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# Deliverable D1.1

## Mapping storage potential in Europe

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DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
DATA	Data sets, microdata, etc.	
DMP	Data management plan	
ETHICS	Deliverables related to ethics issues	
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OTHER	Software, technical diagram, algorithms, models, etc.	

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# I Executive Summary

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The Store2Hydro project aims to revolutionize electricity storage by retrofitting existing hydropower facilities into pumped storage facilities. This initiative is critical for addressing the challenges posed by the increasing integration of intermittent renewable energy sources like wind and solar into the electrical grid. By converting traditional hydropower plants into pumped storage facilities, the project seeks to maximize renewable energy utilization, reduce curtailment, and improve grid stability.

The report focuses on mapping and categorizing hydropower plants across Europe that could be converted to a pumped storage facility. It identifies potential sites and evaluates what kind of adjustments need to be made for the conversion to a pumped storage power plant, based on various criteria, including headwater and tailwater volumes, turbine types, and geographical considerations. The categorization system developed in this study helps prioritize future investments and optimize resource allocation for sustainable energy infrastructure.

Three main generic groups are explored: high head storage capacity, low head storage capacity, and hybrid hydro systems. The report also details the methodology used for data collection and analysis, including the use of satellite imagery and geographical data to assess power plant schemes. The potential storage capacity is calculated under different scenarios, highlighting the significant role of pumped storage hydropower in supporting the transition to a renewable energy future.

## Results:

- **Scenario 1** - Maintaining the current base load and finding additional full load hours: Small adjustment power plants could add **37.87 TWh/yr** of cumulated turbinning storage and **52.3 TWh/yr** of cumulated pump storage.
- **Scenario 2** - Converting Base Load to Regulating Pumped Storage: Small adjustment power plants could add **58 TWh/yr** of cumulated turbinning storage and **87 TWh/yr** of cumulated pump storage.
- **Scenario 3** - Conversion of only one unit for Cost Efficiency: Small adjustment power plants could add **15.29 TWh/yr** of cumulated turbinning storage and **22.9 TWh/yr** of cumulated pump storage.

Overall, the Store2Hydro project demonstrates the feasibility and benefits of converting existing hydropower plants into pumped storage facilities, providing a robust solution for enhancing energy storage and grid regulation capabilities in Europe.



## 2 Introduction

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The transition towards sustainable electricity sources is accelerating globally, driven by the Paris Agreement and concerns over energy security. [1] This shift necessitates a significant reduction in reliance on fossil fuels. One major challenge in this transition is the storage capacity for electricity, especially with the increasing addition of volatile energy sources like wind and solar. Modernized and flexible reversible hydropower systems are poised to play a crucial role in addressing the supply and demand imbalance.

The Store2Hydro project aims to revolutionize electricity storage by integrating reversible pump turbine technology into existing hydropower facilities. This approach could enhance Europe's **cumulative electricity storage capacity** by over 22 TWh per year, supporting the storage of energy generated from wind and solar sources. By **cumulative electricity storage capacity** the cumulated energy storage over one year is described. Therefore the energy storage which is achieved in one cycle multiplied by the number of cycles in a year. This potential increase is substantial when compared to the global predictions for added battery storage of 0.4TWh per year as seen in [3] and added thermal storage capacities of 0.88TWh per year by 2025 and 2030, respectively. [4] The increase of 22TWh per year is an ambitious aim however, it is achievable since 22TWh/y is only 10 percent of the EU 27 + UK + Switzerland + Norway, hydropower energy storage capacity.

In this report, the focus is placed on the mapping of installed hydropower plants that could be converted to reversible pump turbines, to enhance Europe's electricity storage capacity. Additionally, these power plants are identified and categorized to provide a comprehensive overview of the potential for expanding hydropower-based electricity storage. This mapping effort is deemed crucial for the optimization of resource allocation and the prioritization of future investments in sustainable energy infrastructure. Both high head and low head power plants are being investigated for conversion to pumped storage facilities. However the categorization by head is found to be unsuitable and therefore a new classification was implemented. One method to facilitate this conversion, is by retrofitting power plants with reversible pump turbines and a booster pump, however other methods are possible as well. The booster pump would prevent the cavitation which occurs due to the geographical height difference between the tailwater and the turbine main axis.

Additionally, another promising area under investigation is the development of hybrid hydro systems. These systems combine traditional hydropower technologies with virtual energy storage solutions.

The potential explored in this project is divided into three generic groups, as outlined below:

1. High head storage capacity,  
Existing Francis turbines are planned to be retrofitted by pump turbines and equipped with an additional booster pump to prevent cavitation caused by low pressure.
2. Low head storage capacity  
Run-of-river power plants and their river stretches will be utilized as energy storage systems.
3. Storage technologies and combinations.



Existing Hybrid hydro systems, which combine traditional hydropower technologies with virtual energy storage solutions.

A more detailed description of these three generic groups will follow in section [3.4](#).



## 3 Research

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### 3.1 Sources

The research strategy aims to create a robust base for the study by initially focusing on publicly available data. This approach ensures that the initial research is both accessible and broad in scope, laying a base for further investigations. In later stages, specific power plant owners will be contacted to obtain more detailed and proprietary information. This additional data will enable a deeper analysis, adding precision and depth to the project findings. At this stage of the project the focus was placed on the data collection. Certain information, such as the coordinates, the runner type and the country were investigated for all power plants in Europe. After meeting certain criteria the flow rate, hydraulic head, power, annual production, head- and tailwater capacity were researched or calculated in case, no sources were found. In [subsection 3.5](#), the research is described in further detail.

### 3.2 Database

A cloud-based version of Excel is currently used as a shared database. The advantage of Excel is that all team members have access to the latest data, allowing a shared database to be maintained. This setup enables data to be added and modified directly in the cloud, ensuring consistency and accessibility of information. Additionally, collaboration is facilitated as all changes are available in real-time, preventing issues with version control.

### 3.3 The three generic groups

During the research, it became evident that the initial three generic groups were not a suitable categorization for this type of data structure. The issue primarily lies with group 2, as the term "low head" does not align with the description of run-of-river power plants. The definition of low, medium, and high head varies by country. Due to the absence of a universally accepted standard or a clear line between them, this definition proves to be inconsistent and impractical for broader application. For instance, some run-of-river power plants equipped with Kaplan runners have a hydraulic head exceeding 40 meters. This clearly does not qualify as "low head". However, these power plants also do not fit within the "high head" group, which specifically requires Francis runners due to the original booster pump design.

The primary focus of the generic group of High Head Storage is the conversion of existing power plants, which are equipped with Francis turbines, into pumped turbines. This process involves exchanging the existing Francis runner with a pump turbine runner with the addition of a booster pump to prevent cavitation. These modifications represent the minimal changes required to transform a standard impoundment power plant, equipped with Francis runners, into a pumped storage hydropower plant. Consequently, these adjustments are considered *relatively small*, as outlined in the proposal. Although referred to as "high head" in the proposal, a more accurate description for this generic group might be *Reservoir-to-Reservoir Storage (= RtR Storage)*.

The second generic group, Low Head Storage, is also renamed for more clarity as *Run-of-*



*River Storage (=RoR Storage)*. These power plants utilize river stretches for energy storage. Based on these observations, a new categorization system was developed to better reflect the varied storage potential across these generic groups.

The third generic group remains titled "Other Storage Combinations" and focuses on existing hybrid hydro systems, which combine traditional hydropower technology with virtual energy storage solutions.

### 3.4 Power Plant Categorization

To efficiently evaluate the feasibility of converting existing power plants into pumped storage power plants, a categorization system was developed. This categorization ranks the power plants after the simplicity of the conversion. Additionally, it outlines the challenges that may need to be addressed when converting a power plant into a pumped storage facility. An example for such challenges might be the need for additional piping or the damming of the tailwater. This system organizes the power plants in the database into distinct categories, facilitating easier management and rapid assessment of each plant's potential.

Additionally, these categories provide a structured approach to prioritize future data collection efforts, helping to identify which types of power plants offer the greatest promise for increased energy production. This classification is essential for optimizing resource allocation and directing research towards the most impactful areas. For the sake of simplicity, for this report, the power plants are categorized as *small adjustment RtR*, *small adjustment RoR*, *medium adjustment* and *large adjustments*.

#### 1. Small adjustments

The minimal modifications required to transform a standard impoundment power plant, equipped with Francis runners, into a pumped storage hydropower plant requires, exchanging the existing Francis runner with a pump turbine runner with the addition of a booster pump to prevent cavitation. Consequently, these adjustments are considered *relatively small*, as outlined in the proposal. This means however that no other modifications need to be made. Further details on the requirements for power plants to be classified under the "small adjustments" category are provided in [section 4](#).

#### 2. Medium adjustments

When the minimum requirements for conversion to a pumped storage facility are exceeded, and additional modifications such as piping are necessary, the power plants are classified under the "medium adjustment" category. Despite these extra adjustments, the required changes remain minimal compared to constructing a new pumped storage hydropower plant. In [section 5](#) the category is explained in further detail.

#### 3. Large adjustments

When more changes are needed than for the *medium adjustments* category the power plants are put into the *large adjustments* category. For these the needed piping is more extensive than for the medium adjustments category and even further structural engineering might be needed. The conversion to a pumped storage plant is still possible

however the investments might outweigh the benefits. The category and its subcategories are further explained in [section 6](#).

#### 4. Not possible

Power plants with outlets into saltwater or those equipped with Pelton runners are excluded due to high conversion costs and environmental concerns. Converting Pelton turbines would require constructing a new cavern, akin to building a new power station. Although some research exists on using saltwater tailwaters, the environmental impact remains uncertain, leading to their exclusion. Additionally, power plants with a capacity below 10 megawatts are not considered for further investigation due to their limited potential.

Using the data collected for power plants that only require small adjustments, further filtering can be conducted to identify power plants with similar properties, enabling effective clustering. This clustering approach will streamline the analysis, facilitating the identification of common characteristics and opportunities for improvement across similar types of power plants.

A more in depth description of each category will be provided in the chapters which are named after their categories.

### 3.5 Methodology

The Energy Charts website [2] served as the starting point for identifying the locations and names of potential candidates. After obtaining the names, further research was conducted using various sources. The initial step focused on identifying the turbine type to exclude power plants with Pelton runners, as these are unsuitable, for the Store2Hydro project, for either Reservoir-to-Reservoir (RtR) or Run-of-River (RoR) high potential classifications. The primary objective of this research was to collect essential data, including installed capacity, annual production, and other parameters required for the calculations outlined in [3.6](#).

The subsequent step involved obtaining a clear understanding of the power plant schemes. While some sources provide detailed information about specific sites, such information is often insufficient. To address this limitation, satellite imagery and geographical data were analyzed. In most cases, this approach was the only reliable method for accurately identifying the corresponding headwater and tailwater and the associated outlet.

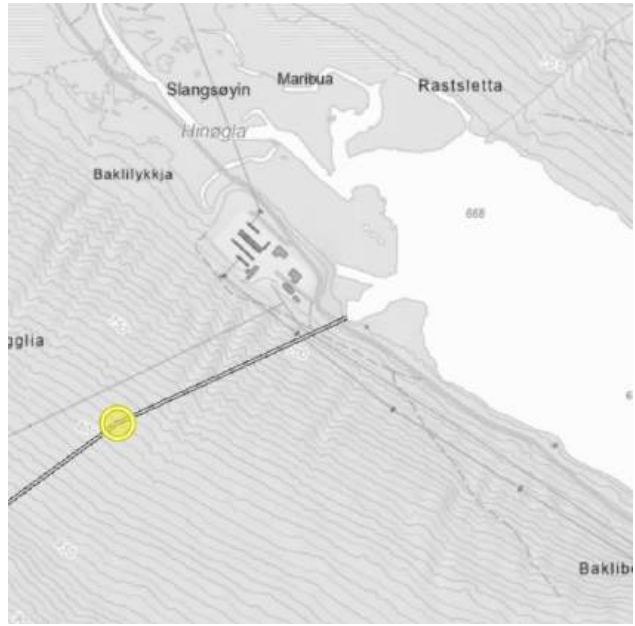
The combination of the aforementioned points determines their categorization.

For Norway, for example, the NVE Atlas was used to identify the pipelines and outlets [7]. In [Figure 1\(b\)](#) the pipelines are depicted, allowing the tailwater and the outlet to be easily identified.





(a) Outlet seen from the Satellite image



(b) Outlet and piping seen in the NVE Atlas

Figure 1: Comparison of the outlet seen on the Satellite image and from the NVE Atlas

The design head of the power plants was generally available in the public available Data for most power plants. However the definition of the available head is quite often not given. The assumption was therefore taken that the head was the net head. Therefore the vertical height difference between the surface level of the headwater and the surface level of the tailwater considering hydraulic losses, which is therefore the head available to the turbine. As the hydraulic head losses are usually of negligible size in comparison to the net head it is not considered in this report.

To obtain all necessary data, some basic calculations were made. Generally, finding the discharge of the machines and the useable volume of the headwater was possible however for some public data they were not available and therefore they had to be calculated.

The estimated design discharge  $Q[\frac{m^3}{s}]$  was calculated from the design head  $H_m$  and the installed capacity  $P[W]$  as follows

$$Q = \frac{P\eta}{\rho g H} \quad \left[ \frac{m^3}{s} \right] \quad (1)$$

For which  $\rho[\frac{kg}{m^3}]$  is the density of water,  $\eta$  is the efficiency of the machine which was conservatively estimated at 90% and  $g[\frac{m}{s^2}]$  is the gravitational acceleration.

The useable capacity of the headwater was calculated using the surface area of the reservoir or the surface area of the river stretch up to the preceding transverse structure, along with the corresponding depths, as follows

$$V_{hw} = A_{surface} \cdot \Delta h \quad [m^3] \quad (2)$$

The depths,  $\Delta h$ [m], were only determined when no headwater volume data were available. For rivers affected by shipping,  $\Delta h$  was estimated to be 15 cm.

In cases where sufficient data were unavailable, a stochastic approach was employed to obtain the required results. This method uses outcomes from cases with available data to infer general trends that apply to all cases. An example of this approach is provided in 4.1.2.

### 3.6 Calculating the gained Storage Potential

Several scenarios are considered for calculating the potential, each differing in the amount of base load that must be provided. The amount of the current base load is determined based on the capacity factor  $CP$  of each power plant. The capacity factor is calculated by dividing the annual production  $E_{an.pr.}$ [Wh] by the product of the power at the best efficiency point  $P_{bp}$ [W] and the total hours in a year

$$CP = \frac{E_{an.pr.}}{P_{bp} \cdot h_{year}}. \quad (3)$$

It is used to estimate the potential of each site. This is a theoretical approach, and each power plant will require further investigation under numerous other conditions at a later stage. However, with limited publicly available data, this method provides a practical overview of multiple power plants.

In addition to evaluating storage potential, the emptying time was calculated for each hydropower plant where sufficient data were available. The emptying time  $t_{empty}$ [h] represents the duration required for the hydropower plant to deplete the headwater from its maximum to its minimum allowed level while operating at full load. This metric was assessed to align with the expectations outlined in the project proposal, which emphasized identifying storage systems capable of sustaining operation for more than a few hours.

For the purposes of this project, "more than a few hours" was interpreted as a minimum of four hours. Consequently, all the results presented here adhere to this criterion.

The calculations above were used to develop different scenarios to demonstrate the potential achieved under varying initial conditions. This resulted in a total of three distinct scenarios.

It is also important to note that two potentials were calculated. Since the installation of a pump is planned for the sites, the potential to use energy from the grid was calculated as the pump potential  $E_{add.pump}$ [GWh/yr], and the potential to generate energy was calculated as the turbine potential  $E_{add.turbine}$ [GWh/yr]. The detailed calculation for each potential is provided below.

#### 3.6.1 Scenario 1 - Maintaining the current base load and finding additional full load hours

In Scenario 1, the goal was to increase the plant's full load operating hours by converting the power plant into a pump storage facility. Since the approach was to maintain the current energy production, the potentially available full load hours were calculated to determine the additional energy that could be generated in one year. Maintaining the current energy output is mandatory, as it remains essential for meeting the grid's current energy demands.



The current full load hours  $h_{full}$  [h/yr] of the plant were calculated using the plant's capacity factor  $CP$  multiplied with the hours of the year  $h_{h/yr}$  [h] to establish its baseline workload:

$$h_{full} = CP \cdot h_{year} = CP \cdot 8760 \quad [\text{h/yr}] \quad (4)$$

The calculations also assume a 10% reduction in annual full load operating hours  $h_{loss} = h_{year} \cdot 10\%$  to account for maintenance and downtime. While this 10% estimate serves as a placeholder, it may vary based on site-specific conditions and will be updated as more accurate data becomes available.

It is important to consider that the pump turbine can operate in either pumping mode or turbine mode. Accounting for expected efficiency losses due to factors such as pumping through pipes, the additional full load operating hours  $h_{add} = h_{year} - h_{full} - h_{loss}$  are divided into turbine mode  $h_{add.turbine} = h_{add} \cdot 40\%$  and pumping mode  $h_{add.pump} = h_{add} \cdot 60\%$ . The 60/40 split is an initial assumption and will be refined as more detailed information becomes available.

The added **cumulative energy storage per year** is determined by multiplying the additional available operating hours, as outlined above, by the power capacity of the system:

$$E_{add.turbine} = P_{bp} \cdot h_{add.turbine} \quad [\text{GWh/yr}] \quad (5)$$

As for the energy that is used for pumping  $E_{add.pump}$  [GWh] the power capacity of the system is multiplied by the additional available pumping hours per year

$$E_{add.pump} = P_{bp} \cdot h_{add.pump} \quad [\text{GWh/yr}] \quad (6)$$

### 3.6.2 Scenario 2 - Converting Base Load to Regulating Pumped Storage

As the electrical grid incorporates an increasing number of renewable energy sources, characterized by their intermittent nature, the addition of more Pumped Storage Hydropower (PSH) becomes essential. PSH maximizes renewable utilization by storing excess energy generated during high output periods, ensuring it is available when needed. This technology also reduces curtailment, thereby preventing the waste of renewable energy that cannot be immediately used or stored. Additionally, PSH supports grid resilience by providing rapid and reliable power, enhancing the grid's stability and its ability to handle disruptions and fluctuations.

With the growing integration of volatile renewable sources such as wind and solar, the need for traditional base load hydropower plants reduces. Scenario 2 explores the possibility of completely converting the base load of the selected power plants to a regulating pumped storage system. In this scenario, when volatile energy sources produce excess energy, the converted pumped storage power plants can pump and store this energy for later use. It is estimated that 10% of the annual full load hours will be lost due to maintenance and other plant downtime. Of the remaining full load hours, 60% will be used for pumping and 40% for turbinning the stored water as mentioned in more detail in [subsubsection 3.6.1](#). This approach results in more full load hours available for pumping, thereby enhancing energy storage and grid regulation capabilities.



### 3.6.3 Scenario 3 - Conversion of only one unit for Cost Efficiency

In this scenario, the base load production of the power plants remains unchanged, similar to Scenario 1, as the energy produced is still required due to the insufficient capacity of other renewable sources to provide enough base load electricity. The strategy involves utilizing the remaining unused full load hours for pumping and turbinning.

The only difference from Scenario 1 is that, in this case, only one machine in the power house is converted into a pump turbine, rather than the entire power plant. This results in a lower potential for energy storage but requires minimal adjustments, has the lowest impact, and incurs the lowest investment costs.

For scenario 3 as only one machine is converted the calculations take the simplification, that the capacity factor is the same for all machines in the power plant. Therefore current full load hours  $h_{full}$  of the plant were calculated using the plant's capacity factor to establish its baseline workload. Thus, these full load hours are used for one machine as well. The calculations also assume a 10% reduction in annual full load operating hours  $h_{loss} = h_{year} \cdot 10\%$  to account for maintenance and downtime.

It is important to consider that the pump turbine can operate in either pumping mode or turbine mode. Accounting for expected efficiency losses due to factors such as pumping through pipes, the additional full load operating hours  $h_{add} = h_{year} - h_{full} - h_{loss}$  are divided into turbine mode  $h_{add.turbine} = h_{add} \cdot 40\%$  and pumping mode  $h_{add.pump} = h_{add} \cdot 60\%$ . The 60/40 split is an initial assumption and will be refined as more detailed information becomes available.

The potential added energy  $E_{add.turbine}$  is determined by multiplying the additional available operating hours, as outlined above, by the power capacity of the system  $P_{bp}$  and afterwards divided by the number of turbines  $n$ , as only one is converted to a pump turbine:

$$E_{add.turbine} = \frac{P_{bp} \cdot h_{add.turbine}}{n} \quad [\text{GWh/yr}] \quad (7)$$

As for the energy that is used for pumping  $E_{add.pump}$  the power capacity of the system is multiplied by the additional available pumping hours and afterwards divided by the number of installed turbines

$$E_{add.pump} = \frac{P_{bp} \cdot h_{add.pump}}{n} \quad [\text{GWh/yr}] \quad (8)$$

## 3.7 Mapping Storage Potential

To perform a comprehensive analysis of energy storage potential across Europe, Power BI, a visualization tool developed by Microsoft, was utilized. This tool allowed the data to be projected onto a map, providing a detailed and spatially accurate representation of energy storage potential across various regions.

The analysis focused on two *small adjustment* categories, which were visualized separately for clarity. In the section dedicated to *small adjustment* RtR and RoR sites, two separate maps were created, each using green dots to represent potential locations in different countries across Europe. Additionally, a separate map illustrating power plants that require medium and large adjustments are presented in the [section 5](#) for medium adjustments and [section 6](#) for large adjustments.

## 4 Power plants requiring small adjustments

In order for a power plant to be selected for the *small adjustments* category it needs to fulfill a number of prerequisites as follows,

1. dammed head- and tailwater,
2. connected to tailwater via piping,
3. minimum volume for head- and tailwater and
4. the tailwater which is freshwater.

Firstly, the tailwater of the power plant needs to be dammed to facilitate pumping. If the tailwater is an undammed river, pumping cannot be securely facilitated. This has many technical as well as environmental reasons. Power plants that were not able to fulfill these requirements are mentioned in [subsection 6.2](#).

Additionally, the power plant must be connected to the tailwater via piping. Many existing power plants have a small river downstream of the outlet, which leads to the tailwater. This complicates the installation of a booster pump as no pressure can be built up in an open water way. In such cases, investment costs would significantly increase due to the need for constructing piping from the turbine to the tailwater. Power plants that were not able to fulfill these requirements are mentioned in sections [5.1](#) and [6.3](#) whereas the first has less than 1 km to the tailwater and the second has more than 1 km.

Another requirement is that the headwater needs to have a certain volume as the energy storage is required to be of several hours. Therefore some calculations were made with the useable volume of the headwater  $V_{hw}$  [m<sup>3</sup>] and the given discharge of the turbine mentioned in [subsection 3.5](#). With the discharge  $Q$  the turbinning time  $T_{turb}$  can be calculated as follows

$$T_{turb} = \frac{V_{hw}}{Q} \cdot 3600 \quad [\text{h}] \quad (9)$$

As the upper reservoir is emptied and the water level drops, the hydraulic head decreases, which typically leads to a reduction in turbine efficiency. However, the resulting increase in turbinning time is negligible given the number of power plants under consideration, and will therefore be disregarded in this analysis. Power plants that were not able to fulfill these requirements are mentioned in [subsection 6.2](#).

A power plant may be deemed unsuitable for conversion if its tailwater is saltwater. Although this criterion only affects a relatively small number of power plants, it is included here for the sake of thoroughness. Important to note is that power plants which fall into the *small adjustments* category do not automatically add a large amount of storage. It is possible to filter for the amount of storage of the power plants. The category is meant to give a general overview which power plants could be transformed to a pumped-storage power plant with relatively small adjustments. Power plants that failed to meet these standards were also categorized and are mentioned in more detail in sections [5](#) and [6](#). These could still be considered to be transformed to a pumped-storage power plant, it would however take a significant amount of adjustments rather than *relatively small adjustments* as written in the proposal.

#### 4.1 RtR requiring small adjustments - 1a

This category includes power plants that utilize water from two reservoirs, artificially connected by pipes, to generate energy without involving any river in water transport. Only power plants with an installed Francis runner are suitable for this setup. Based on Google Maps images, the location of the outlet could be identified in most cases, making it easier to assess the feasibility of installing a booster pump—a crucial modification for fitting into this category. In the database, this category is referred to as 1a.

##### 4.1.1 Examples - 1a

To show the characteristics of the *small adjustment RtR* category, this section presents and analyzes two examples. The discussion highlights the specific attributes that qualify these power plants for inclusion in this category.

##### Exemplary Norwegian power plant - 1a

A Norwegian power plant serves as an exemplary model of a RtR facility, requiring only small adjustments. The relevant data for this power plant is presented in [Table 1](#).

Installed Capacity	25 MW
Annual Production	112 GWh
Capacity factor	51.14%
Headwater volume	$1.6 \cdot 10^6 \text{ m}^3$
Hydraulic head	290 m
Discharge	$9.8 \text{ m}^3/\text{s}$

Table 1: Data for the Norwegian power plant

Most importantly the runner of the power plant is currently a Francis runner. Both, the headwater and the tailwater are dammed as seen in the bottom right and bottom left corner of [Figure 2](#). Both have an acceptable volume with which the power plant can store energy for several hours. In addition to visually checking if the power plant is suitable the storage time is calculated by using [Equation 9](#) as follows,

$$T_{turb} = \frac{V_{hw}}{Q} = \frac{1.6 \times 10^6 \text{ m}^3}{9.8 \text{ m}^3 \text{ s}^{-1}} = 52 \text{ h.} \quad (10)$$

Furthermore the power plant sits right next to the tailwater, which simplifies the pumping process. The piping can be seen in [Figure 2](#) in blue and shows that both head and tailwater are connected via piping. From satellite images the outlet is visible and can further be confirmed by using the NVE Atlas. It is evident that the power plant belongs to the Reservoir to Reservoir (RtR) category because, unlike a Cascade system, its headwater and tailwater are not connected by a river.



Figure 2: The exemplary power plant in Norway, which represents one of the RtR power plants requiring only small adjustments.

### Exemplary French power plant - 1a

The power plant is located in France in the vicinity of Grenoble. The power plant has Francis runners installed which is a requirement for *small adjustment RtR* power plants. The data for this power plant is given in [Table 2](#).

Installed Capacity	116 MW
Annual Production	210 GWh
Capacity factor	20.7%
Headwater volume	$50.8 \cdot 10^6 \text{ m}^3$
Hydraulic head	298 m
Discharge	$45 \text{ m}^3/\text{s}$

Table 2: Data for the French power plant

Both headwater and tailwater are dammed, as seen in [Figure 3](#) and have sufficient volume to be used as energy storage of several hours. Once again in addition to visually checking if the headwater reservoir is large enough, the storage time is calculated by using [Equation 9](#) as follows,

$$T_{turb} = \frac{V_{hw}}{Q} = \frac{50.8 \times 10^6 \text{ m}^3}{45 \text{ m}^3 \text{ s}^{-1}} = 348 \text{ h.} \quad (11)$$

For this power plant the discharge was public available data and therefore did not have to be calculated. The power station is right next to the tailwater and the outlet is visible on satellite images as well. Because of all these factors this power plant can be placed in the *small adjustments* category.



Figure 3: A power plant in France, which represents one of the RtR power plants requiring only small adjustments

#### 4.1.2 Small adjustment RtR - Resulting Potential

In [Figure 4](#), a map illustrates all identified small adjustment RtR power plants to date. As shown on the map, the majority of these power plants are located in Norway. Initially, a total of 97 small adjustment power plants were identified through a filtration process applied to the raw data. Since the focus is on power plants with significant storage capacity, greater than a few hours, a filter was applied to include only power plants with an emptying time greater than 4 hours. As described in [subsection 3.6](#), the emptying time of the headwater for each power plant was calculated. Whenever enough data for the calculation of the emptying time was available it was used to determine whether a power plant could reach the required 4 hours. For plants with insufficient data, the potential storage capacity was statistically estimated as already introduced in [subsection 3.6](#). The estimation was calculated as follows: For power plants with sufficient data, the percentage of those with an emptying time exceeding 4 hours was determined. This percentage was then used to estimate the proportion of power plants with insufficient data, that likely have an emptying time greater than 4 hours.

Following the above-described scenarios [subsection 3.6](#), we calculated the potential energy storage for each scenario within this category. The results are as follows:

- Scenario 1 - Maintaining the current base load and finding additional full load hours: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 16.15 TWh and  $E_{add.pump}$  of 24.23 TWh was calculated.
- Scenario 2 - Converting Base Load to Regulating Pumped Storage: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 29.4 TWh and  $E_{add.pump}$  of 44.1 TWh was calculated.
- Scenario 3 - Conversion of only one unit for Cost Efficiency: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 8.81 TWh and  $E_{add.pump}$  of 13.22 TWh was calculated.





Figure 4: Mapping of small adjustment RtR power plants without filtering

## 4.2 RoR requiring small adjustments - 1b

To qualify for this category, power plants must utilize water from a river cascade. Both the headwater and tailwater must originate from the same river and has to be dammed. The size of the reservoirs is also a critical factor. Specifically, the tailwater must have sufficient volume to enable pumping, and the headwater must be large enough to provide storage for more than a few hours. In this category, not only power plants with Francis runners are suitable, but those with Kaplan runners would also fit as they can be retrofitted with an axial pump in combination with a booster pump to enable pumping and turbining. In the database, this category is referred to as 1b.

### 4.2.1 Examples - 1b

To show the characteristics of the *small adjustment RoR* category, this section presents and analyzes two examples. The discussion highlights the specific attributes that qualify these power plants for inclusion in this category.

#### Exemplary Swedish power plant - 1b

The Power Plant is situated in Sweden on the Indalsälven River, which features numerous power plants along its stretch. The data for this power plant is given in [Table 3](#). The power station is located along the dam and has Kaplan runners installed. As mentioned in [subsection 4.2](#) for the *small adjustment RoR* category Kaplan runners are also acceptable.

Installed Capacity	147.6 MW
Annual Production	841.3 GWh
Capacity factor	65.1%
Headwater volume	$6.9 \cdot 10^6 \text{ m}^3$
Hydraulic head	28.5 m
Discharge	$580 \text{ m}^3/\text{s}$

Table 3: Data for the Swedish power plant

The storage time is calculated by using [Equation 9](#) as follows,

$$T_{turb} = \frac{V_{hw}}{Q} = \frac{6.9 \times 10^6 \text{ m}^3}{580 \text{ m}^3 \text{ s}^{-1}} = 4.7 \text{ h.} \quad (12)$$

As seen in this example, most power plants in the *small adjustment RoR* category have a lower storage time than power plants in the *small adjustment RtR* category. However, because the capacity factor is crucial in determining the amount of yearly storage added, run-of-river (RoR) power plants also add a significant amount.





Figure 5: The power plant in Sweden, which represents one of the high potential RoR power plants

#### Exemplary Greek power plant - 1b

This power plant is located in Greece 50km west of Thessaloniki and has Francis runners installed. The data for this power plant is given in Table 4. As seen in Figure 6 both head and tailwater are dammed and are of sufficient size to be pumped. The power station is located in the dam and therefore close to the head and tailwater which reduces friction losses in pipes significantly.

Installed Capacity	108 MW
Annual Production	129 GWh
Capacity factor	13.6%
Headwater volume	$14 \cdot 10^6 \text{ m}^3$
Hydraulic head	42 m
Discharge	$303 \text{ m}^3/\text{s}$

Table 4: Data to the Greek power plant

The storage time is calculated by using Equation 9 as follows,

$$T_{turb} = \frac{V_{hw}}{Q} = \frac{14 \times 10^6 \text{ m}^3}{303 \text{ m}^3 \text{ s}^{-1}} = 14 \text{ h.} \quad (13)$$

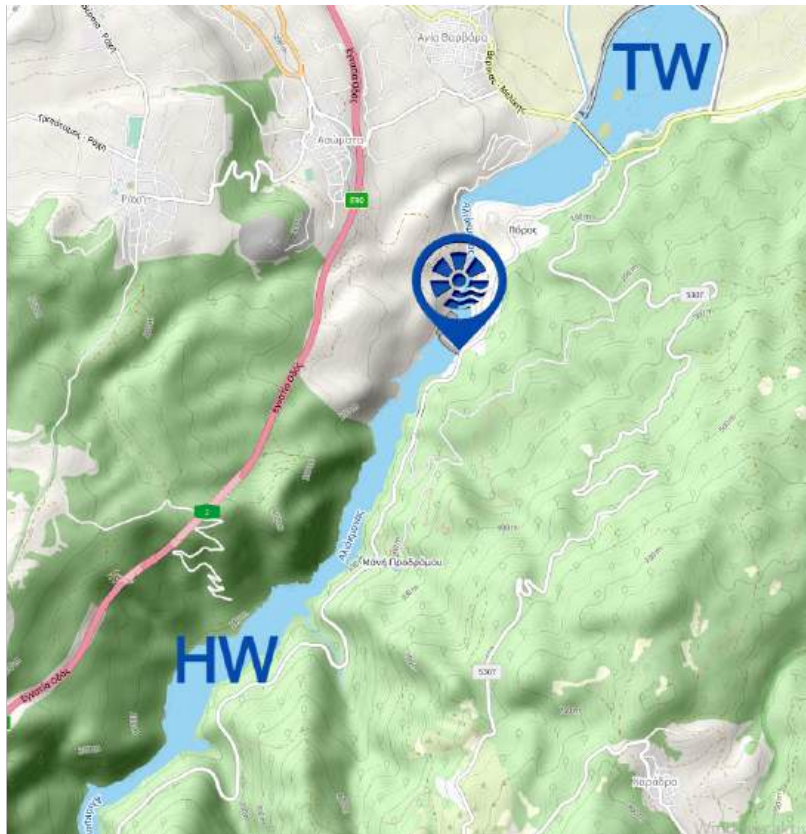


Figure 6: The power plant in Greece, which represents one of the RoR power plants requiring small adjustments.

#### 4.2.2 Small adjustment RoR - Resulting Potential

In [Figure 7](#), a map illustrates all identified *small adjustment* RoR power plants to date. As shown on the map, suitable power plants can be found across Europe. Initially, a total of 57 small adjustment power plants were identified through a filtration process applied to the raw data. As described in [subsection 3.6](#), the emptying time of the headwater for each power plant was calculated.

Since the focus is on power plants with significant storage capacity, greater than a few hours, a filter was applied to include only power plants with an emptying time greater than 4 hours. As described in [subsection 3.6](#), the emptying time of the headwater for each power plant was calculated. Whenever enough data for the calculation of the emptying time was available it was used to determine whether a power plant could reach the required 4 hours. For plants with insufficient data, the potential storage capacity was statistically estimated as already introduced in [subsection 3.6](#). The estimation was calculated as follows: For power plants with sufficient data, the percentage of those with an emptying time exceeding 4 hours was determined. This percentage was then used to estimate the proportion of power plants with insufficient data, that likely have an emptying time greater than 4 hours.

Following the above-described scenarios [subsection 3.6](#), we calculated the potential energy storage for each scenario within this category. The results are as follows:

- Scenario 1 - Maintaining the current workload and finding additional full load hours: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 18.72 TWh and  $E_{add.pump}$  of 28.08 TWh was calculated.
- Scenario 2 - Converting Base Load to Regulating Pumped Storage: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 28.6 TWh and  $E_{add.pump}$  of 42.9 TWh was calculated.
- Scenario 3 - Conversion of only one unit for Cost Efficiency: An additional storage turbine energy potential  $E_{add.turbine}$  of approximately 6.48 TWh and  $E_{add.pump}$  of 9.72 TWh was calculated.





Figure 7: Mapping of small adjustment RoR power plants without filtering

### 4.3 Other Storage Combinations

Furthermore, one of the promising areas for hydropower advancements is the development of hybrid hydro systems, which combine traditional hydropower technologies with virtual energy storage solutions. This approach enhances operational flexibility, reduces mechanical wear on components, supports the integration of renewable energy sources, and provides the potential for increased storage capacity.

A notable example of this innovation is the XFLEX HYDRO Vogelgrun project, which provides a practical demonstration of these benefits.

The Vogelgrun demonstrator investigates the hybridization of a run-of-river hydropower plant with a battery energy storage system (BESS). By combining a 650 kW/370 kWh battery with the existing turbine-generator unit, the system improves frequency response dynamics while significantly reducing mechanical stress on turbine components. The hybrid configuration effectively divides frequency containment reserve (FCR) tasks between the turbine and battery, optimizing energy delivery and extending equipment lifespan. This project highlights the scalability and effectiveness of hybrid hydro systems as a cornerstone for advancing sustainable and resilient energy infrastructure.[5]

Figure 8 illustrates the Vogelgrun prototype setup.

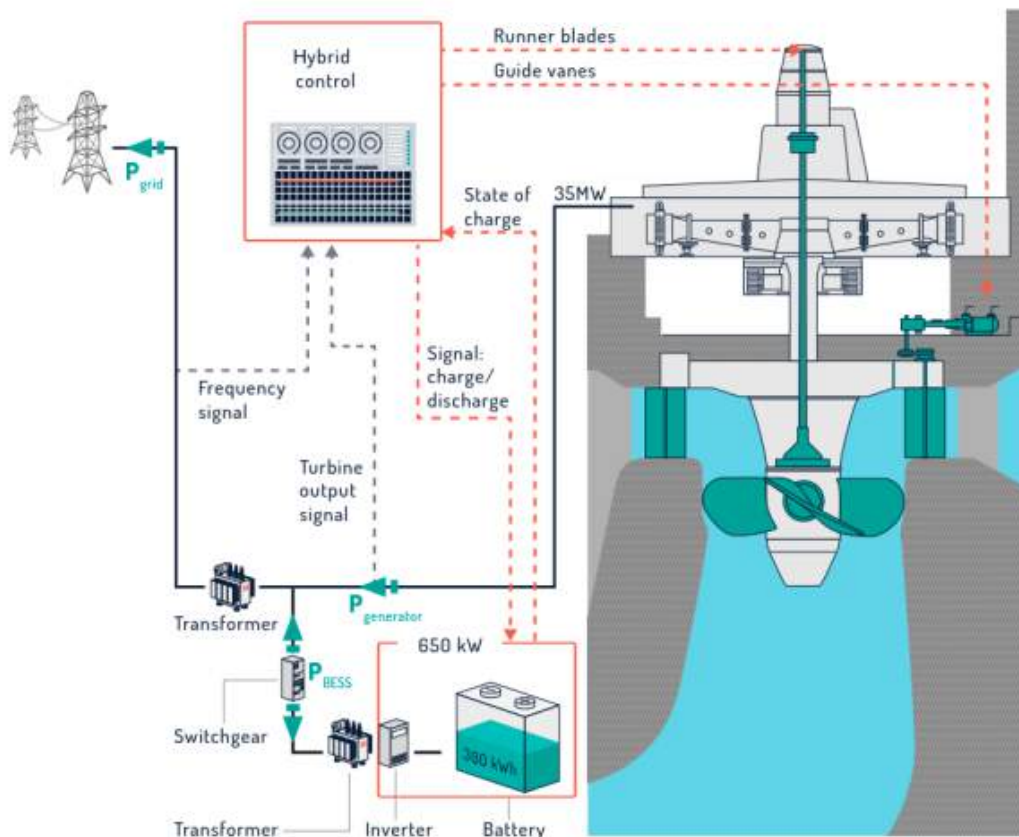


Figure 8: Vogelgrun Setup [5]

Similarly, the hydropower plant at Wallsee-Mitterkirchen represents a promising project in integrating battery storage with hydropower in Austria. Operational since 2023, this system provides 16 MW of primary frequency regulation, combining 8 MW from a 14,200 kWh lithium-ion battery system and 8 MW from the hydropower plant's Kaplan turbine. The "Blue Battery" stabilizes grid frequency at 50 Hz, compensating for fluctuations caused by volatile renewable sources like wind and solar. [8] [9]

Since solutions like the Vogelgrun demonstrator and Wallsee-Mitterkirchen can be implemented in many locations across Europe and are less dependent on the specific type of hydropower plant than on the distribution of other renewable energy sources, the identification of suitable sites for such systems has been deferred to a later stage of the project. This decision allows the research to focus initially on understanding the distribution of other renewable sources, such as wind and solar energy, which play a critical role in determining the practicality and efficiency of hybrid setups.

Once the distribution of renewable energy sources becomes clearer, detailed analyses can be conducted to identify the most appropriate locations for implementing hybrid hydro systems.



## 5 Power plants requiring medium adjustments

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For many power plants the condition of having relatively small adjustments cannot be met for this project. Some fail to meet one or two conditions which were mentioned in [section 4](#), while others are entirely incompatible. Therefore the *medium adjustments* and *large adjustments* category was created. Not only do these categories make sure that a completeness of the database can be assured but it also helps in case more extensive adjustments are acceptable. The *medium adjustments* category includes power plants where the modifications exceed being just the installation of the pump turbine runner and the booster pump. Mostly further piping or some other form of structural modifications are needed for the conversion to a pump-storage power plant.

Additional nuanced gradations have been made in the *medium adjustments* category. This makes further filtering more accessible, in case some forms of installments are preferable over others. For many of the power plants the location of the outlet is a key factor why the severity of the needed modifications exceed the definition of *small adjustments*. With the needed installment of piping the investment costs would increase significantly and therefore these cases were put in the *medium adjustments* category. This makes further filtering more accessible in case some forms of installments are preferable over others. The following further subcategories were defined:

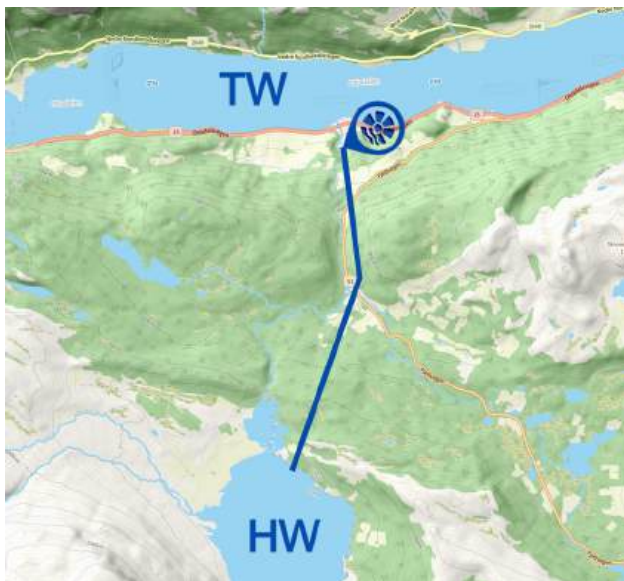
### 5.1 Power plants with tailwater within one kilometer - 2a

This subcategory consists of power plants for which the outlet of the power plant is located less than 1 kilometer away from the tailwater. The connection between these two could be by a small river, a channel or some other form of an open water way in which it is impossible to build pressure with a booster pump. It is important to mention that for these cases a tailwater exists which is dammed and has a sufficient size in order to be used for pumping. Therefore the only restricting factor for these cases is the connection to the tailwater reservoir.

#### 5.1.1 Example - 2a: Another Norwegian power plant

An example of a power plant categorized as 2a is a power plant also located in Norway. Initially, an examination of the head and tailwater, as seen in [Figure 9\(a\)](#) suggests that only small adjustments are required for the conversion. However, a more detailed investigation, as illustrated in [Figure 9\(b\)](#), reveals that the connection from the outlet to the tailwater is an open channel. Consequently, additional piping needs to be installed, which cannot be considered, per our definition, a small adjustment.





(a) Overview of the head and tailwater



(b) Detailed view of the outlet

Figure 9: A Norwegian power plant

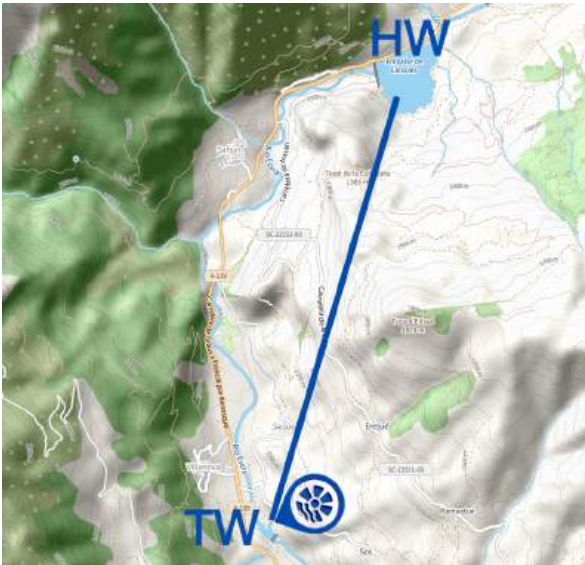
## 5.2 Power plants with small tailwaters - 2b

For this subcategory, the tailwater is dammed but too small for the power plant to realistically consider pumping. In some cases, basic calculations were performed using the volume of the tailwater and the estimated discharge of the pump. If the resulting pumping time was deemed too short to be practical, the power plants were classified under this category.

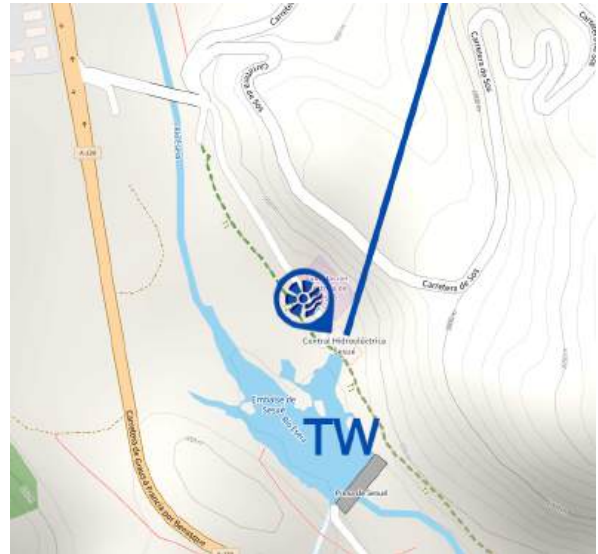
However, in many instances, it was not possible to determine the tailwater volume. Consequently, some tailwaters were analyzed using satellite images. If the volume appeared insufficient, the corresponding power plant was included in this category. In order to convert power plants from this category to pumped storage plants the tailwaters need to be enlarged in addition to the aforementioned adjustments in [section 4](#).

### 5.2.1 Example - 2b: A Spanish power plant

The power plant in Spain is a classic example of a power plant of class 2b. As seen in [Figure 10\(a\)](#) already after a first look its visible, that the tailwater is much smaller than the headwater. Technically pumping would be possible but realistically the pumping time is so low that this power plant falls into the 2b category. Important to note is however that the tailwater is dammed as seen in [Figure 10\(b\)](#). If it was not dammed the power plant would belong in category 3b, see [subsection 6.2](#).



(a) Overview of head and tailwater



(b) Detailed view of the tailwater

Figure 10: Spanish power station

## 6 Power plants requiring large adjustments

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If the needed adjustments are more than for the *medium adjustments* category the power plants were placed in the *large adjustments* category. Once again more nuanced gradations were made in this category in case some adjustments are preferable.

Power plants with an outlet into saltwater or those equipped with a Pelton runner are immediately excluded. In the case of Pelton turbines, the investment costs for converting to a pumped storage facility would be significantly high. This is because the conversion would require the construction of a new cavern, which is comparable to building an entirely new power station. As for the tailwaters which consist of salt water, there has been some research in that field as seen in [6], however, because of the unforeseen impact on the environment these power plants are also excluded. Additionally, power plants with a capacity below 10 megawatts are not considered for further investigation, as their potential remains low even when other conditions are met.

### 6.1 Power plants with small headwater-3a

This subcategory is made up of power plants where the size of the headwater is not sufficient. As stated in the proposal the goal is to add long term storage capacity which is there defined as storage of greater than a few hours. Therefore for this subcategory basic calculations were made as seen in [section 4](#) in the equations [1](#) and [9](#).

Most of the power plants that fit into this category are RoR power plants as these naturally have smaller headwater volumes and higher discharge.

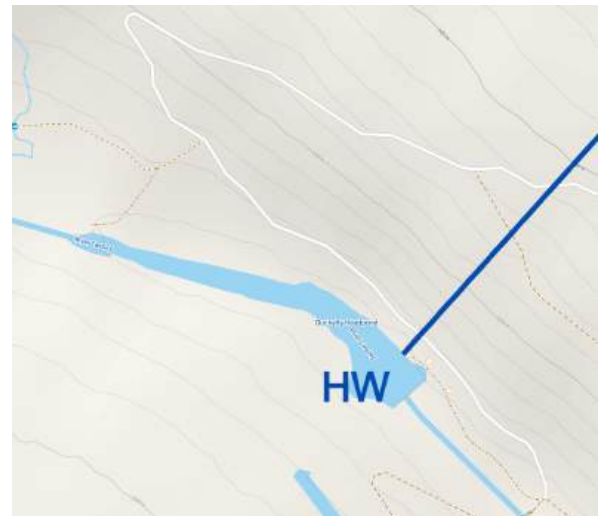
#### 6.1.1 Example - 3a: A Scottish power plant

The power station, located in the northern part of Scotland, serves as an example of a category 3a power plant. An initial examination of the head and tailwater reveals that the headwater is significantly smaller than the tailwater, as shown in [Figure 11\(a\)](#). Geographically, there is a larger reservoir situated above the visible headwater, but it is not feasible to pump water to this upper reservoir. Consequently, either the current headwater must be enlarged, or piping must be installed to connect to the larger, more distant reservoir. These modifications require substantial investments, categorizing the power plant under *large adjustments*.





(a) Overview of head and tailwater



(b) Detailed view of the headwater

Figure 11: Scottish Power station

## 6.2 Power plants with the outlet into an undammed river - 3b

The research revealed that approximately 30% of all identified power plants fall into this category. Power plants whose outlets discharge into an undammed river are classified within this subcategory. The key distinction from category 2b is the absence of a downstream reservoir for potential pumping. It is important to note that a dammed river is considered a reservoir. Consequently, a power plant could be classified under the *small adjustments* category if all other conditions are met.

For power plants in this subcategory, converting to a pumped storage facility requires the tailwater to be dammed and transformed into a reservoir. This type of structural modification involves significant investments and must be evaluated for sustainability. Therefore, these power plants fall into the *large adjustments* category.

### 6.2.1 Example - 3b: A Czech power plant

This power station in the Czech Republic is an example of a category 3b power plant. As illustrated in Figure 12(a), the headwater is sufficiently large for long-term storage. However, downstream of the power plant, it is evident that the tailwater is not dammed. Without a dammed tailwater, pumping is not feasible. Therefore, constructing a tailwater reservoir would be necessary for the conversion. This construction involves significant investments and must be evaluated for sustainability and therefore the power plant falls into the category of *large adjustments*.



(a) Overview of head and tailwater



(b) Detailed view of outlet and the river as tailwater

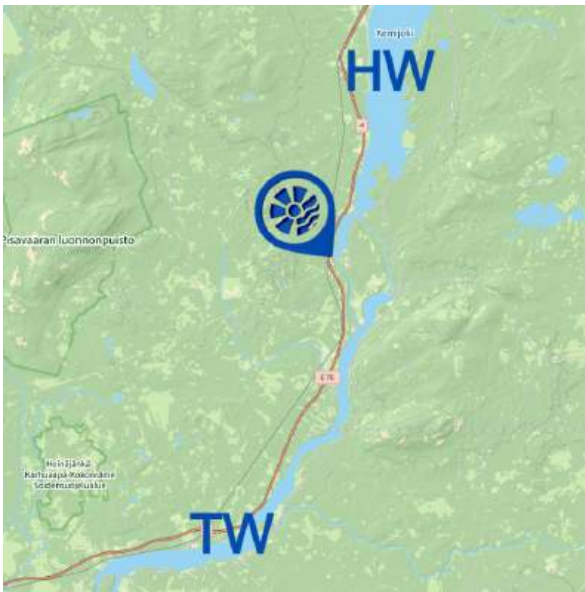
Figure 12: Czech Power station

### 6.3 Power plants with tailwater further away than one kilometer - 3c

Similar to the subcategory 2a here the outlet of the power plant is connected to the tailwater reservoir by an open water way in which no booster pump can be installed. The difference in this case is however that the distance to the tailwater reservoir is bigger than 1 kilometer. Therefore for the transformation to a pumped storage plant some extensive piping needs to be installed. If the distance is much too large other modifications might need to be done as well.

#### 6.3.1 Example - 3c: A Finnish power plant

A power plant, located 100 kilometers north of Oulu in Finland, features large headwater and tailwater reservoirs, as shown in Figures 13(a) and 13(b). However, the outlet of the power plant is connected to the tailwater reservoir via a river, as seen in the detailed view in Figure 13(b). For the conversion, additional piping needs to be installed. The river connecting the outlet to the tailwater reservoir is 3 kilometers long, which disqualifies the power plant from the 2a category and places it in the 3c category.



(a) overview of the head and tailwater.



(b) Detailed view of the connecting river between outlet and tailwater reservoir.

Figure 13: Finnish hydropower plant

## 6.4 Power plants located on navigable rivers - 3d

In many countries of Europe, rivers play a crucial role in commercial shipping, which imposes legal restrictions on their use for energy storage or other water management practices. These regulations aim to maintain consistent water levels to prevent disruption of cargo traffic. Consequently, the potential for water level variation and therefore the energy storage potential at sites along navigable rivers is significantly reduced. These constraints ensure that shipping operations remain unaffected, but they limit the feasibility of utilizing storage systems in such areas. The power plants in this category fall under this restrictions.

To estimate the potential for this category, a different approach was employed. It was assumed that one additional pump would be installed alongside the existing units. The pump's capacity was defined to ensure a storage duration exceeding 4 hours =  $t_{min}$ . For this calculation, the maximum usable headwater volume  $V_{Useable}$  was determined using the average width  $b$ , the distance  $l$  to the preceding power plant and  $\Delta h$  which represents the permissible water level variation, calculated as follows

$$V_{useable} = b \cdot l \cdot \Delta h. \quad (14)$$

In the next step, the maximum capacity of the pump is calculated to ensure that the headwater is not completely filled within 4 hours. The flow rate is determined by dividing the usable headwater volume  $V_{hw}$  by the time threshold as follows

$$Q_{Pump} = \frac{V}{t_{min}}. \quad (15)$$

This equation calculates the pump's power requirement by incorporating the flow rate  $Q_{Pump}$ ,  $h$  hydraulic head, and the water density  $\rho$ , ensuring the pump can handle the defined operational constraints

$$P_{Pump} = Q_{Pump} \cdot H_{hydraulic} \cdot g \cdot \rho. \quad (16)$$

In calculating the pump storage potential, it was assumed that the installed pump operates 90% of the time annually  $= 0.9 \cdot t_{year}$ . Three example sites along the Danube River, one of the largest rivers in Europe, were analyzed. Using data from these sites, the pump storage potential was determined.

$$E_{pump} = P_{Pump} \cdot t_{year} \cdot 0.9 \quad (17)$$

This computed potential served as the basis for estimating the potential of the entire Danube River. Specifically, the example sites collectively span 80.5 km of the river, and the calculated potential was proportionally scaled to the full 2,850 km length of the Danube. This approach provides a broad estimation of the river's storage capacity by extrapolating localized data. The up-scaled potential for the entire Danube is 5.5 TWh/year.



## 7 Results

As different scenarios were considered the resulting added yearly storage capacity varies from scenario to scenario.

In **Scenario 1**, the goal was to increase the plant's full load operating hours by converting it into a pumped storage facility, while ensuring the current energy production is maintained to meet the grid's demands. For this case the annual added cumulative storage capacity is 37.87 TWh/yr when only considering turbinning.

**Scenario 2** proposes converting the whole base load which is produced by the hydropower plants to be available for pumped storage to enhance energy storage and regulation capabilities. As the second scenario uses the whole power plant all year round the annual added cumulative storage is by far the greatest with 58 TWh/yr alone for turbinning.

**Scenario 3** is the most conservative approach, involving the conversion of only one machine while maintaining the base load of the plant. The resulting annual added cumulative storage capacity, when considering only turbinning, is 15.29 TWh/year. This is a significant amount, especially considering that only one machine is converted to a pump turbine.

As a differentiation in RtR (Reservoir to Reservoir) and RoR (Run of River) was also made, the added yearly storage capacity for turbine and pump is shown in more detail in [subsubsection 4.1.2](#) for the results of the RtR power plants, in [subsubsection 4.2.2](#) for the RoR power plants and in tables 5 and 6 all results are listed.

With the continuous development of the energy sector, new potential power plants are constantly emerging. Therefore, the database will get ongoing updates to ensure it remains as complete and accurate as possible.

$E_{add.turbine}$	Scenario 1 [TWh/yr]	Scenario 2 [TWh/yr]	Scenario 3 [TWh/yr]
Small adjustment RtR	16.2	29.4	8.8
Small adjustment RoR	18.7	28.6	6.5
<b>Sum:</b>	<b>37.87</b>	<b>58.0</b>	<b>15.29</b>

Table 5: Results Turbine Potential

$E_{add.pump}$	Scenario 1 [TWh/yr]	Scenario 2 [TWh/yr]	Scenario 3 [TWh/yr]
Small adjustment RtR	24.2	44.1	13.2
Small adjustment RoR	28.1	42.9	9.7
<b>Sum:</b>	<b>52.3</b>	<b>87.0</b>	<b>22.9</b>

Table 6: Results Pump Potential

Furthermore, a comparison of the number of power plants per category was visualized in [Table 7](#).



	Number of Power Plants
Small adjustment RtR	97
Small adjustment RoR	58
Medium adjustment	65
Large adjustment	500

Table 7: Results



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