or technological shortages. European project developers, operators, and equipment manufacturers are well-positioned to take advantage of the growing opportunities arising from major investments in modernising existing hydropower infrastructure and building new plants, both within Europe and internationally. As the EU and national governments work to strengthen supply chains for technologies that are vulnerable to third-country dependencies, hydropower emerges as a practical and immediate solution<sup>22</sup>.

### 3.3 Digitalisation of hydropower in the EU

Among the challenges being faced by hydropower in Europe, the ageing of the European fleet is one of the most pressing ones. Hydropower has in fact been providing renewable electricity around in the region for over a century. Inevitably, this also means that many of the power plants in the EU are quite old, given their extremely long lifetimes.

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<sup>20</sup> *Ibidem*.

<sup>21</sup> Eurelectric, "What is hydropower?", 2024 (<https://www.eurelectric.org/in-detail/hydropower/>).

<sup>22</sup> *Ibidem*.

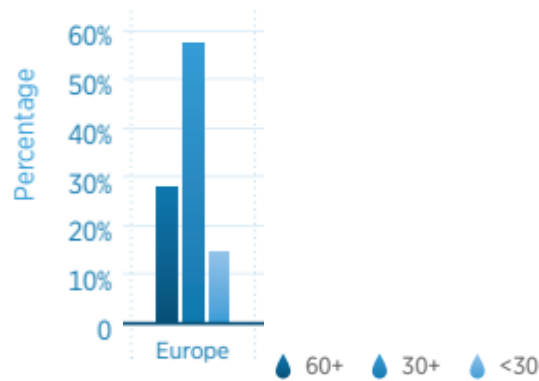


Figure 6 Breakdown of hydropower fleet. Source: IRENA, “The changing role of hydropower: Challenges and opportunities”, 2023 ([https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA\\_Changing\\_role\\_of\\_hydropower\\_2023.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf))

The European hydropower fleet is reaching a tipping point, where a large share of the installed capacity will soon require upgrades, refurbishment or possibly retirement. In all cases, maintaining capacity will require substantial investments in either capacity additions or maintenance costs. Nevertheless, not all capacity needs to come from new projects: existing facilities can be expanded, and non-powered dams can be retrofitted to generate electricity<sup>23</sup>.

The advanced age of a large share of the European hydropower fleet does not only constitute a pressing challenge though. It is also the perfect opportunity to modernise aging plants. By leveraging the latest technological advancements, including cutting-edge components, plants can enhance their efficiency, flexibility, and sustainability. Digitalisation, artificial intelligence, and big data can further improve operations and decision-making, enabling hydropower to meet the complex demands of current and future power systems with high shares of variable renewables, and continue providing reliable energy services<sup>24</sup>.

Upgrading assets with modern components designed for wider operational ranges, faster ramping, and multiple start-stop cycles, along with innovative O&M schemes, offers numerous benefits. Digitalisation can enhance data availability, facilitate better decision-making, and improve plant control capabilities. This can lead to more efficient operations, reduced O&M costs, and extended plant lifetimes. Intelligent digital control strategies and monitoring will allow operators to collect more data and better understand plant behaviour under various conditions, leading to better management and more flexible operations. Predictive maintenance strategies, enabled by digitalisation, can further reduce O&M costs and increase plant availability<sup>25</sup>.

The digitalisation of HPPs, apart from the improvement of predictive maintenance allowing for the prolongation of the lifetime, reduction of the outage time, and addressing cyber-security risks, involves increasing the overall efficiency and, thus, the produced energy, with no additional impacts on the river ecosystems. It is estimated that digitalisation can improve the efficiency of existing HPPs by 1% and increase both power and generation i.e. by improving the operation and the turbine response during start and stop cycles, thus allowing to extend the electromechanical equipment life, preventing failures, providing ancillary services and reducing maintenance<sup>26</sup>. Through digitalisation measures, it is also possible to avoid spilling of water by better distributing the flow among the different turbine units. This can lead to an increase in the annual generation by up to 11%, although this is very site-specific<sup>27</sup>. The EU supports hydropower research by funding projects that demonstrate the potential of the technology and aim to reduce its environmental impact. In particular, support to projects with focus

<sup>23</sup> IRENA, “The changing role of hydropower: Challenges and opportunities”, 2023 ([https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA\\_Changing\\_role\\_of\\_hydropower\\_2023.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf)).

<sup>24</sup> *Ibidem*.

<sup>25</sup> *Ibidem*.

<sup>26</sup> Emanuele Quaranta et al., “Assessing the energy potential of modernizing the European hydropower fleet”, 2021, *Energy Conversion and Management* (<https://doi.org/10.1016/j.enconman.2021.114655>).

<sup>27</sup> *Ibidem*.

on digitalisation and innovation will support the efficient retrofitting of existing plants and help improve the sustainability of hydropower<sup>28</sup>, as the iAMP-Hydro project aims to demonstrate.

## 4 Cyprus

### 4.1 Overview of Energy and Electricity Sector in Cyprus

Cyprus's energy sector is heavily reliant on imported fossil fuels, primarily oil, which accounts for the majority of electricity generation (83%<sup>29</sup>). In line with EU requirements, the country has been taking measures towards the diversification of its energy mix by incorporating more renewable energy sources. In 2022, 16.8% of the electricity in the country was generated by renewables, mostly solar PVs and wind (accounting respectively for 73% and 27% of electricity generation from RES).

Cyprus is particularly vulnerable to the impacts of climate change due to its geographical location and climatic conditions, with water resources constituting one of the main areas of concern<sup>30</sup>. Cyprus faces in fact significant challenges with water scarcity, which is expected to worsen with climate change. Reduced rainfall and increased evaporation rates due to higher temperatures will exacerbate water shortages<sup>31</sup>. This is critical for a country that already relies heavily on limited water resources for agriculture, drinking water, and other needs.

Notwithstanding the challenges posed by climate change and the heavy dependence on imports of primary energy from abroad (Cyprus has a rate of energy self-sufficiency of only 6%<sup>32</sup>), the transition to renewable energies has been defined as “slow” by the country’s environment commissioner Antonia Theodosiou<sup>33</sup>.

The legislative framework governing Cyprus's energy sector includes several key laws and regulations<sup>34</sup>, such as:

- The Regulation of the Electricity Market Law of 2003, which governs the operation and regulation of the electricity market, by transposing the EU Electricity Directive 2019/944.
- The Promotion of Use of Energy from Renewable Sources Law of 2022, aligning with the EU’s renewable energy directives.

In Cyprus, the energy sector’s legal and regulatory framework is overseen by key governmental authorities that ensure compliance with national and European Union energy directives, such as the Cyprus Energy Regulatory Authority (CERA), which acts as the independent regulatory authority responsible for overseeing the electricity and gas markets in Cyprus, and the Ministry of Energy, Commerce, and Industry, contributing to the development and implementation of energy policies in Cyprus<sup>35</sup>.

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<sup>28</sup> European Commission, “Hydropower” ([https://research-and-innovation.ec.europa.eu/research-area/energy/hydropower\\_en#:~:text=The%20EU%20supports%20hydropower%20research%20by%20funding%20projects%20that%20demonstrate,improve%20the%20sustainability%20of%20hydropower.](https://research-and-innovation.ec.europa.eu/research-area/energy/hydropower_en#:~:text=The%20EU%20supports%20hydropower%20research%20by%20funding%20projects%20that%20demonstrate,improve%20the%20sustainability%20of%20hydropower.)).

<sup>29</sup> [Cyprus - Countries & Regions - IEA](#)

<sup>30</sup> Cyprus ranks #42 in the ND- GAIN Country Index, which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience (<https://gain-new.crc.nd.edu/ranking>).

<sup>31</sup> The Cyprus Institute, “Climate Change and Impact” (<https://www.cyi.ac.cy/index.php/ewrc/ewrc-research-projects/climate-change-and-impact.html>).

<sup>32</sup> IRENA, 2024, Cyprus Energy Profile ([https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical\\_Profiles/Europe/Cyprus\\_Europe\\_RE\\_SP.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Cyprus_Europe_RE_SP.pdf))

<sup>33</sup> Cyprus Mail (25 September 2024), “Cyprus’ transition to renewable energy ‘slow’” (<https://cyprus-mail.com/2024/09/25/cyprus-transition-to-renewable-energy-slow>).

<sup>34</sup> Cyprus Energy Regulatory Authority, Legislation (<https://www.cera.org.cy/en-gb/nomothesia/details/energiaki-apodosi-nomos>).

<sup>35</sup> AGP Law, 2024, “The Legal Sector of Energy in Cyprus: Laws, Challenges, Opportunities, and the Way Forward” (<https://www.agplaw.com/the-legal-sector-of-energy-in-cyprus-laws-challenges-opportunities-and-the-way-forward/#:~:text=In%20Cyprus%2C%20key%20legal%20frameworks,with%20EU%20renewable%20energy%20directives.>).

At the same time, Cyprus has been actively pursuing digitalisation to modernise its energy sector. Key policies include<sup>36</sup>:

- The National Digital Strategy 2020-2025, which aims to accelerate digital transformation across various sectors, including energy. It focuses on enhancing digital infrastructure, promoting digital skills, and integrating digital technologies.
- The National Broadband Plan 2021-2025, which seeks to improve digital connectivity, which is crucial for the implementation of smart grids and other digital energy solutions.

These efforts are part of Cyprus's broader strategy to enhance energy security, reduce greenhouse gas emissions, and transition to a more sustainable energy system.

## 4.2 Hydropower in Cyprus

Because of its small size, semi-arid climate, and lack of large rivers, Cyprus has very limited hydropower resources and does not have any significant hydropower plants contributing to its electricity generation<sup>37</sup>. The limited availability of water resources in Cyprus makes large-scale hydropower development unfeasible. Nevertheless, Cyprus has a few small-scale hydropower facilities, mostly contributing to water storage and management, rather than to electricity generation.

The limited focus of the country on hydropower is reflected in Cyprus' NECP. The plan primarily emphasizes the development of solar and wind energy due to the country's favourable climatic conditions for these renewable sources and does not refer to any impactful role for hydropower.

## 4.3 Challenges and barriers to digitalisation of hydropower in Cyprus

The issue of digitalisation and modernisation of the hydropower sector in Cyprus is not relevant due to the country's very limited hydropower resources and to the absence of any significant hydropower plant contributing to electricity generation in Cyprus. The lack of hydropower in Cyprus is mainly due to its limited water resources. The country experiences a dry climate with relatively low and variable rainfall, which makes it challenging to maintain the consistent water flow needed for large-scale hydropower generation. Most of the existing dams and reservoirs in Cyprus are designed for water storage and management rather than for electricity production.

## 4.4 Potential and opportunities for the digitalisation of hydropower in Cyprus

Because of the lack of hydropower plants in the country, the potential for modernisation and digitalisation of the sector is irrelevant. Nevertheless, there still is some potential for the development of the hydropower sector in Cyprus, especially in the form of micro-hydro installations, which could be feasible in areas with existing water management systems like irrigation canals or small dams, and in the form of Pumped Hydro Storage (PHS). PHS can achieve high RES penetration levels in autonomous power systems, such as Cyprus', avoiding unnecessary RES energy curtailment. The existing water reservoirs in Cyprus provide an important potential for energy storage application, together with additional side benefits, at relatively low cost<sup>38</sup>.

While the potential for traditional hydropower is limited, exploring innovative solutions like pumped hydro storage could provide valuable support for Cyprus's renewable energy goals and enhance energy security.

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<sup>36</sup> Deputy Ministry of Research, Innovation and Digital Policy, 2023, National Digital Decade – Strategic Roadmap ([https://www.gov.cy/media/sites/13/2024/04/DD-2030-Cyprus-Report\\_final.docx.pdf](https://www.gov.cy/media/sites/13/2024/04/DD-2030-Cyprus-Report_final.docx.pdf)).

<sup>37</sup> European Commission: Directorate-General for Energy, *EU energy in figures – Statistical pocketbook 2024*, Publications Office of the European Union, 2024, <https://data.europa.eu/doi/10.2833/802460>

<sup>38</sup> Tzamalīs G. et al., 2022, „Mapping of the Cyprus energy storage potential. Implications in the penetration of renewables and the operational mode of the conventional units“ (<https://www.energy.gov.cy/assets/modules/wnp/articles/202211/13/docs/mapping.pdf>)

## 5 Germany

### 5.1 Overview of energy and electricity sector in Germany

Germany's energy sector is a key player in Europe and in the world. Its *Energiewende* (translated “energy transition”, Germany’s ambitious policy framework aimed at transforming its energy system to be more sustainable and environmentally friendly) is seen as a model for other countries aiming to achieve a sustainable energy future. In order to achieve the *Energiewende* by 2030, 80% of all electricity supply will need to come from renewable energy sources (and 100% by 2035) and coal is to be completely phased out<sup>39</sup>.

The share of electricity generation from renewables in 2022 accounted for 43.7%, placing Germany above the EU average (40.3%)<sup>40</sup>. The largest source of electricity generation in Germany in 2023 was wind (27% of total generation), immediately followed by coal (26.6% of total generation)<sup>41</sup>.

Germany is moderately vulnerable to climate change. The country faces various climate-related risks, including increased frequency of extreme weather events like heatwaves, heavy rainfall, and droughts, which can impact agriculture, water resources, infrastructure, and public health<sup>42</sup>. However, Germany has a strong adaptive capacity, with well-developed infrastructure and robust policies aimed at mitigating these risks<sup>43</sup>.

In Germany, energy policies are primarily established at the national level, mainly by the Federal Ministry for Economic Affairs and Climate Action (*Bundesministerium für Wirtschaft und Klimaschutz, BMWK*), which defines the political agenda and drafts the relevant legislation. The federal laws apply across all German states (*Bundesländer*), with the federal government setting overarching energy policy goals, regulating the energy market, and determining the framework for incentives like feed-in tariffs and market premiums. However, the German states and local governments and municipalities also play a significant role in implementing energy projects and may have their own supplementary policies and incentives.

The main pieces of the energy legislative framework include:

- The Renewable Energy Sources Act (EEG)<sup>44</sup>: the EEG is the cornerstone of Germany's renewable energy policy. It promotes the expansion of renewable energy sources by providing financial incentives and setting targets for their share in the energy mix. The latest amendment in 2023 aims to increase the share of renewables in gross electricity consumption to at least 80% by 2030.
- The Energy Efficiency Act (EnEFG)<sup>45</sup>: the EnEFG obliges public authorities, corporations, and data centres to use less energy on the grounds that climate protection and the energy transition will only succeed if energy consumption in Germany is permanently reduced.
- The Energy Industry Act (EnWG)<sup>46</sup>: the EnWG regulates the electricity and gas markets in Germany. It ensures a reliable, fairly-priced, consumer-friendly, efficient, and environmentally compatible supply of electricity and natural gas. The act also covers access and connection to

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<sup>39</sup> IEA, Germany (<https://www.iea.org/countries/germany>).

<sup>40</sup> IEA, Germany – Renewables (<https://www.iea.org/countries/germany/renewables>).

<sup>41</sup> IEA, Germany, Electricity (<https://www.iea.org/countries/germany/electricity>).

<sup>42</sup> Umwelt Bundesamt, 2021, „Climate Impact and Risk Assessment 2021 for Germany” ([https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc\\_27-2021\\_climate\\_impact\\_and\\_risk\\_assessment\\_2021\\_for\\_germany\\_english\\_summary\\_bf.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_27-2021_climate_impact_and_risk_assessment_2021_for_germany_english_summary_bf.pdf)).

<sup>43</sup> Germany ranks #8 in the ND- GAIN Country Index, which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience (<https://gain-new.crc.nd.edu/ranking>).

<sup>44</sup> EEG 2023 - Gesetz für den Ausbau erneuerbarer Energien ([https://www.gesetze-im-internet.de/eeg\\_2014/BJNR106610014.html](https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html)).

<sup>45</sup> EnEFG - Gesetz zur Steigerung der Energieeffizienz in Deutschland (<https://www.gesetze-im-internet.de/enefg/BJNR1350B0023.html>).

<sup>46</sup> EnWG - Gesetz über die Elektrizitäts- und Gasversorgung ([https://www.gesetze-im-internet.de/enwg\\_2005/](https://www.gesetze-im-internet.de/enwg_2005/)).

the electricity networks, network charges, and rules for the operation, planning, and expansion of the electricity network.

- The Act on Digitisation of the Energy Transition: the Act encourages the launch of the smart grid, smart meter and smart home in Germany, with the goal to enable the development of a digital infrastructure that can connect more than 1.5 million electricity producers and large-scale consumers. The legislation was relaunched in 2023 to accelerate the rollout of smart meters.

When it comes to hydropower, the Federal Water Act (WHG<sup>47</sup>, amended to transpose the EU Water Framework Directive) and water legislation of the Länder play an important role. Provisions §33, §34 and §35 of the WHG on minimum water flow, permeability for aquatic organisms, and fish protection can in fact pose operational challenges and extra costs and require ongoing monitoring and adjustments in order to ensure compliance.

Additionally, the Digitalisation Act (GWB10, the tenth amendment of the German Act on Restraints of Competition)<sup>48</sup>, even though it primarily focuses on enhancing competition law and addressing challenges in the digital economy and does not specifically target the energy sector, includes several provisions which can indirectly impact it, such as: easing data access and sharing, which can facilitate the integration of digital technologies and smart grids and support the transition to a more digitalised and decentralised energy system.

Similarly, the Digital Strategy of the German Government has several impacts on the energy sector, primarily through the promotion of energy- and resource-efficient innovative digital technologies (Clean & Green Tech) and infrastructure improvements. The strategy in fact supports the development and implementation of smart grids and smart meters, it promotes digitally automated control of energy demand in industry, it emphasizes the importance of data access and sharing, which allows for better forecasting, demand management, and integration of renewable energy sources, and it includes measures to enhance cybersecurity, which is critical for the protection of the digital infrastructure of the energy sector and for a reliable and resilient energy supply<sup>49</sup>.

## 5.2 Hydropower in Germany

Pursuant to the Renewable Energy Sources Act (EEG, art. 3.21) the definition of “renewable energy” covers hydropower (including wave, tidal, salinity gradient and marine current energy), wind energy, solar energy, geothermal energy as well as energy from biomass (including biogas, biomethane, landfill and sewage treatment gas and gas from biologically degradable waste)<sup>50</sup>.

In Germany, the country with the largest annual electricity demand and generation capacity in Europe, hydropower accounts for 4.9% of the total electricity generation (25.345,0 GWh). The figure fluctuates over the year because of changing water flows. Hydro is the third largest source of non-combustible renewable electricity in the country (11.1%), after wind (61.7%) and solar (27%)<sup>51</sup>.

In Germany, hydropower is used primarily in the low mountain ranges, on the Alpine foothills, and on the Alps, where slopes are high, as well as on all major rivers. Therefore, over 80 percent of hydroelectric power is generated in the Southern federal states of Bavaria and Baden-Württemberg. Around 86 percent of the total capacity of large hydroelectric plants relies on nine major rivers: Inn, Rhine, Danube, Isar, Lech, Moselle, Main, Neckar and Iller<sup>52</sup>.

<sup>47</sup> WHG 2009 - Gesetz zur Ordnung des Wasserhaushalts ([https://www.gesetze-im-internet.de/whg\\_2009/](https://www.gesetze-im-internet.de/whg_2009/)).

<sup>48</sup> GWB - Gesetz gegen Wettbewerbsbeschränkungen (<https://www.gesetze-im-internet.de/gwb/BJNR252110998.html>).

<sup>49</sup> BMDV, 2023, Digitalstrategie ([https://bmdv.bund.de/SharedDocs/DE/Anlage/K/presse/063-digitalstrategie.pdf?\\_\\_blob=publicationFile](https://bmdv.bund.de/SharedDocs/DE/Anlage/K/presse/063-digitalstrategie.pdf?__blob=publicationFile))

<sup>50</sup> EEG 2023 - Gesetz für den Ausbau erneuerbarer Energien ([https://www.gesetze-im-internet.de/eeg\\_2014/BJNR106610014.html](https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html)).

<sup>51</sup> IEA, Germany (<https://www.iea.org/countries/germany/electricity>).

<sup>52</sup> Umwelt Bundesamt, 2023, „Nutzung der Wasserkraft“ (<https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/nutzung-der-wasserkraft#Strom>).



Figure 7 Overview of hydropower in the individual federal states (source: [www.foederal-erneuerbar.de](http://www.foederal-erneuerbar.de), 2017).

There are currently around 8.300 hydroelectric plants in operation in Germany, 95% of those are classified as small hydroelectric power plants, as they have an installed capacity of one megawatt or less. However, the share of electricity production contributed by small hydropower is only around 14%<sup>53</sup>. The remaining share consists of large hydroelectric plants with an installed capacity of over one megawatt (436 plants) and of pumped storage power plants (31 plants), that can be used to store electrical energy in the form of potential energy in a reservoir.

<sup>53</sup> Bundesverband Deutscher Wasserkraftwerke, "Wasserkraft in Zahlen" (<https://www.wasserkraft-deutschland.de/wasserkraft/wasserkraft-in-zahlen.html>).

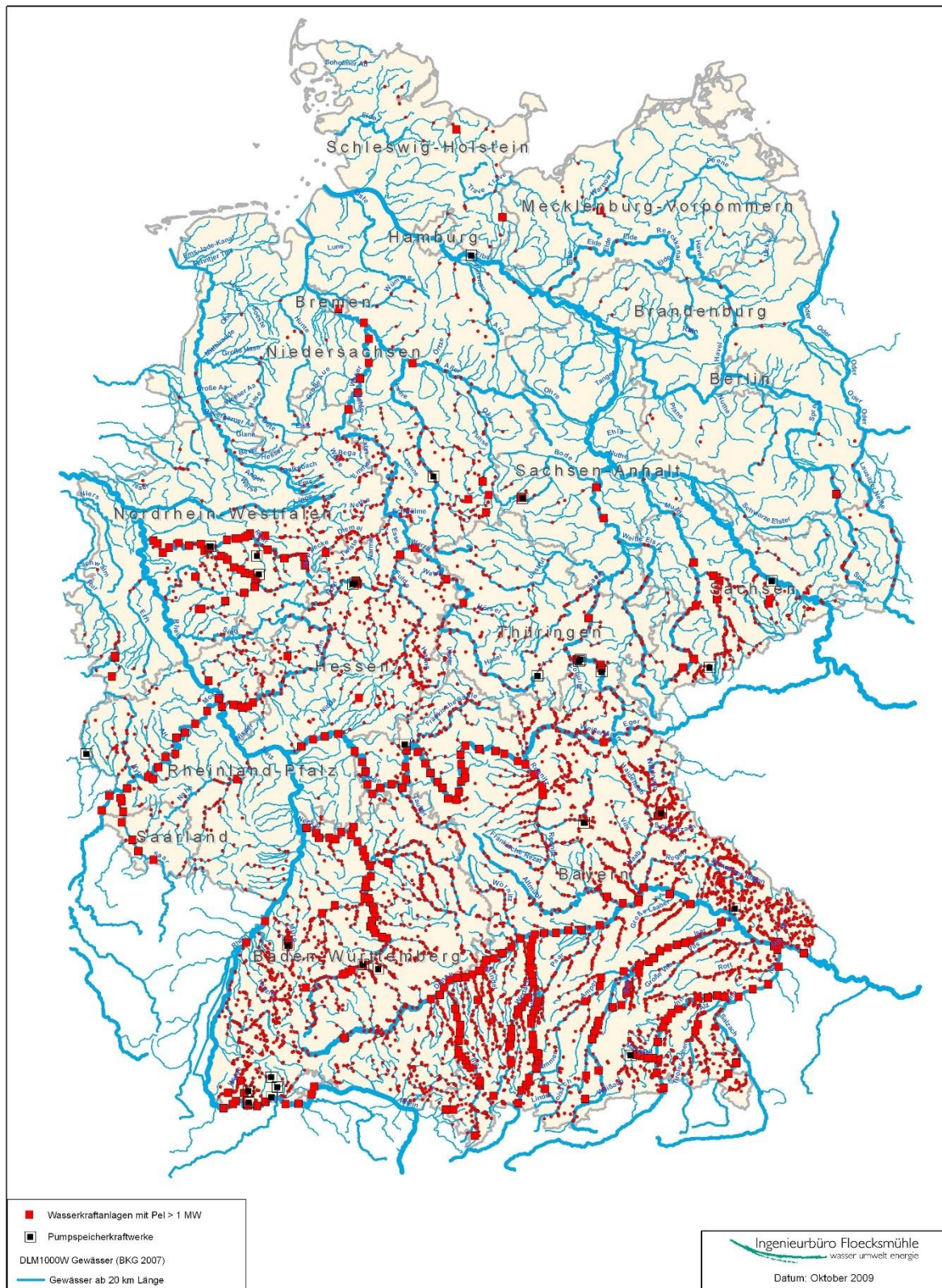


Figure 8 Map of hydropower plants in Germany (Source: Ingenieurbüro Floecksmühle)

### 5.3 Challenges and barriers to the digitalisation of hydropower in Germany

German companies have been involved in developing, building and operating hydroelectric power plants for more than 100 years. Globally, at least half of all hydroelectric power plants are based on German technology<sup>54</sup>.

The first hydroelectric power station in Germany to generate electricity began operations in 1891 in Schöngesing, near Munich. It supplied electricity to the street lighting of the city and is considered a pioneer of modern hydroelectric power stations. This development continued in the early 20<sup>th</sup> century. Hydroelectric power stations were built all over Germany to meet the ever-growing demand for electricity. Well-known plants from this period are the Walchensee power plant in Bavaria and the Rheinfeldern hydroelectric power plant on the Upper Rhine, both still in operation today<sup>55</sup>.

Since the hydropower sector in Germany dates back to the 19<sup>th</sup> century and to the advent of industrialisation, the modernisation and digitalisation of the existing outdated plants is key in order to allow the sector to continue to thrive. Without modernisation, the share of electricity produced by hydro *vis-à-vis* the electricity generated by other renewable sources is expected to fall in the future, as the potential for hydropower use in Germany has largely been exploited, while other renewable energy sources have greater potential and are being further developed.

In addition, climate change poses additional challenges as the increase in dry periods and the constant fluctuation of the water level of rivers, depending on precipitations and evaporation, may have a negative impact on the energy yield of hydropower plants. The Germany Federal Environment Agency commissioned an investigation on the possible effects of climate change on the yield of hydropower plants. According to this study, a reduction in hydropower generation between 1 and 4% can be expected by the middle of the 21<sup>st</sup> century, and by up to 15% for the period thereafter<sup>56</sup>.

Finally, from a regulatory perspective, operators of hydropower plants must comply with stringent environmental and ecological standards, which require significant investments, in order to be able to operate and receive subsidies. The Renewable Energy Sources Act (EEG) obliges operators to design their hydropower plants in an environmentally friendly manner with the objective to minimize negative environmental impacts and improve compatibility for ecosystems (i.e. via the installation of fish passes and fish migration facilities, improvements to water morphology, etc.)<sup>57</sup>.

Finally, approval procedures for the construction of new hydroelectric power plants or for extensive conversion measures of existing ones are a complex and long process, involving demonstration of conformity with the Water Resources Act, a preliminary ecological assessment, a nature conservation planning, and compliance with other regulations (i.e. building law, urban development planning, neighbour law and noise protection)<sup>58</sup>.

### 5.4 Potential and opportunities for the digitalisation of hydropower in Germany

Hydropower in Germany remains an important part of the energy mix. Nevertheless, since most suitable locations for hydropower in Germany have already been deployed, the potential for building new large hydroelectric power plants is rather limited. Instead, significant opportunities lie in the modernisation and increase in the efficiency of existing plants, which are often ageing and in operation since more than a hundred years.

Significant potential also comes from the expansion of the fleet of small hydropower plants in the country. Since the large rivers in Germany are already largely developed for hydropower use, small

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<sup>54</sup> BMWK, "Hydroelectric Power" (<https://german-energy-solutions.de/GES/Redaktion/EN/Text-Collections/EnergySolutions/EnergyGeneration/hydroelectric-power.html>).

<sup>55</sup> Dietze C., 18/12/2024, *EEAktuell*, "Wasserkraftwerke in Deutschland: Wichtige Fakten zu Geschichte, Bedeutung und Zukunft" (<https://erneuerbare-energien-aktuell.de/wasserkraft/wasserkraftwerke-in-deutschland-wichtige-fakten-zu-geschichte-bedeutung-und-zukunft/>).

<sup>56</sup> Umwelt Bundesamt, 2012, „Klimafolgen für die Wasserkraftnutzung in Deutschland und Aufstellung von Anpassungsstrategien“ (<https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4288.pdf>).

<sup>57</sup> Umwelt Bundesamt, 2023, „Nutzung der Wasserkraft“ (<https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/nutzung-der-wasserkraft#Strom>).

<sup>58</sup> Bundesverband Deutscher Wasserkraftwerke, "Wasserkraft und Gewässerschutz" (<https://www.wasserkraft-deutschland.de/wasserkraft/oekologie-und-gewaesserschutz.html>).

hydropower is increasingly coming into focus. Smaller hydropower plants in Germany can in fact use smaller rivers and streams and have great potential to support the regional energy supply.

According to a study from the Berlin-based Energy Watch Group, the modernisation and reactivation of hydroelectric power plants in Germany could provide an additional output of 7.1 gigawatts. This corresponds to an annual electricity generation of 28 terawatt hours<sup>59</sup>.

Another study by the Technical University of Braunschweig presents less optimistic figures: the modernisation of old hydropower plants could bring an additional output of up to 1.9 gigawatts and increase electricity production by up to 9.3 terawatt hours per year<sup>60</sup>.

Finally, the German Hydropower Association (Bundesverband Deutscher Wasserkraftwerke) estimates that, under appropriate conditions, electricity production from hydropower can be increased to 31 terawatt hours (TWh) by 2030. A third each of the increase is to be attributed to modernisation measures, reactivation of systems and new construction.

Even though figures on the potential of hydropower vary significantly among different studies, there is common agreement that the focus today is more on modernisation of existing plants and on construction of smaller plants. In view of the country's ambition to increase the share of renewables in gross electricity consumption to at least 80% by 2030, it is clear that hydropower can serve as a supplementary energy source to compensate for fluctuations in electricity production from wind and solar energy. Due to their flexibility and reliability, hydropower plants remain an indispensable part of the sustainable energy supply in Germany.

## 5.5 Best practices on digitalisation of hydropower in Germany: Uniper's Lamdshut hydropower station

The German multinational company Uniper is undertaking significant efforts towards digitalisation, through COODE, their digital transformation initiative. In Germany alone Uniper has an output capacity of almost 2,000 megawatts, primarily on the Lech, Isar, Main and Danube rivers, and is a significant producer of renewable electricity from hydropower. On those four rivers Uniper operates 99 run-of-river hydroelectricity plants. There are also five storage and five pumped-storage hydroelectricity plants. Combined, these power plants generate around five billion kilowatt hours annually – an amount of electricity that is sufficient to cover the annual needs of over 1.6 million private households and avoid emissions of around 2.8 million tons of CO<sub>2</sub> per year<sup>61</sup>.

In their Landshut hydropower station in Bavaria, where the company headquarters is, Uniper digitalised the sensor readings at their dams, so that employees no longer must manually visit individual sensor points for data readings during inspections. Instead, the information will be accessible online, thus saving employees time and allowing them to focus on visual aspects of the dam inspections, and providing better data quality to improve decision making and remove obstacles in day-to-day operations<sup>62</sup>.

## 6 Greece

### 6.1 Overview of energy and electricity sector in Greece

The commitment of Greece towards a green transition is visible from the country's numerous records achieved in the last few years: the share of renewable electricity production reached a historic high in 2023 in the country (57%) and the sector covered more than half of demand for the first time. In the same year, Greece did not consume any coal power for almost one month (28 days) and in the first 11

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<sup>59</sup> Energy Watch Group, 2024, "Wasserstrom – der neue Gamechanger für Klimavorsorge, Heimatenergien und Gewässernatur" (<https://energywatchgroup.org/wp/wp-content/uploads/2024/03/Wasserkraft-Studie.pdf>).

<sup>60</sup> Stadt und Werk, 24/09/2024, „BDW fordert Wasserkraftstrategie“ (<https://www.stadt-und-werk.de/k21-meldungen/bdw-fordert-wasserkraftstrategie-2/>).

<sup>61</sup> Uniper, „Hydropower in Germany“ (<https://www.uniper.energy/germany/hydropower-germany>).

<sup>62</sup> Uniper, August 2024, ([https://www.linkedin.com/posts/uniper-se\\_coode-hydropower-digitalization-activity-7190984828765249536-w2pr/](https://www.linkedin.com/posts/uniper-se_coode-hydropower-digitalization-activity-7190984828765249536-w2pr/)).

months, the shares of lignite in electricity production and demand coverage landed below the 10% mark for the first time<sup>63</sup>.

The largest source of renewable electricity generation in the country is wind (45,9%), followed by solar (34,5%) and hydro (19,7%).

Because of its geographical and climatic characteristics, Greece is significantly vulnerable to climate change. Greece has in fact a very long coastline, exceeding 15,000 km, of which around 1,000 km are areas highly vulnerable to climate change because of the rise in Greece's average sea level<sup>64</sup>. Additionally, rising temperatures are the cause of more frequent and intense heatwaves and wildfires. At the same time, changes in precipitation patterns are leading to water shortages, affecting agriculture and water supply.

The Hellenic Republic has adopted a National Energy and Climate Plan (NECP or ESEK, as per its Greek acronym), which constitutes the Greek government's strategic plan on climate and energy issues and presents a detailed roadmap for the achievement of specific energy and climate goals by 2030. The NECP has set ambitious targets concerning the use of RES in gross final energy consumption (30%), in gross final electricity consumption (55%), in heating and cooling needs (30%) and in the transport sector (14%)<sup>65</sup>.

The government has recently adopted the first "National Climate Law" (Law 4936/2022), which establishes measures and policies to adapt the country to climate change and ensure the path of decarbonisation by the year 2050 and, among others, prohibits the production of electricity from solid fossil fuels from 31 December 2028.

As in every EU Member State, it is the competent Ministry of Energy, together with the Regulatory Authority for Energy (RAE as per its Greek acronym, recently renamed to the Regulatory Authority for Energy, Waste and Water (RAAEY)) which play the most important role in the drawing and adoption of national energy policies<sup>66</sup>.

Greece is undergoing a profound digital transformation with the goal of fully digitizing the country by 2025. Its Ministry of Digital Governance is the driving force behind the digital transformation, including its Digital Transformation Bible 2020-2025<sup>67</sup>, which outlines Greece's roadmap for digital transformation through 450 projects supported by €6.4 billion from the EU Recovery Fund. Some of the projects are specific to the energy sector (i.e. deployment of smart meters and digitalisation of energy infrastructure).

## 6.2 Hydropower in Greece

Greece is predominantly mountainous, with over 80% of its terrain consisting of mountains, primarily located in the northwestern part of the country. This geography of the region is therefore well-suited for hydropower development.

In 2022, Greece generated over 4 terawatt-hours (TWh) of electricity from large-scale hydropower, accounting for about 8.2% of the country's total electricity production. Small-scale hydropower contributed an additional 630 gigawatt-hours (GWh)<sup>68</sup>.

The development of the hydropower sector in Greece dates back to the establishment of the state-controlled utility Public Power Corporation (PPC) in 1950. Prior to that, only very small plants had been

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<sup>63</sup> Todorović I. 24 January 2024, "Greece breaks records in renewables, energy efficiency in 2023", *Balkan Green Energy News* (<https://balkangreenenergynews.com/greece-breaks-records-in-renewables-energy-efficiency-in-2023/#:~:text=The%20share%20of%20renewable%20electricity,power%20capacity%20topped%205%20GW.>).

<sup>64</sup> World Bank Group, Climate Change Knowledge Portal – Greece (<https://climateknowledgeportal.worldbank.org/country/greece>).

<sup>65</sup> Y. Seiradakis, E. Stazilova, 2025, „Energy Laws and Regulations 2025 – Greece” (<https://www.globallegalinsights.com/practice-areas/energy-laws-and-regulations/greece/>).

<sup>66</sup> *Ibidem*.

<sup>67</sup> Hellenic Republic Government, "Digital Transformation Bible 2020-2025" (<https://digitalstrategy.gov.gr/en/>).

<sup>68</sup> Statista, 2023, „Large-scale hydropower production in Greece from 2013 to 2022” (<https://www.statista.com/statistics/1455200/annual-large-hydro-electricity-generation-greece/>).

put into operation (the plants of Glafkos, Vermio, Almyros in Chania, between 1927 and 1931), with a total installed capacity of 5.8 MW<sup>69</sup>.

Greece generates hydro-powered energy from 18 hydro power plants across the country. In total, these hydro power plants have a capacity of 3.501 MW<sup>70</sup>. To date, PPC is still the owner and operators of all the large hydropower plants in Greece. The table below provides an overview of the operating large plants in the country.

Table 1: Source: Database Earth, „Hydropower Plants in Greece” (<https://database.earth/energy/power-plants/hydro-power/greece>).

Name	Capacity (MW)	Commissioned
<u>Assomata</u>	108.0 MW	1985
<u>Ilarionas</u>	154.0 MW	2011
<u>Kastraki</u>	320.0 MW	1969
<u>Kremasta</u>	437.0 MW	1965
<u>Ladhon</u>	70.0 MW	1955
<u>Louros Dam</u>	10.0 MW	1954
<u>Messochora</u>	160.0 MW	1995
<u>Perdikas</u>	320.0 MW	
<u>Pigae Aaos</u>	210.0 MW	1989
<u>Plastiras</u>	130.0 MW	1959
<u>Platanovryssi</u>	108.0 MW	1997
<u>Polyphyto</u>	124.0 MW	1974
<u>Pournari</u>	334.0 MW	1981
<u>Sfikia</u>	315.0 MW	1985
<u>Smokovo</u>	10.0 MW	1994
<u>Stratos</u>	150.0 MW	1988
<u>Sfykia</u>	160.0 MW	
<u>Thissavros</u>	381.0 MW	1996

Additionally, a number of small hydropower plants owned by PPC, private companies and local municipalities complete the picture.

<sup>69</sup> PPC Group, “Hydroelectric Power Plant” (<https://www.ppcgroup.com/en/ppc-group/business-areas/renewable-energy-sources/hydroelectric-power-plant/>).

<sup>70</sup> Database Earth, „Hydropower Plants in Greece” (<https://database.earth/energy/power-plants/hydro-power/greece>).

The main focus of Greek hydropower plants is not much on electricity generation, but rather mainly to meet the peak load demand<sup>71</sup>. Wind and solar power plants are being built in such quantities that neither demand nor the grid can keep up. Pumped hydropower storage facilities can balance the output from the two intermittent sources and can keep the power system stable for days without wind and with little solar power. The final version of the National Energy and Climate Plan reportedly includes 1.928 MW of energy storage from pumped storage hydroelectric plants by 2030. PPC is therefore currently upgrading two of its existing hydropower plants into pumped storage systems (namely, the Pournari and Kastraki hydroelectric plants) and several other projects are being planned for the next years<sup>72</sup>.

### 6.3 Challenges and barriers to the digitalisation of hydropower in Greece

Climate change poses significant challenges to the hydropower sector in Greece in several ways. Increased evaporation of water due to higher temperatures and longer periods of drought may cause significant falls in the level of reservoirs, reducing the efficiency of hydroelectric and pumped storage units; while changes in rainfall are expected to affect the flow of surface water on which hydroelectric injection is dependent<sup>73</sup>. According to what is reported in the Greek NECP, the hydropower generation potential in the country is expected to decrease by 10% to 20% by 2050, depending on the climate scenario taken into consideration.

Since hydroelectric potential plays an important role in the stability and security of the future energy system, significant focus is also on mitigation measures to limit the negative impact of climate change on the sector, via the development of specific power security plans for hydroelectric and pumped storage units to deal with drought phenomena<sup>74</sup>.

Additional challenges to the operation of hydropower plants come from the regulatory environment. According to the European Water Framework Directive, heavily modified water bodies (HMWB) must comply with the EU's standards of "good ecological potential". Nevertheless, the lack of data (hydromorphological, physicochemical, biological) in Greece makes river basin management, planning of measures and establishment of monitoring systems for heavily modified surface water very difficult<sup>75</sup>. In order to not halt the operation of existing hydropower plants or to not delay the permitting and construction of new plants, measures must be taken as soon as possible in order to allow for a proper collection of data and compliance with the good ecological potential standards. Notwithstanding the age of the Greek large hydropower plants, mostly in operation since more than 30-40 years (see table above), the priority of the Greek government for the hydropower sector does not seem to be modernisation and digitalisation of the existing plants, but rather the modification of existing plants into storage facilities with the addition of a reservoir.

### 6.4 Potential and opportunities for the digitalisation of hydropower in Greece

The annual theoretical hydropower potential in Greece is approximately 80 TWh, while the economically exploitable potential is around 12 TWh. To date, about 40% of this potential has been developed<sup>76</sup>.

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<sup>71</sup> J.K. Kaldellis, 2008, „Critical Evaluation of the hydropower applications in Greece”, *Renewable and Sustainable Energy Reviews*

(<https://www.sciencedirect.com/science/article/abs/pii/S1364032106000669>).

<sup>72</sup> Igor Todorovic, 2024, „Dozens of pumped storage hydropower projects underway in Greece”, *Balkan Green Energy News* (<https://balkangreenenergynews.com/dozens-of-pumped-storage-hydropower-projects-underway-in-greece/>).

<sup>73</sup> Greece – Final updated National Energy and Climate Plan 2021-2030 (submitted in 2025) ([b2fbbef4-ee32-44fc-acce-49737bf492c8\\_en](https://b2fbbef4-ee32-44fc-acce-49737bf492c8_en)).

<sup>74</sup> *Ibidem*.

<sup>75</sup> P. M. Farmaki and A. C. Tranoulidis, 5<sup>th</sup> International Conference on Water Sciences, 2020, “Greek hydropower production and the EU WFD: potentially conflicting interests and sustainable governance of river basins” (<https://sciforum.net/manuscripts/8446/slides.pdf>).

<sup>76</sup> PPC Group, “Hydroelectric Power Plant” (<https://www.ppcgroup.com/en/ppc-group/business-areas/renewable-energy-sources/hydroelectric-power-plant/>).

According to the Greek NECP, “harnessing the hydropower potential is a high priority<sup>77</sup>”. Efforts are therefore being undertaken towards the completion and operation of the large hydropower projects under construction, the gradual exploitation of new sites with significant potential, the exploitation of the potential in irrigation/water projects and reservoirs, and the further development of small hydroelectric projects.

As a result, the total installed capacity of hydroelectric power projects equipped with a reservoir (3.2 GW) is expected to increase particularly after 2030, reaching an installed capacity of 4,7 GW in 2050, with 4.678 MW coming from large hydropower plants and 490 MW from small hydropower plants. At the same time, the total capacity of pumped storage systems is expected to be 1.928 MW by 2030, and to increase significantly to 5.453 MW by 2050<sup>78</sup>.

The exploitation and uptake of innovative digital solutions for the hydropower sector, developed under research projects such as iAMP-Hydro, will be of key importance for all hydropower projects under construction and in the planning in Greece and across Europe, as they will ensure the benefits of hydropower solutions are fully reaped and their potential is fully exploited.

## 6.5 Best practices on digitalisation of hydropower in Greece: the Di-Hydro project

The EU-funded Di-Hydro project, aiming at making hydropower plants smarter, more efficient, and environmentally conscious, also has a use-case in Greece, provided by 3 PPC’s plants: Pournari, Ilarionas, and Thisauros. The Greek use case is centred around optimisation of operation and maintenance through the development and application of sensor nodes, for continuous and structural health monitoring of equipment or infrastructure across the three selected hydropower plants. Machine learning algorithms will be developed and used to analyse vast amounts of operational data, identifying patterns that can predict equipment failures before they occur. This proactive approach to maintenance is expected to significantly reduce downtime, increase the lifespan of critical components, and lower the overall cost of operation. In addition, this use case will include the development of a digital twin (DT) of one of PPC’s hydropower plants, focusing on data integration from sensors and physical sources for better plant monitoring and optimisation<sup>79</sup>.

## 7 Ireland

### 7.1 Overview of energy and electricity sector in Ireland

Ireland put in place an ambitious and comprehensive set of policies and targets to reach net zero by 2050. Its Climate Action Plan includes a target to increase the share of electricity generated from renewable sources up to 80% in 2030, but accelerated implementation of existing policies and sustained efforts are required in order to not miss the target<sup>80</sup>.

The main challenge for the country comes from the transition away from fossil fuels like natural gas. According to the 2024 State of the Energy Union report, fossil fuels account for 86.4% of Ireland’s energy mix, compared to an average of 69% across the EU. Additionally, energy security is a major concern to the government and Ireland’s energy system remains exposed to geopolitical instability and fluctuations in the power market due to its import dependency for fossil fuels (for which Ireland exclusively relies on imports from the United Kingdom) which still accounts for over 80% of the country’s energy consumption.

Natural gas will remain an important part of the country’s energy mix, at least until the mid-2030s, especially to meet peak electricity demand. However, progress has been made with almost 40% of electricity in Ireland now coming from renewable sources. In fact, Ireland is ranked third globally in

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<sup>77</sup> Greece – Final updated National Energy and Climate Plan 2021-2030 (submitted in 2025) ([b2fbbef4-ee32-44fc-acce-49737bf492c8\\_en](https://b2fbbef4-ee32-44fc-acce-49737bf492c8_en)).

<sup>78</sup> *Ibidem*.

<sup>79</sup> Di-Hydro project, „UC#1: Greece” (<https://dihydro-project.eu/use-case-1-greece-ppc/>).

<sup>80</sup> International Energy Agency, “Ireland” (<https://www.iea.org/countries/ireland>).

wind capacity per capita and has the potential to become a key player in Europe's offshore wind market<sup>81</sup>.

Though vulnerability to climate change in Ireland is not as pressing as in other countries<sup>82</sup>, significant reductions are expected in average levels of annual, spring and summer rainfall and climate change is expected to cause water stress for crops, pressure on water supply and adverse impacts on water quality<sup>83</sup>.

The key piece of legislation governing Ireland's energy sector is the Climate Action and Low Carbon Development (Amendment) Act 2021, which sets a legally binding target for Ireland to achieve net-zero greenhouse gas emissions by 2050, establishes carbon budgets and mandates the development of climate action plans every five years. EU directives (namely, the EU's 2023 Energy Efficiency Directive and the EU recast Renewable Energy Directive III) complement the picture.

When it comes to key players on Ireland's energy policy arena, the Sustainable Energy Authority of Ireland (SEAI) is among the most prominent actors. SEAI is in fact the national body responsible for promoting and assisting the development of sustainable energy in Ireland through the provision of data, insights, and support for energy efficiency and renewable energy projects.

Alongside SEAI, the Department of Communications, Climate Action and Environment (DCCAE) is responsible for enacting a range of energy policies and measures to promote the delivery of a more sustainable energy system for the country.

Worth mentioning are also EirGrid (the state-owned company that manages and operates the national electricity grid), Gas Networks Ireland (GNI, which operates the national natural gas network) and the independent Commission for Regulation of Utilities (CRU).

Ireland is also keen in moving forward its digital transition. The Digital Ireland Framework, adopted by the government in 2022, aims to increase adoption of digital technologies by all businesses, and therefore also recognise the importance of digital technologies for the energy sector. According to the document, digital technologies can have an important role to play in reducing energy and resource use and enabling decarbonisation. For example, digital technologies such as sensors, networked devices, and data analytics can help us optimise energy use and decrease emissions<sup>84</sup>.

## 7.2 Hydropower in Ireland

Even though the renewable energy landscape in Ireland is strongly dominated by wind energy (with wind accounting for 87.6% of total electricity generation from renewables), hydropower comes second in the picture, with 1.237 GWh generated in 2023 (corresponding to 9.3% of electricity generated from renewable sources, but to less than 4% of all the electricity generated in the country in the same year<sup>85</sup>).

Ireland has a long history of hydropower generation, and hydropower was the largest contributor to renewable electricity in Ireland until the large-scale development of wind energy at the end of the 20<sup>th</sup> century.

The history of the sector dates right back to the Shannon Hydroelectric Scheme in the 1920s, a groundbreaking project aimed at harnessing the power of the River Shannon, Ireland's longest river. Supplying 85MW electricity, the Ardnacrusha power plant on the Shannon (operating since 1929) was the largest scheme of its kind in the world at the time, and it remains still today Ireland's largest hydroelectric plant. Other significant hydroelectric installations are Cathleen's Fall (Donegal, 45 MW, commissioned in 1951), Poulaphouca (Wicklow, 30 MW, operating since 1944) and Cliff (Donegal, 20 MW, operating since 1950). Turlough Hill (Wicklow) is Ireland's only pumped-storage hydroelectricity

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<sup>81</sup> European Commission Representation in Ireland, "EU Energy Policy" ([https://ireland.representation.ec.europa.eu/strategy-and-priorities/key-eu-policies-ireland/eu-energy-policy\\_en](https://ireland.representation.ec.europa.eu/strategy-and-priorities/key-eu-policies-ireland/eu-energy-policy_en)).

<sup>82</sup> Ireland ranks #21 in the ND-GAIN Country Index, which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience (<https://gain-new.crc.nd.edu/ranking>).

<sup>83</sup> Environmental Protection Agency, "What impact will climate change have on Ireland?" (<https://www.epa.ie/environment-and-you/climate-change/what-impact-will-climate-change-have-for-ireland/>).

<sup>84</sup> Digital Ireland Framework, 2022 ([www.gov.ie/pdf/?file=https://assets.gov.ie/214584/fa3161da-aa9d-4b11-b160-9cac3a6f6148.pdf#page=null](http://www.gov.ie/pdf/?file=https://assets.gov.ie/214584/fa3161da-aa9d-4b11-b160-9cac3a6f6148.pdf#page=null)).

<sup>85</sup> International Energy Agency, "Ireland" (<https://www.iea.org/countries/ireland/electricity>).

plant<sup>86</sup>. It was built between 1968 and 1974 and at that time was the largest civil engineering project carried out in Ireland. It has a total capacity of 292 MW for load balancing during times of peak electricity demand. The scheme uses off-peak power (both fossil-based and renewables) to pump water to an elevated reservoir and converts the stored potential energy in the upper reservoir by letting the water down through hydraulic turbines to boost electrical generation during times of peak demand<sup>87</sup>.

### 7.3 Challenges and barriers to the digitalisation of hydropower in Ireland

Because of geography, Ireland has limited hydropower capacity and the existing potential has already been almost fully exploited. The Irish National Energy and Climate Plan does not even refer to hydropower at all<sup>88</sup>.

Nevertheless, it is worth noting that all major hydropower facilities in Ireland are more than 50 years old and could strongly benefit from modernisation measures and digitalisation processes, as illustrated by the case study of Turlough Hill's digital twin presented below (see chapter 7.5).

Additionally, as for other EU member states, the recent Nature Restoration Law, as well as the Water Framework Directive, pose significant challenges to the further development of the sector.

Namely, the EU Nature Restoration Law<sup>89</sup>, which was adopted in 2024 and aims to restore degraded ecosystems and to improve biodiversity across Europe, while being crucial for the environment, can pose challenges for the hydropower sector in Ireland and in other Member States. Key impacts include:

- Site restrictions: the law mandates the restoration of specific habitats, which can limit the availability of suitable sites for new hydropower projects. Areas that need to be restored or protected may overlap with potential hydropower locations.
- Environmental assessments: hydropower projects will likely face more stringent environmental assessments to ensure they do not negatively impact restored or protected areas. This can increase the time and cost associated with project approvals.
- Operational constraints: existing hydropower facilities might need to adapt their operations to comply with new environmental standards, potentially reducing their efficiency or capacity and facing high investment costs.

As for the EU Water Framework Directive (WFD)<sup>90</sup>, it is considered by some to hinder the development of the hydropower sector due to its stringent requirements for water quality and ecological status in several ways:

- Ecological standards: the WFD mandates that all water bodies must achieve "good" ecological status by 2027. This means that hydropower projects must ensure they do not negatively impact water quality or aquatic ecosystems, which can be difficult given the nature of hydropower operations themselves.
- River Basin Management Plans (RBMPs): Ireland must develop and implement RBMPs that outline measures to protect and improve water quality<sup>91</sup>. Hydropower projects must align with these plans, which can involve significant modifications to existing operations or additional investments in mitigation measures.
- Legal and regulatory compliance: Ireland has already faced legal challenges and scrutiny at EU level for not fully meeting WFD requirements<sup>92</sup>. This creates a regulatory environment where

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<sup>86</sup> Sustainable Energy Authority of Ireland, "Hydroelectric Power" (<https://www.seai.ie/renewable-energy/hydropower/>).

<sup>87</sup> Ireland 2050, "The story of renewable energy in Ireland" (<https://irelandenergy2050.ie/past/renewable-energy/>).

<sup>88</sup> Government of Ireland, 2024, "Ireland's integrated National Energy and Climate Plan 2021-2030" (<https://www.gov.ie/pdf/?file=https://assets.gov.ie/299744/9a308db2-cbd5-46e8-8674-e939dca87263.pdf#page=null>).

<sup>89</sup> Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (<https://eur-lex.europa.eu/eli/reg/2024/1991/oj/eng>).

<sup>90</sup> Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (<https://eur-lex.europa.eu/eli/dir/2000/60/oj/eng>).

<sup>91</sup> Ireland's River Basin Management Plan 2022-2027 (<https://www.gov.ie/en/policy-information/8da54-river-basin-management-plan-2022-2027/>).

<sup>92</sup> Environment Ireland, 11 September 2024, "Meeting Water Framework Directive requirements" (<https://www.environmentireland.ie/meeting-water-framework-directive-requirements/>).

hydropower projects must be meticulously planned and executed to avoid legal repercussions and potential fines.

- Environmental impact assessments: hydropower projects are subject to rigorous environmental impact assessments to ensure compliance with the WFD. These assessments can be time-consuming and costly, potentially delaying project timelines and increasing costs.

#### 7.4 Potential and opportunities for the digitalisation of hydropower in Ireland

While much of Ireland's hydropower resource potential has already been tapped, some opportunities remain for small-scale decentralised generation and an annual growth rate of 0.30% is expected from 2025 to 2029<sup>93</sup>. The map below, provided by the Sustainable Energy Authority of Ireland (SEAI), shows the existing small-scale hydropower plants, as well as the small-scale hydroelectric potential across the country, as identified in a 1985 Department of Energy report, "Small Scale Hydro Electric Potential of Ireland".

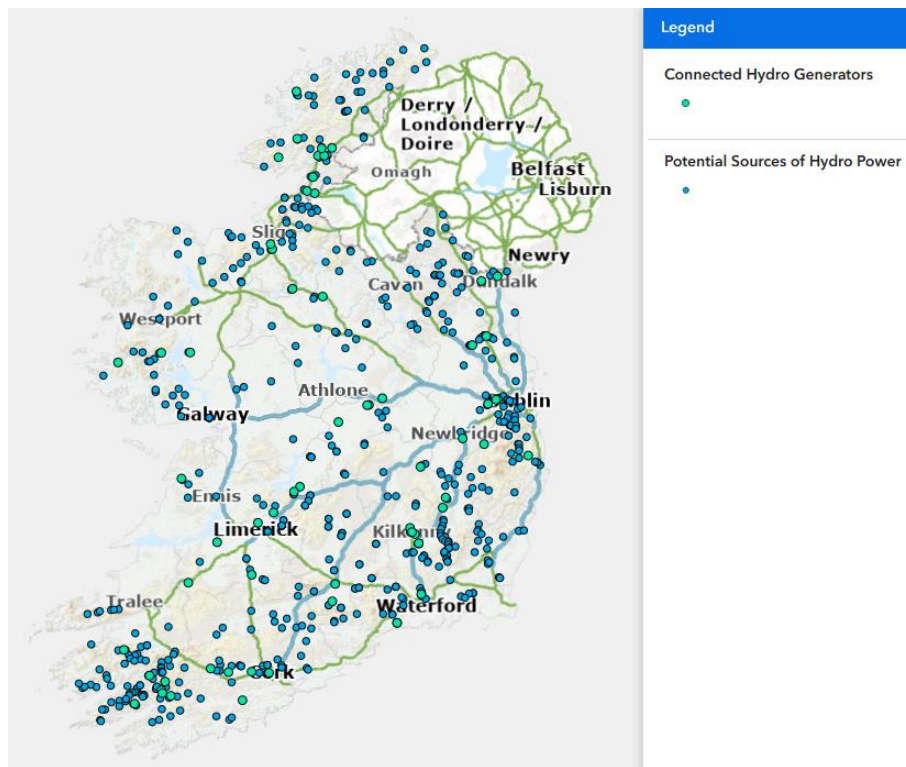


Figure 9 Source: SEAI, "Hydropower map" (<https://www.seai.ie/renewable-energy/hydropower/hydro-power-map>).

Additionally, there is significant potential for increased pumped storage hydroelectric capacity. The Silvermines Hydro Electric Plant in the County Tipperary is currently under construction and is expected to add 296 MW of pumped storage hydroelectric capacity to the national grid by 2031<sup>94</sup>, thus providing a low carbon form of energy storage and doubling the current capacity of the country (currently, the Turlough Hill plant is the only pumped storage hydropower facility in Ireland and it can generate around 300MW of electricity).

Modernisation measures are instead not mentioned in the Climate Action Plan 2021. If modernisation and digitalisation of existing large hydropower plants is not among the government's priorities, it is then up to the private sector to lead by example (as done by ESB in the case study illustrated in the following paragraph), and the uptake of innovative digital technologies for planned and future small hydropower projects should be emphasised in order to maximise operations while respecting the surrounding environment and preserving biodiversity.

<sup>93</sup> Statista, "Hydropower – Ireland" (<https://www.statista.com/outlook/io/energy/renewable-energy/hydropower/ireland>).

<sup>94</sup> Silvermines Hydro (<https://www.silvermineshydro.ie/>).

## 7.5 Best practices on digitalisation of hydropower in Ireland: Turlough Hill's digital twin

Originally designed in the 1960s, with engineering work completed in the 1970s, the Turlough Hill hydroelectric power station in Ireland was reaching the end of its design life. However, the plant, which is the only pumped storage station in Ireland, is still a key asset for its owner and operator, the Irish state-owned utility Electricity Supply Board (ESB), and helps stabilise the local grid at times of peak demand.

As part of the Free Electrons Accelerator Programme (an initiative to connect startups with energy utilities to support and foster innovation), ESB connected with the software provider Akselos. Using its predictive and digital design technology, Akselos created in 2020 the world's first digital twin of a pumped storage station.

The digital twin is essentially a tool with which ESB can simulate many parameters around the day-to-day operation of the plant, and allows them to know what the current loading on the penstock is, predict when, why and where it will fail, understand how to mitigate this risk, and estimate how much life is remaining. Additionally, through the models, ESB will look to assess different modes of operation that might better work alongside renewables, such as storing electricity at different times of the day. Akselos is now working on building a Digital Guardian of the asset, expected to be completed in 2025 and to extend the plant's useful life by up to twenty years. In order to create the Digital Guardian, engineers will connect specially placed sensors to get a real time picture of what is happening in the hydro plant.

According to estimates, the CAPEX invested for Akselos' digital twin technology by a utility can be recouped within a three-year period, just on the basis of improved inspection, and can provide a 20-50% life extension<sup>95</sup>.

## 8 Norway

### 8.1 Overview of energy and electricity sector in Norway

Norway has set ambitious goals to reduce greenhouse gas emissions and create a low-emissions society by 2050. As a country rich in energy resources, Norway is uniquely positioned for the energy transition. Its abundant and affordable hydropower has facilitated the growth of energy-intensive industries and high electrification levels in homes and businesses, all with minimal greenhouse gas emissions. At the same time, as a major oil and gas producer and exporter, Norway will need to support an evolution of its energy sector amid the global energy transition<sup>96</sup>.

The largest source of energy in Norway is hydro (accounting for 43% of total energy supply), though it is followed by oil and natural gas (accounting as a whole for 41,2% of total energy supply). The picture significantly changes if one looks only at the electricity sector, where renewables are strongly dominating the picture with hydro accounting for 89.1% of electricity generation and wind for 9%<sup>97</sup>.

The country's energy sector is guided by legislative frameworks such as the Energy Act (Energiloven), which promotes efficient resource management and a stable electricity market, and the Water Resources Act (Vannressursloven), which aims to ensure sustainable water use. These laws work alongside international climate commitments, such as the EU's Green Deal and Norway's 2030 and 2050 carbon neutrality goals.

Norway is actively pursuing digitalisation across its energy sector to improve efficiency, enhance sustainability, and ensure grid reliability. Current digitalisation policies include the deployment of advanced monitoring systems, smart grids, and AI-based forecasting tools. For instance, Statnett, the

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<sup>95</sup> Heidi Vella, April 2020, "Inside the world's first digital twin of a hydroelectric power station", Power Technology (<https://www.power-technology.com/features/inside-the-worlds-first-digital-twin-of-a-hydroelectric-power-station/?cf-view>).

<sup>96</sup> International Energy Agency, "Norway" (<https://www.iea.org/countries/norway>).

<sup>97</sup> *Ibidem*.

national grid operator, is investing heavily in digital grid solutions to manage fluctuating renewable energy sources.

Norwegian laws and regulations governing the hydropower industry not only establish strict requirements for sustainability, safety, and efficiency but also actively encourage the adoption of digital technologies to meet these goals. Key frameworks like the Energy Act, Water Resources Act, and Nature Diversity Act create a regulatory environment that fosters innovation and incentivises digital transformation.

## 8.2 Hydropower in Norway

Hydropower is the backbone of Norway's energy system, with more than 1,700 hydropower plants in operation. More precisely, there were 1.769 hydropower plants in the country at the beginning of 2023, with a combined installed capacity of 33.691MW<sup>98</sup>, generating around 140 TWh annually. More than 830 of those are small hydropower stations, with a capacity of 1 to 10 megawatts, while more than 580 hydropower plants are even smaller with a capacity of less than 1 MW<sup>99</sup>.

Electricity generation can vary considerably from one year to another and during the year, depending on water inflow. The water inflow is highest during the spring, normally declines towards the end of summer but increases again during the autumn. Inflow is generally very low in the winter months. By using storage reservoirs, flexible hydropower plants can produce electricity even in periods when there is little precipitation and inflow is low. The large available reservoir storage capacity makes it possible to even out production over years, seasons, weeks and days, within the constraints set by the licence and the watercourse itself.

A special feature of the Norwegian hydropower system is in fact its high storage capacity. Norway has half of Europe's reservoir storage capacity, and more than 75 % of Norwegian production capacity is flexible<sup>100</sup>. Production can therefore be rapidly increased and decreased as needed, at low cost.

In terms of vulnerability to climate change, Norway is very well positioned to adapt<sup>101</sup>. Precipitation patterns have changed in the last century and average annual precipitation rose about 20% between 1900 and 2014 and is likely to increase a further 18% by the end of the century. The frequency and intensity of heavy precipitation events are also projected to increase. As a result, rainfall floods are expected to become more frequent and severe. Nevertheless, according to the assessment of climate change adaptation for Norway<sup>102</sup>, runoff changes could positively affect the country's hydropower generation overall, although investments in reservoir capacity and power infrastructure may be required to fully capture the anticipated benefits<sup>103</sup>.

Norwegian hydropower plants vary significantly in size and age, with many built during the mid-20<sup>th</sup> century. While older plants require upgrades to maintain efficiency, newer plants increasingly incorporate digital technologies like automation and real-time monitoring.

The largest hydroelectric power plant in Norway is Kviteseid power plant, in use since 1981 and with an installed capacity of 1,240 MW. Annual production of electricity by this plant is 3,131.2 GWh.

Norwegian regulations ensure hydropower development aligns with sustainability goals. For example, the Nature Diversity Act (Naturmangfoldloven) mandates protection of biodiversity during plant operations. The Energy Act (Energiloven) requires operators to maintain system reliability through efficient resource use. The Water Resources Act (Vannressursloven) ensures minimum water flow for ecosystems downstream of reservoirs.

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<sup>98</sup> Energy Facts Norway, "Electricity production" (<https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/#:::text=Hydropower%20is%20stil%20the%20mainstay,of%20Norway's%20total%20power%20production.>).

<sup>99</sup> Statista, „ Number of hydro power stations in Norway as of March 2023, by size" (<https://www.statista.com/statistics/1045048/number-of-hydro-power-stations-in-norway-by-size/>).

<sup>100</sup> *Ibidem*.

<sup>101</sup> According to the ND-GAIN Matrix, Norway is the 185th most vulnerable country and the 3rd most ready country in the world (<https://gain-new.crc.nd.edu/country/norway>).

<sup>102</sup> CICERO and Vestlandsforskning, 2018 "Oppdatering av kunnskap om konsekvenser av klimaendringer i Norge" (<https://www.miljodirektoratet.no/globalassets/publikasjoner/m1209/m1209.pdf>).

<sup>103</sup> International Energy Agency, "Norway Climate Resilience Policy Indicator" (<https://www.iea.org/articles/norway-climate-resilience-policy-indicator>).

### 8.3 Challenges and barriers to the digitalisation of hydropower in Norway

While laws encourage innovation, some regulatory and operational factors hinder digitalisation of hydropower in Norway:

- **GDPR compliance:** data privacy rules, such as the General Data Protection Regulation (GDPR), impose strict requirements on data collection and processing. Hydropower operators must ensure that monitoring systems collecting environmental or operational data do not inadvertently violate privacy standards, adding complexity to digitalisation efforts.
- **Licensing delays:** the need for regulatory approval when implementing new technologies, such as AI-based monitoring systems or automated flood management tools, can slow innovation. Lengthy licensing processes required under the Energy Act or Water Resources Act can delay the deployment of digital solutions.
- **Cybersecurity requirements:** hydropower systems, as critical infrastructure, must comply with stringent cybersecurity laws. These requirements can increase costs and act as a barrier, particularly for smaller operators.

### 8.4 Potential and opportunities for the digitalisation of hydropower in Norway

Norway is today Europe's biggest producer of hydropower, and within the top 10 in the world. Its hydropower resources have given the country industrial development, wealth creation, light and heating for more than a hundred years.

More than 100 years after the first hydroelectric power plant was built in Norway, nearly all of the country's electricity production is based on hydropower. Norwegian hydropower technology is at the forefront globally and Norwegian companies export their technology around the world.

Norway still has a huge potential for small hydropower plants along with renovation and expansion of existing hydro plants<sup>104</sup>. Studies have shown that it is possible to develop additional 20 GW of new capacity in the Norwegian hydropower without construction of additional reservoirs<sup>105</sup>.

Nevertheless, with the average age of Norwegian hydropower plants being 45 years (most of the country's hydropower plants were built between 1950 and 1990, as shown in the graph below) and with many of them showing signs of fatigue and needing to be constantly maintained or refurbished<sup>106</sup>, modernisation measures are key in order to ensure that future generations can also benefit from renewable electricity generated from hydro.

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<sup>104</sup> Parmita Saha, Johannes Idsø, "New hydropower development in Norway: Municipalities' attitude, involvement and perceived barriers", *Renewable and Sustainable Energy Reviews*, 2016, (<https://www.sciencedirect.com/science/article/pii/S1364032116300028>).

<sup>105</sup> Sustainable Water & Energy Solutions Network, „The HydroBalance Project: Energy Storage from Hydropower in Norway Supporting Intermittent Renewable Electricity Generation in Europe”, 2020 ([https://www.un.org/sites/un2.un.org/files/2020/09/the\\_hydrobalance\\_project-energy\\_storage\\_from\\_hydropower\\_in\\_norway\\_supporting\\_intermittent\\_renewable\\_electricity\\_generation\\_in\\_europe.pdf](https://www.un.org/sites/un2.un.org/files/2020/09/the_hydrobalance_project-energy_storage_from_hydropower_in_norway_supporting_intermittent_renewable_electricity_generation_in_europe.pdf)).

<sup>106</sup> NVSK – Norwegian Hydropower Centre (<https://www.ntnu.edu/nvks/about>).

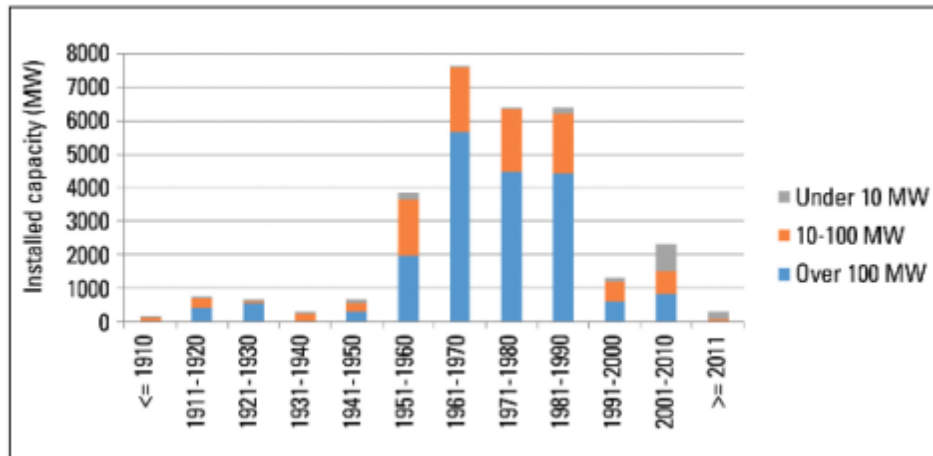


Figure 10 L. Lia, T. Jensen, K.E.Stensbyand, G. Holm Midttømme, A.M. Ruud, 2015, "The current status of hydropower development and dam construction in Norway"  
[https://www.ntnu.no/documents/381182060/641036380/Leif%20Lia\\_FINAL.PDF/32bac8f3-b443-493b-a1eb-e22ce572acd9](https://www.ntnu.no/documents/381182060/641036380/Leif%20Lia_FINAL.PDF/32bac8f3-b443-493b-a1eb-e22ce572acd9).

According to a report recently published by a Norwegian Government Energy Commission, expansion or upgrade<sup>107</sup> of existing hydro generating capacity could bring to a heap of societal benefits (energy savings and surplus power to cover economic growth). If hydropower was upgraded and expanded, then Norway could produce up to 10 TWh of electricity by 2030, the Report's authors say<sup>108</sup>. At the same time, researchers suggest that upgrades alone could give Norway 15% more energy capacity<sup>109</sup>. Additionally, from an environmental perspective, upgrading is regarded as the most favourable type of project due to its minimal environmental impact. Currently, there is a significant number of dam upgrade projects (i.e. among projects with capacities greater than 10 MW, only about 30% are new developments<sup>110</sup>).

On the topic of modernisation, Norwegian laws and regulations governing the hydropower industry also actively encourage the adoption of digital technologies to meet the country's energy and climate goals. Key frameworks like the Energy Act, Water Resources Act, and Nature Diversity Act create a regulatory environment that fosters innovation and incentivises digital transformation.

- Energy Act (*Energiloven*)<sup>111</sup>: Driving operational efficiency
  - The Energy Act ensures reliable energy supply while promoting the efficient use of resources. Its provisions indirectly incentivise digitalisation by enabling technologies that improve compliance and performance:
  - Licensing flexibility: the Energy Act allows hydropower companies to incorporate advanced tools like digital twins to optimise operations. These tools simulate real-time plant behaviour, improving efficiency and reducing downtime, while ensuring compliance with licensing requirements monitored by the Norwegian Water Resources and Energy Directorate (NVE).
  - Support for market innovations: the Act's focus on energy market stability aligns with digital tools that predict demand and manage grid contributions. Predictive analytics

<sup>107</sup> Upgrading is defined as the implementation of measures relating to the mechanical and electrical equipment, to increase efficiency. Extension projects instead include i.e. new catchment areas, increasing the size of reservoirs or increasing the overall size of installations (L. Lia, T. Jensen, K.E.Stensbyand, G. Holm Midttømme, A.M. Ruud, 2015, "The current status of hydropower development and dam construction in Norway").

<sup>108</sup> Aker Solutions, 2023, „Hydropower – energy transition wildcard“ (<https://www.akersolutions.com/news/news-archive/2023/hydropower-the-wildcard/>).

<sup>109</sup> *Ibidem*.

<sup>110</sup> L. Lia, T. Jensen, K.E.Stensbyand, G. Holm Midttømme, A.M. Ruud, 2015, "The current status of hydropower development and dam construction in Norway"  
[https://www.ntnu.no/documents/381182060/641036380/Leif%20Lia\\_FINAL.PDF/32bac8f3-b443-493b-a1eb-e22ce572acd9](https://www.ntnu.no/documents/381182060/641036380/Leif%20Lia_FINAL.PDF/32bac8f3-b443-493b-a1eb-e22ce572acd9).

<sup>111</sup> <https://lovdata.no/dokument/NL/lov/1990-06-29-50>

enhance energy forecasting, ensuring hydropower plants remain competitive in Norway's evolving energy market.

- Water Resources Act (*Vannressursloven*)<sup>112</sup>: Encouraging Smarter Resource Management
  - This law ensures the sustainable use of water resources, creating opportunities for digital innovation to enhance compliance and operational sustainability:
  - Real-time monitoring incentives: by mandating the protection of aquatic ecosystems and proper water usage, the Act promotes the deployment of Internet of Things (IoT) sensors and Artificial Intelligence (AI) systems. These technologies automate flow monitoring, ensuring that minimum environmental flows are maintained while maximizing energy production.
  - Flood management through automation: provisions for flood risk reduction encourage the use of predictive tools and automated reservoir management systems. These technologies allow hydropower plants to mitigate risks during extreme weather, aligning operational goals with legal responsibilities.
  - Streamlined reporting requirements: the Act's requirements for transparent water usage reporting incentivise digital solutions that automate data collection and submission to the Water Resources and Energy Directorate (NVE), reducing administrative costs and ensuring compliance with high accuracy.
- Nature Diversity Act (*Naturmangfoldloven*)<sup>113</sup>: Encouraging ecosystem-friendly innovation
  - The Nature Diversity Act emphasises biodiversity preservation and ecosystem-based management, creating opportunities for hydropower operators to use digital tools like AI and remote sensing to align operations with legal requirements. For example, AI can support the precautionary principle by reducing uncertainties in environmental impact assessments, while drones and sensors can monitor fish migration or sedimentation, ensuring compliance with the Act's goals.

## 8.5 Best practices on digitalisation of hydropower in Norway

Norway offers several examples of best practices in digitalising its hydropower sector. Few of them are reported in the list below:

- Statkraft's digital twin technology: Statkraft, Norway's largest hydropower company, has adopted digital twins to enhance plant operations. These virtual replicas simulate plant performance, enabling predictive maintenance and real-time optimisation. The use of digital twins has significantly reduced downtime and improved plant efficiency while supporting compliance with environmental and operational regulations. Additionally, in order to increase the efficiency of its renewable assets, Statkraft is exploring other modern sensor technologies, advanced data analyses, algorithms, machine learning and increased automation to provide new insights into the state of their power plants. Examples include Remote Operated Vehicle's (ROV) for inspections of waterways, surveillance drones, creek intakes and dams, injections to reduce cavitation, modelling of components. The goal is to utilise the entire life expectancy of parts and components, while avoiding failures and unplanned downtime at the power plants<sup>114</sup>.
- Artificial Intelligence (AI) in flood management: hydropower plants in flood-prone areas have begun using AI-based predictive models to manage reservoirs during extreme weather events. These systems enable automated adjustments to water levels, reducing flood risks while ensuring sufficient water reserves for energy production. It is thanks to the Norwegian startup 7Analytics<sup>115</sup>, which trains machine learning algorithms on vast quantities of data ranging from weather to land use. The AI then learns to accurately predict how natural disasters will unfold

<sup>112</sup> <https://lovdata.no/dokument/NL/lov/2000-11-24-82>

<sup>113</sup> <https://lovdata.no/dokument/NL/lov/2009-06-19-100>

<sup>114</sup> Statkraft, „What we're working on" (<https://www.statkraft.com/what-we-do/innovation/what-were-working-on/>).

<sup>115</sup> 7Analytics: <https://7analytics.ai/>

and tell you exactly how the water from a rainfall or a storm will travel through a community or to individual assets like buildings or roads<sup>116</sup>.

- NVE's digital platforms for licensing<sup>117</sup>: the Norwegian Water Resources and Energy Directorate (NVE) has implemented digital platforms to streamline licensing and reporting processes. Operators can now submit water flow and environmental data through online systems, simplifying compliance and reducing delays.

## 9 Romania

### 9.1 Overview of energy and electricity sector in Romania

Romania's energy mix is very diverse, encompassing coal, natural gas, nuclear, hydroelectric, and other renewable sources. Historically, coal and natural gas have dominated electricity production, followed by hydroelectric and nuclear power. However, there has been a notable shift towards renewable energy in recent years, with wind and solar power gaining prominence. The country operates two nuclear reactors at the Cernavodă Nuclear Power Plant, which provide a substantial portion of its electricity. Additionally, Romania has significant natural gas reserves and production facilities, making it a key player in the regional natural gas market. Romania also engages in electricity trade with neighbouring countries like Hungary, Bulgaria, Serbia, Ukraine, and Moldova<sup>118</sup>.

Romania has an energy mix based on 71% fossil fuel, which places the country above the level of the EU average (69%). However, when it comes to the electricity mix, renewables are leading with a share of almost 43% (with hydro covering 25.6%), while fossil fuels have a 37.4% quota and nuclear accounts for around 20%<sup>119</sup>.

In November 2024, the Romanian government approved the country's first energy strategy in 17 years up to 2035, identifying energy storage as a key priority. The target for the share of renewable energy in gross final energy consumption is 41.1% by 2035 and 86.1% by 2050, and it will be achieved mainly by increasing the installed capacity of hydro, wind, solar and geothermal energy production, as well as by partial electrification of heating and cooling systems<sup>120</sup>.

Even though in the past years wind energy grew significantly, with many wind farms now operational, and solar energy is becoming increasingly important, especially in the Southern regions, the country still needs to accelerate its clean energy transition. Despite a significant reduction in greenhouse gas emissions since the early 1990s, recent years have seen a stagnation in this decline. The country's reliance on fossil fuels, an aging vehicle fleet, and poorly insulated buildings contribute to higher energy use and carbon intensity<sup>121</sup>.

Legislation and policies will play a key role in order to ensure the shift to a clean energy system. However, there are still many legislative and practical obstacles in the way of efficient development of renewable projects that should be swiftly addressed, such as impediments to large-scale projects, delayed endorsements for wind projects and a lack of grid extensions and enforcements<sup>122</sup>.

On top of the National Energy Strategy mentioned above, relevant national laws include:

- The Energy Law (Law No. 123/2012), regulating the production, transmission, distribution, and supply of electricity and natural gas.

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<sup>116</sup> Sion Geschwindt, 15 May 2024, "Norwegian startup trains AI to predict natural disasters", *The Next Web* (<https://thenextweb.com/news/norwegian-startup-7analytics-training-ai-predict-floods>).

<sup>117</sup> NVE, „Licensing“ (<https://www.nve.no/licensing/>).

<sup>118</sup> US International Trade Administration, "Romania – Country commercial guide: Energy", 2024 (<https://www.trade.gov/country-commercial-guides/romania-energy#:~:text=ANRE%20informs%20that%20in%20Romania,in%20the%20share%20of%20electricity>).

<sup>119</sup> International Energy Agency, "Romania" (<https://www.iea.org/countries/romania/electricity>).

<sup>120</sup> Catalina Mihai, 22 November 2024, "Romanian government approves energy strategy", Euractiv (<https://www.euractiv.com/section/politics/news/romanian-government-approves-energy-strategy/>).

<sup>121</sup> Capozza I., 2024, "Decarbonising Romania's economy", *OECD Economics Department Working Papers*, No. 1812, OECD Publishing, Paris (<https://doi.org/10.1787/256205df-en>).

<sup>122</sup> Anca Rusu, "Energy Laws and Regulations 2025 – Romania" (<https://www.globallegalinsights.com/practice-areas/energy-laws-and-regulations/romania/>).

- The Renewable Energy Law (Law No. 220/2008), promoting the use of renewable energy sources and providing incentives for renewable energy projects.
- The Energy Efficiency Law (Law No. 121/2014), setting out measures to improve energy efficiency across various sectors, including industry, transport, and buildings.

Worth mentioning is Offshore Law, approved in May 2024 after extensive legislative debates, one of the most important legal acts that may influence the Romanian energy mix in the future as it unlocks the offshore wind potential of the Black Sea. While offshore energy is still in its pioneering stage and there are still many milestones to be reached in terms of secondary legislation to enhance the permitting process, grid connection, concession procedures, and the offtake rules, having a primary framework is one of the most relevant moves towards reaching a decarbonised electricity system<sup>123</sup>. Additionally, Romania's National Recovery and Resilience Plan (PNRR), approved by the EU in October 2021 and providing EUR 28.5 billion of funding to the country, focuses on the green transition and on digitalisation, dedicating a substantial component to independence from fossil fuels and promotion of green energy. Among the main measures are the acceleration of energy production from RES, the improvement of energy efficiency, and the retraining of the workforce affected by the transition. The PNRR also aims to strengthen digital infrastructure and to support vulnerable households towards a sustainable energy transition.

In terms of actors in the Romanian energy sector, the main key players are:

- Government and regulatory bodies: the Ministry of Energy develops policies and strategies, while the Romanian Energy Regulatory Authority (ANRE) regulates the market.
- Transmission and distribution operators: Transelectrica manages high-voltage transmission, and Distribution System Operators (DSOs) handle distribution to end-users.
- OPCOM, the energy market operator which oversees market trading and transparency.
- Energy producers and consumers, such as state-owned and private companies, prosumers, and consumers participating in energy production and usage.
- Investors and financial institutions funding energy projects.
- Research and development institutions, non-governmental organisations (NGOs), and industry associations supporting innovation and advocacy<sup>124</sup>.

In parallel, the digital transformation has gained political importance in Romania over the last few years, and currently benefits from significant amounts of EU funding. Romania dedicates 21.8% of its total Recovery and Resilience Plan to digital (EUR 5.8 billion). Under Cohesion Policy, an additional EUR 3 billion (10% of Romania's total Cohesion Policy funding) is allocated to the country's digital transformation<sup>125</sup>. The recently approved National Action Plan for the Digital Decade for Romania<sup>126</sup> provides the strategic framework to guide the country's digital transformation by 2030, while the dedicated Authority for the Digitalisation of Romania (ADR), under the Ministry of Research, Innovation, and Digitalisation, leads the country's digital transformation efforts. It focuses on implementing digital government initiatives, such as the government cloud and national interoperability platform.

<sup>123</sup> *Ibidem*.

<sup>124</sup> ICLG, "Renewable Energy Laws and Regulations", 2025 (<https://iclg.com/practice-areas/renewable-energy-laws-and-regulations/romania>).

<sup>125</sup> Authority for the Digitalisation of Romania, "Report on the state of the Digital Decade 2024", 2024 (<https://www.adr.gov.ro/wp-content/uploads/2024/10/Report-on-Digital-Decade-2024-Romania-Executive-Summary.pdf>).

<sup>126</sup> PNADD cu-obs-integrate-30-sept-2024.docx

## 9.2 Hydropower in Romania

Hydropower is the main source of electricity generation in Romania, accounting for 25.6% of total generation in 2022<sup>127</sup>, corresponding to around 6.6 GW and 15 TWh of energy produced. There are between 545 and 674 hydropower plants in the country, but there are no official and complete numbers available<sup>128</sup>.

The first hydropower plant of the country was established in 1884 on the Peles river to lighten the gardens of Peles Castle, the summer residence of the kings of Romania. The main period of hydroelectric development occurred between 1950 and 1990, during which 115 hydropower stations were built with state support. Since the fall of the Communist regime in 1989, hydropower development has primarily been driven by private investors and suppliers, heavily subsidised by the state since 2008. By 2015, Romania had around 200 large hydropower plants with a total installed capacity of 6443 MW, and approximately 466 small hydropower plants (less than 10 MW) with a total capacity of 586 MW<sup>129</sup>.

All large hydropower plants (defined as hydropower plants with installed capacity >10 MW) in the country are operated by HIDROELECTRICA, a public company owned for 80% by the Romanian government, while the small hydropower plants are mostly privately owned. Hidroelectrica is now planning expansion and modernisation of infrastructure (including 714 MW of new hydropower)<sup>130</sup>.

Small hydropower plants, even though they make up 70% of all hydropower plants in number, produce about 2000 GWh/year, representing only 11.1% of total hydropower and 3.1% of Romania's total electricity production<sup>131</sup>.

The recent surge in small hydropower plant construction (2010–2014) was driven by the implementation of the EU Renewable Energy Directive, supported by substantial subsidies from EU funds and national funds allocated under Law No. 220/2008 (the Romanian Renewable Energy Law). These subsidies were available during the 2007–2013 programming period but were eliminated in the 2014–2020 period. However, "green certificates" continued to be allocated by the Romanian state, financed by a fee on final energy consumers. These subsidies will remain available until 2030 for plants commissioned by December 2016<sup>132</sup>.

Nevertheless, as climate change becomes more and more manifest, the volume of water resources available for hydropower production is expected to decrease. Climate change forecasts indicate a shift towards a drier climate in many parts of Europe, and Romania is considered highly vulnerable to climate change<sup>133</sup>. Several droughts (i.e. the one in 2022, the most severe ever recorded in the country) have already shown the impact of climate change on water supplies, hydropower generation (which dropped to a historical low), agricultural production and waterway navigation. As a result of climate change, a decrease between 11 and 30% of electricity generated from hydropower is expected to affect Romania by 2050<sup>134</sup>. Moreover, extreme floods may impact hydropower generation by

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<sup>127</sup> International Energy Agency, "Romania" (<https://www.iea.org/countries/romania/electricity>).

<sup>128</sup> G. Costea, M. T. Pusch, D. Bănăduc, D. Cosmoiu, A. Curtean-Bănăduc, "A review of hydropower plants in Romania: Distribution, current knowledge, and their effects on fish in headwater streams", 2021, *Renewable and Sustainable Energy Reviews* (<https://doi.org/10.1016/j.rser.2021.111003>).

<sup>129</sup> These figures might be underestimated due to the lack of reliable official statistics on the total number of hydropower plants and their operational status.

<sup>130</sup> World Bank Group, „Country Climate and Development Report – Romania”, 2023 (<https://www.presidency.ro/files/userfiles/CCDR%20Romania%2C%20Fall%202023.pdf>).

<sup>131</sup> G. Costea, M. T. Pusch, D. Bănăduc, D. Cosmoiu, A. Curtean-Bănăduc, "A review of hydropower plants in Romania: Distribution, current knowledge, and their effects on fish in headwater streams", 2021, *Renewable and Sustainable Energy Reviews* (<https://doi.org/10.1016/j.rser.2021.111003>).

<sup>132</sup> *Ibidem*.

<sup>133</sup> Romania ranks #89 in the ND- GAIN Country Index, which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience (<https://gain-new.crc.nd.edu/ranking>).

<sup>134</sup> G. Costea, M. T. Pusch, D. Bănăduc, D. Cosmoiu, A. Curtean-Bănăduc, "A review of hydropower plants in Romania: Distribution, current knowledge, and their effects on fish in headwater streams", 2021, *Renewable and Sustainable Energy Reviews* (<https://doi.org/10.1016/j.rser.2021.111003>).

damaging storage reservoirs and power plants, as well as by making it necessary to use reservoirs for flood control purposes<sup>135</sup>.

### 9.3 Challenges and barriers to the digitalisation of hydropower in Romania

Digitalisation in the Romanian energy sector is still in its early stages compared to other EU countries. Investments in new technologies are still sporadic and often depend on external funding. Many components of Romania's energy infrastructure are technologically outdated, making the integration of digital solutions complex and costly. Finally, there is a skills gap in new technologies among the workforce in the energy sector.

When it comes to the hydropower sector, similarly to the situation in other EU countries, the country's aging infrastructure is in need of modernisation. Hidroelectrica own older assets, most of which require an upgrade or need to be decommissioned<sup>136</sup>. Nevertheless, the utility is aware of the weaknesses of its plants and plans maintenance, refurbishment and modernisation projects, and installation of state-of-the-art surveillance equipment, with a total estimated value of more than €600 million. Such measures will allow the facilities in Hidroelectrica's portfolio to achieve environmental standards in line with EU requirements<sup>137</sup>.

### 9.4 Potential and opportunities for the digitalisation of hydropower in Romania

Romania has approximately 24,700 kilometres of watercourses, including 1,245 kilometres along the Danube River. The Siret, Mures, and Olt rivers are the hydrographic basins with the highest potential, after the Danube. Mountain areas contribute to about 80% of the total potential of inland rivers thanks to their abundant flows and steep slopes. Thanks to its favourable hydro-morphological features, Romania boasts significant hydropower potential, yet experts estimate that only 40% of it is currently being utilised<sup>138</sup>. The figure is even higher if we only look at small hydropower: annual electric energy produced by small hydropower plants may be roughly estimated to be about 2000 GWh/year, while the estimated total small-hydro potential of Romania is about 4000 GWh/year<sup>139</sup>.

On top of the modernisation measures already being undertaken by Hidroelectrica on its portfolio (see previous chapter), the construction of new facilities based on the untapped hydropower potential of the country, and the development of new pumped storage capacity based on the prioritisation of storage according to Romania's national energy strategy, offer therefore a great opportunity for the digitalisation of the sector.

### 9.5 Best practices on digitalisation of hydropower in Romania: Hidroelectrica's refurbishment plans

Hidroelectrica has recently launched procurement procedures for major retrofitting projects of its hydropower facilities, such as the modernisation of electrical substations related to the hydropower plants, the retrofitting of the Vidraru plant, of the Brădişor plant, and of the high-capacity energy pumping stations in Lotru HPP scheme. These procedures, to be carried out as of 2024 will play an important role in the digitalisation process of the hydro sector in Romania.

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<sup>135</sup> World Bank Group, „Country Climate and Development Report – Romania”, 2023

(<https://www.presidency.ro/files/userfiles/CCDR%20Romania%2C%20Fall%202023.pdf>).

<sup>136</sup> World Bank, “Romania Systematic Country Diagnostic”, 2018

(<https://documents1.worldbank.org/curated/en/163231530905789689/pdf/128059-SCD-PUBLIC-P160439-RomaniaSCDBackgroundNoteEnergy.pdf>).

<sup>137</sup> B. Badea, E. Crisan, I. Iacob, D. Iordanescu, B. Popa, C. Popescu, “Hydropower in Romania: current strategies and future projects”, 2021, *The International Journal on Hydropower and Dams* (<https://www.hydropower-dams.com/articles/hydropower-in-romania-current-strategies-and-future-projects/>).

<sup>138</sup> A. Axenia, 2025, „Hydropower in Romania: Cooperation is Key to the Future of Energy”

(<https://eea.innovationnorway.com/article/hydropower-in-romania-cooperation-is-key-to-the-future-of-energy>).

<sup>139</sup> G. Costea, M. T. Pusch, D. Bănăduc, D. Cosmoiu, A. Curtean-Bănăduc, “A review of hydropower plants in Romania: Distribution, current knowledge, and their effects on fish in headwater streams”, 2021, *Renewable and Sustainable Energy Reviews* (<https://doi.org/10.1016/j.rser.2021.111003>).

Additionally, in 2023, the company's Project Management Department managed a project on Information Technology and Digitalisation. The project focuses on an integrated information system for recording and processing information received, generated, and transmitted within the Hidroelectrica – DMS (Document Management System) workflows.

An additional example of best practices in the country come from Balkan Hydroenergy SRL (RO), a company based in Timisoara, Mures County. The company aimed to boost its development and economic competitiveness by upgrading existing equipment with advanced technologies. The project increased the power output for five of six small hydro facilities and improved energy efficiency by up to 15%. Investing in enhanced communication infrastructure also provides real-time data for quick maintenance and operational decisions, giving Balkan Hydroenergy a competitive market edge. The refurbishment also reduces environmental risks from potential accidents. Additional innovative solutions for connecting dispatchers with power plants and improving security and monitoring were provided by the Norwegian company City AS<sup>140</sup>.

## 10 Spain

### 10.1 Overview of energy and electricity sector in Spain

In 2022, Spain relied on imports for 77.8% of its total energy supply, the fifth highest dependency among EU Member States. Due to the current geopolitical situation, Spain plans to leverage its renewable energy potential to cut this import share to 50% by 2030<sup>141</sup>. Within this context, the green transition is progressing at an intense rate in Spain. Renewable energy sources contributed 56% to the electricity mix in 2024 with an 11% increase in production compared to the previous year (a national record) and a capacity of 149 Terawatt hours (TWh)<sup>142</sup>. This rise in renewable energies is crucial to achieving the objective of representing 81% of the national electricity supply by 2030. The first RES in electricity generation in Spain in 2023 was wind (accounting for 22.5% of electricity generated), followed by solar PV (15.1%) and hydro (10.9%)<sup>143</sup>.

In February 2019, the Spanish government introduced a strategic energy and climate framework, which includes a climate law, the National Energy and Climate Plan (NECP), and a just transition strategy.

In May 2021, Spain enacted the Climate Change and Energy Transition Law<sup>144</sup>, aiming for climate neutrality by 2050 and setting energy and climate targets for 2030, subject to regular review. The latest update of the NECP in 2024 projects an 81% RES share in electricity generation by 2030, and a 48% RES share in final energy consumption, well above Spain's indicative 43% share resulting from EU legislation. The law also incorporates sector-specific regulations, such as halting new licenses for oil and gas exploration and extraction. It designates the NECP as the primary climate planning tool, adhering to the EU's Governance Directive. Additionally, the law established a Citizens' Climate Assembly, which presented its recommendations in May 2022<sup>145</sup>.

The 2019 just transition strategy sets up a regulatory framework for State aid related to coal mine closures, covering exceptional costs and support for mining areas. The Just Transition Institute coordinates this effort through agreements with the affected regions.

Additionally, the National Energy Efficiency Fund (FNEE) is designed to finance economic and financial support mechanisms, technical assistance, training, information, and other measures aimed at

<sup>140</sup> A. Axenia, 2025, „Hydropower in Romania: Cooperation is Key to the Future of Energy”

(<https://eea.innovationnorway.com/article/hydropower-in-romania-cooperation-is-key-to-the-future-of-energy>).

<sup>141</sup> European Parliamentary Research Service, “Spain’s climate action strategy”, 2024 ([https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/767171/EPRS\\_BRI\(2024\)767171\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/767171/EPRS_BRI(2024)767171_EN.pdf)).

<sup>142</sup> Ignacio J. Domingo, 25/02/2025, “Advances in renewable energy and the rise of Green Hydrogen in Spain” ([https://www.moeveglobal.com/en/planet-energy/green-energy/spain-renewable-energy-transition-green-hydrogen#:~:text=The%20green%20conversion%20is%20progressing,149%20Terawatt%20hours%20\(TWh\).](https://www.moeveglobal.com/en/planet-energy/green-energy/spain-renewable-energy-transition-green-hydrogen#:~:text=The%20green%20conversion%20is%20progressing,149%20Terawatt%20hours%20(TWh).))

<sup>143</sup> International Energy Agency, “Spain” (<https://www.iea.org/countries/spain/electricity>).

<sup>144</sup> Spain’s Climate Change and Energy Transition Law, 2021 (<https://www.boe.es/buscar/act.php?id=BOE-A-2021-8447>).

<sup>145</sup> European Parliamentary Research Service, “Spain’s climate action strategy”, 2024 ([https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/767171/EPRS\\_BRI\(2024\)767171\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/767171/EPRS_BRI(2024)767171_EN.pdf)).

enhancing energy efficiency across various energy-consuming sectors. These efforts contribute to meeting the targets set by the National System of Energy Efficiency Obligations (SNOEE), in line with the Energy Efficiency Directive (Art. 7, EED 2018/2002/EU, Art. 8, EED 2023/1791/EU). The Fund is overseen by the Ministry for the Ecological Transition and Demographic Challenge (MITERD) through the Secretary of State for Energy and is managed by the Institute for Energy Diversification and Saving (IDAE)<sup>146</sup>.

In terms of digitalisation, Spain has implemented several policies and initiatives to drive digital transformation across various sectors. The main one is the Digital Spain 2026<sup>147</sup>. Launched in 2020, this agenda aims to enhance competitiveness, economic growth, and societal welfare through digital transformation across various sectors, including energy. It focuses on infrastructure and technology, digitalizing the economy, and improving digital skills among the population. Efforts to digitalise the energy sector are also present: in March 2025, the Spanish Association of Electricity Companies (aelēc) and the Spanish Association for Digitalisation (DigitalES), have signed a collaborative agreement to promote innovation and digitalisation in the energy sector. The agreement puts the basis for the development of joint projects in areas including the deployment of connectivity and the integration of innovative technology solutions and tools in the respective sectors of the two associations<sup>148</sup>.

## 10.2 Hydropower in Spain

Spain is a country with high hydropower potential, developed over more than 100 years. Today, its hydro generation system is among the most efficient globally, leveraging the country's topography and numerous dams. This makes hydroelectric energy one of the most established and mature renewable sources in Spain's energy mix.

Hydroelectric power was the primary electricity source in Spain for much of the 20<sup>th</sup> century. The first hydroelectric power station was built in Barcelona in 1881, marking the start of an era of innovation in electricity generation. The development of technologies like alternating current greatly improved the ability to transport electricity over long distances, making hydroelectric power a viable and competitive option nationwide. In the mid-20<sup>th</sup> century, the construction of large reservoirs, such as those at Aldeadavila on the Duero River and the Alcántara reservoir on the Tagus, enabled the supply of a significant portion of the country's electricity demand. These reservoirs became key components of the energy system due to their generation capacity and role in regulating water flows<sup>149</sup>.

Although hydroelectric production has seen a relative decline compared to other renewable energies in recent years, its strategic importance and ability to complement wind and solar energy keep it central to the energy transition. Spain has a total reservoir capacity of 55,000 hm<sup>3</sup>, with approximately 40% dedicated to hydroelectric generation – a significant proportion at both European and global levels. Larger power plants are crucial for balancing the country's energy needs, especially to offset the intermittency of other renewable sources like wind and solar.

Currently, Spain has an installed hydroelectric capacity of 17,792 MW, representing 19.5% of the national total. The regions with the highest installed capacity are Catalonia, Galicia, and Castile and Leon, due to their abundant water resources. This capacity is distributed across more than 800 hydroelectric plants of various sizes, with 75% being run-of-river plants<sup>150</sup>. The key players in the Spanish hydropower sector are Iberdrola (operating over 120 plants with more than 11,000 MW of

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<sup>146</sup> Odyssee-Mure, “Spain profile” (<https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/spain.html>).

<sup>147</sup> España Digital 2026 (<https://espanadigital.gob.es/en/implementation-agenda>).

<sup>148</sup> Jonathan Spencer Jones, 07/03/2025, “Spanish industry associations partner on digitalisation in the energy transition”, *Smart Energy International* (<https://www.smart-energy.com/industry-sectors/digitalisation/spanish-industry-associations-partner-on-digitalisation-in-the-energy-transition/>).

<sup>149</sup> Tomàs Bigordà, 12/11/2024, “The legacy of hydroelectric energy in Spain: History and future”, *Renovables Verdes* (<https://en.renovablesverdes.com/the-largest-hydroelectric-plants-in-spain/>).

<sup>150</sup> *Ibidem*.

installed capacity<sup>151</sup>), Endesa and Naturgy, which together own almost 90% of the installed hydropower capacity in the country<sup>152</sup>.

Among the largest plants, 20 have an installed capacity of over 200 MW, collectively accounting for 50% of the total hydroelectric capacity. Additionally, small hydropower plants are spread throughout Spain, providing electricity to remote areas with minimal environmental impact<sup>153</sup>.

Spain has a low vulnerability to climate change<sup>154</sup>. Adaptation challenges still exist, but the country is well positioned to adapt. Nevertheless, droughts caused by climate changes could severely affect the sector by reducing generation from hydropower, as happened already in 2016-2017 when a severe drought in Western Europe curtailed Spanish hydropower output by as much as 50%, pushing electricity prices to an all-time high and raising greenhouse gas emissions, as fossil fuel-fired generators compensated for the lost hydropower<sup>155</sup>.

Hydropower remains a vital part of Spain's energy tradition. Despite its reduced prominence with the rise of other renewable energies, it continues to be a cornerstone of the electricity sector, both for its clean energy generation and its stabilising role in the national electricity system.

### 10.3 Challenges and barriers to the digitalisation of hydropower in Spain

The hydropower sector in Spain faces challenges which are common to other EU Member States, such as long permitting process and compliance with highly demanding environmental standards<sup>156</sup>. Common are also the barriers limiting the digital transformation of the sector. First, regulatory uncertainty surrounding concessions and water rights (many of which are due for renewal or renegotiation) makes long-term investment planning difficult for operators. Second, despite progress in broader energy digitalisation policies, there is limited dedicated support for digital retrofitting in hydropower. In fact, while Spain has introduced measures to enhance digital innovation in electricity grids and smart metering, specific strategies to support the integration of digital tools in hydropower plants are largely lacking.

Challenges also arise from the decentralised nature of water resource governance, which involves multiple regional authorities and complicates the implementation of standardised solutions across the country.

### 10.4 Potential and opportunities for the digitalisation of hydropower in Spain

Spain is a country with high hydropower potential. Hydropower capacity is expected to continue to grow at a moderate rate of 40 to 60 MW per year and the sustainable economic potential is in the range of more than 1 GW, reflecting the room for growth that this technology still has<sup>157</sup>. In this regard, the most promising proposals focus on the modernisation and rehabilitation of existing plants, to improve their performance. Similarly, there is a commitment to pumped storage plants, which can store energy and release it when demand increases, contributing to the stability of the electricity grid. Spain presents strong opportunities for the digital transformation of its hydropower sector. With a large number of plants built in the 1960s and 1970s, there is significant scope for modernisation

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<sup>151</sup> Iberdrola Spain, „Iberdrola España's decisive role in the development and production of hydroelectric power in the country” (<https://www.iberdrolaespana.com/about-us/business-lines/hydroelectric-power>).

<sup>152</sup> Juan I. Pérez-Díaz, 09/09/2019, “Key challenges for hydropower in Spain”, presentation at EERA JP Hydropower kick-off event ([https://www.eera-set.eu/component/attachments/?task=download&id=295:JPerez\\_Key-Challenges-for-Hydropower-in-Spain](https://www.eera-set.eu/component/attachments/?task=download&id=295:JPerez_Key-Challenges-for-Hydropower-in-Spain)).

<sup>153</sup> Tomàs Bigordà, 12/11/2024, “The legacy of hydroelectric energy in Spain: History and future”, *Renovables Verdes* (<https://en.renovablesverdes.com/the-largest-hydroelectric-plants-in-Spain/>).

<sup>154</sup> Spain ranks #27 in the ND- GAIN Country Index, which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience (<https://gain-new.crc.nd.edu/country/spain>).

<sup>155</sup> International Energy Agency, “Spain Climate Resilience Policy Indicator” (<https://www.iea.org/articles/spain-climate-resilience-policy-indicator>).

<sup>156</sup> Juan I. Pérez-Díaz, 09/09/2019, “Key challenges for hydropower in Spain”, presentation at EERA JP Hydropower kick-off event ([https://www.eera-set.eu/component/attachments/?task=download&id=295:JPerez\\_Key-Challenges-for-Hydropower-in-Spain](https://www.eera-set.eu/component/attachments/?task=download&id=295:JPerez_Key-Challenges-for-Hydropower-in-Spain)).

<sup>157</sup> Tomàs Bigordà, 12/11/2024, “The legacy of hydroelectric energy in Spain: History and future”, *Renovables Verdes* (<https://en.renovablesverdes.com/the-largest-hydroelectric-plants-in-Spain/>).

through digital retrofits. Technologies such as real-time monitoring, advanced control systems, predictive maintenance, and digital twins could play a vital role in extending the lifespan of existing plants and optimising operations. Furthermore, the increasing integration of variable renewable energy sources into the grid creates an incentive for digitally enhanced hydropower, particularly to provide ancillary services and flexibility. The deployment of smart automation tools could also support water resource management under drought conditions, optimising water use across multiple objectives, including energy, irrigation, and environmental flows.

The promotion of digital solutions is also aligned with Spain's broader digitalisation strategy, "España Digital 2026", which includes initiatives for digital infrastructure and data-driven innovation. By integrating hydropower into these national digital efforts, synergies could be realised with other sectors, including agriculture and civil protection.

Finally, the Strategic Project for Economic Recovery and Transformation (PERTE) for Water Cycle Digitalisation, approved in 2022, aims to mobilise 3.06 billion euros from the Recovery and Resilience Facility to enhance the efficiency and sustainability of the urban water cycle through digital transformation<sup>158</sup>. Even though the initiative is not directly targeted at hydropower, it can generate positive spillover effects on the hydropower sector (thanks to the enhanced water management, data integration and infrastructure upgrades).

### 10.5 Best practices on digitalisation of hydropower in Spain

Some Spanish utilities have already taken steps to embrace digital technologies. In 2021, the Spanish Iberdrola signed an agreement with the Norwegian company Volue to digitalise its hydropower production planning through Volue's software. This digitalisation journey is intended to enhance the management of the utility's hydropower plants by putting in place a solution to support the market bidding and dispatching processes that unlocks the flexibility of the generation portfolio and boosts the digitalisation that the energy management processes require in the green transition. Through a standard software suite, Iberdrola will be able to optimally manage the production of its hydropower plants across all the power markets in Spain<sup>159</sup>.

Another promising initiative is Endesa's project to create digital twins of its hydroelectric plants, to improve their operation, management and maintenance. These digital twins allow personnel and suppliers to conduct virtual visits to the plants, viewing installed equipment and infrastructure. The initiative began with a pilot at the El Pintado plant in Seville in 2023, utilizing 360° cameras and lidar technology to create a high-resolution 3D model. This project has since expanded to nine other plants. The system also integrates relevant documentation, such as plans, photographs, diagrams, manuals, and databases, linked to individual equipment and systems for easy access. Additionally, a "diagnostic twin" has been developed, which receives over 6,000 real-time data points, including temperature, pressure, speed, and vibration. This allows for future value estimation and alerts if input values deviate from projected ranges<sup>160</sup>.

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<sup>158</sup> PERTE for Water Cycle Digitalisation ([https://commission.europa.eu/projects/perte-digitalization-water-cycle-development-projects-improve-efficiency-urban-water-cycle\\_en#:~:text=DEVELOPMENT%20OF%20PROJECTS%20TO%20IMPROVE%20THE%20EFFICIENCY%20OF%20THE%20URBAN%20WATER%20CYCLE,-Copyright%3A%20Ministry%20of&text=With%20over%20EUR%20200%20million,of%20the%20urban%20water%20cycle.](https://commission.europa.eu/projects/perte-digitalization-water-cycle-development-projects-improve-efficiency-urban-water-cycle_en#:~:text=DEVELOPMENT%20OF%20PROJECTS%20TO%20IMPROVE%20THE%20EFFICIENCY%20OF%20THE%20URBAN%20WATER%20CYCLE,-Copyright%3A%20Ministry%20of&text=With%20over%20EUR%20200%20million,of%20the%20urban%20water%20cycle.)).

<sup>159</sup> Elizabeth Ingram, 10/05/2023, "Iberdrola to digitalize hydropower production planning with Volue's software", *Renewable Energy World* (<https://www.renewableenergyworld.com/hydro-power/technology-equipment/iberdrola-to-digitalize-hydropower-production-planning-with-volues-software/>).

<sup>160</sup> Jonathan Spencer Jones, 30/01/2024, "Endesa models hydroelectric plants with digital twins", *Power Engineering International* (<https://www.powerengineeringint.com/digitalization/endesa-models-hydroelectric-plants-with-digital-twins/>).

# 11 Digitalisation of hydropower in Africa, Central Asia, and South America

## 11.1 Africa: Focus on Ethiopia

### Hydropower in Ethiopia

Hydropower is a cornerstone of Africa's electricity supply, contributing 40% of the power in the Sub-Saharan region. Despite this, nearly 90% of the continent's hydropower potential remains untapped, representing the largest proportion of unexploited capacity globally. As energy demand rises, harnessing this potential will be essential for expanding Africa's energy sector and achieving net zero targets<sup>161</sup>.

In 2022, Africa's hydropower capacity grew by 2.6 GW, reaching 37.7 GW and generating at least 150 TWh<sup>162</sup>. However, this progress falls significantly short of what is required to meet energy goals. Development of hydropower is hindered by ongoing regulatory and market challenges, resulting in a backlog of projects that have received permission but have not commenced construction. These obstacles can lead to delays or cancellations, directly impacting decarbonisation efforts. Private investment is crucial in advancing hydropower projects across the continent<sup>163</sup>.

Hydro is by far the main source of electricity generation in Ethiopia (96.7%), with 16.770 GWh being generated in 2022<sup>164</sup>. With a total installed capacity of 4,824 MW, Ethiopia is the first country in Africa in terms of installed capacity<sup>165</sup>. However, the country has one of the lowest levels of annual energy consumption per capita in the world (944 kWh in 2020<sup>166</sup>) and only 55% of the population had access to electricity in 2022<sup>167</sup>.

Development of hydropower started in the early 1930s with the first Aba Samuel dam commissioned in 1932 with an installed capacity of 6.6 MW. After that, the country has not made significant progress in hydropower development up until the last decade when the construction of dams saw a significant boom<sup>168</sup>. Nevertheless, climate change is posing significant risks to the sector: in 2022, drought affected primarily Central and East Africa, and Ethiopia, Kenya and Somalia experienced between 30-60% less rainfall from October to December – the region's longest and most severe drought on record<sup>169</sup>. Diversification of the generation mix (in favour of solar, wind and geothermal), will be key to pursue a more climate-resilient power system and reach economic development objectives<sup>170</sup>.

The Ethiopian energy sector, including hydropower, is governed by the Energy Proclamation No.810/2013 (as amended) and the Council of Ministers Energy Regulation No.447/2019. Additionally, the Ethiopian Energy Authority (EEA), the sector's regulator, issues various directives, codes, and standards that apply to investors in the hydropower market. The Energy Proclamation establishes the regulatory framework for energy generation, transmission, and distribution, while the Energy Regulation details the consent and permit procedures and provides guiding principles on tariffs. These regulations outline the substantive and procedural rules for businesses in the energy sector, including hydropower.

<sup>161</sup> International Hydropower Association, "Hydropower in Africa" (<https://www.hydropower.org/region-profiles/africa>).

<sup>162</sup> REN21, 2023, "Renewables 2023 Global Status Report" (<https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023-Energy-Supply-Module.pdf>).

<sup>163</sup> International Hydropower Association, "Hydropower in Africa" (<https://www.hydropower.org/region-profiles/africa>).

<sup>164</sup> International Energy Agency, "Ethiopia" (<https://www.iea.org/countries/ethiopia/electricity>).

<sup>165</sup> International Hydropower Association, "World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero", 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

<sup>166</sup> TRAIDE Ethiopia, "Challenges encountered by hydro-power dams in Ethiopia and associated business opportunities", 2023 (<https://traide.org/wp-content/uploads/Hydropower-BOR-TRAIDE-foundation.pdf>).

<sup>167</sup> World Bank Group, 24/01/2025, "Lighting Up Eastern Africa: How Greater Access to Energy is Creating Jobs and Improving Public Services in Rural Ethiopia" (<https://www.worldbank.org/en/news/feature/2025/01/24/lighting-up-eastern-africa-access-to-energy-afe-rural-ethiopia#:~:text=As%20part%20of%20the%20country's,from%20just%2020%25%20in%202015>).

<sup>168</sup> International Hydropower Association, "2018 Hydropower Status Report", 2018 (<https://www.hydropower.org/publications/2018-hydropower-status-report>).

<sup>169</sup> REN21, 2023, "Renewables 2023 Global Status Report" (<https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023-Energy-Supply-Module.pdf>).

<sup>170</sup> International Energy Agency, "Ethiopia" (<https://www.iea.org/countries/ethiopia/electricity>).

As for water legislation, in 1999 Ethiopia introduced the Federal Water Resource Management Policy, aimed at enhancing and promoting national efforts towards the efficient, equitable, and optimal utilisation of Ethiopia's water resources for significant socioeconomic development on a sustainable basis. This policy sets the general framework for the utilisation, protection, and management of water resources. Specifically, the hydropower policy, as outlined in part 2.3.3.1 of the Policy, aims “to enhance efficient and sustainable development of the water resources and meet the national energy demands as well as cater [to] external markets to earn foreign exchange”<sup>171</sup>.

Even though Ethiopia ranks in the first position among the top countries in Africa by capacity added in 2022 (with 750 MW of added capacity)<sup>172</sup>, the country still has an estimated exploitable hydropower potential of 45,000 MW, with approximately 30,000 MW of hydropower production at various sizes estimated to be economically feasible, generating 162 TWh of electricity. In fact, the country produces only about 10% of its economically feasible hydropower generation potential, corresponding to around 16TWh of generated capacity, which is clearly insufficient to serve a population of more than 125 million people<sup>173</sup>.

More than half of this potential located in the Abbay and Omoriver basins. These basins are home to Ethiopia's largest hydropower projects, including the nearly completed 6,450 MW Grand Ethiopian Renaissance Dam (GERD) and the 1,870 MW Gibe III project. Once fully operational, GERD will be the largest hydropower project in Africa. However, its development is controversial due to potential impacts on neighbouring Egypt and Sudan, both of which rely heavily on the Nile River for their water needs. The schedule for filling the reservoir and the operational management of the plant remain contentious issues<sup>174</sup>.

Additionally, Ethiopia has about 17 identified sites of hydropower potential sites ranging from 60 MW to 2,000 MW in the pipeline and expected to be largely developed by the private sector as independent power producers (IPPs)<sup>175</sup>. In fact, even if currently Ethiopian Electric Power (EEP), the state-run electricity producer, owns and operates 14 hydropower stations across the country (including GERD), going forward IPPs are expected to play a greater role in the hydropower sector as EEP focuses more on the existing facilities<sup>176</sup>.

Small hydropower could also play a significant role in the country, as it is best suited for rural areas with no grid access. Ethiopia has in fact a total theoretical potential for small hydropower schemes of about 100 MW<sup>177</sup>.

#### Digitalisation of hydropower in Ethiopia

As in the rest of the world, hydropower plants in Africa are also aging, and some countries in the continent rely for most of their electricity on those aging plants. Modernisation programmes are therefore crucial to accelerating the continent’s transition to clean energy and are urgently needed as 60 per cent of hydropower facilities in Africa are over 20 years old<sup>178</sup>.

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<sup>171</sup> Addleshaw Goddard, “An Investor’s Guide to Hydropower in Africa” (<https://www.addleshawgoddard.com/globalassets/insights/energy/investors-guide-to-hydropower-in-africa.pdf>).

<sup>172</sup> International Hydropower Association, “World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero”, 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

<sup>173</sup> Ashebir Dingeto Hailu, „Ethiopia Hydropower Development and Nile Basin Hydro Politics, 2021, *AIMS Energy* (<https://www.aimspress.com/article/doi/10.3934/energy.2022006?viewType=HTML>).

<sup>174</sup> Addleshaw Goddard, “An Investor’s Guide to Hydropower in Africa” (<https://www.addleshawgoddard.com/globalassets/insights/energy/investors-guide-to-hydropower-in-africa.pdf>).

<sup>175</sup> International Hydropower Association, “2018 Hydropower Status Report”, 2018 (<https://www.hydropower.org/publications/2018-hydropower-status-report>).

<sup>176</sup> Addleshaw Goddard, “An Investor’s Guide to Hydropower in Africa” (<https://www.addleshawgoddard.com/globalassets/insights/energy/investors-guide-to-hydropower-in-africa.pdf>).

<sup>177</sup> Ashebir Dingeto Hailu, „Ethiopia Hydropower Development and Nile Basin Hydro Politics, 2021, *AIMS Energy* (<https://www.aimspress.com/article/doi/10.3934/energy.2022006?viewType=HTML>).

<sup>178</sup> International Hydropower Association, 10/07/2023, “Africa’s hydropower modernisation opportunities” (<https://www.hydropower.org/blog/mapping-africas-hydropower-potential>).

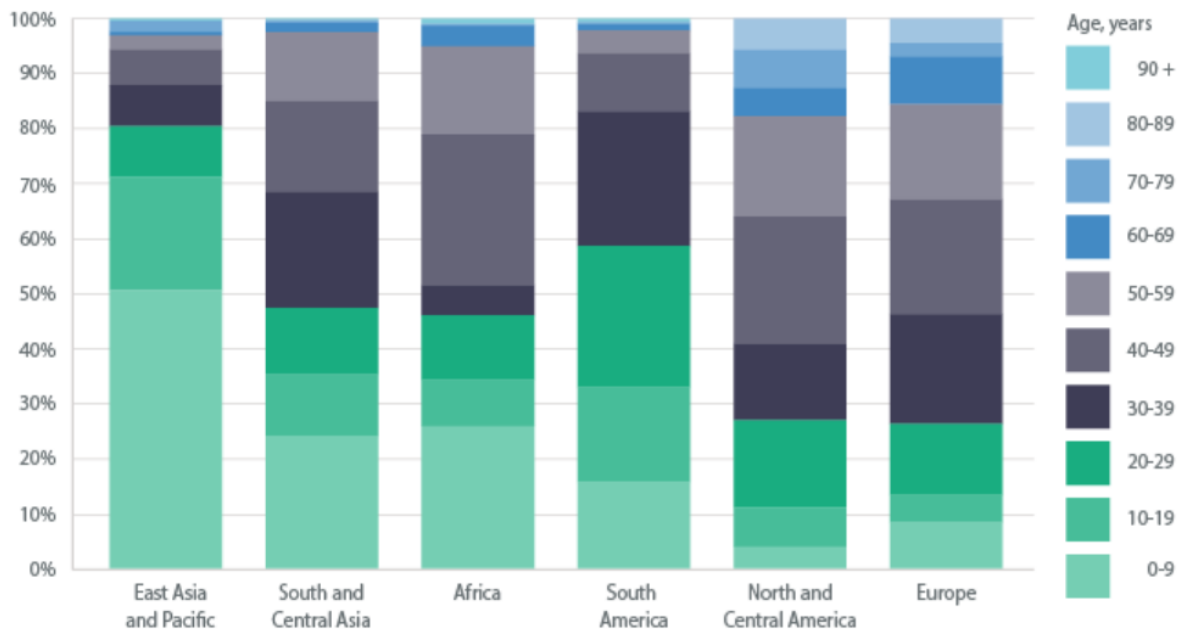


Figure 11 Age profile of installed hydropower capacity, 2022. Source: International Hydropower Association, "World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero", 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

Aging technology can cause mechanical issues that slow down the efficiency of operations and electricity production. According to the International Hydropower Association (IHA)<sup>179</sup>, in East Africa, where Ethiopia is located, 6 hydropower plants (corresponding to 938 MW of installed capacity in the region) are in medium need for modernisation<sup>180</sup>, while 7 of them (corresponding to 625 MW of installed capacity in the region) are in high need of modernisation<sup>181</sup>. Ethiopia has a number of existing hydro facilities in need of modernisation that play a major role in the Eastern Africa Power Pool (EAPP) and the country alone has more than 100 MW of ageing hydropower<sup>182</sup>.

Modernisation of the hydropower sector goes hand in hand with digitalisation. The digitalisation of hydropower technologies and operation and maintenance practices is in fact well-established in many mature energy markets, becoming a cornerstone of modernisation programmes. These projects now incorporate new digital controls, intelligent condition monitoring systems, remotely operated systems, and supervisory control and data acquisition systems to enhance the operation and management of existing stations<sup>183</sup>.

A recent publication by the Policy Center for the New South<sup>184</sup> highlights that digitalisation is crucial for unlocking Africa's renewable energy potential, addressing the continent's low electrification rates. Modernisation projects for existing hydropower assets must therefore integrate digitalisation into their designs to ensure optimal performance.

Best practices on the digitalisation of the hydropower sector are already available in Ethiopia: in January 2021, it was announced that Voith Hydro's digital solutions are to be installed at the Gilgel

<sup>179</sup> African Development Bank Group, "Africa Hydropower Modernisation Programme", 2023 ([https://www.afdb.org/sites/default/files/documents/publications/hydropower\\_modernisation\\_report.pdf](https://www.afdb.org/sites/default/files/documents/publications/hydropower_modernisation_report.pdf)).

<sup>180</sup> According to the report, "Medium need" means that plants are running old technologies but not experiencing major mechanical problems limiting their production, or that plants are partially compromised and running at somewhat reduced capacity because of a specific electrical, mechanical or civil issue, regardless of age.

<sup>181</sup> According to the report, "High need" means that plants are running old technology (30y+) and are currently experiencing repetitive outages or mechanical issues limiting their productivity (e.g. unit(s) out of service, safety issues, repetitive forced outages), or that plants are severely compromised with several (or all) units out of service and/ or incapable of producing at all, regardless of their age.

<sup>182</sup> African Development Bank Group, "Africa Hydropower Modernisation Programme", 2023 ([https://www.afdb.org/sites/default/files/documents/publications/hydropower\\_modernisation\\_report.pdf](https://www.afdb.org/sites/default/files/documents/publications/hydropower_modernisation_report.pdf)).

<sup>183</sup> African Development Bank Group, "Africa Hydropower Modernisation Programme", 2023 ([https://www.afdb.org/sites/default/files/documents/publications/hydropower\\_modernisation\\_report.pdf](https://www.afdb.org/sites/default/files/documents/publications/hydropower_modernisation_report.pdf)).

<sup>184</sup> Rim Berahab, 05/09/2018, "Is Digitalization the Future of Energy in Africa?" (<https://www.policycenter.ma/opinion/digitalization-future-energy-africa>).

Gibe II hydropower plant in Ethiopia, allowing owner Ethiopian Electric Power (EEP) to carry out more efficient maintenance planning. The contract enhances the plant's modernisation with state-of-the-art digital solutions for maintenance, planning, execution, reporting, and spare parts management. The project will lead to reduced maintenance and operating costs while ensuring high system availability. Voith Hydro will also offer spare parts and employee training to ensure sustainable improvements. The system securely stores all documentation and asset data, enabling reliable planning and monitoring of key performance indicators, and timely initiation of maintenance activities. It supports real-time monitoring of organizational performance, cost tracking, and downtime analysis, using predefined KPIs based on maintenance best practices<sup>185</sup>.

## 11.2 Central Asia: Focus on Kyrgyzstan

### Hydropower in Kyrgyzstan

The Kyrgyz Republic's mountainous terrain, its plentiful water resources and its position as an "upstream country", make hydropower the most important energy source. Hydropower is in fact the main source of electricity in the country, accounting for 85.9% of electricity generation (corresponding to 11.928 GWh), and for 100% of total generation from renewables<sup>186</sup>, making Kyrgyzstan one of the countries with the highest share of renewable electricity in the world<sup>187</sup>.

The main actor in the energy sector is the State Committee on Industry, Energy and Subsoil Use, which since 2016 has overseen the development and implementation of a uniform state policy in the sector, including water-energy and fuel resources, renewable energy sources and the industrial potential of the country.

The State Agency for Regulation of the Fuel-Energy Sector (the Energy Regulator) is vested (among the others) with the authority to issue licenses for energy sector activities, develop tariff-setting methodologies and set tariffs for electricity, heat and natural gas, and develop and supervise the reporting and monitoring framework for the performance of energy sector companies.

Additionally, in January 2016 the Kyrgyz Government established Open Joint Stock Company "National Energy Holding Company" to manage state-owned shares in the power sector companies.

One of the most relevant pieces of legislation for the hydropower sector is the recent law on Renewable Energy, signed by the President of the Republic in 2022 and establishing the legal, organisational, economic, and financial framework and mechanisms for regulating relations between the state, producers, suppliers, and consumers of renewable energy sources<sup>188</sup>.

The government emphasises energy security, alongside efficiency, and sustainable development, throughout all its policies. Enhancing energy security and efficiency is in fact crucial due to fluctuations in hydropower production (particularly low during winter months), dependence on hydrocarbon imports, and outdated, inefficient infrastructure that results in high losses. The National Energy Program for 2008-2010, which includes an integrated plan for the development of the fuel-energy complex up to 2025, remains the primary long-term policy document for the energy sector. Among its objectives, the Plan aims to expand hydro and coal-fired generation capacity to boost national electricity supply and increase exports<sup>189</sup>.

Kyrgyzstan has in fact an estimated hydropower generation potential of 140–170TWh (and an economically feasible potential of 60 billion kWh), but only about 30% is being utilised<sup>190</sup>.

To encourage investment into hydropower infrastructure, the government exempts renewable energy companies from VAT when importing equipment and offers power purchasing agreements for electricity generation. Major capacity generation projects are financed in large part by international

<sup>185</sup> Carrieann Stocks, 14/04/2021, "Digital Developments", *International Water Power and Dam Construction* (<https://www.waterpowermagazine.com/analysis/digital-developments-8669591/?cf-view>).

<sup>186</sup> International Energy Agency, "Kyrgyzstan" (<https://www.iea.org/countries/kyrgyzstan/electricity>).

<sup>187</sup> International Energy Agency, "Kyrgyzstan energy profile" (<https://www.iea.org/reports/kyrgyzstan-energy-profile>).

<sup>188</sup> US International Trade Administration, "Kyrgyz Republic – Energy", 2024 (<https://www.trade.gov/country-commercial-guides/kyrgyz-republic-energy>).

<sup>189</sup> *Ibidem*.

<sup>190</sup> International Hydropower Association, "Hydropower in South and Central Asia" (<https://www.hydropower.org/region-profiles/south-and-central-asia>).

finance institutions and offer an opportunity for private foreign companies to enter and compete in the Kyrgyz hydropower market<sup>191</sup>. For example, in early 2024, the World Bank discussed financing several hydropower projects in Kyrgyzstan, including the 1.86GW Kambarata 1, which will have a 5.4 billion m<sup>3</sup> reservoir volume, generating 5.6TWh<sup>192</sup>. Located on the Naryn River and designed to generate 5.6 billion kWh per year, once completed, Kambarata-1 will be one of the largest hydropower plants in Central Asia. Additionally, the European Bank for Reconstruction and Development (EBRD) will provide Chakan GES, the state-owned hydropower operator of nine small hydro power plants, with a financial package of US\$ 13.8 million to finance the rehabilitation and modernisation of the Lebedinovskaya plant, with an installed capacity of 7.6 MW<sup>193</sup>.

Additional projects to unlock the country's untapped hydro potential include construction of the remaining two 120 MW units at Kambarata-2, the Verkhne-Naryn HPP cascade (over 200 MW), offering an additional 5 TWh of generation, the the Kazarman and Suusamyr- Kokomerren hydropower plant cascades which together would add over 2,465 MW<sup>194</sup>, and additional small-scale cascade projects on the Naryn River, which could lead to 237MW and 439MW if completed<sup>195</sup>.

### Digitalisation of hydropower in Kyrgyzstan

Kyrgyzstan's hydro-rich energy sector is characterised by aging infrastructure and the existing hydropower plants mostly consist of Soviet-era equipment in need of updates. Opportunities exist for governmental projects requesting consulting services or undertaking work to renovate existing hydropower plants. Nevertheless, the emphasis seems to be on modernisation measures in general, rather than specifically on digitalisation measures.

For example, the Toktogul Hydropower Plant, currently the country's largest plant, is undergoing reconstruction of its generating units, which will add 60 MW to its capacity. The modernisation of unit No. 4 began in February 2025, following successful upgrades to units No. 1, No. 2, and No. 3. Once completed, Toktogul HPP's total capacity will rise to 1,440 MW, extending its operational lifespan by 25 to 30 years. Additionally, the Uch-Kurgan Hydropower Plant has recently started modernising its unit No. 2, aiming to increase its capacity by 9 MW<sup>196</sup>.

## 11.3 South America: Focus on Colombia

### Hydropower in Colombia

Colombia has become a leader in clean energy transition policy, serving as an inspiring example of a fossil fuel-producing country committed to climate action. This commitment is based on a long-term decarbonisation pathway, energy and economic diversification, and a just transition.

Colombia's share of renewables in final energy consumption was as high as 29.7% in 2021, significantly higher than the IEA average of 14%. Additionally, renewables constituted 75% of Colombia's electricity generation, compared to the IEA average of 30%. 98.2% of renewable electricity generation in the country comes from hydropower, which accounted for 64% of total electricity generation in 2023 (corresponding to 57.244 GWh)<sup>197</sup>. However, Colombia's hydroelectricity has a low storage capacity and extreme weather events (droughts or rains) put the availability of hydropower to the test.

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<sup>191</sup> US International Trade Administration, "Kyrgyz Republic – Energy", 2024 (<https://www.trade.gov/country-commercial-guides/kyrgyz-republic-energy>).

<sup>192</sup> International Hydropower Association, "Hydropower in South and Central Asia" (<https://www.hydropower.org/region-profiles/south-and-central-asia>).

<sup>193</sup> International Hydropower Association, "World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero", 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

<sup>194</sup> Investment Portal Kyrgyz Republic, "Key industries – Hydroenergy" (<https://invest.gov.kg/about-kyrgyz-republic/key-industries/>).

<sup>195</sup> International Hydropower Association, "Hydropower in South and Central Asia" (<https://www.hydropower.org/region-profiles/south-and-central-asia>).

<sup>196</sup> Sergey Kwan, 19/02/2025, "Kyrgyzstan Advances Hydropower Modernization Efforts", *The Times of Central Asia* (<https://timesca.com/kyrgyzstan-advances-hydropower-modernization-efforts/>).

<sup>197</sup> International Energy Agency, "Colombia" (<https://www.iea.org/countries/colombia/electricity>).

These figures echo Colombia’s ambitious commitments towards decarbonisation: at COP26, Colombia announced a net zero target and a bold Nationally Determined Contribution (NDC), aiming for a 51% reduction in greenhouse gas (GHG) emissions by 2030. These goals are reflected in the E2050 Strategy, the Energy Transition Law, and the Climate Action Law<sup>198</sup>.

The growth of Colombia's hydroelectric sector has been propelled by private initiatives and public-private partnerships. Key players in this industry include EPM, Isagen, and Celsia, which manage both large-scale and smaller hydroelectric plants to supply electricity for domestic consumption and export. Colombia offers a comprehensive package of benefits for sustainable investments, including in sustainable hydroelectric projects. Key benefits include:

- A 15-year income tax exemption for electricity generated from wind, biomass, agricultural waste, solar, geothermal, or sea energy, starting from 2017.
- A 50% income tax deduction for investments in research, development, and production of electric energy from non-conventional sources.
- VAT exemptions for equipment, machinery, and services related to the production and use of non-conventional energy sources, as well as for the measurement of potential resources and efficient energy management<sup>199</sup>.

Thanks to its abundant water resources (Colombia is the sixth country in the world with the largest water resource, with 2,360 km<sup>3</sup> of water per year), the Colombian hydropower sector has a potential for installed capacity of 65 GW, according to the Mining and Energy Planning Unit (UPME)<sup>200</sup>.

The sector is already rapidly growing: Colombia ranks 1<sup>st</sup> among the countries in South America in terms of hydropower capacity added in 2022 (with 618 MW of additional hydropower capacity added in that year)<sup>201</sup> and in 2023 (with an addition of 643 MW)<sup>202</sup>, and additional projects are already in the pipeline.

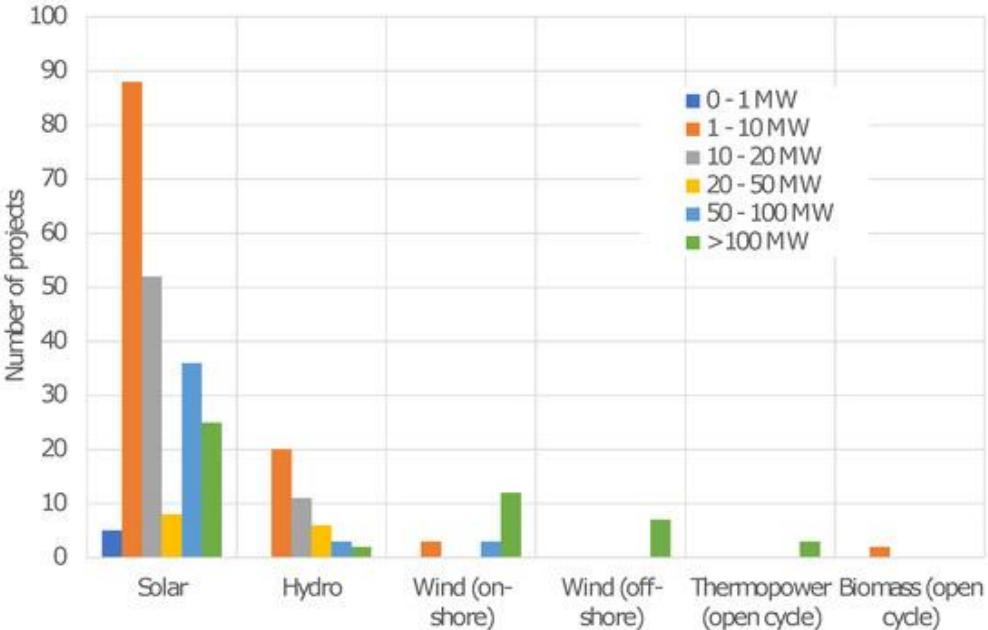


Figure 12 Non-conventional renewable energy sources planned projects by capacity range with expected operation from 2023 in Colombia. Source: Aldemar Leguizamo-Perilla et al., 2023, „Digitalisation and Modernisation of Hydropower Operating Facilities to Support the Colombian Energy Mix Flexibility”, *Energies* (<https://www.mdpi.com/1996-1073/16/7/3161>).

<sup>198</sup> International Energy Agency, “Colombia 2023 – Energy Policy Review” (<https://www.iea.org/reports/colombia-2023/executive-summary>).

<sup>199</sup> PROCOLOMBIA, 20/02/2025, “Hydroelectric power: Discover the country where rivers illuminate cities” (<https://investincolombia.com.co/en/resources/invest-hydroelectric-energy>).

<sup>200</sup> *Ibidem*.

<sup>201</sup> International Hydropower Association, "World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero", 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

<sup>202</sup> International Hydropower Association, “Hydropower in South America” (<https://www.hydropower.org/region-profiles/south-america>).

The biggest facilities include Porce III, Guatapé, San Carlos, El Guavio, and Betania are spread across diverse regions of Colombia. The soon-to-be-completed Hidroituango plant, located in Antioquia, will provide 17% of the country’s electricity demand, with an installed capacity of 2,400 MW and a reduction in emissions of 4.4 million tons of CO<sub>2</sub> per year<sup>203</sup>.

Hydropower and its untapped potential offer several opportunities for Colombia: not only it grants the country energy independence, as its electricity supply can be derived from domestic resources, but it also offers the country a chance to diversify its export portfolio. Colombia has already experience in exporting electricity abroad, but as the generation from hydropower grows, Colombia’s renewable electricity could reach new destinations in the world. Additionally, hydropower offers the compelling opportunity to set the foundation for the green hydrogen industry in Colombia<sup>204</sup>.

Digitalisation of hydropower in Colombia

As in other countries, hydropower plants in Colombia have been in operation for several decades. In Latin America and the Caribbean, an estimated 70 GW of capacity will need short- or medium-term modernisation, at around USD 32 billion<sup>205</sup>.

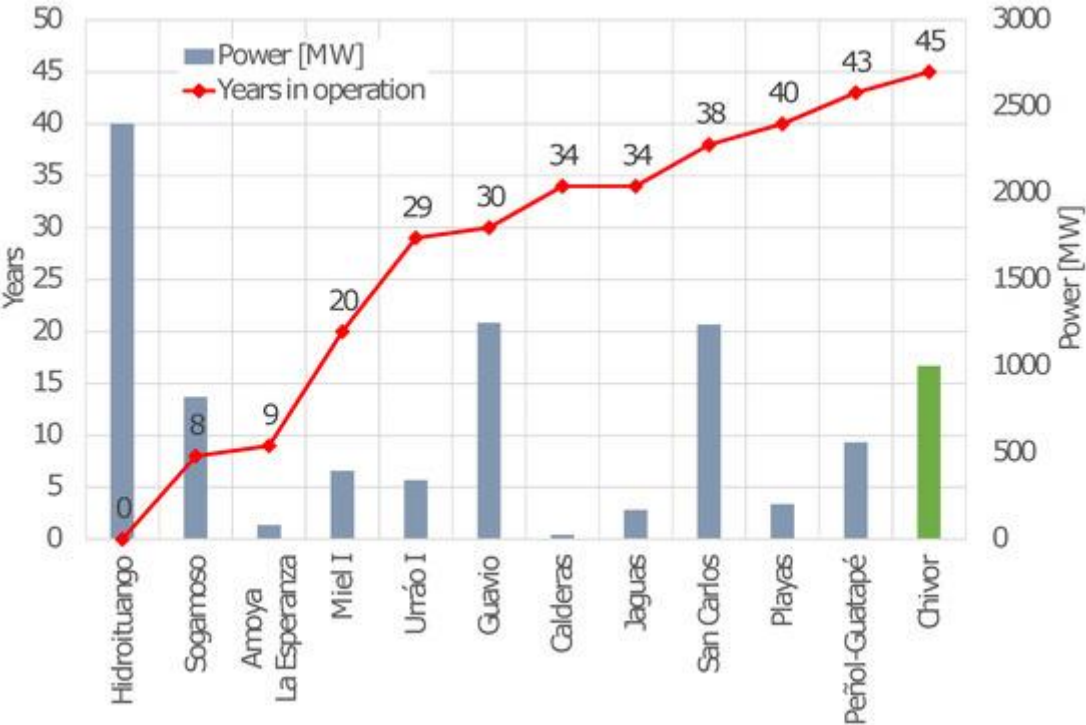


Figure 13 Age and installed capacity of Colombian hydropower plants. Source: Aldemar Leguizamo-Perilla et al., 2023, „Digitalisation and Modernisation of Hydropower Operating Facilities to Support the Colombian Energy Mix Flexibility“, Energies (<https://www.mdpi.com/1996-1073/16/7/3161>).

Modernisation measures are therefore essentials in order to enhance the hydropower sector's resilience and ensure its continued contribution to energy security. Within Colombian utilities, initiatives are already registered on extending the useful life of reservoirs for periods of 50 years, through several refurbishment and modernisation measures, including i.e. the monitoring of power plants for failure prediction based on data analysis and digital transformation processes with modern platforms for commercial management based on specialised Industry 4.0 tools<sup>206</sup>.

<sup>203</sup> International Hydropower Association, "World Hydropower Outlook 2023 – Opportunities to Advance Net-Zero", 2023 (<https://indd.adobe.com/view/4201016f-a51a-4f6f-998b-ec85219d1dfd>).

<sup>204</sup> PROCOLOMBIA, 20/02/2025, "Hydroelectric power: Discover the country where rivers illuminate cities" (<https://investincolombia.com.co/en/resources/invest-hydroelectric-energy>).

<sup>205</sup> REN21, 2023, "Renewables 2023 Global Status Report" ([https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023\\_Energy-Supply-Module.pdf](https://www.ren21.net/wp-content/uploads/2019/05/GSR-2023_Energy-Supply-Module.pdf)).

<sup>206</sup> Aldemar Leguizamo-Perilla et al., 2023, „Digitalisation and Modernisation of Hydropower Operating Facilities to Support the Colombian Energy Mix Flexibility“, Energies (<https://www.mdpi.com/1996-1073/16/7/3161>).

Even though digitalisation development in Latin America is still behind compared to Europe and the United States, such development is not homogenous, as it could be expected in such a diverse region. The leading countries in the region in this regard are Chile, Colombia, Argentina, Brazil and Costa Rica<sup>207</sup>. The main barriers and challenges faced by the hydropower sector in Latin America as it undergoes digital transformation includes the following<sup>208</sup>:

- Technological integration: integrating advanced digital technologies with existing hydropower infrastructure is complex and requires significant effort to ensure compatibility and efficiency.
- Cybersecurity risks: the increased use of digital technologies heightens the risk of cyberattacks, making cybersecurity a critical concern.
- Financial constraints: the initial investment required for digitalisation is substantial, posing a financial challenge for many hydropower projects.
- Skill gaps: there is a need for skilled personnel who are proficient in modern digital tools and techniques, necessitating ongoing training and development.
- Regulatory hurdles: navigating the regulatory landscape can be challenging, as compliance with various regulations is essential for successful digitalisation.

Notwithstanding the existing challenges, best practices of digitalisation of hydropower plants in Colombia already exist, as in the case of the Chivor hydropower plant. Chivor is a 1000-MW hydropower plant that represents the main asset of AES Colombia. It is in operation since 1977 (Chivor I) and 1982 (Chivor II). The project is located at Santa María, Boyacá (160 km northeast from Bogotá, the capital city of Colombia), and was built to operate at least for 50 years. Considering that this hydropower plant had an initial operational expectancy until 2025, AES Colombia has been executing several projects to extend the operational time for 50 more years, including the construction of new intake systems, renovations of conduction tunnel linings, renovation of electrical equipment, and digital transformation of the company. The digitalisation measures consist of the implementation of an information management platform based on specialised applications that use Industry 4.0 technologies. Such a platform allows reducing risks and uncertainties, and facilitates the implementation of appropriate models to optimise energy trading transactions<sup>209</sup>.

## 12 Concluding remarks and policy recommendations for the digitalisation of hydropower in the EU

The European Union's hydropower sector stands at a critical juncture. As the most established form of renewable electricity generation in Europe, hydropower continues to play a pivotal role in ensuring system reliability, energy storage, and grid flexibility. However, the sector is increasingly challenged by ageing infrastructure, evolving environmental regulations, and the pressing need for digital innovation. Over 70% of hydropower plants in the EU are over 30 years old, with many nearing the end of their design life. This situation presents a unique opportunity: the digitalisation and modernisation of the existing fleet can substantially improve operational performance, extend asset lifespans, and contribute to the EU's broader energy and climate objectives.

The iAMP-Hydro project demonstrates that modernising and digitalising existing infrastructure can improve efficiency, flexibility, and sustainability without increasing ecological impact. Through targeted policy support, digital technologies can be effectively leveraged to prolong asset lifetimes, enhance predictive maintenance, reduce operational costs, and increase capacity.

Despite these opportunities, several barriers remain. The complexity of regulatory frameworks, lack of standardisation, uncertainty around licensing renewals, and exposure to volatile electricity markets

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<sup>207</sup> Alexander Arch et al., 2019, „The Digital Revolution of Hydropower in Latin American Countries” (<https://www.researchgate.net/publication/344033513> The Digital Revolution of Hydropower in Latin American Countries en).

<sup>208</sup> *Ibidem*.

<sup>209</sup> Sandra Giraldo et al., 2021, “Digital Transformation of Energy Companies: A Colombian Case Study”, *Energy*, (<https://www.mdpi.com/1996-1073/14/9/2523>).

continue to hinder investment in digitalisation of the EU hydropower plants. Moreover, hydropower projects often face challenges in aligning with EU environmental legislation, such as the Water Framework Directive and the Nature Restoration Law, which, while crucial for biodiversity protection, may limit flexibility for infrastructure upgrades and innovation.

In response to these findings, the following policy recommendations are proposed at the EU level to support the digitalisation of hydropower:

- *Standardisation and enhanced cybersecurity*: the unique nature of each hydropower plant, in terms of both design and operation, poses a challenge to digitalisation. This underscores the importance of standardisation, which can facilitate the digitalisation process and enable compatibility and information sharing among different actors and across borders. Additionally, as many hydropower projects are considered critical infrastructure, enhanced cybersecurity measures will be necessary to prevent security-related issues<sup>210</sup>.
- *Integration into EU energy and climate frameworks*: digitalised hydropower should be explicitly acknowledged within the implementation of the Renewable Energy Directive, the Electricity Market Design, and the EU Digital Strategy. Digital upgrades should be recognised as sustainable investments under the EU Taxonomy and included in National Energy and Climate Plans of EU Member States.
- *Access to finance and investment de-risking*: EU financial instruments such as InvestEU, Horizon Europe, the Innovation Fund, and the LIFE Programme should continue to provide support for hydropower digitalisation projects. The development of tailored financial mechanisms, including long-term remuneration models and power purchase agreements, is essential to reduce investment risk, particularly for small and medium-scale operators.
- *Policy coherence and regulatory flexibility*: the implementation of environmental directives must be accompanied by mechanisms that enable digital innovation in hydropower. The use of AI-enabled environmental monitoring, digital twins, and real-time data tools should be encouraged to support compliance with the Do No Significant Harm (DNSH) principle and other environmental obligations.
- *Support for research, innovation, and skills development*: continued support through Horizon Europe and similar initiatives is crucial to accelerate innovation in hydropower digitalisation. In parallel, capacity-building programmes should be developed to ensure that plant operators and regulators are equipped with the necessary digital competencies.
- *Exploitation of existing infrastructure*: the retrofitting of non-powered dams and the development of hidden hydropower potential within existing water management infrastructure should be promoted. Such projects present low-impact opportunities to enhance renewable generation with minimal environmental disturbance.
- *Knowledge sharing and regional coordination*: a dedicated EU platform should be established to foster the exchange of best practices, case studies, and lessons learned from digitalisation projects across Member States. Particular attention should be given to cooperation in transboundary river basins and regions with similar hydrological and technological conditions.

In conclusion, the digital transformation of hydropower is not only a technological necessity but a strategic opportunity. By enabling smarter, more resilient, and environmentally sustainable operations, digitalisation will allow the European hydropower sector to remain a central pillar of the clean energy transition. A coherent and supportive EU policy framework will be instrumental in unlocking this potential and ensuring long-term sustainability and competitiveness of hydropower in the European Union.

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<sup>210</sup> IRENA, “The changing role of hydropower: Challenges and opportunities”, 2023 ([https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA\\_Changing\\_role\\_of\\_hydropower\\_2023.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Changing_role_of_hydropower_2023.pdf)).

