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## Facilitating energy storage to allow high penetration of intermittent renewable energy

# Environmental performance of existing energy storage installations

### Deliverable D.3.1

Source: (ESB)

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## Acknowledgements

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The work for this report has been coordinated by University College Cork (UCC) and Malachy Walsh and Partners, Engineering and Environmental Consultants (MWP).



| Author(s) | | |
|---|---|---|
| **Name** | **Organisation** | **Email** |
| Annicka Wänn | UCC | Annicka.wann@gmail.com |
| Paul Leahy | UCC | Paul.leahy@ucc.ie |
| Monica Reidy | MWP | Monica.reidy@mwp.ie |
| Sean Doyle | MWP | Sean.doyle@mwp.ie |
| Helen Dalton | MWP | Helen.dalton@mwp.ie |
| Peter Barry | MWP | Peter.barry@mwp.ie |

## Table of Contents





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## Table of Figures

# Table of Tables

## List of Abbreviations

| | | |
|---|---|---|
| AA- CAES | ... | Advanced adiabatic compressed air energy storage |
| BBM | ... | Building block methodology |
| CAES | ... | Compressed air energy storage |
| CCGT | ... | Combined cycle gas turbine |
| CCS | ... | Carbon capture and storage |
| $CO_2$ | ... | Carbon dioxide |
| DO | ... | Dissolved oxygen |
| EIA | ... | Environmental impact assessment |
| EST | ... | Energy storage technologies |
| GEP | ... | Good Ecological Potential |
| GES | ... | Good environmental status |
| GHG | ... | Greenhouse gas |
| GW | ... | Gigawatt |
| GWh | ... | Gigawatt hour |
| HMWB | ... | Heavily Modified Water Body |
| HP | ... | Hydropower |
| IBA | ... | Important Birds Areas |
| kW | ... | Kilowatt |
| kWh | ... | Kilowatt hours |
| LCA | ... | Life cycle analysis |
| $CH_4$ | ... | Methane |
| MS | ... | Member States |
| MW | ... | Megawatt |
| MWh | ... | Megawatt hour |
| PHES | … | Pumped hydro energy storage |
| RES | ... | Renewable energy sources |
| RES-e | ... | Renewable electricity sources |
| SHP | ... | Small Hydropower |
| TSO | ... | Transmission system operators |
| TW | ... | Terawatt |
| TWh | ... | Terawatt hour |


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# Glossary

| | |
|---|---|
| Adiabatic process | A term used in thermodynamics to describe a process that occurs without heat loss or heat gain |
| Anadromous | Fish species whose reproduction takes place in freshwater and growing phase in the sea. Migration back to freshwater is for the purpose of reproduction. |
| Environmental aspect | Is a feature or characteristic of an activity, product or service that interacts with and affects the environment |
| Base load | The minimum amount of power that a utility company must make available to the grid to cover a given regions continuous energy demand |
| Catadromous | Fish species whose reproduction takes place in the sea and growing phase in freshwater (opposite of anadromous) |
| Cavern configuration | Referring to a powerhouse (turbine, generator, pumps etc) that is located below ground in an excavated cavern with access via a tunnel |
| Cumulative impact | The impact on the environment that occurs from the incremental impacts of the actions when added to the past, present, and reasonably foreseeable future actions. Can be minor individual actions that collectively become significant |
| Dead Storage | Is the volume of space below the dams lowest outlet |
| Diabatic process | A term used in thermodynamics to describe a process that involves heat loss or heat gain |
| Diadromous | Fish whose life cycle takes place partly in fresh and partly in marine waters. Distinction can be made between catadromous and anadromous species. |
| Draft tube | The draft tube is a conduit that connects the runner exit to the tail race where the water is discharged from the turbine. The primary function of the draft tube is to reduce the velocity of the discharged water to minimize the loss of kinetic energy at the outlet. |
| Ecological flow | Is used interchangeably with natural flow |
| Environmental flow | The quantity, quality and timing of water flow required to sustain freshwater and estuarine ecosystems. It aims to simulate but is not a substitute for the natural flow of the river |
| Environmental impact | Refers to a change in the environment that can be positive or negative. Environmental impacts are caused by environmental aspects. |
| Head | Head is pressure created by the difference in elevation between the upper and lower reservoir water surface. Higher head will produce greater pressure and therefore more power. Head also determines what type of turbine to use. |
| High Impact | Modified term from the Glossary of Impacts in EPA (Ireland) (2002) to include two definitions; significant impact by its character and magnitude and duration or intensity alters a sensitive aspect of the environment; and profound impact which obliterates sensitive characteristics. |
| Hydropower | Known also as an impoundment and usually refers to a large hydro power |


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|---|---|
| | facility that uses a dam to store river water in a reservoir. The higher the water level in a reservoir (i.e head) the more potential energy is available for power generation. Often used for peak load generation. |
| Large Hydropower | Usually refers to hydro power facilities with an installed capacity of more than 10MW |
| Life cycle analysis | A method used to assess the environmental impact associated with all stages of a product or service (from cradle-to-grave) |
| Low impact | Modified term from the Glossary of Impacts in EPA (Ireland) (2002) to include two definitions; imperceptible impact capable of measurement but without noticeable consequences; and slight impact, which causes noticeable changes without affecting its sensitivity |
| Medium Impact | Modified term from the Glossary of Impacts in EPA (Ireland) (2002) to mean a moderate impact which alters the character of the environment in a manner that is consistent with existing and emerging trends |
| Mid-merit | Are power plants that fill the gap between base load and peak load. |
| Minimum flow | Minimum flow from dams are in place to maintain the ecological quality of a river downstream (i.e. prevent rivers from drying up) |
| Natura 2000 Network | Network of protection areas established under the 1992 Habitat Directive, comprising Special Areas of Conservation (SACs) under the Habitat Directive and Special Protection Areas (SPAs) designated under the 1979 Birds Directive. |
| Natural flow | The flow that would naturally occur in a river without the presence of a dam. Natural fluctuations vary in magnitude on a seasonal basis |
| Peak load | The maximum power requirement of a system at a given time period |
| Penstock | The pipes or tunnels through which the water moves from the reservoir to the power station (pipes can be constructed above or below ground) |
| Potamodromous | Fish species that complete their entire life cycle in freshwater; reproductive and feeding zones |
| Pre-developed Environment | The environment that existed prior to the development of for example a PHES facility. Helps determine the level of environmental impact of the facility. |
| Run-of-river | Known also as a diversion where the hydro facility only uses the water that is available in the natural flow of the river. These facilities will have little or no water storage possibilities and power generation will fluctuates with the natural flow of the river. Not an option for peak load generation. |
| Scoping | Is a method to determine key issues from a broad range of potential concerns for inclusion in EIA studies |
| Sensitive species | Species that can only survive within a narrow range of environmental conditions and whose disappearance is used as an index of pollution or other environmental changes. |
| Sensitivity | Sensitivity of an area is determined by the value of the receiving environment or receptors |
| Shaft configuration | Referring to a powerhouse that is located immediately below the ground surface and constructed in an open excavation or shaft. Access is via an overground superstructure |

| | |
|---|---|
| Small Hydropower | Although definitions vary, it usually refers to hydropower with an installed capacity of less than 10MW |
| Tail race | the tail race is where the water is finally discharged from the turbine |
| Tolerant species | Species that can survive in a wider range of environmental conditions |
| Wind curtailment | During windy conditions when turbines generate more electricity than demand requires, wind will be “dumped” by reducing electricity generation below what it is capable of producing. |

# Environmental performance of existing energy storage installations

Deliverable 3.1

## Executive Summary

### *Introduction*

Recent increases in electricity generation from renewable energy sources in response to EU targets have led to renewed interest in energy storage to help integrate renewable energy into the grid. The EU directive 2009/28/EC states that electricity from renewable sources should be given priority over that from other sources. Large scale energy storage can help to increase the penetration of wind and other variable renewable energy sources. There are two proven energy storage technologies that are achievable on a large scale today: pumped hydro energy storage (PHES) and compressed air energy storage (CAES). There are more than 300 PHES schemes operating in the world, whereas there are only two CAES facilities, one in Huntorf, Germany and the other in Alabama, USA.

The EU-funded project *stoRE* aims to facilitate energy storage in order to allow for higher penetration of variable renewable energy generation. This deliverable describes a key task which aims to determine the environmental performance of existing energy storage facilities. The knowledge gained from the experiences highlighted in six case studies will form the foundation for the rest of the tasks within work package three of stoRE that aim to determine international best practice and to lower environmental barriers to implementing new energy storage schemes.

### *The Benefits of Energy Storage*

There are several positive impacts associated with an increased energy storage capacity. The benefits of bulk energy storage technologies include: black start capabilities, grid flexibility and stability, spinning reserve, auxiliary reserve, peak shaving and regulation control. More energy storage facilities also mean less curtailment of wind power, as the bulk energy storage technologies will absorb excess electricity. At the same time $CO_2$ emissions are mitigated as the avoidance of curtailment displaces electricity from fossil fuel sources. Other technologies, such as open cycle gas turbines can provide peak power during fall-off of wind. However, these technologies cannot store electricity during times when wind production exceeds that which the grid can utilise.

### *The Technologies*

Two main technologies have been studied in this report; CAES and PHES. The latter has been categorised further into three main types:

- Closed-loop: consists of two reservoirs that are separated by a vertical distance, neither of which is connected to another body of water.
- Semi-open: consists of one artificial or modified reservoir and one modified lake or river impoundment with continuous through flow.
- Open-system (pump-back): a system where there is continuous flow of water through both the upper and lower reservoir.



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The reason for the subcategories is that these three main types behave very differently in terms of water management and will therefore have different environmental impacts during operation. In addition, even though there are different types of open-system PHES, the pump-back PHES is the most common type. It is therefore important to note that when referring to the open-system category, this deliverable deals exclusively with the environmental impacts from the operation of pump-back PHES.

## *The Case Studies*

Six case studies were chosen from five of the partner countries. The sixth partner country, Denmark, does not have any CAES or PHES facilities and could therefore not form part of this report. Five different PHES facilities were chosen in terms of age, pre-developed environment and technology to cover as wide a range as possible. Only one CAES was chosen as there only is one in Europe at this time and only two worldwide.

To help determine the environmental performance of the selected cases in the operational phase the magnitude of the environmental impacts has been classified as high, medium or low (see Table 1). The magnitude of the impact will depend on the sensitivity of the receiving environment. The impacts have also been categorised by potential issues/Environmental Impact Assessment terms of reference.

**Table 1: Definitions used to determine operational impact of the case studies**

| Magnitude | Characteristics of impacts |
|---|---|
| Low | Imperceptible impact capable of measurement but without noticeable consequences |
| | Slight impact, which causes noticeable changes without affecting its sensitivity |
| Medium | Moderate impact which alters the character of the environment in a manner that is consistent with existing and emerging trends |
| High | Significant impact by its character and magnitude and duration or intensity alters a sensitive aspect of the environment or profound |
| | Profound impact which obliterates sensitive characteristics |

While bulk energy storage technologies have obvious benefits, for the purposes of the case studies only the negative impacts of operational facilities that reduce the quality of the environment are addressed. Direct and indirect environmental impacts as well as additional impacts have been identified. It is important to note that the list of environmental impacts, in particular those of a cumulative nature, is not exhaustive and other impacts may occur that have not been identified in the deliverable. Due to the life span of the facilities most impacts associated with their operation are considered to be long-term.

Source: KBB

## 1. Case Study – Huntorf

Huntorf is located in the northwest of Germany in Niedersachsen. It was commissioned in 1978 and was the first CAES facility installed worldwide. The facility was installed with a capacity of 290MW but was upgraded to

321MW in 2007. It has a storage capacity of 0.64GWh and has the ability to operate at peak load for about 2 hours per day.

The CAES was constructed into an already stressed environment, where the predominant land use is still agriculture. There are also several large cities in close proximity. It uses two large underground salt caverns to store the compressed air. Each of the caverns is located at a depth between 650-800m and is approximately 40m in diameter. Salt deposits are the most suitable type of geology to use for CAES as these structures are plastic, yet solid and impermeable. The main features of the facility are thus out of sight from local population.

As Huntorf is a diabatic CAES, heat is lost from the air as it compresses. The result is that during decompression the system requires natural gas, as its external heat source, to recover the stored compressed air. This type of CAES is therefore not considered to be a “pure” electricity storage technology, but rather a hybrid system. The requirement for natural gas however, is one third that of conventional gas turbine power plants. In addition to this fuel requirement, further emissions of GHG may be incurred depending on the primary source of electricity that the CAES uses to operate the compressors.

## 2. Case Study – Thissavros

Source: Metka

Thissavros is located in Greece, in the Nestos River Basin close to the Bulgarian border. The River Nestos is shared by Bulgaria and Greece and was already regulated with irrigation dams in Bulgaria prior to the construction of Thissavros. The dam and pump-back PHES was therefore constructed into an already stressed environment but has had an additional impact on the river system. The dam is a 172m rock filled dam, and as such one of the highest dams in Europe. It was commissioned in 1997 and has an installed capacity of 381MW. A further dam was commissioned in 1999 downstream of Thissavros called Platanovrisi. Together the two dams provide electricity generation, peak power and water for irrigation.

Thissavros is located in a very sparsely populated area where the main use of land is forestry. Although the construction of the dam and PHES has made the area more accessible, the visual impact of a 172m rock filled dam does not go unnoticed. Although habitat loss due to land inundation to create Thissavros reservoir is an impact of construction, the long term effects on flora and fauna are attributed to the operational phase. Since Thissavros does not have a fish pass to facilitate fish migration, the direct result is that 20 fish species may be directly affected by ecosystem isolation in Platanovrisi and Thissavros reservoirs. Changing the river environment to a lake environment to create storage has furthermore resulted in thermal stratification. This has had the effect that cold water which is nutrient rich and higher salt concentration is discharged into the downstream river thus changing the environment for native aquatic species. The result has been an influx of non-native species that are quickly becoming the dominant species.

The dam has also inhibited the Nestos River’s role in sediment transport. Although there is currently no issue with sediment accumulating behind the dam, the beaches in the delta region have been found to have much higher erosion rates than accretion rates, whereas prior to the construction of the dam accretion rates were about eight times higher than erosion rates. Although no studies were found on greenhouse gas emissions from the inundated landmass of Thissavros reservoir, emissions should be assumed and accounted for even during operation. Furthermore, depending on the primary electricity source used during pumping additional greenhouse gas


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emissions need to be accounted for. If electricity from renewable energy sources are used then the greenhouse gas emissions will be relatively low, whereas if fossil fuel is used the greenhouse gas emissions will be relatively high.

## 3. Case Study – Kopswerk II

Source: Illwerke vkw

Kopswerk II is located in the west of Austria in the region of Vorarlberg. The semi-open PHES was commissioned in 2008 with an installed capacity of 450MW. The facility utilises the already existing upper reservoir, Kops and the lower reservoir, Rifa. Thus, no extra impoundment was needed to operate Kopswerk II. The semi-open PHES has been constructed into a very complex hydropower and PHES system common in the alpine regions. Therefore, the pre-developed environment was already changed to such a degree that the addition of Kopswerk II has brought very little further environmental impact during operation. It must be noted however, that the water level in the Kops has been observed to fluctuate more frequently since the addition of Kopswerk II as the PHES operates on a daily basis, whereas previously the Kops was only used as annual storage.

## 4. Case Study – Goldisthal

Source: Vattenfall Europa AG

Goldisthal is located in central Germany in the state of Thuringia. The semi-open PHES was commissioned in 2003, over 30 years after the initial geological works first commenced. The facility is situated on the River Schwarza, which has been impounded by two dams to create the lower reservoir. The upper reservoir was also created and is situated approximately 300m above the lower reservoir. The facility has an installed capacity of 1,060MW. The lower dam also boasts a small hydropower facility that produces an additional 1.6GWh annually from the water discharged to the downstream environment.

The positive aspect of this project is that the dams themselves maintain the water level in the river upstream and downstream of the reservoir, whilst the reservoir level itself fluctuates. Although minimum flow is in place the lower reservoir regulates the discharge to the downstream environment, resulting in an alteration in natural river discharge.

Impeding structures, such as weirs and ineffective fish passes, along the river downstream of Golidsthal have made fish migration along the river difficult prior to the construction of Golidsthal. These constructions are now being deconstructed to allow for free fish passage along the river Schwarza and Saale. This is part of the WFD requirements to reestablish river ecosystems and also as compensation for Golidsthal and Leibis-Lichte reservoir.



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## 5. Case Study – Bolarque II

Source: CEDEX/Ministerio de Formento

Bolarque II is situated in central Spain, approximately 120km east of Madrid. The semi-open PHES was commissioned in 1975, utilising the already existing Bolarque reservoir as the lower reservoir. Bolarque dam was commissioned in 1910. Upstream are two further dams, Entrepenas and Buendia, commissioned in 1958 and 1956 respectively. Downstream of Bolarque dam is another dam, Zorita, commissioned in 1947. Bujeda reservoir, almost 300m above, was created as the upper reservoir. The semi-open PHES was thus constructed into an already highly stressed and regulated environment. A further feature of the semi-open PHES is that it also facilitates the water transfer from the Tagus River Basin, via Bujeda to the Segura River Basin almost 300km to the south east.

While most of the environmental impacts on the Tagus River are due to human activities (sewage, industry, agriculture, releasing non-native species into the area, water transfer), the semi-open PHES has almost no environmental impacts during operation.

## 6. Case Study – Turlough Hill

Source: ESB

Turlough Hill is located in east Ireland in the Wicklow Mountains. The closed-loop PHES was commissioned in 1974 and utilises the existing lake, Lough Nahanagan as the lower reservoir. The manmade upper reservoir is located almost 300m above. The installed capacity is 292MW. It is the only PHES facility in Ireland today (2012) and was a major engineering feat of its time.

The main environmental impact has been that the lower lake was lowered by 15m during construction to accommodate the PHES facility. From there it is lowered a further 10m on a daily basis during pumping mode. This has affected the shore line vegetation in terms of species cover. Some heather has slowly encroached on the permanently exposed areas and 40 years after commissioning of Turlough Hill the original water line is still evident.

### *Summary of Negative Environmental Impacts during Operation*

A summary of the negative environmental impacts during operation is given in Table 2. The case studies have helped highlight the main environmental issues during operation. Limitations are to be found in lack of information, range and number of case studies chosen and the actual choice of case studies.

**Table 2: summary of negative environmental impacts during operation highlighted by case studies**

| | | CAES | Pump-back PHES | Semi-open PHES | | | Closed-loop PHES |
|---|---|---|---|---|---|---|---|
| Potential Issues/EIA terms of reference | | Huntorf | Thissavros | Kopswerk2 | Goldisthal | Bolarque2 | Turlough Hill |
| Human Impact | Population | L | L | L | L | L | L |
| | Traffic | L | L | L | L | L | L |
| | Cultural Heritage | L | L | L | L | L | L |
| | Material Assets | L | L | L | L | L | L |
| Ecology and Natural Systems | Biodiversity | L | H | L | H | L | H |
| | Fisheries | L | H | L | M | L | M |
| | Air and Climate | L-H* | L-H* | L-H* | L-H* | L-H* | L-H* |
| | Landscape and Visuals | L | M | L | M | M | M |
| | Water Resources & Quality | L | H | L | M | L | M |
| Physical Environment | Noise & Vibration | L | L | L | L | L | L |
| | Soils, Geology & Sediment Transport | L | H | L | M | L | L |
| | Hydrology & Hydrogeology | L | H | M | H | L | H |

- *Recommended to review each individual case study*
- *Inclusion of combined impacts with existing land uses and pressures*
- *Limited raw data*

## *Conclusions*

The main benefit of PHES and CAES from an environmental perspective is that storing electricity from renewable energy sources will result in a reduction of wind curtailment with consequent reduction in carbon dioxide production. The following sections highlight the main conclusions of the environmental performance during operation as determined by the case studies and literature review.

## CAES

- The case study on the Huntorf CAES facility has highlighted very few environmental impacts during operation. This is partly because the CAES was constructed into a previously modified environment. It is important to note however that there may be further impacts during construction, the analysis of which is beyond the scope of this report.


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- The main drawback of the existing CAES is that it is a hybrid system. This means that it is dependent on an external heat source (i.e. natural gas) to replace the heat lost during the compression stage. The required amount is however, one third that of conventional gas turbines. Using biofuel instead may be a way of making CAES carbon neutral, provided that the biofuel is itself carbon neutral. Advanced Adiabatic CAES systems, which are currently under research, would eliminate the required external heat source.

## Open-system (pump-back) PHES

- Thissavros pump-back PHES has several environmental impacts associated with it, mainly because the dam and PHES facility were constructed simultaneously into a relatively unmodified environment. Since most of the long-term impacts are associated with the initial construction of the dam, a more benign solution would be to retrofit an already existing hydropower scheme with pumps. The receiving environment in such a case would already be heavily modified, resulting in a significantly lower environmental impact of the PHES. Although retrofitting has a lower environmental impact, it is not always an option as some countries or regions may require new developments.

- The construction of a dam for hydro generation results in alteration of the natural flow regime of the river. The flow is controlled primarily to meet electricity demands with little consideration for the environmental needs of the downstream river system. This regulation ultimately reduces or eliminates natural peak flood events and low flow events. While minimum flows[1] are normally maintained, this does not guarantee that the environmental needs are met. The operating regime of the facility could be managed, by means of environmental flow[2], so as to simulate natural flow conditions. In this way the environmental impact could be mitigated but it should be noted that environmental flow is not a perfect substitute for natural flow. Changing operating regimes may also incur a trade-off in reduced operational flexibility and ability to provide fast reserve to accommodate variable renewable energy sources.

- Rivers transport a vast amount of sediment and nutrients to their lower reaches and coastal areas. The presence of a dam on a river will hinder this process by allowing sediment to accumulate behind it instead. Reduced sediment transport to the downstream environment causes a reduced accretion rate that may be detrimental to the coastal and delta areas and ultimately to the flora and fauna that inhabit these.

- Changing a river environment into a lake environment will likely result in thermal stratification[3]. As extraction of water from the lower thermal layers is the norm when operating the turbines the downstream river is affected by colder water and higher salt concentrations from the discharge. A direct result of changing water temperature, velocity and nutrient levels is that the species abundance and diversity can change. Native species may be outcompeted by non-native species that are more adapted to the new conditions.

[1] Minimum flow from dams are in place to maintain the ecological quality of a river downstream (i.e. prevent rivers from drying up)

[2] Environmental flow describes the quantity, quality and timing of water flow required to sustain freshwater and estuarine ecosystems. It aims to simulate the natural flow of the river. Thorough investigation of the environmental requirements are needed to determine EF

[3] Thermal stratification will layer the lake, with the coldest water in the bottom most layer (hypolimnium) and the warmest at the top (epilimnion). Salt and nutrients will also collect at the bottom. The process of thermal stratification refers to the so called ”turn over” of the lake.


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- Fluctuating water levels, resulting from the operating regime, will cause frequent inundation and draw down of shoreline, isolation of spawning areas, loss of habitat and limited regeneration both upstream and downstream. Natural fluctuations vary in magnitude on a seasonal basis whereas operational fluctuations vary on a daily basis at a relatively constant magnitude.

- The presence of a dam hinders both upstream and downstream fish migration. This can be detrimental to fish populations as it can prevent movement between spawning and feeding areas. For upstream migration fish passes may be an option for smaller dams, but for larger dams such as Thissavros the only feasible option is to transport them by trucks or fish lifts. Downstream migration will generally occur via turbines or spillways. Both upstream and downstream migration by artificial means is not fully effective and will result in some fish mortality.

## Semi-open PHES

- Kopswerk II and Bolarque II were constructed in heavily modified environments resulting in low environmental impact during operation. Goldisthal on the other hand was constructed in a less modified environment which has resulted in a greater environmental impact. Therefore potential PHES sites in already modified environments should be considered where available.

- As with the pump-back PHES fluctuating water levels, resulting from the operating regime, will cause frequent inundation and draw down of shoreline, isolation of spawning areas, loss of habitat and limited regeneration both upstream and downstream.

## Closed-loop PHES

- Turlough Hill was specifically designed for peak operation which means that the water level fluctuates through its full active range on a daily basis. This regular mass movement of water inhibits the natural lake processes within the lower lake.

- The shoreline vegetation communities associated with oligotrophic lakes, which are listed on Annex I of the Habitats Directive, is an important characteristic. The artificial modification of the natural water level can reduce the diversity of typical soft water species present. It is unlikely that the natural vegetation of the Lough Nahanagan shoreline can tolerate the artificial lowering of the lake levels and the regular lowering and raising of lake levels associated with the daily operation of the plant.


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# 1. Introduction

The objective of the stoRE project is to facilitate energy storage to allow greater penetration of variable renewable energy. The project is divided into 6 work packages (WP): WP1 – Consortium Management, WP2 – Technology and Needs Overview, WP3 – Environmental Issues, WP4 – Regulatory and Market Framework Analysis on a European Level, WP5 – Target countries Analysis and Recommendations and WP6 – Communications.

WP3 focuses on the environmental considerations relevant to the development and operation of bulk energy storage technologies (EST), specifically pumped hydro energy storage (PHES) and compressed air energy storage (CAES). WP3 will publish three deliverables (D): D.3.1 Documentation of the environmental performance of existing storage facilities, identifying factors affecting their performance, D.3.2 Recommendations for policy makers on the national and European level on improving the environmental regulations facilitating development while protecting the environment and D.3.3 Report with guidelines for the development of PHES in environmentally sensitive areas. The work presented in WP3 has been done in collaboration between University College Cork (UCC) and Malachy Walsh and Partners, Engineering and Environmental Consultants (MWP) with contributions from National Technical University of Athens (NTUA), Helmut Schmidt University (HSU), Energy Economic Group (EEG) and National Renewable Energy Centre of Spain (CENER).

This deliverable, D.3.1, documents the environmental performance of existing PHES and CAES, identifying factors affecting their performance. The work is based on an extensive literature study and on six case studies that have been chosen from five of the six partner countries; Austria, Germany, Greece, Ireland and Spain. No case could be chosen from the sixth partner country, Denmark, as it does not have any PHES or CAES. Efforts have been made to include different types of PHES plants in order to examine the full scope of environmental performance issues affecting PHES, as different schemes may have different associated environmental issues. This also ensures that the information is relevant to the greatest number of cases. Therefore one CAES, one closed-loop PHES, three semi-closed loop PHES and one open-system PHES have been selected for consideration. While the environmental impact of energy storage facilities associated with their development, design, construction, operation and decommissioning may be interlinked, this deliverable focuses only on the operation of existing CAES and PHES facilities.

This deliverable, D.3.1, is laid out in the following chapters. Chapter 2 will briefly discuss the benefits of energy storage. Chapter 3 presents a schematic description of CAES and the three main types of PHES. Chapter 4 will present the case studies in terms of environmental performance during operation. The information presented here is based on information collected from the partners through two extensive questionnaires and other documents available in the public domain. Chapter 5 will further the discussions on the main environmental impacts from operation identified in the case studies. The information presented in this chapter is based on the findings in Chapter 4 and on an extensive literature study. Chapter 6 provides a short summary, draws conclusions and makes some recommendations.


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# 2. The Benefits of Energy Storage

As our society depends on electricity for almost all functions of daily life it is vital that electricity supply equals demand at all times. The demand curve varies over the course of a day, with peaks occurring at times such as morning, early afternoon and evening and ebbing at other times. Electricity generators are broadly categorised into base load, mid-merit and peaking plants depending on the rate at which their output can be increased or decreased in response to changes in demand. Base load generators have slow response times, thus lacking the flexibility that is needed to meet peak demand. Peaking facilities such as hydropower (HP), gas turbines and bulk EST are used to complement base load as these respond quickly to varying electricity demand, thus creating a more flexible grid. Electricity from base load sources, such as nuclear power, coal and lignite plants have highest efficiencies when generating electricity at a constant rate.

The Directive 2009/28/EC on renewable energy sets ambitious targets for all Member States (MS) to reduce carbon dioxide ($CO_2$) emissions by 2020, by increasing its share of renewable energy sources (RES). This directive also enforces priority dispatch to guarantee that the RES that is produced also reaches the market. However, priority dispatch of electricity from RES (RES-e) to the electricity grid coupled with dramatic increases in variable generation from wind and photovoltaic (PV) means that the supply curve will become more variable in the near future. A more variable supply curve in turn, will present a challenge to transmission system operators (TSO) as it will require more management. As electricity cannot be stored directly for long periods of time, or in large scale, peaking facilities are becoming more important to cover potential fall-off in production from wind. Gas turbines and HP are very effective as peaking facilities but the main disadvantage with gas turbines is the large amount of $CO_2$ they produce. For HP the main difficulty is the limited availability of suitable sites because of the specific topographical layout requirements. The most viable sites have already been developed and the still remaining technically viable sites cannot be developed because of environmental concerns.

Another issue with a large installed capacity of variable wind power is wind curtailment. This occurs when supply from wind production exceeds that which the grid can utilise. Some European countries are already experiencing wind curtailment due to power systems not being flexible enough to absorb excess electricity. Gas turbines and HP, although solving the potential immediate loss from wind power, do not solve the issue of wind curtailment. Bulk EST solves both production fall-off from wind and wind curtailment as these technologies can absorb excess electricity when demand is low, and generate electricity when demand is high. Historically, bulk ESTs have been used in connection with base load electricity production, such as nuclear power or coal power, to allow constant power generation as the demand curve fluctuates.
There are several types of bulk ESTs in use today. Deliverable 2.1 of the stoRE project (Zach et al., 2011) provides a summary of the current status, role and cost of energy storage technologies. The most proven bulk ESTs to date are PHES and CAES with over 300 facilities (Deane et al., 2010, Bogenrieder, 2006) and two facilities respectively installed worldwide. Both of these technologies are mature and are used daily on a large scale.

In terms of benefit to society, PHES and CAES have an important role in optimising the physical and financial functioning of the electricity market (Zach et al., 2011). The benefits to society result from the provision of Beaudin et al. (2010):

- black start capability
- more flexibility of the grid
- supply smoothing
- security
- spinning reserve
- auxiliary reserve

- peak shaving
- regulation control

The main benefit of PHES and CAES from an environmental perspective is the reduction of curtailment of wind with consequent reduction in $CO_2$ production. More variable energy sources such as wind in the energy mix will result in a less predictable supply to the electricity market. During periods when supply is greater than demand, PHES and CAES absorb and store excess electricity. When demand is higher than supply, PHES and CAES will restore the balance by supplying electricity to the grid. This means that the absorbed excess wind power will be released again at a later stage when additional power is needed, thus minimising curtailment. Furthermore, increased use of PHES and CAES with high levels of wind will potentially mitigate $CO_2$ emissions by reducing the need for fossil fuel fired thermal generators for system balancing. In 2009 total installed wind power capacity in EU-27 reached 75 GW (EWEA, 2009). This equates to 5% of total electricity generation or an average of 163 TWh per year. This installed capacity means a $CO_2$ mitigation of 60 million tons per year (based on an EU average $CO_2$ production of 364 g $CO_2$/kWh (EEA, 2010)).

# 3. Technology Description

## *3.1. Compressed Air Energy Storage*

The principle of CAES is shown schematically in *Figure 1*. During periods of low demand and high supply, a motor (2) consumes power to compress (1) and store air in underground caverns (4), also known as charging mode. During periods of peak demand, the compressed air is returned to the surface, through expansion, where it is used to burn natural gas in the combustion chambers. The resulting combustion gas is expanded in the gas turbines (3) to spin the generator (2) and produce electricity (Crotogino et al., 2001).

As CAES requires the combustion of fossil fuel to recover the stored energy, this system is not a pure electricity storage technology, but rather, a hybrid system. The fuel requirement is however only one third that of conventional gas turbine power plants.

During compression the air heats up but this heat is removed to allow the air to be cooled to ambient temperatures before storing it. During expansion the air will naturally cool down. However, for the air to enter the combustion chamber it first needs to be heated again using an external source. This process is referred to as a diabatic process and both of the existing CAES facilities use this process. The other alternative is to retain the heat that is given off to the system during compression and restore it to the system during expansion. This process is called advanced adiabatic CAES (AA-CAES) and is still in concept stage (Zach et al., 2011).

The cavern type determines the type of pressure storage; sliding pressure storage or constant pressure storage. Sliding pressure is where the air pressure in the storage cavern changes during charging and discharging. When air is extracted from the caverns the pressure will drop, and when air is injected into the caverns the pressure rises. This means that to compensate in loss of cavern pressure during compression and decompression the cavern size needs to be much larger than the actual volume used. Both of the existing CAES facilities use salt caverns that operate as sliding pressure stores. If no salt cavern can be found, other rock formations can theoretically be used instead and constant pressure storage can be applied. The constant pressure storage requires an equalizing pit above ground to maintain the constant pressure in the store (BBC Brown Boveri).

Salt deposits are the most suitable type of geology to use for CAES as these structures are plastic, yet solid and impermeable (BBC Brown Boveri). Thus, salt caverns are considered to have the lowest risk and lowest costs associated with them.  Salt deposits are usually solution-mined and use significant amounts of fresh or recycled water of which the by-product is salt brine that needs to be treated (Salt Institute, 2011). Competition for the use of salt caverns is extensive as these are also used for oil wastes, natural gas storage and carbon capture and storage to name a few.


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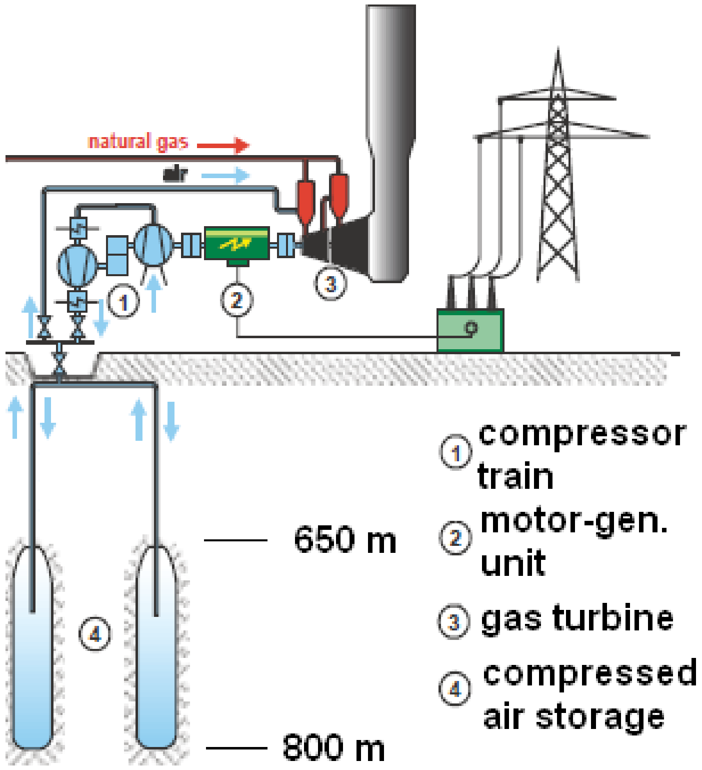


*Figure 1: Schematic figure of a CAES with sliding pressure. Source: (Crotogino et al., 2001)*

## *3.2. Pumped Hydro Energy Storage*

There are 300 existing PHES facilities in operation worldwide. PHES generally accounts for a small percentage of a country's generation portfolio in terms of installed capacity, averaging at about 6 %. Luxemburg boasts the largest percentage of installed PHES in the world, in terms of PHES as % of total energy mix, with 67%. In Europe the majority of PHES facilities are concentrated in the Alpine regions of France, Switzerland and Austria. (Deane et al., 2010)

To fully understand the potential impact of PHES on the surrounding environment distinction must be made between different types of PHES. Therefore, for the purpose of the stoRE project and specifically this deliverable, PHES has been classified into three subtypes based on their water management:

- Open-system PHES
- Semi-open PHES
- Closed-loop PHES

### 3.2.1. Open-system (pump-back) PHES

The open-system PHES is, as the name suggests, a system where there is continuous flow of water through both the upper and lower reservoir. Although there are several types of the open system PHES the most common type is the pump-back PHES. It is therefore important to note that when referring to the open-system category, this deliverable deals exclusively with the environmental impacts from the operation of pump-back PHES. This type of PHES is essentially a


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hydropower scheme with an upstream storage reservoir to which a pumping system has been added to allow water from the river downstream to be pumped back up to the storage reservoir. *Figure 2* shows a schematic image of the pump-back PHES which is usually constructed with a cavern configuration. These schemes can be built as pump-back but they are more commonly created by modifying existing hydropower plants (retrofitting). In fact, most pump-back PHES at this time in Europe are hydropower plants that have been retrofitted with pumps. It is worth noting that the main difference between the pump-pack PHES and the other PHES types is that if the operator switches off the pump for a given time period the plant will in effect become a regular hydropower plant that will still generate power.

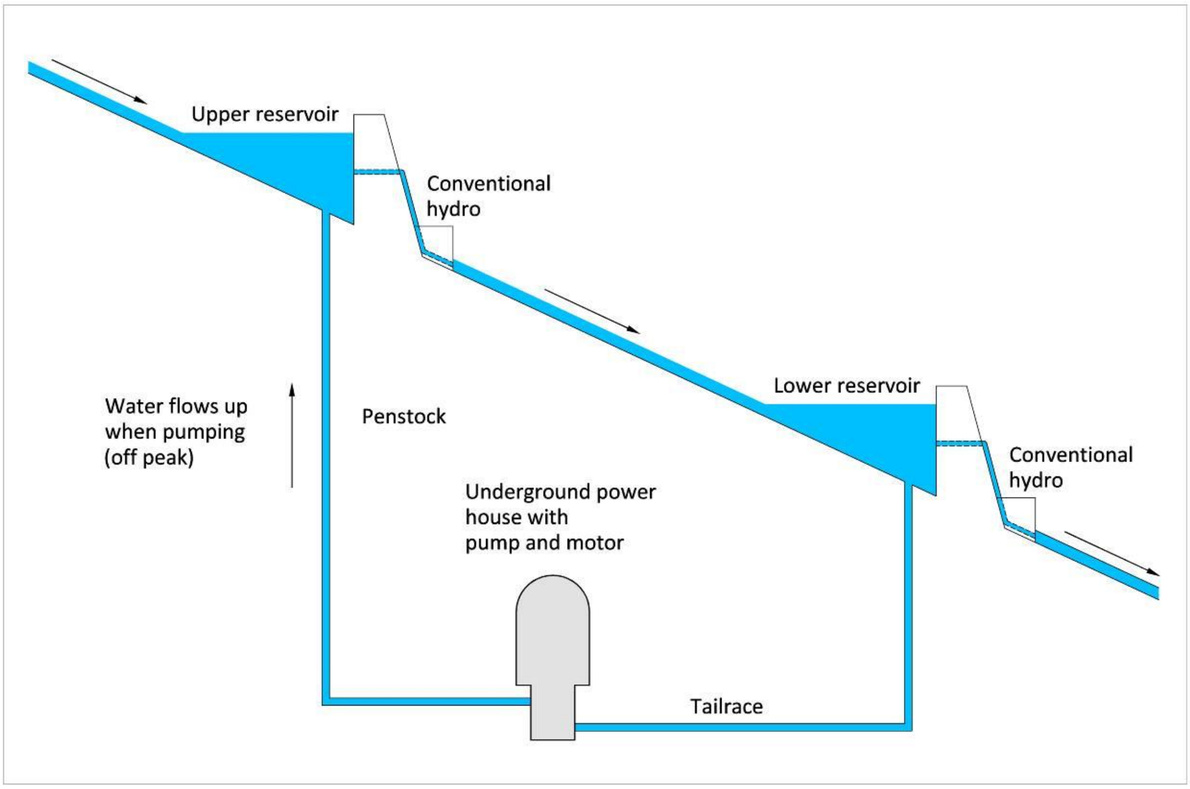


*Figure 2: Schematic description of the pump-back PHES. Source: (MWP, 2011)*

### 3.2.2. Semi-open PHES

The semi-open PHES consists of one artificial or modified reservoir and one modified lake or river impoundment with continuous through flow. *Figure 3* shows the schematics of the semi-open PHES with the powerhouse in cavern configuration. There are several variations of the semi-open PHES, for example in the Alpine region the upper reservoir may be the impounded lake and the lower reservoir may be the man-made one. Another variation of the semi-open PHES is the sea water PHES. In this case, the upper reservoir is a finite man-made reservoir and the lower reservoir is the ocean. So far there is only one sea water PHES in the world, namely in Okinawa, Japan where the PHES facility has an installed capacity of 30MW. This PHES was built in 1981 to investigate seawater pumped-storage technology (Fujihara et al., 1998). There is a more detailed case study done by IEA Hydropower (2006) on the ecosystem conservation measures undertaken at Okinawa as part of the IEA Annex VIII: Hydropower good practices project. As new PHES sites are difficult to develop because of environmental concerns, seawater facilities may be an interesting option. However, this type of PHES poses new and little researched environmental concerns of their own.

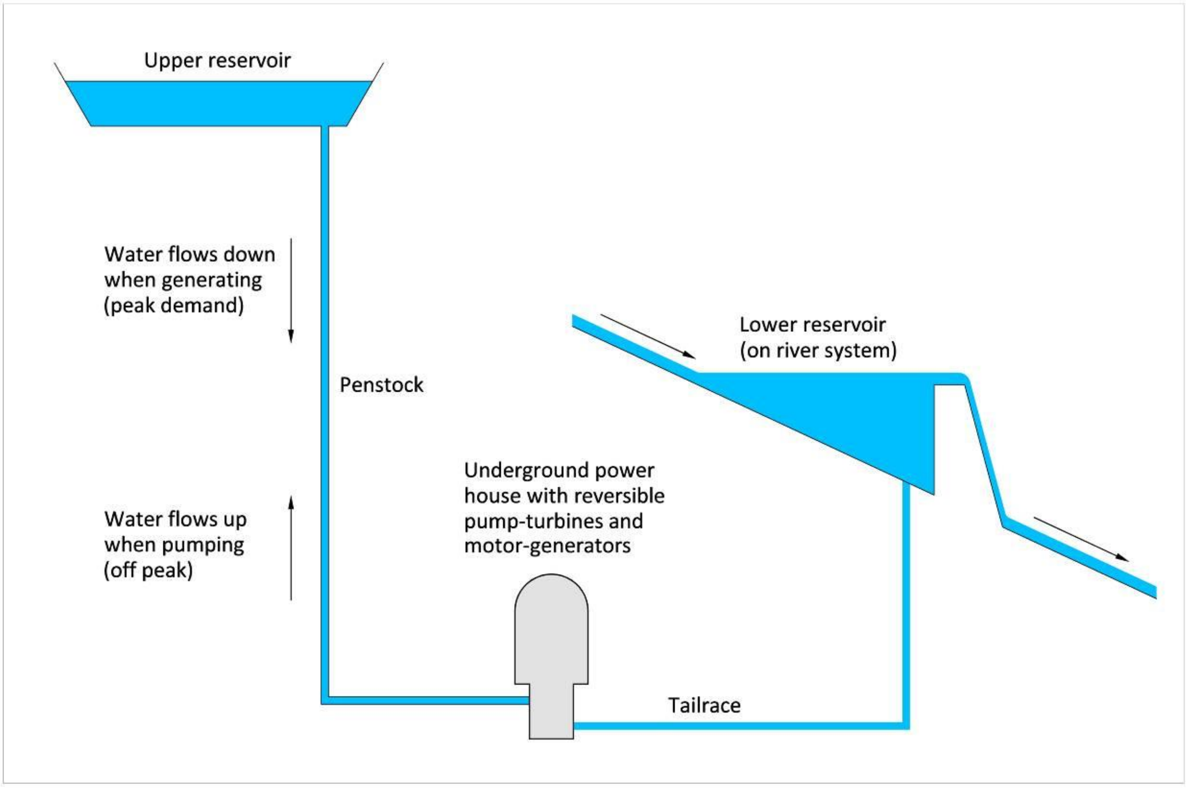


*Figure 3: schematic description of the semi-open PHES. Source: (MWP, 2011)*

### 3.2.3. Closed-loop PHES

The closed-loop PHES consists of two reservoirs that are separated by a vertical distance, neither of which is connected to another body of water. Both reservoirs may be man-made but usually one reservoir is man-made and the other is an existing lake that has been modified to allow for water storage. The same mass of water is transferred between the reservoirs during the pumping and generating cycles. A closed-loop system will still require a small amount of inflow to compensate for water lost through evaporation or infiltration. Although rainfall may provide some compensation for evaporation loss, depending on the regional climate, at least one of the reservoirs must have some catchment associated with it and have a downstream flow path for excess water. The net flow through the system will be insignificant relative to the flow rates for pumping and generation. *Figure 4* shows a schematic description of a closed-loop PHES with the power house in what is known as a cavern configuration. The power house could also exist in a shaft configuration and the penstock could also be visible above ground.


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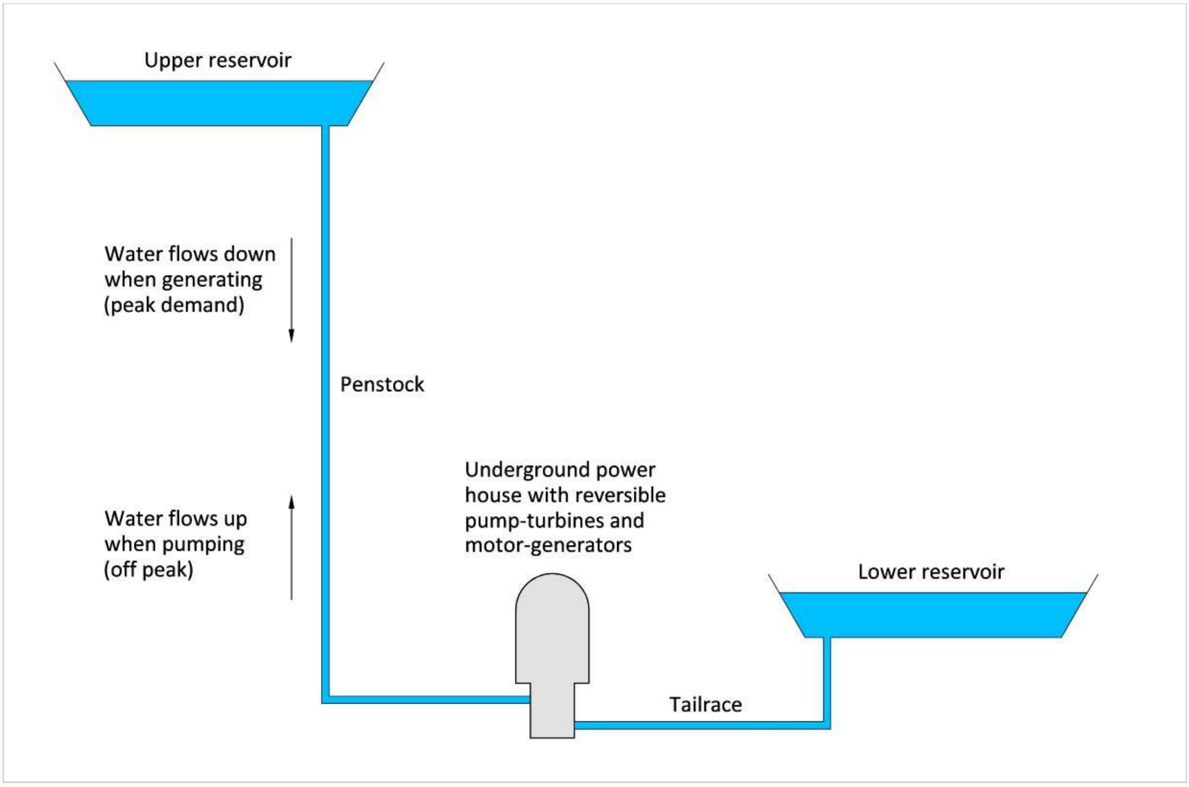


*Figure 4: Schematic description of a closed-loop PHES. Source: (MWP, 2011)*

# 4. Methodology

## Task

The aim of D.3.1 is to provide a review of the environmental performance of selected existing installations from the partner countries, Germany, Austria, Greece, Ireland and Spain. Denmark, although also a partner in the stoRE project, did not form part of this deliverable as it does not have any existing PHES or CAES installations. Therefore at least five case studies had to be chosen and reviewed under the following thematic headings given by the stoRE project:

Human Interaction

- Population
- Transport
- Cultural Heritage

Ecology and Natural Systems

- Biodiversity (terrestrial ecology/aquatic ecology/ornithology)
- Landscape and Visual Impact
- Fisheries quality
- Air and Climate
- Water Resources

Physical Environment

- Noise and Vibration
- Soils and Geology
- Hydrology and Hydro-geology

The relevant thematic headings above can align to the terms of reference under the EIA Directive or are identified as potential environmental issues, which also facilitates the discussion of environmental impacts. The scope of the task did not include Marine Ecology, Sea bed morphology, or leakage risk in terms of salt water risk as these thematic headings refer to coastal sites. At this time there is only one seawater facility worldwide, located in Okinawa Japan and could not form part of the case studies for this deliverable. Flood Risk Analysis relating specifically to “failure of infrastructure” is acknowledged by the assessment team to have significant impact were it to occur. However, the risk of infrastructure failure is so low due to the advanced technology in place to prevent overtopping or dam failure occurring that this thematic heading was not considered in the final assessment and discussions.

## The Assessment Team

The assessment team consisted of engineers, environmental engineers, environmental consultants, ecologists, and EIA practitioners from MWP and UCC.

The team held regular meetings to discuss the case studies, highlights from literature and any emerging issues.

## Case Study Selection

Questionnaire 1 was designed and agreed upon by members of the assessment team. The purpose of this questionnaire was to gain information on the existing PHES facilities in the target



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countries. Questionnaire 1 was circulated to the project partners where they were also asked to flag a particular PHES that could be of technological interest for further study.

The returned information was reviewed by members of the assessment team. Each of the target countries had to be represented by one case study. The assessment team wanted the sample to be inclusive of all four technologies (CAES, closed-loop PHES, semi-open PHES and open-system PHES). A further criterion in choice was the age of the facility. This was important as the EIA directive came into force in 1985. The result being that projects commissioned before 1985 do not have an EIA and projects commissioned after 1985 do have EIAs. The following six case studies were therefore chosen:

**Ireland:** there is currently only one PHES in Ireland, a closed-loop that was commissioned in 1974.

**Greece:** there are only two PHES in Greece, both of which are pump-back PHES. Sfikia was commissioned in 1985 and Thissavros was commissioned in 1997. It was decided that Thissavros would be the case study as there was more information available on this particular facility.

**Germany:** there is only one CAES in Europe and this one is located in Germany. The German partners however also flagged an interesting PHES, the semi-open PHES Golidsthal that is one of the largest PHES in Europe at this time. The PHES was also commissioned in 2003. After consultations between the assessment team and the German partners it was decided that two case studies were to be represented from Germany.

**Austria:** There are several PHES in Austria, but the one that stood out was the semi-open PHES Kopswerk II as this was commissioned in 2008.

**Spain:** there are several PHES in Spain, which meant that the choice of case had to fill the gap between the other cases already chosen. The assessment team felt that the two "new" semi-open PHES could be balanced by one "older" semi-open PHES. Therefore the choice for Spain was the semi-open PHES Bolarque II commissioned in 1975.

## *Information gathering*

Questionnaire 2 was designed and agreed upon by members of the assessment team. The purpose of this questionnaire was to gain information on the specific selected case studies. The questionnaire was designed to incorporate questions addressing all of the thematic headings. This questionnaire was circulated to the project partners.

A literature review was carried out whilst the questionnaire was in circulation. The review focused on the thematic headings trying to discern the main potential impacts from CAES and PHES facilities. It quickly became clear that there was little information available on the known environmental impacts of operational PHES and CAES. There was however ample information on environmental impacts from hydropower and run-off-the-river facilities. As some of the environmental issues are common to hydropower, pump-back PHES and semi-open PHES the information found in the literature could be adapted to suit the issues regarding PHES. However, the lack of information shows that further research in the area of PHES and CAES is needed to get a clear overview of the environmental impacts regarding these facilities.

## *Impact assessment methodology*

The partners returned the completed questionnaires with information on the specific case studies including information under the environmental topics/EIA themes.


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Due to the alignment of the environmental topics / themes with those used under EIA, coupled with the objective of determining the environmental impact of existing installations, an EIA assessment method was adapted and applied to the case studies. The EIA assessment method was taken from the Environmental Protection Agency (EPA - Ireland) guidance on EIA and in particular the suggested Glossary of Impacts. This 2002 EPA guidance, “Guidelines on Information to be contained in Environmental Impact Statements”, includes a glossary to qualitatively assess the significance of environmental impacts. This method was reviewed by the assessment team and adapted and applied to the Case Studies.

The adapted method provided the necessary categories to identify the significance of the environmental impacts of the Case Studies (see Table 1). The environmental impacts of operational PHES have been identified by comparing the post development with the pre-developed or existing environmental conditions of the receiving environment. Certain assumptions based on expert opinion, data and literature were made where a lack of information existed with regard the environmental conditions of the pre-developed environment. The application of the impact assessment is also reflective of current environmental standards and legislation.

**Table 1: Definitions used to determine operation impact of the case studies (EPA (Ireland), 2002)**

| Magnitude | Characteristics of impacts |
|---|---|
| Low | Imperceptible impact capable of measurement but without noticeable consequences |
| | Slight impact, which causes noticeable changes without affecting its sensitivity |
| Medium | Moderate impact which alters the character of the environment in a manner that is consistent with existing and emerging trends |
| High | Significant impact by its character and magnitude and duration or intensity alters a sensitive aspect of the environment or profound |
| | Profound impact which obliterates sensitive characteristics |

The agreed assessment method was applied to each Case Study under the relevant environmental topics and each topic was rated accordingly. The impact assessment was undertaken by the assessment team based on expert opinion, existing data and literature and current environmental impact assessment standards. This is a qualitative assessment method and can be subjective. However, the assessment results were discussed and agreed by the assessment team who have considerable experience and expertise in EIA and the description and mitigation of environmental impacts.

The main issues rated as “High”, were deemed as potentially significant and are discussed further in section 6. It quickly became clear that the same topics identified as potentially significant during the literature review were also identified as High in the case studies.


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# 5. Case Studies

## 5.1. Limitations of case studies

Case studies will always be subjective to certain limitations:

- Range and number: one closed-loop, three semi-open and one pump-back PHES may not be representative of the entire PHES technology. Environmental impacts of PHES will be dependent on the pre-existing environment, location, etc. Therefore the case studies should be taken as an indication rather than absolute truth. For CAES there are only two existing facilities worldwide, which means that information will be limited anyway.
- Choice: the choice of case studies determines the results, as these may not have identified all of the impacts that could be associated with PHES and CAES.
- Lack of information: case studies will only be as good as the information found. Information in the case studies have been taken insofar possible from publicly available resources, information gathered from partners who may or may not have been able to get information directly from facility operators.
-

## 5.2. Structure of case studies

Each case study begins with a short introduction followed by four main headings:

- Technical description
- Pre-developed environment
- Operation impacts
- Summary table of impacts during operation

To help describe the pre-developed environment and the impacts during operation, potential issues/EIA terms of references have been used.

## 5.3. CAES – Huntorf, Germany

Huntorf is situated in the north west of Germany in Niedersachsen near Bremen and about 25km linear distance south of the North Sea (see *Figure 5*). It is the location of the first CAES facility in the world, which was commissioned at the end of 1978. The facility showed that energy storage was possible in flat areas, prior to which energy storage had only been possible with PHES.


*Figure 5: Location of Huntorf (A), Niedersachsen approximately 25km linear distance from the North Sea. Source: (Google Maps, 2011c)*

### 5.3.1. Technical Description

Huntorf CAES was installed in 1978 with a capacity of 290MW. In 2007 the facility was upgraded to 321MW (Radgen, 2009). The main components of the CAES facility are: two salt caverns, a high pressure (HP) and a low pressure (LP) turbine, a generator, a HP compressor and a LP compressor and an aftercooler (see *Figure 6*). The storage capacity at Huntorf is 0.64GWh, and the facility can operate at peak load for about 2 hours per day. The facility is predominately used for tertiary control during the day and peak shaving during the evening if no PHES capacity is available (Crotogino et al., 2001).

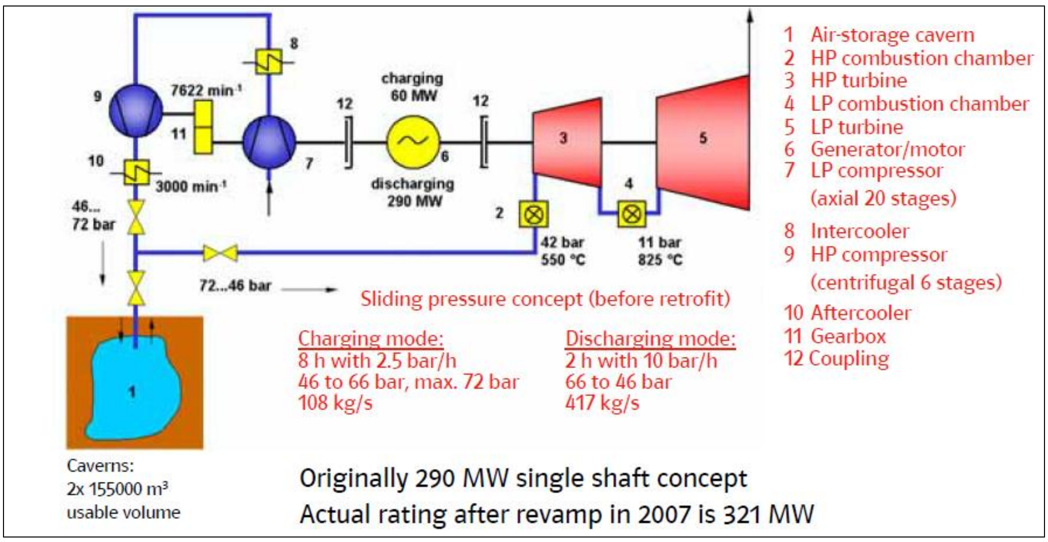


*Figure 6: Schematic layout of CAES facility Huntorf. Source: (Radgen, 2009)*


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The plant utilises salt caverns as these structures have plastic characteristics, yet are solid and impermeable (BBC Brown Boveri). The salt deposits were found at a depth of 500m. For structural integrity a salt layer of at least 100m is required above the caverns. The two salt caverns were excavated at a depth of 650m to 800m, giving each a total depth of 150m. The average diameter of the caverns is approximately 40m, with a maximum diameter of 60m. This gives each cavern a usable volume of approximately 155,000m$^3$. The spacing between the two caverns is 220m. (Crotogino et al., 2001)

The caverns operate using so called sliding pressure. The maximum permissible and operational pressure in the caverns is 72bar and the minimum pressure during regular operation is 43bar. During exceptional circumstances the cavern pressure may fall to a minimum of 20bar. During discharge mode the cavern pressure will drop approximately 10bar per hour for two hours thus dropping 20bar in pressure. During charging mode pressure will increase by 2.5bar per hour for eight hours. This difference is due to the difference in air flow rates through the turbines and the compressors. The sliding pressure also means that the caverns have to be much larger to hold more air than what is actually used during two hours discharge mode. This is so that the additional space and compressed air can compensate for the pressure lost during discharge. (BBC Brown Boveri)

A later addition to the facility has been a natural gas cavern that holds approximately 300,000m$^3$ of natural gas.

### 5.3.2. Pre-developed environment

Human Interaction

Huntorf lies in the area of Elsfleth which is sparsely populated with small villages. There are several larger cities nearby: Oldenburg (~15km west), Bremen (~50 km south east), and Bremerhaven (~60km north east). There is no mass tourism or significant leisure or recreational facilities association with Elsfleth. The land surrounding Huntorf is predominately used for intensive agriculture.

Ecology and Natural Systems

In the upper region of the river basin, crossing into the state of Thüringen there are several potash industries that pollute the Weser river with salt deposits. Although the largest amount is derived from the potash industry other polluters include household sewage, road gritting as well as process industries. Other stress factors to the river basin are due to the heavy metal deposits from resin mining in the upper parts of the river basin that have been found during dredging of coastal and transitional water areas.(FGG Weser, 2007) The surrounding region has been highly modified for agriculture and therefore much of the area outside of sites designated for nature conservation is likely to be of low ecological value.

Physical environment

Huntorf is located in a salt deposit hotspot. The total volume of salt deposits in the area of North Germany is estimated to be more than 80,000km$^3$, which is approximately the equivalent of a cube with 45km long sides. (KBB Underground Technologies)


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### 5.3.3. Operation impacts

Human Interaction

Huntorf is 25km linear distance from the North Sea where a number of off shore wind farms are under construction. Approximately 80 km away in Emden is the location of the first planned HVDC grid connection of an offshore wind farm. This will enable Huntorf to further its function of balancing power and consequently contribute positively to the material assets.

Ecology and Natural Systems

Designated Natura 2000 sites lie in close proximity to the Huntorf CAES facility although the facility itself is not in a designated area (see *Figure 7*). Although Huntorf is close to some of these sites, it does not drain into or have an impact on either and therefore is not considered to impact on the Natura 2000 sites.

In terms of visual impacts the main component of the CAES facility, the salt caverns, is located below ground (see *Figure 8*). The power plant is located above ground housing the turbines, compressors and generator. The facility above ground takes up a space of approximately 0.16km$^2$ and the total height of the building including chimney is approximately 50m (see *Figure 9*). The building houses the turbines and compressors and as such is similar to a natural gas plant. There are also several wind turbines in the area (see *Figure 8*).

Huntorf requires a supply of natural gas at a rate of 11kg/s to operate the turbines. Although the CAES facility requires natural gas to operate, the need for fuel is 1/3 that of a conventional combustion turbine. This means that emission of pollutants such as $CO_2$, $NO_x$ and $SO_x$ produced during combustion are approximately 2/3 less than during conventional combustion processes. (Akorede et al., 2010) Furthermore the emissions of $CO_2$ from Huntorf depend on the primary source of electricity used to operate the compressors.


*Figure 7: The white arrow is pointing to Huntorf CAES facility. The red diagonal lines and the blue diagonal lines are designated areas under the Birds Directive and the Habitat Directive respectively. Source: (EEA, 2011)*

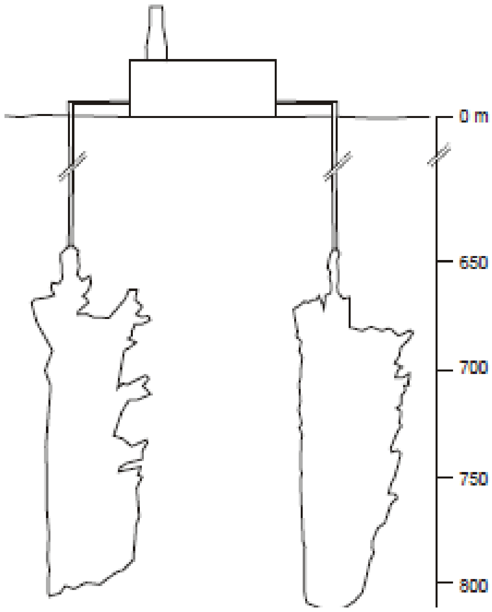


*Figure 8: (left) The two caverns and plant on the same scale. Source: (Crotogino et al., 2001) (right) The plant with wind turbines in the background. Source: (KBB)*

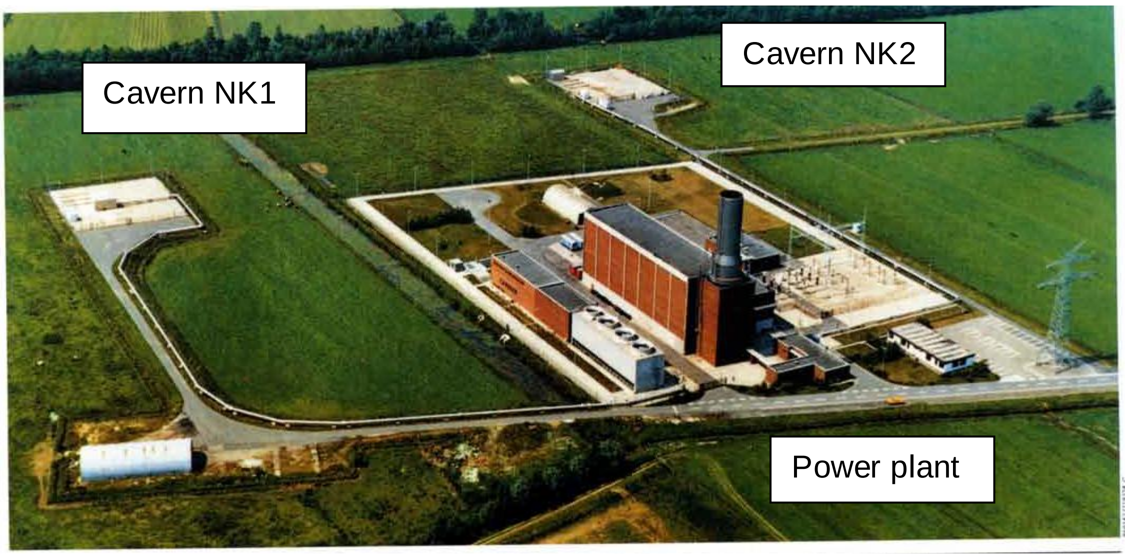


*Figure 9: Aerial view of Huntorf power station. Source: (BBC Brown Boveri, 1986)*

<u>Physical Environment</u>

Scans of the caverns were conducted a few years after construction in 1984 and again in 2001. The images show that the structural integrity of the salt caverns is still intact after more than 25 years of operation (see *Figure 10*).


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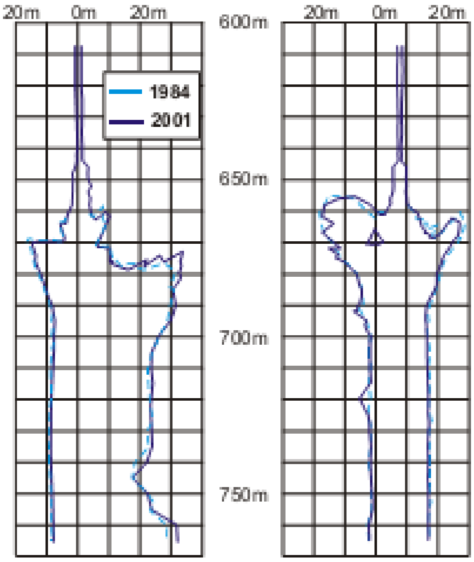


*Figure 10: Depth of the caverns: comparison of sonar survey for NK1 in 1984 and laser survey in 2001. Source: (Crotogino et al., 2001)*

### 5.3.4. Summary of impacts during operation

The main impact during operation of the CAES is its need for additional fossil fuel during combustion, therefore the impact on “Air and Climate” has been deemed low to high as the primary source of electricity used for compression needs to be accounted for as well. All other impacts have been deemed low for Huntorf during operation.

**Table 2: Summary table showing the negative impacts during operation of the CAES facility Huntorf**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | L |
| | Fisheries | L |
| | Air and Climate | L-H* |
| | Landscape and Visuals | L |
| | Water Resources | L |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | L |
| | Hydrology & Hydrogeology | L |

## 5.4. Open-system (pump-back) PHES – Thissavros, Greece

Greece has 103 hydro facilities, including small hydropower (SHP) and HP (ESHA, 2009) of which two are PHES facilities, both pump-back PHES. Thissavros is situated in the Nestos River Basin approximately 30km downstream of the Bulgarian border (see *Figure 11*). The need for energy storage in Greece is twofold; storing excess power from large thermal plants at night and to support high variable RES integration, mainly wind. In Greece, PHES is classified as storage and the operator does not need to pay the TSO when in pumping mode. In turbine mode, fixed electricity selling prices are applied. Thissavros was commissioned in 1997 which meant that an EIA was conducted before construction. The EIA has to be updated every 8-9 years.

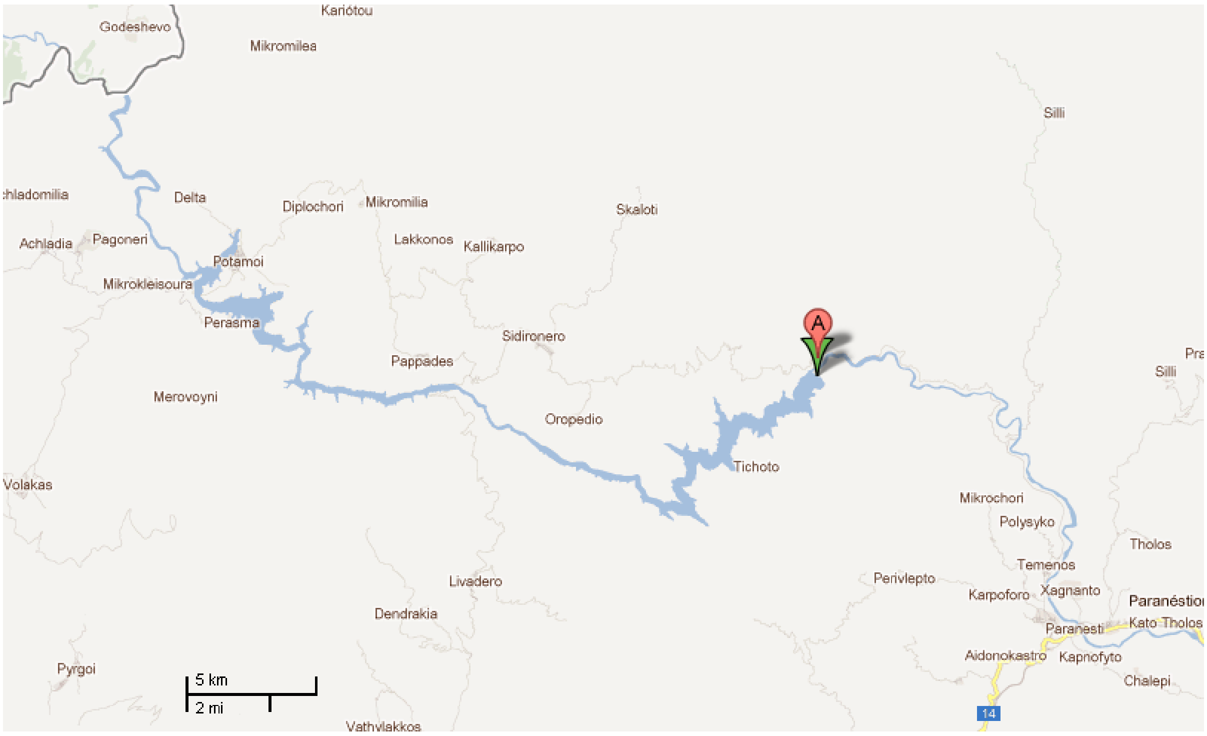


*Figure 11: Thissavros (A), located on the Nestos River approximately 30km downstream of the Bulgarian boarder. Source: (Google Maps, 2011e)*

### 5.4.1. Technical Description

The dam and pump-back PHES facility was commissioned in 1997 and became fully operational in January 1998. Further downstream the Platanovrisi dam and HP facility was commissioned in 1999. Thissavros is operated by the Public Power Corporation (PPC), the biggest electricity supply company in Greece today. The PHES operates on a daily basis to cover peak loads and to balance the surplus from thermal power plants. Together with Platanovrisi secondary functions of the dams are flood control and storage for irrigation. Thissavros dam is 172m high (Greek Commission on Large Dams) and as such one of the highest dam constructions in Europe (see *Figure 12*). The dam is a rock filled dam with a central clay core. The PHES has three Francis reversible pump-turbines each with 127MW installed capacity. Both the penstock and the power house have been constructed underground whereas new transmission lines have been built above ground. The upper and lower reservoirs have a surface area of approximately 20 and 3.25km$^2$ respectively.

A large flood incident occurred at the end of 2005 which was the largest flood in the last 30 years. The flood was successfully dealt with as the dams of Thissavros and Platanovrisi provided


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complete protection of the downstream river basin. Significant amounts of electricity were produced in the two HP facilities without any overflows.

*Figure 12: Thissavros dam – upper reservoir. Source: (Metka, 2010)*

### 5.4.2. Pre-developed Environment

<u>Human Interaction</u>

The area around Thissavros is sparsely populated with about 50,000 people living in the entire river basin. The pump-back PHES is nestled into a mountainous area that is covered by forest on the River Nestos. The primary land use of the area is forestry. Further downstream of Thissavros the land use is mainly agriculture.

The main environmental pressure factor in the basin is agriculture. Uncontrolled solid waste disposal in some parts of the river causes water pollution and environmental problems, especially in times of heavy precipitation. Wastewater treatment installations exist in the area. In Bulgaria, however, organic matter discharged from these installations and untreated wastewaters has a trans-boundary impact.

Prior to construction of Thissavros dam, the area was not highly accessible due to limited road networks.

There are no cultural heritage sites within 20km radius of the site of Thissavros. An archaeological survey was conducted that concluded the area is of no archaeological interest.

<u>Ecology and Natural Systems</u>

The Nestos River Basin begins in Bulgaria, where the river is called the Mesta. The river is almost split in two, with 126km in Bulgaria and 130km in Greece (Ganoulis and Arsov). The irrigation dam, Despatis was constructed in 1967 in Bulgaria. Water has been withheld for industry and agriculture in Bulgaria thus more often than not heavily regulating the river flow into Greece. This has been a source of conflict between the two countries. (Ganoulis, 2000)

There are two hydrometric gauging stations in the basin. Hydrologic and meteorological data are available for the basin for the past 20 years.

The Ministry of Agriculture monitors quality and quantity at four stations on the river. The delta and its coastal zone are more regularly monitored under the auspices of the National Agricultural Research Foundation (NAGREF), Democritus University of Thrace (DUTH) and the Society for Protection of Nature and Ecodevelopment (EPO-Living Lake). Groundwater monitoring of the Nestos delta area is available over a 20 years period over an array of about 20 piezometers and 100 wells under the auspices of Institute of Geology and Mining Exploration (IGME) and DUTH. Various karstic freshwater springs have also been monitored over a long period of time.

The delta region of the Nestos, 440km$^2$, is of great ecological importance and is a designated Ramsar site.

The Nestos River Basin provides habitat for the otter, wolf, fox and deer.

Prior to Thissavros most of the native fish species belonged to the family of cyprinids. The protected species inhabiting the river are Twaite Shad *(Alosa fallax),* Moderlieschen *(Leucaspius delineates)*, Macedonian trout *(Salmo macedonicus)*, Struma river loach *(Cobitis strumicae)*, Strumica Barbel *(Barbus strumicae)*, Bitterling *(Rhodeus Amarus).*

Physical Environment

Prior to the impounding of the Nestos River, the area would be considered a low noise environment with relatively little manmade infrastructure.

Thissavros dam is located in a seismic area. Geological conditions are quite variable. Metamorphic rock is predominant with schistose gneiss, granite gneiss and layers of mica schist being the main components of the bedrock. Pegmatite veins, associated with fault lines and shear zones, are also abundant in the area.

Farming and local activities in the Nestos delta rely on underground wells.

### 5.4.3. Operation impacts

Human Interaction

The primary land use of the area is forestry and there have been no major changes in the way the surrounding land is used since the construction of the dam. The water stored is now being used for irrigation further downstream of the dam. This has had a positive impact on agriculture. The irrigation needs are magnified during the summer season, which corresponds with the full load operation of Thissavros. The two demands thus run in parallel.

The construction of the dam required the construction of access and service roads. This has had a positive impact on the region as the old winding mountain roads and difficult passages have been replaced by 36km of new roads, 7 bridges, viaducts and one tunnel. The now easier access to the area increases prospects for tourism development. It also helps that the dam itself is seen as a technical achievement, thus drawing visitors. The facility is open to the public and mostly for educational purposes.

The impact of the pump-back PHES on Human Interactions can therefore be considered a positive one.

<u>Ecology and Natural Systems</u>

The operating company implements the ISO 14001 standards, and the pump-back PHES is subjected to mandatory ISO monitoring. A Remote Environmental Monitoring System (REMOS), funded by PPC, was installed in three interdependent stations along the Nestos river from the Bulgarian/Greek borders to the deltaic plain, after Thissavros and Platanovrisi dams became operational. Data collected included water level, conductivity/salinity, dissolved oxygen etc.

Most of the Nestos basin and delta forms part of the Natura 2000 network, including the Thissavros dam that was designated in 2008 along with 12 other sites in Greece, see *Figure 13*.

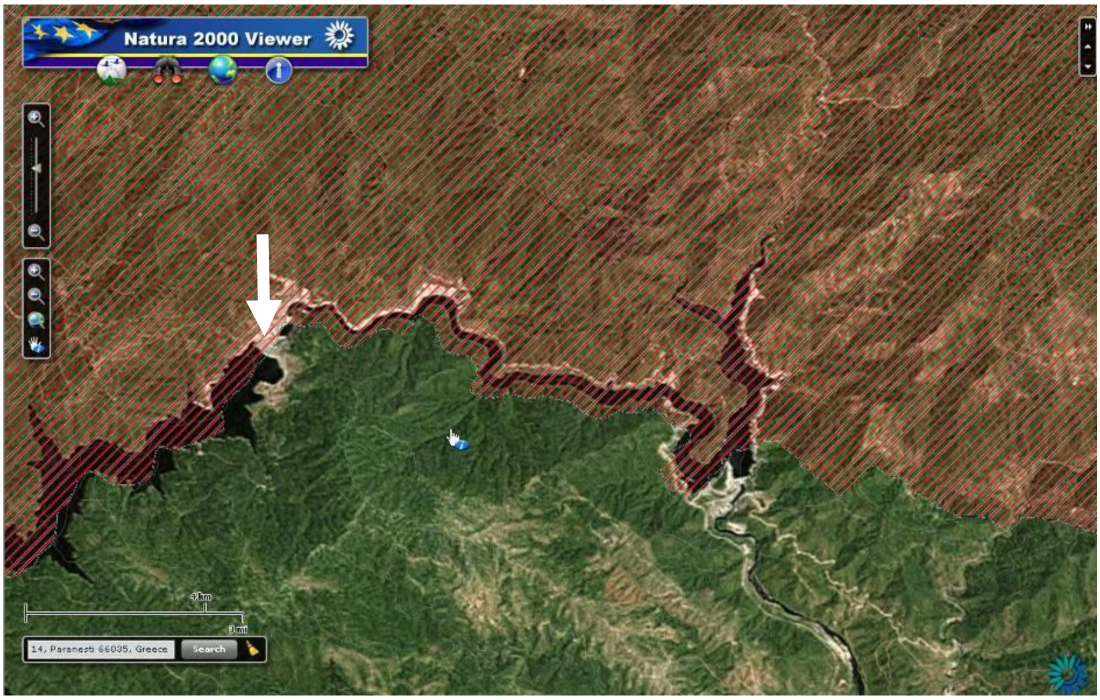


*Figure 13: Thissavros dam (white arrow) and the Nestos River Basin with areas protected under the Birds Directive (red diagonal lines). Source: (EEA, 2011)*

At the moment the slopes of the river Nestos basin are mainly covered with oak forests, and the riparian vegetation consists mainly of aquatic plants. The profound change from a river to a lake ecosystem created by the Thissavros dam has attracted some species of aquatic birds such as cormorants and gulls, both during migration and during winter. The area is also home to several amphibians and reptilians.

A comparison between data on water quality of the Nestos River with data from previous decades indicates no significant changes in water quality as the concentrations of all pollutants were found to be at comparable levels. The quality of river water was deemed "good status" with pollutant concentrations, in the vast majority of cases, below the limits established for drinking water. (Boskidis et al., 2011) The Nestos river basin is managed by the Region of Eastern Macedonia and Thrace. The water quality has been classified as "suitable for irrigation and water supply for other users". In recent years, the quality of the Nestos has improved as a result of reduced industrial activity in Bulgaria (UNECE, 2011).

There have been several long term impacts on the aquatic ecology due to the construction of the Thissavros and Platanovrisi dams. The conversion from a riverine to a lake environment in the upstream section of the Nestos basin has resulted in a significant shift in aquatic population structures both upstream and downstream of the dams. The European perch (*Perka fluviatilis*) has become the dominant species along with the European roach (*Rutilus l'ubilio*). These species are thought to have migrated from tributaries to the Nestos river. Prior to Thissavros most of the native species belonged to the family of cyprinids (carp or minnow family). Among the native species that require strict protection is the wild trout *(Salmo trutta)*. The population is under pressure from illegal fishing and habitat degradation. The wild trout is on the IUCN Red List of Threatened Species and is directly threatened by the non-native rainbow trout (*Oncorhynchus mykiss)*.

There are also no fish passages available on the Thissavros dam to facilitate the migration of fish. Monitoring has shown that 17 fish species in the riverine part of Nestos, 12 species in Thissavros dam-lake and 8 in Platanovrisi dam-lake are affected possibly due to the restriction of upstream and downstream movement of migratory species as a result in ecosystem isolation and loss and degradation of river habitat.

Thermal stratification in the upstream reservoir is also causing problems. The turbine intakes are located near the bottom of the reservoir, which means that there has been a significant reduction in water temperature downstream of up to 15 degrees Celsius in the summer. This change in water temperature has affected the species composition of the fish fauna. An increase in salt concentrations has also been observed downstream of the dam.

Interreg IIIA Greece-Bulgaria Project (2007 – 2013) is monitoring the environmental conditions and the fish fauna populations along the Nestos River and its tributaries. The aim is to reverse the adverse effects produced from river damming and dam operation. The actions will include:

- increase of natural fish fauna species stocks that have suffered population decline
- restoring communication between isolated populations by transfer of brood stocks from upstream to downstream of the dams and vice versa for the species indicated
- improve the fish fauna's natural environment with actions such as the creation of small, artificial acclimatization basins for juveniles along the river bank

During the monitoring through the Interreg program it was concluded that the river is more polluted near the Bulgarian/Greek border with observed heavy metal concentrations from industrial activities, while the quality improves further downstream. Towards the Delta it deteriorates again due to agricultural pollution. According to the EU standards the water quality is characterised as A3 drinking water.

Sediment transport via the Nestos River to the coast has greatly declined due to Thissavros and Platanovrisi. Withholding water and sediment has resulted in degradation of the coastal environments. Climate change scenarios over the next decades predict a temperature increase with simultaneous decrease in precipitation, which will subsequently decrease water resources and may cause a conflict of interest between energy generation and environment. (UNECE, 2011, Myronidis and Emmanouloudis, 2008)

Thissavros dam has had a large landscape impact in the area. The surface area of the reservoir is approximately 20 $km^2$. Extensive landslides during construction have caused further changes to the landscape that have been a cause for complaint in the past. The lower reservoir has a surface area of approximately 3.25 $km^2$. Visually the 172m high rock filled dam is imposing. However, the area is scarcely populated with only one road passing the site. Furthermore, the area is not considered to be a tourist area.

Physical Environment

There are no issues of noise and vibration from the pump-back PHES as the facility is built underground.

Thissavros dam is located in a seismic area. Several landslides were recorded during construction but no other issues with landslides have been recorded since. There is no significant erosion upstream of the dam.

Changes in the hydrological status of part of the system, from river to lake environments, have occurred with the construction of an irrigation (Toxotes, 1966) and two hydropower dams, Thissavros and Platanovrisi, in Greece and an irrigation dam (Despatis, 1967) in Bulgaria. The operation of the dams have permanently modified the natural river flow that combined with other additional impacts (pollution) have led to the deterioration of the habitat's quality and the gradual reduction and / or extinction of fish species populations.

The minimum allowable flow rate from Thissavros is $6m^3/s$. This is about 2% of the total flow discharged as the three turbines can take $285m^3/s$. The minimum flow is in general respected, except for some very dry short periods in the summer, when the flow downstream of Platanovrisi, can be almost zero. It has been recommended that the minimum flow reaching the "Nestos delta" needs to be increased for the purpose of regenerating the delta environment. The operation of Thissavros does not reduce the overall downstream water flow rate during a year; however, the natural flow regime has been significantly modified since the installation of the dams. (Ganoulis and Arsov)

Concerns have been raised regarding degradation of the coastal zone of the Nestos river delta. By measuring accretion rates and erosion rates before and after construction of Thissavros and Platanovrisi results showed that accretion rates in the delta area had dropped significantly. Before the dams were built the total area of accretion was about 8 times larger than that of erosion, whereas after the construction of the dams the area of erosion was 1.5 times larger than that of accretion. This would imply that the dams are hindering the transport of sediment to the coast and subsequently important nutrients. (Xeidakis et al., 2010)

### 5.4.4. Summary of impacts during operation

Several different issues have been highlighted as 'high' impact in the case study of Thissavros (see Table 3). Although the pump-back PHES was built into an already stressed environment in terms of upstream regulation from Bulgaria, the PHES has had additional impacts on the environment. These long term impacts are mostly due to the simultaneous construction of the dam. However the impacts have to be allocated to the entire facility as it is difficult to separate the functions of pumping and generating. The landscape impact has been deemed "high" whereas the visual impact has been deemed "low", giving landscape and visuals an overall grading of "medium".


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**Table 3: Summary table showing the negative impacts during operation of the semi-open PHES Thissavros**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | H |
| | Fisheries | H |
| | Air and Climate | L-H* |
| | Landscape & Visuals | M |
| | Water Resources | H |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | H |
| | Hydrology & Hydrogeology | H |

## *5.5. Semi-open PHES – Kopswerk II, Austria*

The main topography in Austria consists of the Alps (62.8%) making it very well suited for hydropower (Encyclopedia of the Nations, 2007). In fact Austria has more than 2,433 SHP and 156 HP facilities of which 20 are PHES facilities (ESHA, 2009). The main argument for energy storage in Austria is to be able to integrate RES not only in Austria but also in its neighbouring countries, especially Germany. One of the recently constructed PHES facilities is Kopswerk II, located in the state of Vorarlberg in west Austria (see *Figure 14*). The semi-open loop PHES was commissioned in 2008 and is now the largest PHES in the Vorarlberger Illwerke AG hydro group.

An EIA was conducted for Kopswerk II. This was a first in Vorarlberg since all other hydro facilities were constructed prior to EIA legislation (Illwerke vkw, 2011b). Although the project was technical and the EIA scope diverse, the EIA process did not take very long. The reason was that the upper and lower reservoir already existed, only slight modifications were needed and no additional water was required to operate Kopswerk II. Furthermore the PHES also used the existing high voltage power lines in the vicinity. (Illwerke vkw, 2011a)


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*Figure 14: the lower (purple) and upper (A) reservoir Rifa and Kops located in the western most state of Vorarlberg in Austria. Source: (Google Maps, 2011d)*

### 5.5.1. Technical Description

Kopswerk II is a semi-open PHES with its upper reservoir, the Kops, situated at a height of 1,800m that boasts a storage capacity of 127GWh. The lower reservoir, the Rifa, is situated almost 800m below (see *Figure 15*). The water is extracted from the upper reservoir to the lower reservoir via pressure tunnels as well as pressure shafts. The Kops has a large catchment area collecting water from Silvretta reservoir, and other streams finally running off into to the river Ill.

Kopswerk II is part of a complex system of PHES, HP plants and reservoirs common in the alpine region (see *Figure 16*). The Kops reservoir functions as an annual storage for the HP facilities connected to it and as daily peaking storage for Kopswerk II.

Kopswerk II consists of three sets of Pelton turbines, pumps, and generators totalling the installed capacity of the facility to 450MW. Unlike most PHES facilities today that have the turbine and pump integrated into one machine, at Kopswerk II the turbines and pumps are separate. This special technical feature allows the turbines and pumps to constantly operate in counter pressure mode. At the time of construction this was the first of its kind to be installed in the world. This set up allows Kopswerk II to utilize the principle of “hydraulic short circuit” during pumping mode. If the power received from the electric grid is less than what the pumps require, the additional power is achieved through the operation of the turbines thus creating the short circuit. (Illwerke vkw, 2010)

An underground penstock connects the upper and lower reservoir via the area of Tafamunt with an approximate length of 6.6km. The powerhouse is of cavern type, which means it too is constructed underground in a space 60.5m high, 30.5m wide and 88m long.

*Figure 15: (left) lower reservoir Rifa; (right) upper reservoir Kops. Source: (Illwerke vkw, 2008)*

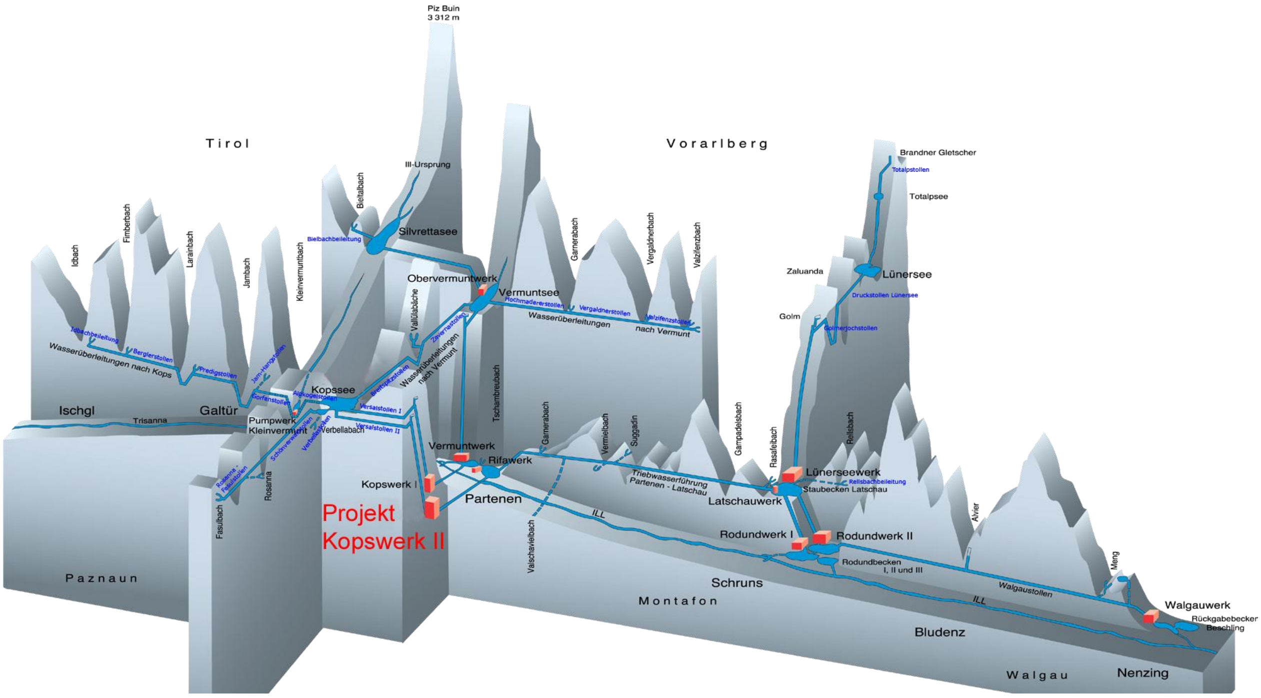


*Figure 16: Complex run-off system Vorarlberg. Source: (Illwerke vkw, 2006)*

### 5.5.2. Pre-developed Environment

<u>Human Impact</u>

The surrounding area of the reservoir Kops is considered sparsely populated by smaller towns, with hills, forest and rivers being the most dominant features. The land is used for forestry as well as (winter-) tourism. Hiking routes are also available around both the upper and the lower reservoirs during the summer months.

As roads existed to both the upper and lower reservoirs before construction of Kopswerk II, only some roads needed additional reinforcement. Minor interference with regular traffic occurred because some roads were closed off during construction.



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There are no cultural heritage sites in the vicinity of Kopswerk II.

Ecology and Natural Systems

The area around the Kops is designated as “important bird areas” (IBA) (see *Figure 17*). The lower reservoir Rifa is located on the western border of the nature reserve. The area is called Verwall-Silvretta and is also a designated Natura 2000 site. Protected birds in the area are: Golden Eagle *(Aquila chrysaetos)*, Black Grouse *(Tetrao tetrix)*, Rock Ptarmigan *(Lagopus muta)*, Black Woodpecker *(Dryocopus martius)*, Honey Buzzard *(Pernis apivorus)*, Eagle Owl *(Bubo bubo)*, Three-toed Woodpecker *(Picoides tridactylus)*, Peregrine Falcon *(Falco peregrines)* and Capercaillie *(Tetrao urogallus)*.

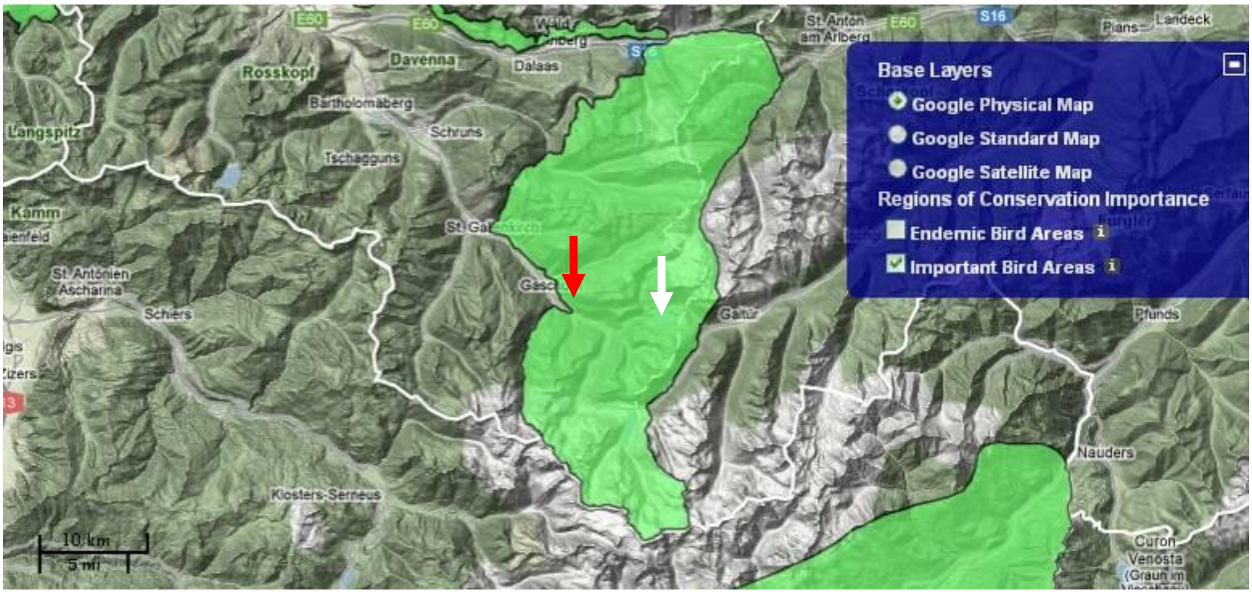


*Figure 17: Designated Important Bird Areas. The white arrow marks the position of Kops Reservoir. The red arrow marks the position of Rifa reservoir. Source: (BirdLife International, 2012)*

The water quality in the nearby river Ill has been classified as grade I – II[4] meaning that low levels of organic or inorganic nutrients are present and there is no significant oxygen deficit. Fish do not naturally occur in the Kops reservoir so rainbow trout is introduced into the reservoir for recreational fishing. These do not reproduce as water temperature in the reservoir is too low, glacial erosion causes turbid waters and the draw-down of the reservoir causes potential spawning areas to dry out. Also there is not enough food available during the winter season. The area is a very popular fishing site and people who want to fish can either buy an annual or daily fish pass. Fish deaths have been observed in the upper reservoir due to high fluctuations in water levels where isolated areas can become dried out. To mitigate this, connection grooves have been built to allow fish that are caught to escape. Fish screens are in place to stop fish from being drawn into the penstock and turbines.

[4] Grade I-V is the ecological classification of surface water that was already in place before the adoption of the WFD. The grading system has been modified slightly to comply with the classification system set up by the WFD.


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Physical environment

The upper reservoir, Kops, was commissioned in 1969, together with Kopswerk I, Rifawerk and Kleinvermunt PHES. To ensure the large storage capacity of the Kops water has been diverted from Silvretta reservoir via the Vermunt reservoir into the Kops. Furthermore, water is diverted to the Kops reservoir from streams that would naturally flow into the River Trisanna and eventually flow into the River Danube.

To add to the complexity of the system the reservoir Partenen is used by the Vermuntwerk as a storage reservoir before passing water on to the Latschau reservoir. Since 1969 Kopswerk I also flows into the Partenen. This meant that the reservoir was too small for the storage capacity needed and thus the Rifa reservoir was built for additional extra storage as required. Since initial construction and in combination with Kopswerk II, the Rifa has been enlarged from 0.6 to 1.27 million $m^3$. The function of the Rifa reservoir has thus been extended to act as the lower reservoir for Kopswerk II as well.

Sediment transport has been an issue in the Kops reservoir, due to weathering sediments flowing into the Kops during major and minor rainfall events, avalanches and snowmelts. The Kops is however, very large and has a vast dead storage. About 10 years ago sediment accumulation could have become a real problem but sediment management has helped to prevent serious consequences of sediment accumulating in front of spillways.

Before construction began a noise level of 48dB, caused by regular traffic, was measured in residential area in the vicinity of the lower reservoir. During the winter season the area becomes crowded by tourists and the noise level rises.

### 5.5.3. Operation Impacts

Human Impact

The impact of operation of Kopswerk II on human activities is limited. The facility is open to the public and is a popular place for school visits. The use of the area has not changed and it is still a very popular (winter-) tourism area.

Ecology and Natural Systems

As Kopswerk II integrates into an already existing infrastructure very little complaints have arisen regarding visual impacts. Kopswerk II utilises the already existing Kops reservoir, which has been used by Kopswerk I since 1969, as its upper reservoir and also utilises an already existing lower reservoir, the reservoir Rifa.

There is no minimum flow rate imposed on Kopswerk II it is a semi-open loop system. The lower reservoir is constructed as an overflow basin that can discharge water into the nearby River Ill if the water level becomes too high. There are maximum and minimum water levels that need to be maintained in both upper and lower reservoirs. The water level in the upper reservoir can drop approximately 80m annually. For the lower reservoir water level fluctuates by 14m. Kops reservoir is used for annual storage, whereas the Rifa is used for daily operation purposes. No further abstraction was needed to fill either upper or lower reservoir as these already existed.

Rapid draw-down of the reservoir due to PHES operations can cause areas in the Kops reservoir to dry out quickly causing some fish deaths. To mitigate this, connection grooves have been built to allow fish that are caught to escape. As the head between the upper and lower reservoirs is almost 800m any fish caught in the penstock would die due to the high pressures. Fish screens are


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therefore used as an effective tool to mitigate this risk. Split vertical screens (30mm bar gap) are used in both the lower and the upper reservoir.

Physical Environment

As most of the mechanical components of the PHES are located below ground there are no major sources of noise or vibration from the facility.

Ground water monitoring, of hydrochemical parameters such as temperature, pH and conductivity, is conducted at 19 stations; five stations are monitored on a weekly basis and the rest are monitored every two weeks. However, the hydrochemistry of the upper and lower reservoirs surface waters are not monitored.

There are several systems in place to prevent overfilling of either the upper or lower reservoir. In the upper reservoir there are relief wells with a discharge building, in the lower reservoir there is an overflow basin into the nearby River Ill. Both upper and lower reservoirs can discharge water if water levels become too high.

Both upper and lower reservoir embankments are constructed from concrete. Remote monitoring of the dams takes place to ensure there are no deformations of the dam or water leaks. Disturbances are automatically reported by computers and remote systems. There are stand-by emergency procedures in place should the structural integrity of the dams be compromised. Avalanches are common in these areas, which is also part of the reason why there is so much monitoring and stand-by emergency centres.

### 5.5.4. Summary of impacts during operation

As Kopswerk II utilizes an already existing upper and lower reservoir and in effect has been retrofitted, the operating environmental impacts of Kopswerk II PHES are low. As Table 4 shows there will be a “low” to “high” impact on air and climate depending on what primary electricity source is used during pumping mode. Also hydrology impacts has been deemed “medium” as the fluctuations in the Kops reservoir cannot be allocated to Kopswerk II alone since there were other existing HP and PHES systems using the same water resource prior to its commissioning.


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**Table 4: Summary table showing the negative impacts during operation of the semi-open PHES Kopswerk 2**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | L |
| | Fisheries | L |
| | Air and Climate | L-H* |
| | Landscape & Visuals | L |
| | Water Resources | L |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | L |
| | Hydrology & Hydrogeology | M |

## *5.6. Semi-open PHES – Goldisthal, Germany*

Germany has 84 HP and 7512 SHP facilities (ESHA, 2009), of these 23 are PHES facilities (Deane et al., 2010). It also has one of only two CAES facilities in the world. The need for energy storage to facilitate intermittent renewable energy technologies is becoming more urgent as Germany plans to close its nuclear power plants by 2022 (BBC, 2011). It is therefore expected that there will be a larger increase of RES-e, which will result in higher electricity fluctuations from sources such as wind. In some regions in Germany 50% of electricity supply is generated by wind. Without energy storage it will be difficult to integrate large amounts of RES-e *(DENA, 2010)*.

Energy storage is classified according to the service it provides. A PHES in pumping mode is classified as normal load since the 1st of January 2008 meaning that the provider has to pay a grid fee for every MWh consumed. The fee depends on the TSO and the voltage level. The fee also means that some PHES cannot compete with gas fired power plants on the European Energy Exchange (EEX) anymore. Fortunately, new facilities built before 2019 are liberated from the grid fee. In turbine mode the storage facility is regarded as a normal power plant that sells its electricity at the EEX. Any additional power or balancing power can either be sold at the EEX or regulated with the TSO.

Goldisthal is situated in central Germany in the state of Thuringia (see *Figure 18*). The search for an appropriate site was conducted in 1965, during the former German Democratic Republic (GDR). Goldisthal was selected as the most appropriate site for a PHES. In 1975 geological mining work, forest harvesting, road constructions and pre-construction measures were initiated. A total of 2.05km$^2$ was deforested to accommodate the upper and lower reservoirs. By the 1980's however, the project had run into financial difficulties and the build stopped. Extensive rock and earth works had already been completed by this time. In 1989 GDR and West Germany became one country and in 1990 the EIA Directive was transposed into German law. A new decision had to be made about continuing the construction of Goldisthal. As the construction had commenced long before 1990 there was no legal requirement to produce an EIA, however, the utility company Vereinigte Energiewerke AG (VEAG) decided to submit a simplified environmental assessment in the interest of good relations with the public and environmental bodies. There was opposition to the development, foremost from the environmental organisation Friends of the Earth Germany also called the BUND. VEAG and the BUND settled outside of court with VEAG paying 7million Deutsche Mark to set up the nature foundation David, which aims to promote nature conservation and renewable energy sources in the new federal states. Some of the other environmental requirements were to reinstate the bird species Capercaillies *(Tetrao urogallus)* to the area and to reforest possible areas. In 1997 the construction of the PHES was able to continue. Goldisthal was finally commissioned in 2003 and since 2004 all four turbines have been operating constantly. Since the 1st of July 2002 Golidsthal has been owned and operated by Vattenfall Europe Generation AG & Co. KG. (Vattenfall Europe, 2003)


*Figure 18: Goldisthal (A) located in the state of Thuringia in central Germany. Source: (Google Maps, 2011b)*

### 5.6.1. Technical Description

Goldisthal is a semi-open PHES with a man-made upper reservoir and an impounded lower reservoir (see *Figure 19*), through which the River Schwarza flows. The impoundment consists of two rock filled dams, one located at each end of the reservoir. During pumping and generating mode the water level is lowered and raised in the lower reservoir respectively as water is pumped from the lower to the upper reservoir or vice versa. The dams help maintain the water level in the river thus preventing the river from drying up, whilst the water level within the impoundment is allowed to fluctuate.

The PHES facility has a capacity of 1,060MW and a storage capacity of 8.5GWh. The main dam, on the downstream end of the impoundment also has a SHP facility that uses the height difference of the water level within the impoundment and the water level in the downstream river. The SHP produces an additional 1.6 GWh per year.

*Figure 19: Goldisthal - the upper and lower reservoir (left to right). Source: (Vattenfall Europa AG)*

The height difference between the upper and lower reservoir is approximately 300m. The main components, pumps, turbines and generators, are located in an underground cavern with a length of 137m, a height of 49m and a width of 26m. There are two sets of underground penstocks with an approximate length of 1.1km each.

Goldisthal operates using four reversible “Francis-pump turbine”, each with a capacity of 265MW. Reversible means that these machines either operate in pumping or in generating mode. Two of them have a fixed rotational speed and two have variable rotational speed. This set up creates more flexibility during operation and is essential to meet peak power demands.

The upper and lower reservoir has an approximate surface area of $0.55km^2$ and $0.78km^2$ respectively. In the lower reservoir the dam located upstream, the so called “pre-dam”, has an approximate height of 26m and a length of 120m. The downstream dam, the so called “main dam” has an approximate height of 67m and a length of 220m.

### 5.6.2. Pre-developed Environment

Human Interaction

The area around Goldisthal has always been sparsely populated, with a landscape and topography dominated by forests and hills. The area was not associated with mass tourism. Roads did not exist to the upper reservoir and the main access road to surrounding towns travelled straight through the now lower reservoir. There are no cultural heritage sites in the vicinity of the PHES. A pre-development archaeological survey was conducted; however the results are not in the public domain. The main environmental value of the area around the PHES lies in its nature reserves.

Ecology and Natural Systems

The lower reservoir of Goldisthal borders on a nature reserve called Schwarzatal while the upper reservoir is within the protected area of Wurzelberg-Farmde. There is also a bird sanctuary nearby as well as the Schwarzatal Flora-Fauna-Habitat that forms part of the Natura 2000 sites. Capercaillies *(Tetrao urogallus)*, Black stork *(Ciconia nigra)* and bat species would have been dominant in the area before construction began. As these species are protected, one of the conditions of operation of the PHES was to re-establish these species to the area.

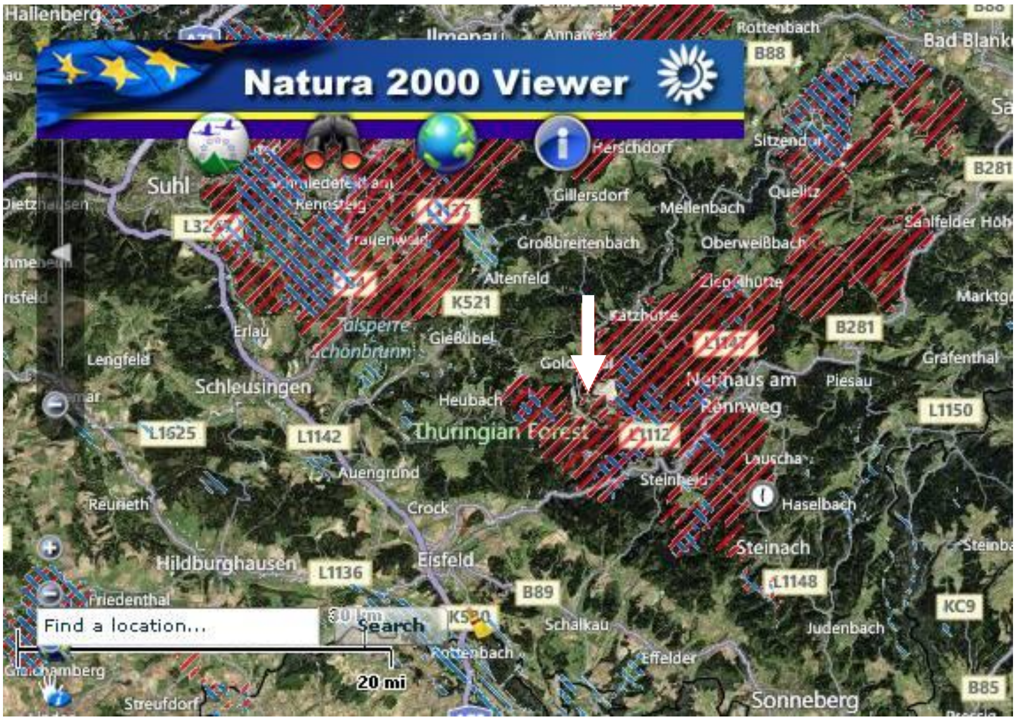


*Figure 20: The white arrow marks the location of the lower and upper reservoir of Goldisthal. The red and blue diagonal lines show the designated Birds Directive and the Habitat Directive Sites respectively. Source: (EEA, 2011)*

Goldisthal is located on the River Schwarza a tributary of the River Saale, which in turn is a tributary of the River Elbe. The Schwarza therefore belongs to the Elbe River Basin and rises about five kilometres upstream of Goldisthal in the Scheibe-Alsbach reservoir. This reservoir was constructed in 1944 to store water for ship navigation further downstream during drier months. During the wet season the main rivers would be navigable but during dry months they were not navigable. In 1986 the purpose of the Scheibe-Alsbach reservoir was extended to include district water supply as well. In 1992 this reservoir was dredged to increase the total volume by 100,000m$^3$. The River Schwarza has therefore been regulated since 1944.

By 1882 it was observed that migratory fish had difficulty living further downstream in the River Saale because of low water quality. Although water quality has since greatly improved so that fish populations, such as eel *(Anguilliformes sp.)*, salmon *(Salmo salar)*, burbot *(Lota lota)*, sturgeon *(Acipenseridae sp.)*, sea trout *(Salmo trutta)* and lamprey, can be replenished in the rivers once more, the main limiting factors are weirs and other impeding structures making fish migration in the Saale and the Schwarza difficult. Some fish passes are in place but most of these are ineffective as fish either cannot find the entrance to the passes or the fish pass is not suitable for the species that need to use them. Additionally, larger reservoirs further upstream on the river Saale have been found to lower water temperatures by 5°C compared to the average in the river Saale over a distance of approximately 100km. This change in water temperature however has shown to be positive for some species as conditions for trout *(Salmo trutta)*, graylings *(Thymallus thymallus)*, and salmon spawning have improved. (Karol, 2007)

Native fish of the Schwarza include brown trout (Salmo trutta), bullhead *(Cottus gobio)* and lamprey, of which the latter two are protected under the Habitats Directive. Further downstream in the town of Unterweissbach a fish hatchery for trout was set up in 1975. The introduction of rainbow trout, a non-native species, has resulted in competition with brown trout for habitat. It has also been observed that the bullhead has been put under a lot of stress due to the competition between the trout species (Karol, 2007).

Physical Environment

A geological fault zone exists near the site of Goldisthal, the Neuhammar shear zone.

The River Schwarza has already undergone hydrological and hydromorphological changes due to the construction of several weirs along its length. The most significant of these impacts is likely to have been caused by the construction of Scheibe-Alsbach in 1944 due to its storage and regulatory functions. The later construction of Goldisthal PHES can therefore be assumed to have had an additional impact on the river Schwarza.

### 5.6.3. Operation Impacts

Human Interaction

The main land use in the area surrounding Goldisthal PHES is forestry. Even though part of the forest was removed to accommodate the PHES, the primary land use has remained unchanged. Although unemployment levels remain high in the area, the PHES has brought employment for around 50 full time workers and 80 additional maintenance jobs.

The facility is open to the public and has become quite a popular site to visit. The area around Goldisthal has become a popular site for hiking and other tourist attractions.

The amenity value of the area around the PHES lies in the nature reserves. The construction of Goldisthal has increased tourism in the area.

Ecology and Natural Systems

Although no improvements have been made to the facility in terms of environmental upgrading, there are guided tours at Goldisthal to specifically create awareness for PHES and its beneficial impact on the environment.

German energy companies and also the general public are calling for an EIA to be completed following the construction of the PHES. They suggest Goldisthal as an ideal candidate for an environmental assessment as it is a relatively new build, very large, and lies in close proximity to an area of ecological importance.

There is no ongoing monitoring of the surrounding ecology by the operators. The nature conservation organisations monitor certain aspects, such as water quality behind the lower dam and invertebrates and other fauna living between the rocks on the downstream side of the dam. Sensitive flora and fauna are unlikely to tolerate the artificial fluctuations within the lower reservoir as well as below the dam.

Since 2006 fishing is permitted in the lower reservoir which is stocked with rainbow trout for recreational purposes. No fish deaths have been recorded in connection with the operation of the PHES.

Water conditions are improving in the River Saale, and weirs and other constructions are either being dismantled or altered to facilitate fish migration, in both the Saale and the Schwarza rivers. The River Schwarza may become an important spawning ground for Brown Trout, Grayling and Salmon in the future. (Karol, 2007) The Schwarza was nominated as the river landscape of 2006/2007 and within one to two years the river will be “freed” of weirs and other constructions hindering migration of fish with the exception of Goldisthal and the Scheibe-Alsbach reservoir. The “freeing” of rivers is part of the WFD requirements to compensate for Golidsthal and the district supply reservoir Leibis-Lichte. This second reservoir was constructed in 2005 and lies on a tributary to the Schwarza.

Visually there are no major issues with either the upper or lower reservoir although both are large. This is because measures have been taken to conceal the facility into the environment. In terms of impact on the landscape these have been deemed higher as part of the river Schwarza has been transformed into an impounded lake to accommodate the PHES.

Physical Environment

There is no noise or vibration associated with Goldisthal as the powerhouse and penstock are underground.

The lower reservoir was created by damming the river Schwarza at both ends. The normal fluctuation range is about 20m over an 8 hour period. Sensitive flora and fauna are unlikely to tolerate the artificial fluctuations within the lower reservoir.

The minimum flow from the reservoir to the river Schwarza is 100l/s. The maximum flow is 23m$^3$/s and is set to protect against flood.

### 5.6.4. Summary of impacts during operation

The case study on Goldisthal has highlighted several “high” impacts. This is mostly due to the fact that the lower reservoir had to be created by damming a section of the River Schwarza, which has had long term impacts that are attributed to the operation of the dam.


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**Table 5: Summary table showing the negative impacts during operation of the semi-open PHES Goldisthal**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | H |
| | Fisheries | M |
| | Air and Climate | L-H* |
| | Landscape & Visuals | M |
| | Water Resources | M |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | M |
| | Hydrology & Hydrogeology | H |

## 5.7. Semi-open PHES – Bolarque, Spain

Spain has 553 SHP, 282 HP (ESHA, 2009), and 25 PHES. Bolarque II, situated in central Spain, was commissioned in 1975. It is unique in the sense that it facilitates the now controversial 300km long aqueduct transferring water from the Tagus River Basin in central Spain to the Segura River Basin in the south-east. The need for energy storage in Spain comes from weak interconnections to the European grid and currently high penetration of variable renewable energy sources. Without further energy storage facilities additional renewable energy deployment may be limited.

Bolarque II is a semi-open PHES that utilizes the Bolarque reservoir as its lower reservoir. Bolarque reservoir is located at the convergence of two rivers, Tagus and Guadiela, downstream of two large dams, Buendia and Entrepenas respectively. The dam includes the HP station Bolarque I, which generates electricity from the water discharged downstream into the Zorita reservoir. The upper reservoir of the PHES facility is a man-made construction approximately 300m above Bolarque reservoir, called Bujeda Reservoir (see *Figure 21*).


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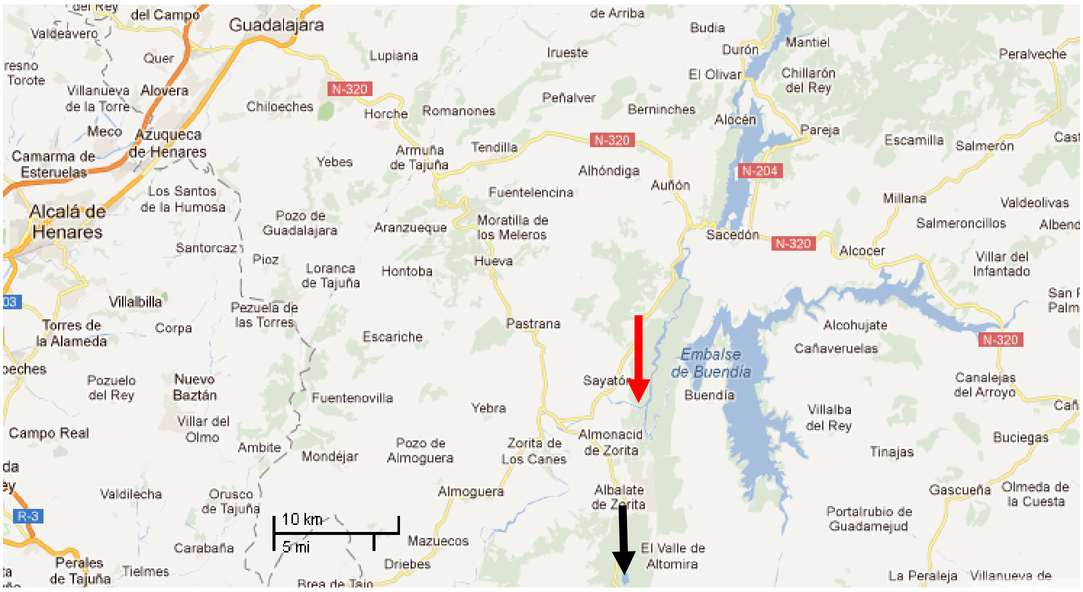


*Figure 21: The lower reservoir Bolarque (red arrow) and the upper reservoir Bujeda (black arrow), located approximately 120 km east of Madrid in central Spain. Source:(Google Maps, 2011a)*

### 5.7.1. Technical Description

Bolarque II, commissioned in 1975, is a semi-open PHES that utilizes Bolarque Reservoir as its lower reservoir. The upper reservoir, Bujeda reservoir, which can store a volume of 6 million m$^3$, is a man made construction situated almost 300m above in the adjacent mountain. Above ground penstocks are visible leading up into the mountain to a height of approximately 245m above Bolarque reservoir from where the penstocks continue underground through the mountain to the upper reservoir nestled into the mountain ridge (see *Figure 22*). The installed capacity of Bolarque II is 208MW.

However, Bolarque II was not solely built for PHES purposes. In 1933 the idea of large scale water transfer from the Tagus river basin to the Segura river basin was conceived. This idea was not realized until 1970 when work on an almost 300km long aqueduct began and was completed in 1979. The Segura River Basin is located in south-eastern Spain where some of the most cultivable lands are located. Unfortunately the same area suffers from water shortages that are greatly exaggerated during times of drought. The start of the aqueduct can be seen at the bottom of *Figure 22*. This outlet is at the opposite end of the reservoir to the PHES intake.

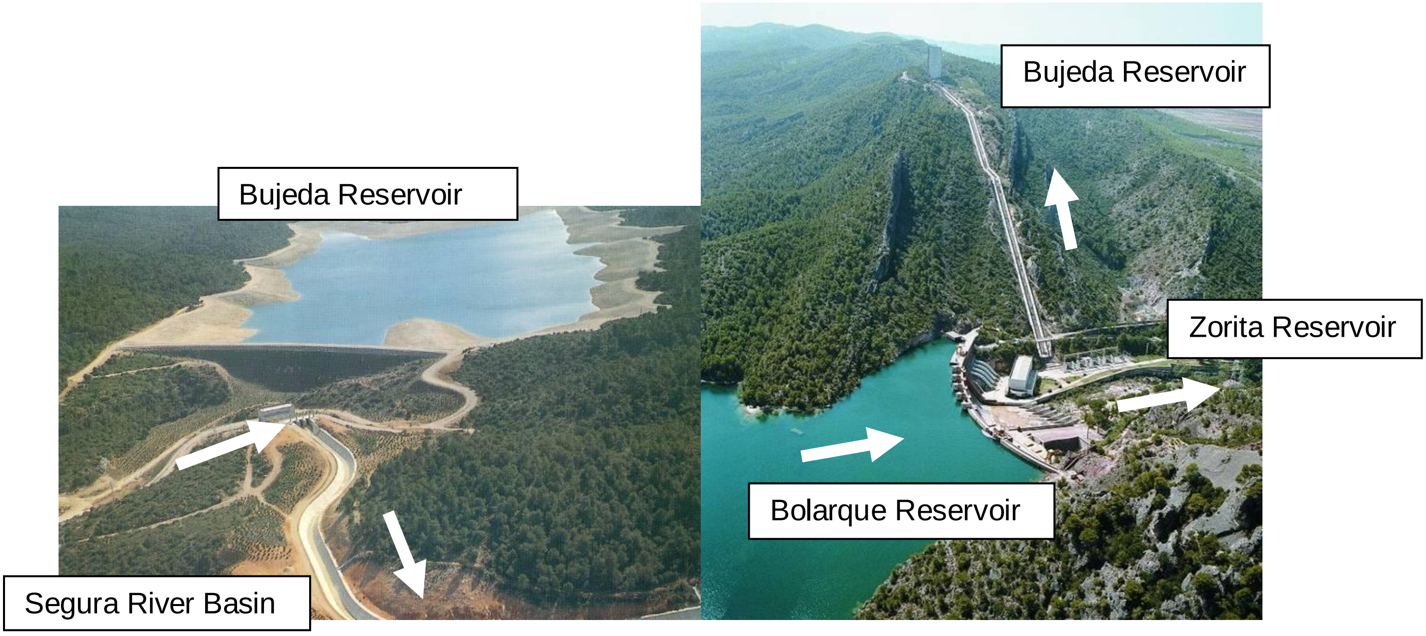


*Figure 22: (left) upper reservoir, Bujeda. The aqueduct at the bottom is the start of the transfer to the Segura River Basin. (right) lower reservoir, Bolarque, with visible penstocks leading up the mountain towards the upper reservoir, Bujeda Reservoir. Source: (left): (Semprem), (right): (CEDEX/Ministerio de Formento)*

### 5.7.2. Pre-developed Environment

<u>Human Impact</u>

Bolarque dam is situated on the convergence of the Tagus and the Guadiela rivers in the upper region of the Tagus River Basin. The Tagus River Basin is shared by Spain and Portugal. Due to the change in topography and climate from the upper reaches to the lower reaches the Tagus River Basin supports vastly distinct and different ecosystems.

Bolarque dam was first constructed in 1910 but due to modifications was not finalised until 1951 (Lorenzo-Lacruz et al., 2010). The Buendia, Entrepenas dams are located further upstream from Bolarque and were constructed in 1958, 1956 respectively. The Zorita dam located downstream of Bolarque was constructed in 1947. The Tagus basin has thus been regulated for a long time. The main functions of Bolarque dam is to distribute the water collected from the two dams, Entrepenas and Buendia and utilize it for the irrigation supply system in the area, district water supply system and power generation.

The area of Buendia, Entrepenas and Bolarque is commonly known as the Sea of Castile. This area has drawn tourists for decades because of its natural environment, scenic views, recreational fishing and wildlife.

The area around Bolarque dam is sparely populated with smaller towns and villages. The site is located about 120km east of Madrid. The landscape is dominated by forests and hills and the primary land use is agriculture.

Roads, gridline, dam, power house infrastructure existed at Bolarque reservoir.

There is a cultural heritage site called “Almonacid de Zorita” and “Zorita de los Canes y Pastrana”. This area is a designated “Historic-Artistic Grouping” due to its medieval cultural heritage, including the Castle of Zorita.

Further downstream of the Bolarque dam before the Zorita dam is the Jose Cabrera nuclear power plant. This plant was commissioned in 1968. Due to a discovered deficient security system in 2003, it was shut down in 2006 on ministerial orders. The site is planned to be cleared by 2015. There is also a meteorological station located in vicinity of the nuclear power plant.

Ecology and Natural Systems

The area of Buendia, Entrepenas and Bolarque is commonly known as the Sea of Castile. During construction, $114km^2$ of natural habitat was inundated to allow for storage. The habitats most affected were riverside woods and groves, the river, cliff-nesting sites, Mediterranean bush, scrub oak, gall oak and black pine. (Soria, 2003) Bolarque, Buendia and Entrepenas have a maximum storage capacity of 31 million $m^3$, 1,638 million $m^3$ and 835 million $m^3$ respectively. These large reservoirs are very likely to emit greenhouse gases (GHG) particularly following inundation.

Physical Environment

There are no sites of geological interest in the area. The classification of soil and geology in the area is secondary and quaternary terrains, gypsum, sandstone and clay.

As aforementioned, the area of Buendia, Entrepenas and Bolarque is commonly known as the Sea of Castile. This is because vast areas around the Tagus and Guadiela and Bolarque rivers, totalling $114km^2$, were inundated once the dams were in place. Thus as a result of the construction of Bolarque, Buendia and Entrepenas, there has been a profound change from a river ecosystem to a vast lake ecosystem which has destroyed natural habitat and created new ecosystems.

### 5.7.3. Operation Impacts

Human Impacts

The Tagus-Segura transfer that was constructed simultaneously with Bolarque II, is an economic asset to the surrounding region, with profit from the income collected for each $m^3$ of water transferred. Madrid has to date received €162 million in compensation whereas Castilla-La Mancha located at the headwaters of the Tagus has received €72 million (2003). The received compensation is distributed in proportion to population among the regions of Madrid, Castilla- La Mancha and Extremadura. (Soria, 2003)

Ecology and Natural Systems

Natura 2000 sites came into effect in Spain from 1990 onwards. Today the area of Bolarque and Bujeda are both within Natura 2000 sites and IBA sites (see *Figure 23*). Some of the protected birds in the area are Griffon Vulture *(Gyps fulvus)*, Peregrine Falcon *(Falco peregrines)*, Eurasian Eagle-Owl *(Bubo bubo)*, Common Kingfisher *(Alcedo atthis)*, Bonelli’s Eagle *(Aquila fasciata)*, Golden Eagle *(Aquila chrysaetos)*, Booted Eagle *(Aquila pennata)* and Short-Toed Snake Eagle *(Circaetus gallicus)*.



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Although the area is protected, several invasive species are causing problems in the Tagus. The reservoirs are stocked with a large number of fish that are competing for habitat. Other invasive species causing problems include the American crab *(Procambarus clarkia)*, signal crayfish *(Pacifastacus leniusculus)*, mollusc *(Corbicula fluminea)* and slider turtle *(Trachemys scripta)*. Land based animals such as the mink *(Mustela vison)*, that is a transmitter of disease and competes with native fauna, and the racoon *(Procyon lotor)* are being monitored. (Gobierno de espana et al., 2011)

The above ground penstock and almost 70m high surge tank at the top of the mountain has an additional visual impact on the landscape.

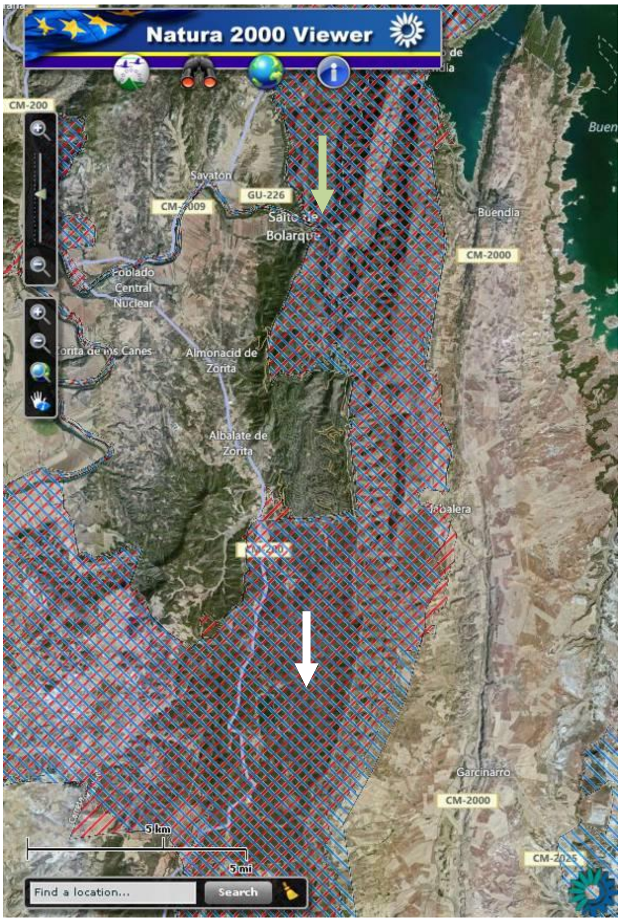


*Figure 23: The upper reservoir (white arrow) and lower reservoir (green arrow) are located in a Natura 2000 site protected by the Habitat Directive (blue diagonal lines) and the Birds Directive (red diagonal lines).*

The water balance in the Tagus has been profoundly affected by the Tagus-Segura Transfer. The semi-closed PHES has had no impact on the water balance, except in facilitating the transfer.

Although fishing for trout *(Salmo trutta)* is not permitted in the lower reservoir at the moment, the surrounding area is a popular fishing site. There is no fish monitoring or cooperation between the power generation facility and the fisheries. The “Confederacion Hidrografica del Tajo” does however monitor the waters for water quality.

The emissions associated with Bolarque – Bujeda are based on the primary electricity source used to operate the pumps.

Additional water resources have not been needed to operate Bolarque II PHES.


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The water transfer to the Segura River Basin is highly strategic and controversial. It involves political decisions at a national level and has been the source of territorial conflicts, especially during periods of drought. (Garrote et al., 2007) To ensure enough resources are kept in the Tagus river, a minimum volume of 240 million $m^3$ has to be stored in the Entrepenas-Buendia reservoirs at all times. The total volume that the two reservoirs can store is approximately 2,500 million $m^3$. If water levels fall below 240 million $m^3$ no water transfer is deployed. Since the beginning of 1979 the volume transferred has gradually increased from approximately 250 million $m^3$ to 600 million $m^3$ in the late 1990s. This is a result of increased consumption for both irrigation and water supply, although it is clear that growth in tourism in the southeast has also greatly increased water supply requirements (Soria, 2003). The transfer is however only meant for district water supply and irrigation.

The impact of reduced water flow in the Tagus is reflected in changing river dynamics, the disappearance of floods and in the degradation of river banks which are gradually being colonised by marsh vegetation. (Soria, 2003) Further impacts are likely to include reductions in riffles (important feeding areas), living space, spawning habitat and an increase in temperature putting fish under stress, increase in body temperature and metabolic rate (Geis, 1982).

Regular water quality monitoring is a requirement of the WFD. Therefore annual physical, chemical and biological monitoring is conducted at the Bolarque dam. The springs in the area are monitored on a regular basis. The reservoirs, Entrepenas, Buendia and Bolarque have received “good status”. The PHES facility would have no impact on water quality to the Tagus Basin.

Physical Environment

The impacts of the transfer have been severe on the Tagus River downstream of the Bolarque dam. A minimum flow of $30m^3/s$ with a mean annual flow of $150m^3/s$ was set in place prior to the diversion. After the diversion was in place the minimum flow has dropped to as little as $6m^3/s$, during the summer months, causing the river reaches to run very low. Low rainfall coincides with maximum use of water during the summer periods. According to the Ministry of Environment (MIMAM) the transferred water accounts for 60% of the natural flow in the Tagus (1000 million $m^3$/year). Further stress is placed on the Tagus River as water transfer increases at the same time as natural inflow into the Tagus have been reduced by 10%. The natural inflow is expected to reduce an additional 4 – 10% due to climate change by 2030. (Soria, 2003)

With the WFD transposed into Spanish legislation the Tagus River Basin is the focus for restoration. The “Confederación Hidrográfica del Tajo” is said to be planning a limit of approximately 100 million $m^3$/year for the transfer. The WFD plan for the Tagus River Basin hopes to have implemented an environmental flow release regime from Bolarque by 2021. (Gobierno de espana et al., 2011)

Between 1980 and 2006 there has been a decrease in water volumes reaching Portugal in the lower reaches of the Tagus River Basin. This affects the Albufeira Convention, which obliges Spain to discharge 2,700 million $m^3$ annually. (Gobierno de espana et al., 2011)

### 5.7.4. Summary of impacts during operation

Since the Tagus was already highly regulated prior to the construction of Bolarque II and also the extensive use of the Tagus-Segura transfer, the overall environmental impact of the PHES is deemed to be low (see Table 6). The semi-open PHES is deemed “medium” landscape and visual impact because of its above ground penstock and will have “low” to “high” impact of GHG emissions depending on what primary electricity source is used to operate the pumps.

**Table 6: Summary table showing the negative impacts during operation of the semi-open PHES Bolarque II**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | L |
| | Fisheries | L |
| | Air and Climate | L-H* |
| | Landscape & Visuals | M |
| | Water Resources | L |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | L |
| | Hydrology & Hydrogeology | L |

## *5.8. Closed-loop PHES – Turlough Hill, Ireland*

Ireland has a few hydropower schemes across the country and one PHES facility, Turlough Hill situated in the heart of the Wicklow Mountains (see *Figure 24*). Commissioned in 1974, Turlough Hill was a major engineering feat of its time and public interest was widespread. The facility was constructed by the ESB with the advice and assistance of the consulting engineers Lahmeyer International of Germany. Today, most people do not know Turlough Hill exists and the service it provides for electricity users each day. The facility, with an installed capacity of 292 MW, is being refurbished since 2010 and is planned to come online in the spring of 2012. During this time wind farm owners have noticed more frequent curtailment. Ireland has some of the best wind and wave resources in Europe, but energy storage is needed to integrate the intermittent electricity and to help mitigate wind curtailment.

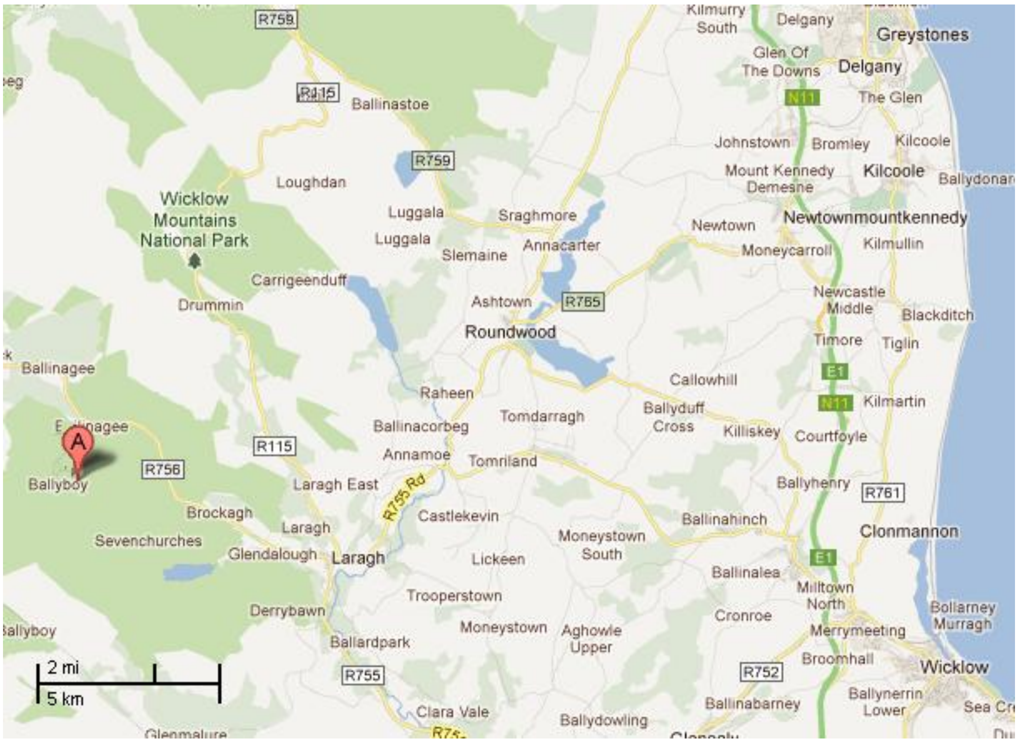


*Figure 24: Turlough Hill (A) located in the heart of Wicklow Mountains. Source: (Google Maps, 2011f)*

### 5.8.1. Technical Description

Turlough Hill is a closed loop PHES meaning that it is isolated from other water bodies (see *Figure 25*). The lower reservoir, Lough Nahanagan, is an existing lake whereas the upper reservoir is man-made. There is an almost 300m head separating the two lakes. The plant is used on a daily basis generating during peak hours and pumping during off peak hours. The water level in the lower reservoir has an operating range of 10m during each cycle.

The power house is built underground in a cavern with a length of 82m, width of 23m and a height of 28m. There are four reversible pump turbines each with a capacity of 73MW, which gives the facility a total capacity of 292MW. There is one pressure shaft and one tailrace feeding the four machines. Both were excavated in granite and lined with steel and concrete respectively.

The upper reservoir comprises a rock filled almost oval shaped embankment with an asphaltic lining. The reservoir can hold 2.3 million $m^3$ of water and has a maximum operating depth of 19.4m. An under floor drainage gallery collects and monitors any seepage through the asphaltic concrete lining.



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*Figure 25: Turlough Hill – lower reservoir (left) upper reservoir (right). Source: (ESB)*

Trash screens are in place preventing potentially damaging metal and other items entering the penstock and affecting the pump turbines.

It is important that the occurrence of overtopping of the embankment of the upper reservoir is prevented as this is likely to damage the rock fill dam. To prevent overtopping there are several systems in place: regular pressure measurements of the water depth, and automatic shutdown of pumps and valves to discharge water. The lower reservoir can also discharge water in cases of high water levels.

A civil engineer is based onsite who takes hydrometric reading once a week. Alignment points are checked once a year and audits with ESBI, the chief engineer and the dam safety committee is also conducted on an annual basis. A risk management plan is in place and practised annually.

### 5.8.2. Pre-developed Environment

<u>Human Impact</u>

The site is situated near the Wicklow Gap in the mountainous county of Wicklow. It lies approximately 60km linear distance south of Dublin and approximately 6.4km from Glendalough.

Glendalough is an important heritage site, known for the hermit St. Kevin who founded a monastic city in the 6th century at this location. It was a centre of learning and pilgrimage to which Irish Kings brought gifts of gold. The importance of the pilgrimage centre can be seen in the original trail that was improved by the Leinster Monarchs, carefully paved with stone into a fair imitation of a Roman Road, which is now known as St. Kevin's Road. This route of pilgrimage survived from its early beginnings down to the famine year of 1847. The road runs straight through the site of Turlough Hill and was partly exposed during construction.

Large scale mining of copper, lead and zinc started in 1800 in the area of Wicklow Gap. One of these mines, a lead mine, existed on the Glendasen River just below Lough Nahanagan. Water from Lough Nahanagan, which used to drain into the Glendasan River, was used to drive water-wheels, which in turn, operated pumps to drain excess water from the lead mines. Ruins of miners' cottages and tips of mine tailings can still be found in the Glendasan Valley on the approach to Turlough Hill.

The area has always been sparely populated although it has also been a popular destination for hill walkers and tourists. Land use is dominated by sheep grazing and some forestry. A main road, the Wicklow Gap Road, exists to the north of the site. However, access to Lough Nahanagan is difficult.

Ecology and Natural Systems

The two dominant vegetation habitats in the area are blanket bog and heath. Peat erosion is found frequently on the peaks and slopes, which is a natural process due to weathering but likely to have been accelerated by overgrazing.

Common mammals in the area include: Deer, hybrid between red and sika (*Cervus Nippon* and *Cervus elaphus)*, Hare *(Lepus timidicus hibernicus)* and Badger *(Meles meles)*. Among the birds, Meadow Pipit *(Alauda cervensis)*, Skylark *(Alauda arvensis)*, Raven *(Corvus corax)* and Red Grouse *(Lagopus lagopus)* inhabit the Wicklow Mountains. The Peregrine Falcon *(Falco peregrines)* can be found nesting in the cliffs of Turlough Hill (NPWS).

Lough Nahanagan is a corrie lake most likely oligotrophic characterised by low levels of nutrients. Information on the composition of fish species in the lake prior to construction of Turlough Hill was not available.

The site lies about 1km south of the Wicklow Gap and is located in an area of high scenic and amenity value.

Physical Environment

The area is characterised as a very low noise environment.

The site is underlain by granite termed the Glendalough Adamellite. There is evidence of past glaciation in the form of glaciated morainic ridges with inner cirque moraine and a corrie lake. There is a minor NW-SE trending fault to the northeast of the lower Lake Nahangan. Peat is the dominant spatial coverage at the site of the upper reservoir and would likely have covered the area of the reservoir prior to its development. The soil surrounding the lower Lough Nahanagan is peaty podzol. To the northeast, this is underlain by a granite till, while at the opposite, south side of the Lough, there is bedrock underlying the peaty podzol.

The site of Turlough Hill is in an area of high precipitation underlain by poor aquifer.

Lough Nahanagan had a natural variation in high and low water levels of 6m. A sluice at the outlet of Lough Nahanagan and a channel once connected the Lough to the Glendasan River. This is related to past lead mining further downstream where a weir and millrace still exist.

### 5.8.3. Operation Impacts

Human Impact

During the past almost 40 years Wicklow has become a popular tourist destination. Turlough Hill is in itself a tourist attraction and a popular site to visit. The ESB provide guided tours by appointment. The Wicklow Gap and the area of Glendalough has developed into a popular tourist destination due to its high scenic value and heritage importance and its close proximity to Dublin.

During the ongoing refurbishments, traffic to Turlough Hill has increased as trucks carrying heavy equipment and machinery access the site. This has caused some interference with tourist busses, cyclists and motorcyclist visiting the area.

Turlough Hill employs 45 staff, of which 40% are from the Wicklow town and surrounding area. The rest are from the area of Bray, approximately 40km northeast of Turlough Hill. Turlough Hill has had a positive employment impact on the area of Wicklow.

The ESB lease the area around Turlough Hill to farmers and beekeepers. The staff at Turlough Hill have brought in their own wireless telecommunication system, utilise their own water springs, and use their own electricity. They have their own water purification system, sewage treatment and waste management. Locally, Turlough Hill is hidden away and isn't considered to have significant operational effects on its surroundings but provides electricity to the Irish grid.

There is the potential for visual impact from the nearby national monuments. The site is however, screened from Glendalough by the Camaderry Mountain and valley side. St. Kevin's Road was launched as a waymarked way in 2001 by Coillte. Furthermore, visual impact of the upper reservoir is lessened by replanting of vegetation along the embankment.

Ecology and Natural Systems

The ESB has implemented an Environmental Management System, following the ISO standards 14001. External audits are conducted twice a year, which is mandatory under ISO procedures although not a legal requirement under Irish law. There is an in-house environmental coordinator stationed at Turlough Hill who manages potential pollutants such as oils and wastes. There is a constant drive for improvement, which means that new environmentally friendly technologies for operating the PHES are always sought and investigated.

Turlough Hill is situated in designated Natura 2000 sites under the Habitat Directive and the Birds Directive (see *Figure 26*). The Peregrine Falcon, in particular, likes to nest on the cliffs above Lough Nahanagan and is protected under the Birds Directive (NPWS).

Lough Nahanagan is a glaciated corrie lake and as such, naturally supports very little fish. Frogs however, are in abundance in the lake. It is not known what fish species occupied the lake prior to its modification. It is likely that habitat loss of shoreline vegetation has occurred as the lake was lowered to a new level during construction. The operational levels of the lake are lower than the natural levels and are artificially altered on a daily basis. Additionally, as the lake was lowered, two islands have emerged.

Lough Nahanagan has been deemed "good status" under the WFD, whereas the Glendasan River has been given "poor status" due to its poor fish population. Water is used by the PHES on a daily basis to pump and generate. There is however no net loss.


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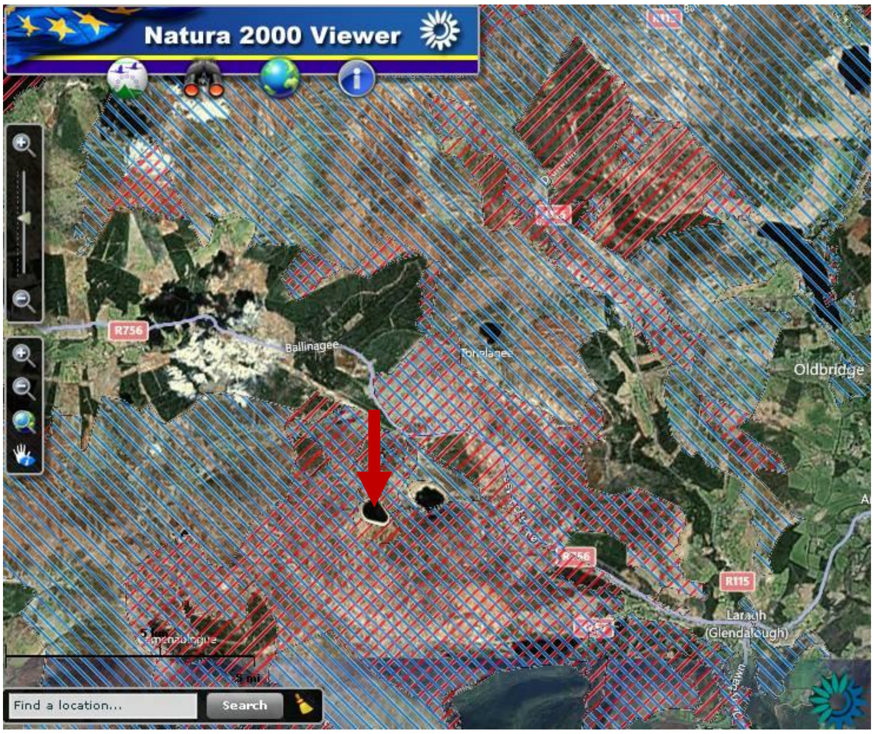


*Figure 26: The upper and lower (red arrow) reservoir is located in areas protected by the Habitat Directive (blue diagonal lines) and by the Birds Directive (red diagonal lines). Source: (EEA, 2011)*

Depending on the primary source of electricity used to drive the pumps at Turlough Hill, the PHES will be “releasing” more or less $CO_2$ emissions. When the pumps at Turlough Hill use RES-e the emissions will be less than when using fossil fuel derived electricity.

Physical Environment

There is no issue with noise emissions from the facility as the power house, the source of the majority of noise, is located below ground. Noise is thus only monitored in the power house for health and safety reasons.

The removal of blanket peat at the top of the mountain to construct the upper reservoir may have increased vulnerability of adjacent blanket peat to erosion processes. The accelerated erosion process may also be due to grazing and the increase in hill walkers in the area.

The lower lake was permanently lowered by 15m during construction to accommodate the PHES. This water level drops a further 10m on a daily basis during pumping mode. Natural lake processes have thus been either significantly altered or lost.

### 5.8.4. Summary of impacts during operation

Turlough Hill has highlighted several environmental impacts during operation. Biodiversity has been deemed “high” because of the loss of shoreline along the natural lake due to the water level being lowered initially and fluctuating during operation. Air and Climate is another highlighted impact that may be “low” or “high” depending on what the primary electricity source is. The third “high” impact is changes in hydrology due to daily fluctuation of 10m in the lower lake.

**Table 7: Summary table showing the negative impacts during operation of the closed-loop PHES Turlough Hill**

| Potential Issues/EIA Terms of Reference | | Negative Operation impacts |
|---|---|---|
| Human Interaction | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | H |
| | Fisheries | M |
| | Air and Climate | L-H* |
| | Landscape & Visuals | M |
| | Water Resources | M |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | L |
| | Hydrology & Hydrogeology | H |

# 6. Discussion of Significant Environmental Impacts from Operation

The six different case studies have highlighted several aspects of environmental impact during operation. A summary table can be found in Table 8 where each aspect has been classified as high, medium or low.

The following sections will analyse and discuss the high impacts of each technology. A further table, highlighting the interactions between separate aspects, will be offered at the end of each technology section.

**Table 8: Summary table of negative impacts during operation highlighted from the case studies**

| | | CAES | Pump-back PHES | Semi-open PHES | | | Closed-loop PHES |
|---|---|---|---|---|---|---|---|
| Potential Issues/EIA terms of reference | | Huntorf | Thissavros | Kopswerk2 | Goldisthal | Bolarque2 | Turlough Hill |
| Human Impact | Population | L | L | L | L | L | L |
| | Traffic | L | L | L | L | L | L |
| | Cultural Heritage | L | L | L | L | L | L |
| | Material Assets | L | L | L | L | L | L |
| Ecology and Natural Systems | Biodiversity | L | H | L | H | L | H |
| | Fisheries | L | H | L | M | L | M |
| | Air and Climate | L-H* | L-H* | L-H* | L-H* | L-H* | L-H* |
| | Landscape and Visuals | L | M | L | M | M | M |
| | Water Resources & Quality | L | H | L | M | L | M |
| **Physical Environment** | Noise & Vibration | L | L | L | L | L | L |
| | Soils, Geology & Sediment Transport | L | H | L | M | L | L |
| | Hydrology & Hydrogeology | L | H | M | H | L | H |

- *Recommended to review each individual case study*
- *Inclusion of combined impacts with existing land uses and pressures*
- *Limited raw data*

## *6.1. Compressed Air Energy Storage*

The main impact highlighted by the Huntorf case study is its need for additional fossil fuel (natural gas) to operate.

## 6.1.1. Air and Climate

Although conventional CAES is seen as a non-pure storage due to its usage of natural gas in the combustion chamber, the need for fuel is 1/3 that of a conventional combustion turbine, thereby producing about two-thirds less pollutants (Akorede et al., 2010). The pre-compressed air from the storage caverns effectively eliminates the need of the turbine input compressor stage, which utilizes ~60% of the mechanical energy produced by a standard combustion turbine. The largest part of emissions for CAES comes from fuel and fuel delivery averaging 285g $CO_2$eq./kWh. (Denholm and Kulcinski, 2004) This however is still lower than GHG emissions from fossil generation that produce between 475 and 1300g $CO_2$eq./kWh (Gagnon et al., 2002). In order to examine the total GHG emissions from CAES a complete LCA would need to be undertaken in the context of the primary electricity source. *Figure 27* shows that the intercept between CAES and PHES occurs at about 425tonnes $CO_2$eq./GWh from primary generation, which is approximately the minimum emission from currently available fossil generation technologies such as the highest efficiency CCGT. The result is that when the stored energy generated from gas, oil or coal, CAES becomes the lowest GHG emitting storage technology over the entire lifecycle. Only when the stored energy is generated from nuclear or renewable energy is CAES a higher emitter than PHES. (Denholm and Kulcinski, 2004)

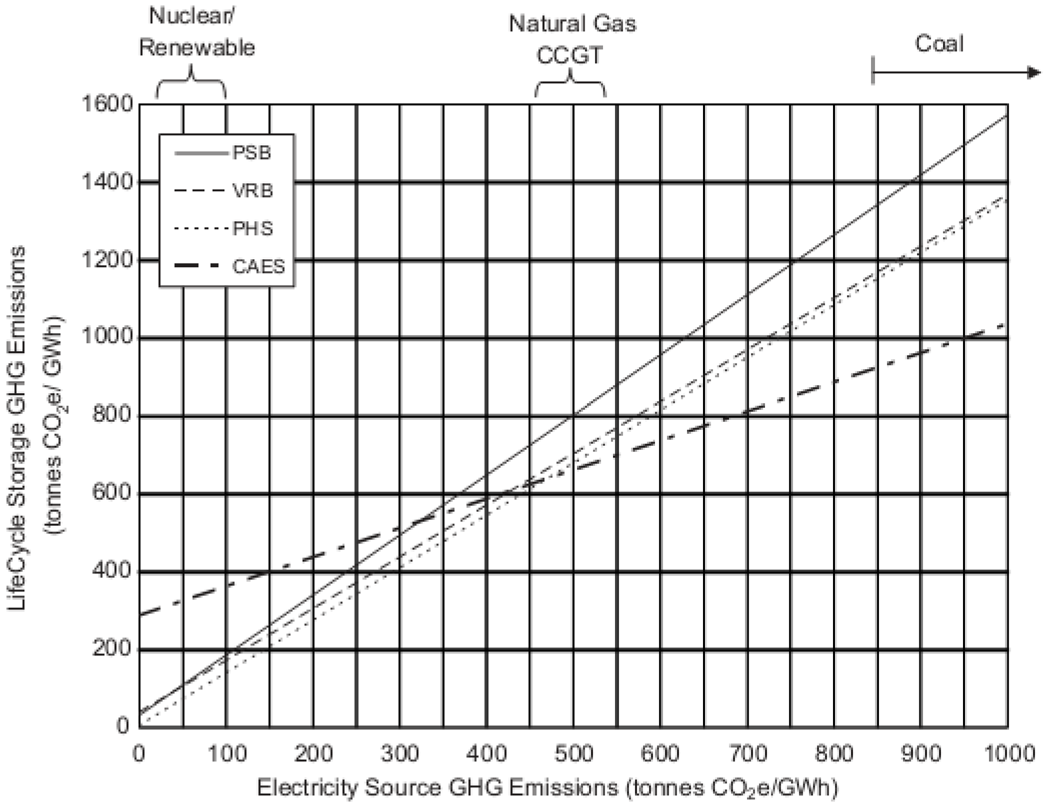


*Figure 27: Life cycle GHG emissions from electricity storage. Source: (Denholm and Kulcinski, 2004)*

The major limiting factor for CAES is thus its dependency on natural gas. However, one study (Denholm, 2006) suggests replacing natural gas with farm-derived biomass fuel. As biomass crops are a renewable energy source, these are usually carbon neutral over the entire life-cycle, which would mean reducing the GHG emissions from CAES systems substantially.

Developing the concept of an adiabatic CAES can result in zero direct $CO_2$ emissions, as these plants store and recover the heat given off during air compression. The EU-funded AA-CAES


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project, comprising 19 partner countries, has investigated the feasibility and performance of the adiabatic technology and has developed concepts for the most promising plant configuration and component design. (Bullough et al., 2004)

## *6.2. Open-system (pump-back) PHES*

There is generally some ambiguity as to whether the environmental impacts of a pump-back PHES should be attributed to its function as an energy storage facility or as a hydro generation facility. In most cases, pump-back PHES schemes are constructed by incorporating a pumping system into an already existing hydro scheme (i.e. retrofitting) so as to facilitate energy storage. The most significant operational environmental impacts will already have been realised by the existence of the dam and hydro scheme. Therefore, the existing environment is already significantly modified from its original condition and the additional impacts due to the addition of pumps are likely to be significantly less. The Thissavros pump-back PHES however, was constructed simultaneously with the dam, as an integrated system in a relatively unmodified environment. Therefore the operational environmental impacts of the PHES (i.e pumping) and hydro generation are difficult to separate and are attributed to both. The result is that Thissavros case study highlights several 'high' operational impacts on the Nestos river system. For the purpose of comparing the operational impacts of a retrofitted scheme with a new build, the Thissavros scheme was analysed in its actual form and also as a notional retrofitted scheme (see Table 9).

**Table 9: Summary table of negative impacts from operation of pump-back highlighted in Thissavros compared with a notional Thissavros (had it been retrofitted)**

| Potential Issues/EIA Terms of Reference | | Thissavros | (notional)Thissavros (had it been retrofitted) |
|---|---|---|---|
| Human Impact | Population | L | L |
| | Transport | L | L |
| | Cultural Heritage | L | L |
| | Material Assets | L | L |
| Ecology & Natural Systems | Biodiversity | H | L |
| | Fisheries | H | L |
| | Air and Climate | L-H* | L-H* |
| | Landscape & Visuals | M | L |
| | Water Resources | H | M |
| Physical Environment | Noise & Vibration | L | L |
| | Soils & Geology | H | L |
| | Hydrology & Hydrogeology | H | L-M |

### 6.2.1. Biodiversity

Since the Thissavros PHES facility was constructed in combination with the dam consequently blocking the river, the resulting impacts have to be attributed to both the generating and the pumping mode of the PHES. Thus the pump-back PHES may be contributing to a decline and even the extinction of species that depend on longitudinal movements (Larinier, 2001) along the waterway. Fish are highly dependent on longitudinal movement and this will be discussed further under section 6.2.2.

Although habitat destruction due to inundation of vast areas is attributed to construction, the long term impact of habitat loss and habitat fragmentation is an impact that is attributed to operation. Habitat fragmentation can be both longitudinal and lateral, where longitudinal hindrance is by the presence of the dam and lateral hindrance occurs via the expansion of the river to a lake that may make it impossible for certain terrestrial species from crossing from one side to the other.

Local measures to protect specific habitats may be effective; although in the long-term compensation and enhancement programs will be much more beneficial. However, large drawdown zones in reservoirs may not be appropriate for habitat restoration, as drawdown causes erosion and sedimentation that in turn may impact on aquatic, riparian and terrestrial habitats. (Trussart et al., 2002) Suggestions for successful restoration programs to restore terrestrial habitat as well as measures promoting vegetation or control erosion following impoundment can be found in (Trussart et al., 2002).

As Thissavros operates on a daily basis as a pump-back PHES it can be assumed that frequent and rapid drawdown in water level will occur, resulting in enhanced variation in pore water pressures as the water drains out of the banks, inducing increased erosion events. The severity of any one event however, depends on the length of time the power station is in operation and thus for how long the banks are saturated. (Locher, 2004) Fluctuations in discharge patterns will affect riparian vegetation downstream of the dam in terms of species cover and diversity due to alteration of the natural waterlogging and inundation regime. The result of these changes may be that riparian tall woody shrub species are replaced with ephermerals such as grasses, gramonoids and tolerant semi-aquatic herb which may provide some structural stability to river banks. There is still however, the risk of limited regeneration and recruitment as seedlings cannot establish on the banks where water levels rise rapidly on a daily basis and wash them away, leaving shorelines bare. According to Petts (1988) as cited in Larinier (2001) fluctuating water levels and velocities due to power output from the peaking plant may inhibit fish spawning behaviour, sweep juveniles downstream during high flow or leave eggs or juveniles stranded by sudden reduction in flow . Since PHES facilities are operated from an economic perspective rather than an environmental one (Zhao and Davison, 2009), generating when demand is high and pumping when demand is low, the result of a free electricity market has led to more variable flows (Renöfält et al., 2010). This may ultimately have devastating effects on the river ecosystem in terms of water quality, sediment transport, riparian vegetation, macroinvertebrates and migratory aquatic species (Locher, 2004). Changing the way the facility is operated to better accommodate the needs of the ecosystem may help to maintain the habitats for each species (see *Figure 32* in chapter 6.2.6).

According to Hynes (1970) as cited in World Commission on Dams (2000) many insects need to migrate up or downstream as well, such as the glochidia larvae of freshwater mussels that are carried by host fish, or the mayflies and stoneflies that move upstream to lay their eggs so as to counteract the drift downstream of their larvae. Migration is thus blocked by a dam to varying degrees.

It is important to note that different fish species have different tolerances to temperatures and changes in temperatures as well as DO levels in their habitats. The modified habitat often create environments that are more suited for non-native and exotic plant, fish, snail, insect and animal species with the result that non-native species often out-compete the natives. This in turn results in a modifies ecosystem that may become unstable, nurture disease vectors or are no longer able to support the historical environmental and social components.(World Commission on Dams, 2000) In the Thissavros reservoir Perch (*Perca fluviatilis*) has become the dominant species although it did not exist in that ecosystem prior to construction, showing that changes in habitat are also changing the species balance.

### 6.2.2. Fisheries

Fish migrate because they require different environments for different stages in their life cycle; reproduction, juvenile production, growth, and sexual maturation (World Commission on Dams, 2000). Potamodromous species such as pike (Esox lucius), brown trout (Salmo trutta fario) and lake trout (Salmo trutta trutta) complete their entire life-cycle in freshwater. Diadromous species on the other hand spend their life-cycle partly in freshwater and partly at sea (Porcher and Travade, 2002). Diadromous species can be further categorised into anadromous and catadromous species. Anadromous species, such as Atlantic salmon (Salmon salar), Allis shad (Alosa alosa), sea lamprey (Petomyzon) marinus) and sturgeon (Sturio sturio) migrate downstream as juveniles and migrate upstream as adults for reproduction. Catadromous species such as eel (Anguilla Anguilla) have the opposite lifecycle. Anadromy is much more common than catadromy (Larinier, 2001). In this context it is therefore important to consider both upstream and downstream migration.

Although migration is blocked by the presence of a dam, it must be mentioned that natural waterfalls also represent obstacles to upstream fish migration. As many dams are built on such falls, the dam itself does not represent a barrier to fish passage (Trussart et al., 2002). The Nestos River with Thissavros dam and Platanovrisi are not such dams and as such are possibly affecting 37 fish species due to physical restrictions to migration. Different types of fish passes are therefore under consideration for the Nestos catchment. For a fish pass to be considered effective, fish should find the entrance and negotiate it without delay, stress or injury (Larinier, 2002). Fish passes are usually designed for one specific type of fish (Porcher and Travade, 2002) and knowledge of the behaviour of the target species, hydrology, hydraulics, topography of the site, etc, is of vital importance to constructing the appropriate type of fish passage (Larinier, 2002).

In the case of Thissavros, a fish ladder is not a feasible option as the dam is 172m high and the fish ladder would have to possibly be up to 2km or more in length depending on the fish species that have to be facilitated. According to Schmetterling (2003) as cited in Schilt (2007), probably the most effective method is trucking and although this is very costly and causes stress to the fish it can be successful in the short term in re-establishing an upstream population. A more long term solution may be to install a fish lift (Schilt, 2007). Not all HP dams are as high as Thissavros though and other types of fish passes may be an option. It is worth noting that not all dams need a fish passage. To determine if a fish passage is necessary the flow chart presented in Porcher and Travade (2002) may be of assistance (see *Figure 28*).

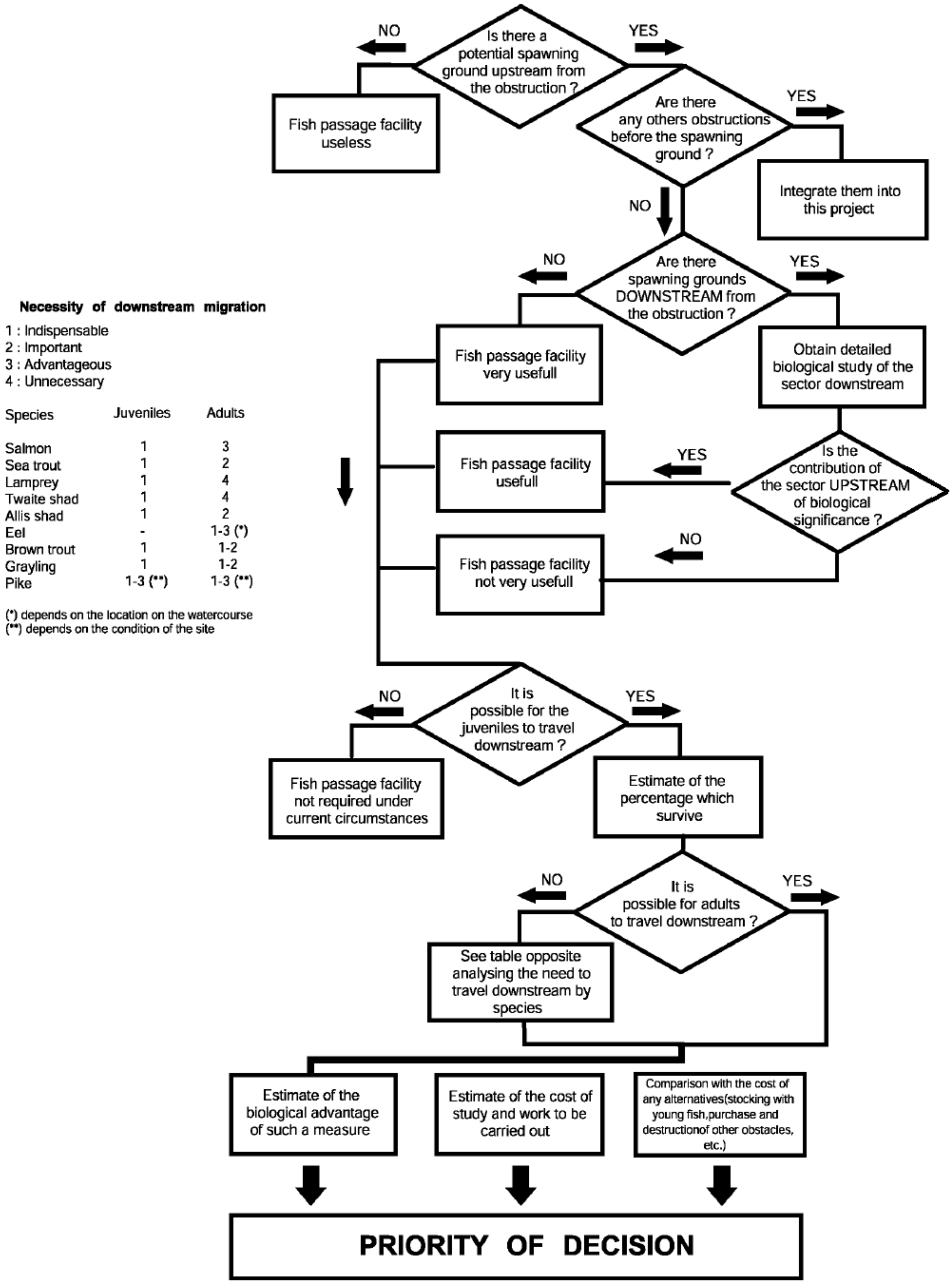


*Figure 28: Flow chart for evaluating the need for a fish facility to restore fish passage for potamodromous and diadromous species. Source: (Porcher and Travade, 2002)*

It is important to note, however, that fish passes always cause delays. With delays come vulnerability to predation below the dam (Porcher and Travade, 2002), while prolonged stays in unsuitable zones may cause injury and fatigue from unsuccessful repeated attempts to pass (Larinier, 2001). Creating free passage for fish migration is only one aspect of fish stock management, however. Other aspects include, water quality, spread of disease, alterations in habitat quality and new fisheries grounds (Porcher and Travade, 2002).

For downstream migration, the rule is that fish do not use fish passes. Migration occurs either via surface passage or juvenile bypasses through turbines or spillways. Each of these passages is associated with different problems. The surface passage, if the outfall is sited and constructed properly, is the most benign type of passage route and diverts the least amount of water from the turbines. (Schilt, 2007) Most injuries and mortalities are caused by the passage through spillways and turbines (Trussart et al., 2002). It is worth remembering that the more water released from spillways to facilitate fish passage the less water is available for power generation in a hydro facility. A knock-on effect is that spilled water is forced deep underwater where increased pressure may cause the water to become supersaturated with air. This in turn may cause stress and death in fish downstream of the spillway. Potential fish predators have been observed to congregate at spillway tailraces. (Schilt, 2007) Injuries are caused by shearing effects, abrasions against spillway surfaces and physical impact against energy dissipaters. Ski–jump spillways are preferable if there is a pool with sufficient volume at the base, as these allow fish to free fall. (Larinier, 2001) The turbines shear stress and turbulence cause a lot of the damage and these forces are believed to occur within several different parts of the turbine (Mufeed Odeh et al., 2002). Mortality rates for a Francis turbine have been found to range between 5% to over 90% whereas mortality rates for a Kaplan turbine range from under 5% to approximately 20%. One reason is Francis turbines are usually installed under higher heads and the sudden decrease in pressure to which levels of response varies between fish species. (Larinier, 2001) Another reason is that fish are more likely to be severed by the runner in a Francis turbine than by the blades of a Kaplan turbine. However, most of the research of the adverse biological effects of turbulence is focused on the draft tube and the draft tube outlet to the tailrace (Mufeed Odeh et al., 2002).

Both upstream and downstream long distance migrating fish may either take advantage of, or temporally and spatially avoid, varying environmental conditions such as temperature, flood stage, trophic resources, or other variables (Schilt, 2007). Therefore, optimum timing of migration is an important dimension that needs to be considered as part of the operating regime of the pump-back PHES. In general impounded rivers pass fish downstream more slowly than free flowing rivers, the former thus reducing the survival of fish in the artificially modified environment (Williams et al., 2005). Furthermore, regulating river discharge during migratory periods for fish may cause a sharp decrease in migratory populations (Larinier, 2001). According to Petts (1988), as cited in Larinier (2001), fluctuating water levels and velocities due to power output from the peaking plant may inhibit spawning behaviour, sweep juveniles downstream during high flow or leave eggs or juveniles stranded by sudden reduction in flow.

### 6.2.3. Air and Climate

For Thissavros, two sources of GHG emissions need to be taken into account during operation; reservoir emissions and those from the primary electricity source that the PHES is storing. If the pump-back PHES were retrofitted the only source of GHG emissions will be the primary electricity source, as the reservoir GHG emissions will be allocated to the existing HP facility and dam.

Although there is consensus in the research community that inundated reservoirs emit GHG, differing opinions exist regarding the overall contribution. The area of GHG emissions from inundation and other sources are therefore an area which requires further investigation.


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If biomass is left in place whilst flooding an area it will decay both aerobically, producing $CO_2$, and anaerobically, producing both $CO_2$ and $CH_4$. If the biomass is cleared prior to flooding, a net increase in atmospheric carbon can also be expected. (Denholm and Kulcinski, 2004) It is also important to note that there is now also consensus that most natural lakes and rivers are major sources for GHG emissions as these, like man-made reservoirs, transport carbonic sediment from the surrounding ecosystem via waterways to the atmosphere (Raadal et al., 2011).

Raadal et al., (2011) has found that there are large variations in calculations of GHG emissions from reservoirs, varying from 0.2 tonnes to 152 tonnes $CO_2$-eq./GWh, which gives a mean value of 54.5 tonnes $CO_2$-eq./GWh including gross emissions from flooded land. When excluding the emissions from flooded land the value drops to 2.9 tonnes $CO_2$-eq./GWh, implying that GHG emissions from flooded land could be the most significant source of emissions. These variations can for the most part be explained by difference in GHG emissions from flooded land and the data may not represent "net" emissions for which the reservoirs are responsible. It is important to note that in previous studies no account has been provided on the level of GHGs the flooded land would have emitted in the absence of the reservoirs (International Energy Agency, 2002). There are certain parameters that affect the emissions from reservoirs and need to be taken into account (Gagnon and van de Vate, 1997):

- Size. The area of reservoir per kWh generated by the plant or group of plants in the river basin.
- Climate. Biodegradation occurs in all climates. Cold water and ice cover will reduce the rate of decay, whereas reservoirs in temperate climate may be a relevant addition to local and regional GHG budget (Eugster et al., 2011). Reservoirs in arid regions may be acting as carbon sinks (International Energy Agency, 2002).
- Ecosystem. Depending on ecosystem flooded; tropical, peat lands, arid land, alpine, etc emissions will vary. The original vegetation may have been a $CO_2$ sink before flooding.
- Time. The lifespan to calculate the overall $CO_2$-equivalent per kWh is important as GHG emissions are assumed to be heavily frontloaded. The overall GHG emissions will therefore be different if a lifespan of 50-75 years is used as opposed to 100 years.

The other main source of GHG emissions from PHES is the primary electricity source used. During pumping mode, the PHES will operate its pumps using the available electricity from the grid. Therefore, depending on whether that source is from RES-e, nuclear power or fossil fuels, the GHG emissions will vary significantly. *Figure 27* shows that when PHES is used to store RES-e or nuclear power the GHG emissions are very low ranging from 10 to 100 tonnes $CO_2$-eq./GWh. The overall GHG emissions are greater if PHES is used to store fossil fuel generated power with emissions ranging between 475 and 1300 tonnes $CO_2$-eq./GWh (Gagnon et al., 2002).

### 6.2.4. Water Resources and Quality

The heading "Water Resources and Quality" is probably the most difficult to assess as water quality depends on so many different factors and interacts with several of the other headings; "hydrology and hydrogeology", "soils, geology and sediment transport", "biodiversity","fisheries" and "population". In this document water quality effects mainly refer to changes in dissolved oxygen (DO), nutrient levels, temperature and turbidity as a result of anthropogenic influences. These changes are to a great extent a direct result of the existence of a dam but also of the fluctuations in flow releases from the dam. The impact from Thissavros has been deemed "high", although a retrofitted pump-back PHES would most likely still have a "medium" impact due to the existence of the dam and associated impacts.

Constructing a dam on a river will alter a natural river environment into a modified lake environment, thus significantly changing the hydrology and hydrogeology of the system. Lake environments tend to undergo thermal stratification, particularly in the warm summer months, dividing the water into three different layers; epilimnion, metalimnion and hypolimnion. The uppermost layer, the epilimnion, is a warmer less dense layer than the bottom layer; the hypolimnion has much cooler and denser water. In between these two layers is the metalimnion where strong vertical temperature gradients occur that may be up to 1°C/m (see *Figure 29*). Another effect of thermal stratification is that the hypolimnion becomes isolated from sources of oxygen, associated with respiration and decay. DO concentrations are widely observed to decrease progressively with depth in mesotrophic and eutrophic lakes until reaching the layer of sediment at the bottom of the lake (see *Figure 29*). Important to note is that salt concentrations and nutrient levels are higher in the lower layers of a thermally stratified lake as water density is higher there.

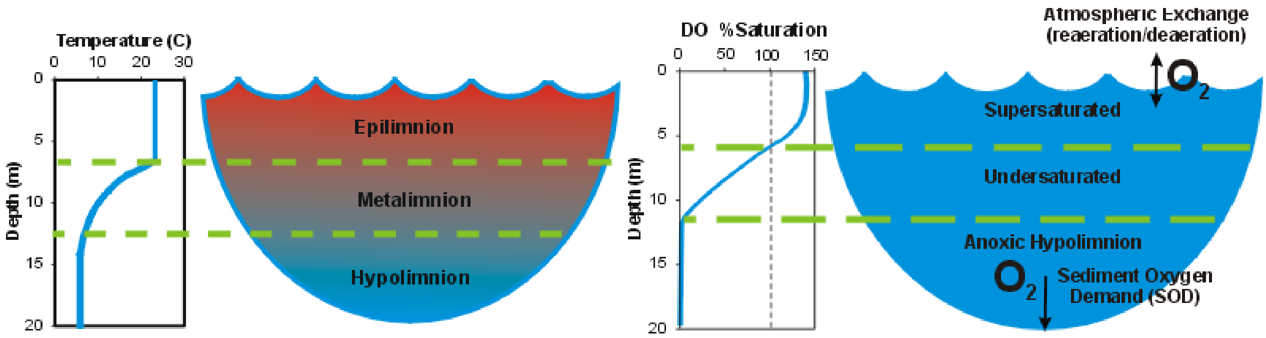


*Figure 29: (left) A hypothetical summer profile depicting a vertical temperature gradient for the layers. Source: (Ourlake, 2009b). (right) A hypothetical profile of dissolved oxygen (DO) saturation vertically through a lake. Source: (Ourlake, 2009a)*

Although thermal stratification is a natural process, a thermally stratified lake associated with a dam may have negative impacts on the downstream environment. According to Petts (1988) as cited in Larinier (2001) the limnology of the reservoir determines the quality of the dam-release; surface-release reservoirs act as nutrient traps and heat exporters whereas deep-release reservoirs export nutrients and cold water. Most dams used for electricity generation off-take water from levels as low as possible to use as much of the reservoir capacity as possible, implying that the downstream environment would experience frequent fluctuations in temperature and DO levels (Locher, 2004) as well as higher salt concentrations as the power station releases cold water from the hypolimnion layer in the reservoir into the warmer water of the downstream receiving environment. Thissavros confirms this fact as its turbine intakes are located near the bottom of the reservoir and a reduction in temperatures downstream, of up to 15°C, and higher salt concentrations have been recorded during summer months.

According to Petts (1988), Bradka and Rehackova (1964) as cited in Larinier (2001) changes in water temperature and DO concentration levels have been observed to be the main causes of reduced spawning success and fish mortality downstream of dams. On the one hand, during high water periods, water may be spilled over the crest potentially releasing over-saturated water with oxygen and nitrogen levels that may be lethal for fish (Larinier, 2001, World Commission on Dams, 2000). According to Schilt (2007) and Bechara et al., (1996) as cited in Larinier (2001) on the other hand supersaturated water, resulting from high pressures caused by stilling basins below spillways forcing water and air into the depths may cause high fish mortality up to 100km downstream of the dam. Important to note is that different fish species have different tolerances to temperatures and changes in temperatures as well as DO levels in their habitats.

The main causes of turbidity, or a lack of clarity, are suspended sediment loads due to erosion, industrial wastes and sewage from human interaction with the river, and plankton or bottom feeding organisms that stir up sediments in the water (Ourlake, 2009c). According to Klumpp et al., (2003) as cited in Pacca (2007), as flow velocity decreases within the reservoir particle deposition increases and lowers the turbidity of the water, which also allows for increased light penetration. Where pollutants occur discharges from peaking power stations may cause pulses of polluted water downstream rather than a general dilution effect that would be associated with baseload operation (Locher, 2004). Sediment releases from behind the dam, at inopportune times, by means of flushing may cause sediment to settle downstream on coarse bed material covering important habit for small organisms. This will be discussed further in section 6.2.5. It is also important to note that the Nestos River had been modified by several dams further upstream prior to the construction of the Thissavros dam. Various existing and past anthropogenic pollution sources also adversely affect water quality. Therefore, while the Nestos river system has suffered major impacts to its water quality, not all of them can be attributed to the Thissavros dam and PHES facility.

Mitigation of water quality issues associated with reservoirs is among the most difficult to achieve. However, certain solutions can go a long way. Some water supply reservoirs have multiple level draw-off points for spillways (Locher, 2004, Acreman and Ferguson, 2010) which would ensure release of oxygen rich and ambient water temperatures. Another way to ensure sufficient oxygenation would be to inject air in the turbines (Locher, 2004). Turbidity can be mitigated by protecting shorelines that are sensitive to erosion, or by changing flow regime management to reduce downstream erosion. Furthermore, most reservoirs are a focal point for watershed catchment for municipal, industrial and agricultural wastewaters. These contribute to increased water quality issues in reservoirs. Stakeholders must therefore properly assess and manage these activities to ensure high water quality. This can be done by mechanical elimination of waste and wastewater treatment and by preventing excessive doses of fertilisers and pesticides in the watershed area. (Trussart et al., 2002)

### 6.2.5. Soils, Geology & Sediment Transport

An estimated 10 billion tons of sediment is transported, mostly by rivers, to the world's oceans each year. Sediment erosion and transport is a natural process that replenishes river banks, beaches and delta areas. (Chernicoff et al., 2001) Construction of dams along rivers interrupts this process by slowing down currents upon reaching the reservoir causing sediment to accumulate in the reservoir and behind the dam (Nilsson, 2009). The Nestos River and Thissavros dam are no exceptions to this process. Prior to construction the accretion rates were about 8 times higher than erosion rates downstream of the dam in the delta region. After construction the erosion rates of the same beaches had become 1.5 times higher than accretion. This may require a future coastal defence budget. (World Commission on Dams, 2000)

The sediment in the Nestos is accumulating behind Thissavros dam and over time enough sediment accumulation will result in a loss of reservoir capacity that in turn will reduce generating capacity (Hartmann, 2004) as well as causing abrasions of turbines and other components (McCully, 1996). The rate of sediment accumulation in reservoirs depend on the size of the reservoir relative to the amount of sediment flowing into it (McCully, 1996) therefore a river in sediment-rich regions will fill reservoirs faster than rivers running over coarse material (Nilsson, 2009). An average sedimentation rate regarding hydropower plants for Europe and Russia has been found to be 0.73 % (Basson, 2008). Other calculation put the estimated annual loss of storage due to sedimentation in Northern Europe and Southern Europe at 0.20 % and 0.17 % respectively (White, 2001). Also it has been found that the highest rates of loss of storage occur in small reservoirs and the lowest rates occur in the largest (White, 2001). *Figure 30* shows this relationship between loss of storage and reservoir size based on data from 1,105 US reservoirs.


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This is consistent with Thissavros reservoir, which is very large, where sediment accumulation has not been identified as an issue. One reason for large reservoirs being virtually unaffected by sediment accumulation is its larger dead storage capacity that takes a long time to fill (Habersack and Schneider, 2001). Invariably, all reservoirs sooner or later lose their storage capacity to sediment accumulation necessitating sediment management (Hartmann, 2004).

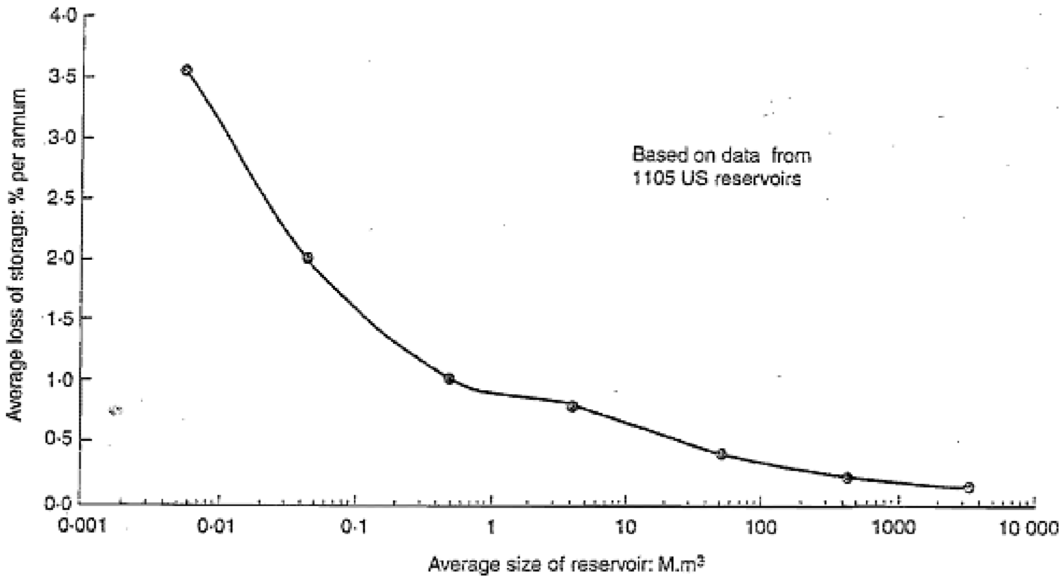


*Figure 30: Reservoir size versus the rate of loss of storage based on data from 1105 US Reservoirs. Source: (White, 2001)*

Distinction must be made between suspended load and bedload as they behave differently with respect to transport and flushing characteristics from sources in the catchment to the reservoir. As bedload consists of heavier and coarse materials these have been shown to travel a mean length of about 200 m during a small flood event (Habersack and Schneider, 2001). This would imply that during any single event bedload material is not transported directly from catchment area into the reservoir but rather, is deposited along the way. The particles will then be remobilised during the next event until finally reaching the reservoir, usually settling at the upstream end of the reservoir (White, 2001). Suspended material which consists of lighter and finer materials, on the other hand will be transported directly from its source to the deposition zone, behind the dam, during an individual flood event. A further distinction has to be made between large and small events. A large event could be a flood event occurring every 10 years, whereas a small event would be floods that occurr on an annual basis. Large flood events have been found to carry 1,000 times more sediment than small ones. (Habersack and Schneider, 2001)

White (2001) and Trussart et al., (2002) describe the three most effective and common ways for operators to manage sediment. The first is to minimise the sediment loads entering reservoirs. This can be done through catchment conservation programs, such as promoting afforestation and farming practises that reduce soil erosion (McCully, 1996), and engineering measures to control erosion in the catchment area or by upstream trapping of sediments in “check dams” or bypassing high sediment loads. The success of these methods however, depends on the reference conditions in the water basin (Hartmann, 2004). The second way to manage sediment is to minimise deposition of sediment in the reservoir. Operators have the possibility to flush suspended loads through the reservoir before it settles, thus avoiding sedimentation (Hartmann, 2004, Habersack and Schneider, 2001). This method is however, not without environmental consequences. The third way to manage sediment is to remove already accumulated sediment from reservoirs, which is done either through operational (flushing) or mechanical (dredging) measures (Hartmann, 2004). The most effective way of flushing requires an extreme change in


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reservoir operation. By drawing down the reservoir to the top of the flushing outlets the velocity and volume of the flow are sufficient to scour and remove sediment (White, 2001). Dredging on the other hand physically removes sediment, including bedload, from the reservoir to relocate it outside. This can be a very time consuming and thus expensive process but sometimes the only solution (Hartmann, 2004).

Not only does trapped sediment diminish or eliminate beaches and backwaters that provide native fish habitat and reduce or eliminate riparian vegetation that provides nutrients and habitat for aquatic and waterfowl species downstream of the facility (World Commission on Dams, 2000) but both flushing and dredging reservoirs are also associated with environmental consequences . Flushing affects a much wider area than dredging as large amounts of sediments are remobilised and discharged downstream. Fine sediment may settle over coarse bed material downstream thus covering important living space for small organisms. To mitigate this negative impact flushing operations should take place regularly and with smaller amounts rather than one single event with a large sediment discharge. Post-flushing operation can also help to distribute fine sediment over a wider area. Dredging has a more local environmental impact on organisms. Sometimes water is lowered to excavate on dry bed causing a loss in those organisms inhabiting that area. Natural recolonisation cannot always be assured and is dependent on organisms drifting downstream from upper sections of the river. (Hartmann, 2004) Dredging also results in the permanent loss of sediment from a system.

### 6.2.6. Hydrology and Hydrogeology

The hydromorphology or physical characteristics of the shape of the Nestos River were profoundly altered by the construction of the dam. This has significant impacts on the hydrology and hydrogeology as well as the ecology of the water system.

The significance of a river's flow regime for sustaining biodiversity and ecological integrity is well known (Poff and Zimmerman, 2010). Consequently dams have considerable impact not only on the downstream ecosystem, which in many cases extends several hundred kilometres below the dam (Richter and Thomas, 2007), but also on the upstream ecosystem. *Figure 31* below shows that dam control reduces the natural river peak flows and increases flow during times of very low natural flows.

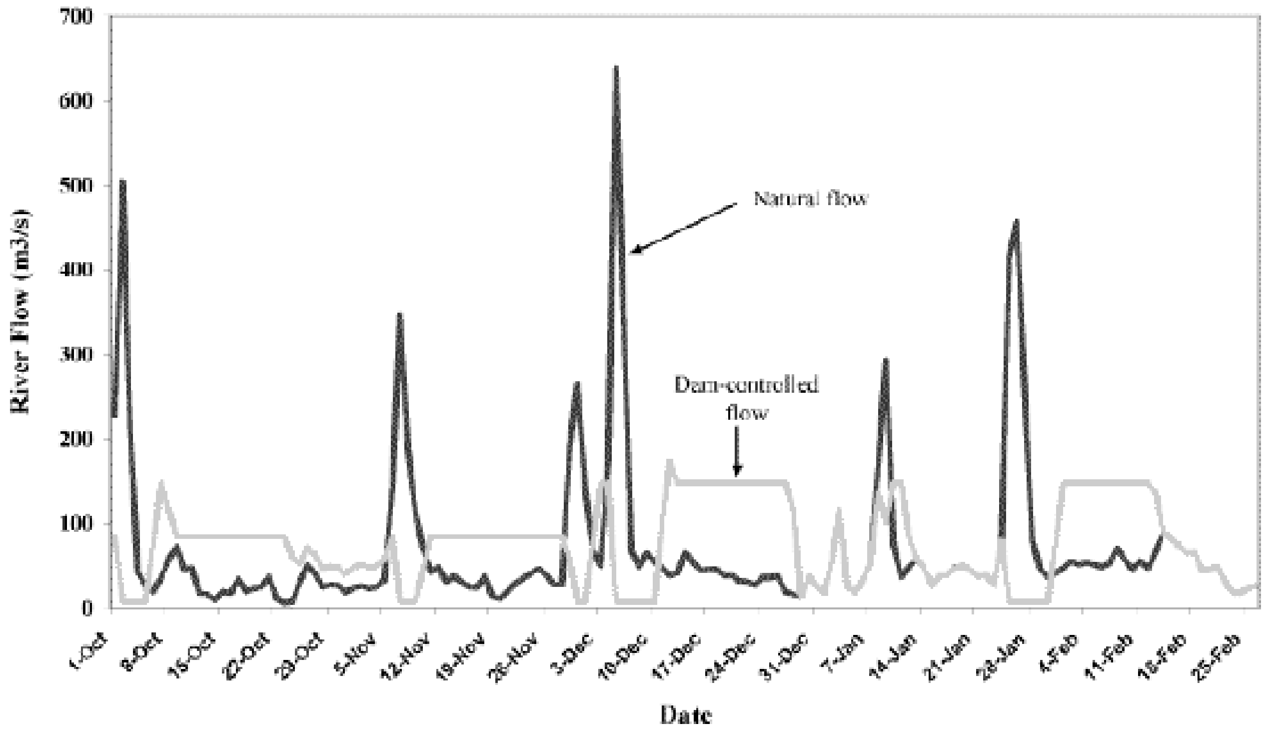


*Figure 31: Operation of a flood-control dam on the Green River in Kentucky, USA results in substantially lowered flood peaks, followed by extended high-flow releases of stored floodwater (based on 1978 data). Source: (Richter and Thomas, 2007)*

In many European rivers today it is common to find closely stacked cascades of dams, which is also true for the Nestos River. The dam operators will usually employ a minimum flow that more often than not is the result of a rule of thumb, to ensure the needs of the downstream catchment are met. Such rules allow dam operators to release a constant flow which may not be ecologically appropriate (Acreman and Ferguson, 2010). In fact, inadequate minimum flow may cause two large societal consequences; either the ecosystem does not get what it needs and thus continues to degrade or potential human uses of the water will be unnecessarily curtailed or limited (Richter et al., 2006). The WFD 82 project, conducted in the U.K concluded that a simple generic rule cannot apply to all rivers but rather that each waterbody had to be analysed on a case by case basis and be based on ecological requirements of different communities or species or life stages (Acreman and Ferguson, 2010), i.e. achieve environmental flow.

The WFD directive does not use the term environmental flow or natural flow explicitly, but requires EU Member States to achieve “good ecological status” (GES) by 2015 in all waterbodies. A waterbody that has been physically modified, such as Thissavros can be designated as a heavily modified water body (HMWB), and will thus have to reach an alternative objective of “good ecological potential” (GEP), which required the implementation of reasonable mitigation measures and best practise management, i.e. appropriate environmental flow releases (Acreman and Ferguson, 2010). Ultimately this means that designating HMWBs is an economic issue, meaning that if the modification has high economic value such Thissavros it can remain intact (Acreman and Ferguson, 2010). On the other hand if the dam is not of economic value it should be removed or operated in a way that will achieve GES in that waterbody. Environmental flow should thus be viewed as an iterative process that through monitoring and evaluation should change as more information becomes available (Richter et al., 2006).

With these potential and mostly negative effects it is not a surprise that some are calling for a re-naturalisation of flow which ultimately will conflict with the demand of electricity generation. (Renöfält et al., 2010) However, perhaps a better solution is to ask whether flow-governed processes can be mimicked by means other than flow, or whether small amounts of water can be used more efficiently to support ecosystem processes (Renöfält et al., 2010). Others are suggesting that dams can be used as tools for the mitigation of hydrological impacts by changing the operating rules (Ray and Sarma, 2011). It may be possible to change the operating regime of large storage dam(s) that control flow and then change the operating regime of the other dams in the cascade to compensate for loss of peak power production and still reach better environmental flows (Richter and Thomas, 2007). An option may be to construct a regulating pond below the dam that would regulate the high discharge during operation to allow for a continuous flow even during off-peak flow (Ray and Sarma, 2011). Another solution would be to install a semi-open PHES, such as in the Bolarque II case study that would utilise the upper reservoir of the dam as its lower reservoir and a new upper reservoir would be constructed for the PHES. Then the dam itself would need less storage and could operate to allow for environmental flow without loss of generating capacity which the PHES would compensate for. This would in turn allow more of the natural inflow to the hydro reservoir to be passed on to the downstream environment. (Richter and Thomas, 2007)

Fish are often sensitive indicator of flow alterations whereas aquatic and riparian species will respond to multiple hydrologic drivers (Poff and Zimmerman, 2010). It is important to stress that environmental flow remains a mitigation measure and not a substitute for nature conservation and protection of free-flowing rivers (Renöfält et al., 2010). Nevertheless, environmental flow can go a long way in increasing habitat availability for aquatic organisms. In the case of Thissavros, where minimum flow is already in place, the primary target should be to make one or several components of the flow regime more like the natural conditions (Renöfält et al., 2010). The study by, Richter et al., (2006) suggested an environmental flow framework that could help discern the ranges of low flow, high pulse and flood levels, how long they should last, how often they should occur within the year or among years and how rapidly flows can change from one condition to another. *Figure 32* shows a conceptual approach of how to build an environmental flow release for one year. The continuous line represents the natural flow over one year and the blocks represent the flow regime by a HP or pump-back PHES required to maintain a healthy ecosystem. The so called building block methodology (BBM) establishes that riverine species rely on basic elements of the flow regime which are naturally very site-specific. (Acreman and Ferguson, 2010)

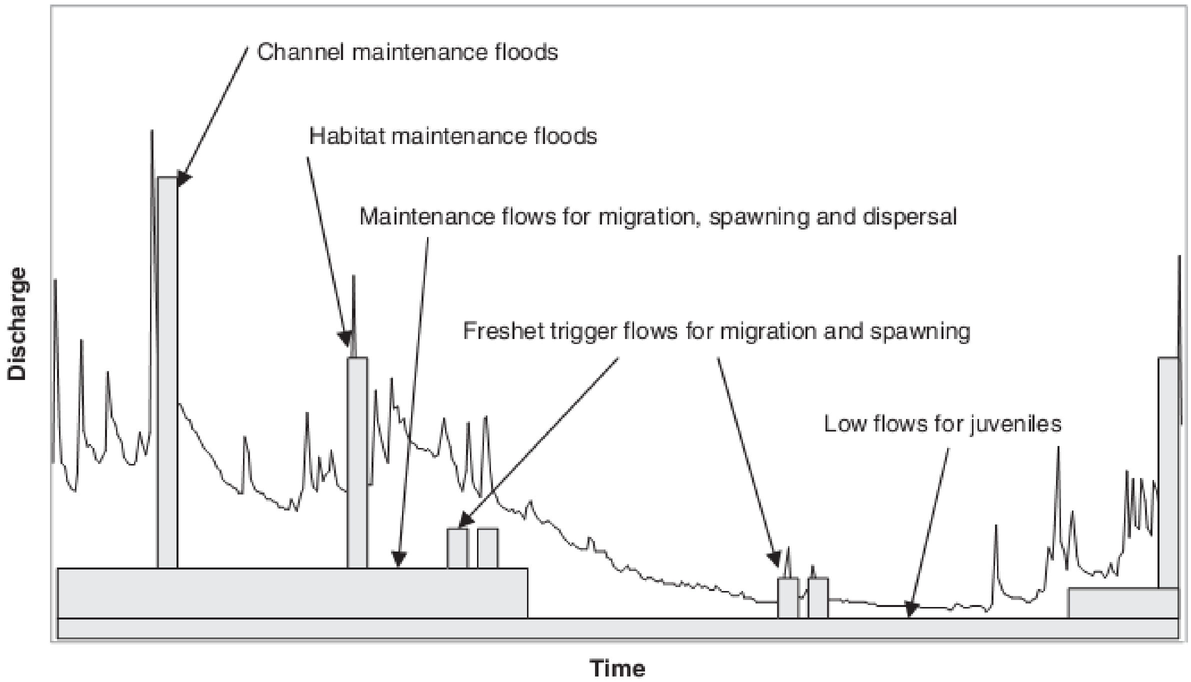


*Figure 32: A conceptual approach of how to build an environmental flow release regime, where the continuous line represents the natural flow hydrograph for one year and the blocks represent the flow regime by a HP or a pump-back PHES required to maintain a healthy ecosystem. Source: (Acreman and Ferguson, 2010)*

Important to note in *Figure 32* is that it only shows the required flow during one year which would perhaps imply the same flow regime can be employed each year. However, flow regimes in natural riverine systems vary considerably over different time periods over days, months, years and even decades. Some natural flow requirements have even been found to be contradictory. This is nevertheless consistent with biological records for natural systems, which show that due to hydrological variations some years are good for some species and poor for others and vice versa. It may therefore be necessary to design a series of flow release regimes that are used on a rotating basis. (Acreman and Ferguson, 2010)

### 6.2.7. Interactions of open-system (pump-back) PHES

The interaction between specific environmental aspects and effects, identified during operation, are already addressed in the preceding chapters. A matrix has been generated to summarize the relevant interactions and contains previously discussed environmental aspects on both axes.

| | |
|---|---|
| | Major Interaction |
| | Minor Interaction |
| | No Interaction |


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**Table 10: Summary Matrix of the interactions between specific environmental aspects**

| | Population | Traffic | Cultural Heritage | Material Assets | Biodiversity | Fisheries | Air & Climate | Landscape & Visuals | Water Resource & Quality | Noise & Vibrations | Soils, Geology & Sediment Transport | Hydrology & Hydrogeology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Population | | | | | | | | | | | | |
| Traffic | | | | | | | | | | | | |
| Cultural Heritage | | | | | | | | | | | | |
| Material Assets | | | | | | | | | | | | |
| Biodiversity | | | | | | | | | | | | |
| Fisheries | | | | | | | | | | | | |
| Air & Climate | | | | | | | | | | | | |
| Landscape & Visuals | | | | | | | | | | | | |
| Water Resource & Quality | | | | | | | | | | | | |
| Noise & Vibration | | | | | | | | | | | | |
| Soils, Geology & Sediment Transport | | | | | | | | | | | | |
| Hydrology & Hydrogeology | | | | | | | | | | | | |

## 6.3. Semi-open PHES

The three case studies of semi-open PHES, Goldisthal, Kopswerk 2 and Bolarque II, have shown that although they are classed the same in terms of technical description, each site is different and therefore also has different associated impacts (see Table 11). Of the three semi-open PHES, Goldisthal has been deemed to have the most impact on its surrounding environment during operation. While the existing aquatic environment was effected by anthropogenic influences the additional impact of impounding the river at Goldistal increased the environmental pressures on the river system. Kopswerk 2 in contrast can be seen as a positive addition to the Vorarlberg Illwerke Hydro Group as it utilises an already existing upper and lower reservoir, which means that the water that is being stored in the Kops Reservoir is in fact being used in a much more efficient way. Bolarque in a similar way was constructed into a significantly regulated environment where the lower reservoir existed. The operation of the upper reservoir has had little impact on the surrounding environment. One could perhaps argue that for environmental flow reasons Bolarque II is an asset as more water can be discharged downstream from the lower reservoir, Bolarque I


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whilst not losing important generating capacity. The impacts that have been deemed “high” will be discussed further in this section.

**Table 11: Summary table of negative impacts from operation of Semi-open PHES highlighted by three of the cases studies**

| Potential Issues/EIA Terms of Reference | | Goldisthal | Kopswerk II | Bolarque II |
|---|---|---|---|---|
| Human Impact | Population | L | L | L |
| | Transport | L | L | L |
| | Cultural Heritage | L | L | L |
| | Material Assets | L | L | L |
| Ecology & Natural Systems | Biodiversity | H | L | L |
| | Fisheries | M | L | L |
| | Air and Climate | L-H* | L-H* | L-H* |
| | Landscape & Visuals | M | L | M |
| | Water Resources | M | L | L |
| Physical Environment | Noise & Vibration | L | L | L |
| | Soils & Geology | M | L | L |
| | Hydrology & Hydrogeology | H | M | L |

### 6.3.1. Biodiversity

Construction of dams and the subsequent creation of reservoirs, as in the case of Goldisthal, may be detrimental to terrestrial habitat and animals, as the habitats are inundated. Although local measures to protect specific habitats may be effective; in the long-term compensation and enhancement programs in the surrounding area is likely be much more beneficial. For example, as part of the permission to be allowed to operate Goldisthal, the Capercaillies population had to be reinstated to the surrounding area. According to Petts (1988) as cited in Larinier (2001) fluctuating water levels and velocities due to varying power output from the peaking plant may inhibit spawning behaviour, sweep juveniles downstream during high flow or leave eggs or juveniles stranded by sudden reductions in flow. Suggestions of successful restoration programs to restore terrestrial habitat as well as measures promoting vegetation or control erosion following impoundment can be found in Trussart et al., (2002).

Downstream of the dam, fluctuations in discharge patterns may affect riparian vegetation in terms of species cover and diversity due to waterlogging and inundation. The result of these changes may be that riparian tall woody shrub species are replaced with ephermerals such as grasses, gramonoids and tolerant semi-aquatic herbs which may provide some structural stability to river banks. For macroinvertebrates fluctuations in discharge often account for a reduction in species diversity and abundance, as well as loss of edge and snag habitat. (Locher, 2004, World Commission on Dams, 2000) By changing the way the facility is operated to better accommodate the needs of the ecosystem i.e environmental flow may help to maintain the habitats for each species.


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### 6.3.2. Air and Climate

As the lower reservoir of Goldisthal was created by inundating a large area of land, the concern of GHG emissions that continues to be released during operation becomes a concern. There is consensus in the research community that inundated reservoirs emit GHG, although divergences are found in the how much the overall contribution is. It is therefore difficult to know how much the lower reservoir of Goldisthal emits, without further research. Kopswerk 2 and Bolarque II do not have to take the reservoir emissions from inundation into account. The other source of emission that is important for all semi-open PHES is the primary source of electricity used to operate the pumps as this will determine the level of impact that the facility has in terms of GHG emissions (see *Figure 27*).

As the impact of GHG emissions are similar to that discussed under open-system PHES, please see section 6.2.3 for further information.

### 6.3.3. Hydrology & Hydrogeology

Hydrology and hydrogeology has not been highlighted as a “high” impact from operation of Bolarque II or Kopswerk 2 as these have not altered the movement of water in any significant way. The lower reservoir of Goldisthal on the other hand was created by impounding the River Schwarza with two dams, thereby creating a large artificial lake that fluctuates on a daily basis. Although minimum flow is in place the lower reservoir regulates the discharge to the downstream environment, resulting in an alteration in natural river discharge.

The lower reservoir is constantly discharging water to the downstream river through a SHP facility situated in the lower dam. The minimum flow is 100l/s but discharge from the reservoir can be as much as 230 times that of minimum flow if the lower reservoir is at its highest water level. This constant changing discharge level may result in changing migration cues due to changes in seasonality of flows resulting in reduced macroinvertebrate food supplies that may ultimately cause reduction in downstream fish populations (Locher, 2004). Although the dams and the impoundment were built to allow the lower reservoir to fluctuate without causing the river upstream and downstream of the impoundment to fluctuate, the question remains if the 100l/s is enough for fish populations to thrive in the River Schwarza. Fish seem to be a sensitive indicator of flow alterations whereas aquatic and riparian species will respond to multiple hydrologic drivers (Poff and Zimmerman, 2010).

Goldisthal cannot be held solely accountable for low levels of the fish populations in the Schwarza River as the river environment was already compromised in regards to fish populations prior to the construction of the semi-open PHES. Actions are being taken by the community and fisheries to rectify the issues preventing the establishment and migration of fish populations in the Schwarza. The re-naturalisation of the river is also being justified as a means to compensate for Goldisthal and a recently constructed large reservoir storing water for district water supply. This approach is in line for the WFD and it demands that if a weir construction is not of economic value it should be removed or made passable for fish migration in order to achieve GES in that waterbody while at the same time keeping a modification that is of high economic value (Acreman and Ferguson, 2010).

It is important not to use a generic rule of thumb for all rivers when determining flow regimes (Acreman and Ferguson, 2010) but rather to study each river type case by case to understand what that specific river ecosystem needs. The primary target where minimum flow is in place should therefore be to make one or several components of the flow regime more like the natural conditions (Renöfält et al., 2010). This may be a possible solution for Goldisthal in helping to reduce its operational impact on the receiving aquatic environment. The environmental flow


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framework suggested by Richter et al., (2006) could help discern the ranges of low flow, high pulse and flood levels, how long they should last, how often they should occur within the year or among years and how rapidly flows can change from one condition to another (see *Figure 32*). It is important to note however, that *Figure 32* only shows one year which would imply the same flow regime each year. However, it is important to consider over several years as flow regimes in natural riverine systems vary considerably over different time periods over days, months, years and even decades. Some natural flow requirements have even been found to be contradictory. This is nevertheless consistent with biological records for natural systems, which show that due to hydrological variations some years are good for some species and poor for others. It may therefore be necessary to design a series of flow release regimes that are used on a rotating basis. (Acreman and Ferguson, 2010)

### 6.3.4. Interactions of semi-open PHES

The interaction between specific environmental aspects and effects, identified during operation, are already addressed in the preceding chapters. A matrix has been generated to summarize the relevant interactions and contains previously discussed environmental aspects on both axes.

| | |
|---|---|
| | Major Interaction |
| | Minor Interaction |
| | No Interaction |

**Table 12: Summary Matrix of the interactions between specific environmental aspects**

| | Population | Traffic | Cultural Heritage | Material Assets | Biodiversity | Fisheries | Air & Climate | Landscape & Visuals | Water Resource & Quality | Noise & Vibrations | Soils, Geology & Sediment Transport | Hydrology & Hydrogeology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Population | | | | | | | | | | | | |
| Traffic | | | | | | | | | | | | |
| Cultural Heritage | | | | | | | | | | | | |
| Material Assets | | | | | | | | | | | | |
| Biodiversity | | | | | | | | | | | | |
| Fisheries | | | | | | | | | | | | |
| Air & Climate | | | | | | | | | | | | |
| Landscape & Visuals | | | | | | | | | | | | |
| Water Resource & Quality | | | | | | | | | | | | |
| Noise & Vibration | | | | | | | | | | | | |
| Soils, Geology & Sediment Transport | | | | | | | | | | | | |
| Hydrology & Hydrogeology | | | | | | | | | | | | |

## 6.4. *Closed-loop PHES*

Turlough Hill has highlighted the main impacts during operation (see Table 13) that need further consideration. The impacts deemed significant and will be discussed further are biodiversity, air and climate and hydrology and hydrogeology.

**Table 13: Summary table showing the negative impacts during operation of the closed-loop PHES Turlough Hill**

| Potential Issues/EIA Terms of Reference | | Turlough Hill |
|---|---|---|
| Human Impact | Population | L |
| | Transport | L |
| | Cultural Heritage | L |
| | Material Assets | L |
| Ecology & Natural Systems | Biodiversity | H |
| | Fisheries | M |
| | Air and Climate | L-H* |
| | Landscape & Visuals | M |
| | Water Resources | M |
| Physical Environment | Noise & Vibration | L |
| | Soils & Geology | L |
| | Hydrology & Hydrogeology | H |

### 6.4.1. Biodiversity

Lough Nahanagan is an upland oligotrophic lake that has been modified for use as a lower reservoir for Turlough Hill PHES. Oligotrophic lakes are listed on Annex I of the Habitats Directive. In Ireland, oligotrophic lakes occur frequently in the uplands and many of these have been designated as Natura 2000 sites. Oligotrophic corrie lakes such as that at Lough Nahanagan are of relatively recent geological origin, dating to the last major glaciation, circa 10,000 years before present. Such lakes tend to be relatively deep and contain nutrient poor cold hypolimnetic (distinctly stratified) water, with limited natural mixing of waters. Oligotrophic lakes are nutrient poor as they possess a limited lake catchment area, in nutrient poor catchment geology (e.g. siliceous geology over lain by acid soils combined with low intensity agriculture and little fertilization. The modification of these lakes to facilitate PHES affects the natural physical characteristics of the lake, which in turn affects their biology.

The shoreline vegetation communities associated with these lakes is an important characteristic. Hydromorphology, water chemistry and climate can reflect the aquatic vegetation of a lake (The Freshwater Ecology Group TCD and Compass Informatics, 2007). Acidification, eutrophication, increased recreational use of lakes, and the effects of lake regulation for hydro-electric schemes are considered major threats to the survival of soft water lake vegetation. All such pressures tend to reduce the diversity of typical soft water species present in affected lakes (Murphy, 2002). It is unlikely that the natural vegetation of the Lough Nahanagan shoreline can tolerate the artificial lowering of the lake levels and the regular lowering and raising of lake levels associated with the daily operation of the plant.


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According to Petts (1988) as cited in Larinier (2001) Fluctuating water levels and velocities due to power output from the peaking plant may inhibit spawning behaviour or leave eggs or juveniles stranded by sudden reduction in flow. Little is known about the fish population in the pre-developed environment at Turlough Hill. Due to its low nutrient concentration it is likely that the lake supported a small fish population. While Lough Nahanagan is not connected to a river, closed loop systems can maintain an outflow to a river however, they do prevent the movement of fish from the river to the lake/lower reservoir.

### 6.4.2. Air and Climate

As aforementioned in section 6.1.1, air and climate in terms of primary source of energy is an important factor to consider for both PHES and CAES. To minimise the GHG footprint during operation it would therefore be crucial to consider operating the pumps of a closed-loop PHES (and any PHES) with RES-e or nuclear rather than fossil fuel (see *Figure 27*).

### 6.4.3. Hydrology & Hydrogeology

The natural hydrological state of Lough Nahanagan has been modified by the daily lowering (pumping) and raising (generating) of lake levels during the operation of Turlough Hill PHES. This in turn alters the natural physical characteristics such as increasing the mixing of the different layers within the lake. One of the characteristics of oligotrophic lakes is the clarity of its water; it is likely that this characteristic is impacted through the regular disturbance of the lake bed and a subsequent increase in suspended solids.

The construction of Turlough Hill has resulted in a permanent lowering of the natural lake, Lough Nahanagan, by 15m and the exposure of two small islands. The water level drops a further 10m during pumping mode. The natural lake would also have fluctuated prior to the closed-loop PHES but only by 6m. As a consequence of this previous shore line mainly comprises exposed rock. Some heath has slowly encroached and 40 years after the commissioning of Turlough Hill the original water line is still evident. The hydromorphology or physical characteristics of the shape and boundaries of Lough Nahanagan have been permanently altered, which in turn influences the biota of the lake.

### 6.4.4. Interactions of closed-loop PHES

The interaction between specific environmental aspects and effects, identified during operation, are already addressed in the preceding chapters. A matrix has been generated to summarize the relevant interactions and contains previously discussed environmental aspects on both axes. These interactions have been identified for operation [O] phases, of the given case studies.

| | |
|---|---|
| | Major Interaction |
| | Minor Interaction |
| | No Interaction |

**Table 14: Summary Matrix of the interactions between specific environmental aspects**

| | Population | Traffic | Cultural Heritage | Material Assets | Biodiversity | Fisheries | Air & Climate | Landscape & Visuals | Water Resource & Quality | Noise & Vibrations | Soils, Geology & Sediment Transport | Hydrology & Hydrogeology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Population | | | | | | | | | | | | |
| Traffic | | | | | | | | | | | | |
| Cultural Heritage | | | | | | | | | | | | |
| Material Assets | | | | | | | | | | | | |
| Biodiversity | | | | | | | | | | | | |
| Fisheries | | | | | | | | | | | | |
| Air & Climate | | | | | | | | | | | | |
| Landscape & Visuals | | | | | | | | | | | | |
| Water Resource & Quality | | | | | | | | | | | | |
| Noise & Vibration | | | | | | | | | | | | |
| Soils, Geology & Sediment Transport | | | | | | | | | | | | |
| Hydrology & Hydrogeology | | | | | | | | | | | | |

# 7. Summary and Conclusions

## 7.1. Summary

The objective of the stoRE project is to facilitate energy storage to allow greater penetration of variable renewable energy. WP3 focuses on the environmental considerations relevant to the development and operation of bulk energy storage technologies, specifically pumped hydro energy storage (PHES) and compressed air energy storage (CAES). This deliverable, D.3.1 has documented the environmental performance of existing PHES and CAES and identified factors that affect their performance during operation. PHES has been categorised further into three main types; closed-loop, semi-open and open-system (pump-back) PHES. Although there are several types of the open system PHES the most common type is the pump-back PHES.

The work is based on an extensive literature study and on six case studies that were chosen from five of the six partner countries; Austria, Germany, Greece, Ireland and Spain. No case was chosen from the sixth partner country, Denmark, as it does not have any PHES or CAES. While the environmental impact of energy storage facilities associated with their development, design, construction, operation and decommissioning may be interlinked, this deliverable focused mainly on the operation of existing CAES and PHES facilities.

There are several positive impacts associated with an increased energy storage capacity. Bulk EST solves both production fall-off from wind and wind curtailment as these technologies can absorb excess electricity when demand is low, and generate electricity when demand is high. Further benefits to society include: black start capability, more flexibility of the grid, supply smoothing, security, spinning reserve, auxiliary reserve, peak shavings and regulation control. From an environmental perspective PHES and CAES can provide two main benefits; allowing higher penetration of wind by reducing curtailments and the consequent reduction in GHG emissions.

The case studies have consisted of one CAES, one closed-loop PHES, three semi-closed loop PHES and one open-system PHES to ensure that the information gathered is relevant to the greatest number of cases. Each case study has begun with a short introduction followed by three main headings: technical description, pre-developed environment and operation impacts. To help describe the pre-developed environment and the impacts during operation, potential issues/EIA terms of reference have been used. The environmental impacts of operational PHES have been identified by comparing the post development with the pre-developed or existing environmental conditions of the receiving environment. In order to identify the most significant factors affecting environmental performance the potential issues/EIA terms of reference have been classified as high, medium or low. The high impacts for each technology were then analysed and discussed further in section 5.

The operational impacts associated with Huntorf CAES are relatively low. Air and Climate has been deemed low to high depending on what the primary source of energy is that the CAES stores and also the dependency on additional fuel to operate.

Thissavros, a pump-back PHES has highlighted several significant issues due to the size and scale of the dam, and its siting in a relatively unmodified and large river environment. Although most of the impacts occur because of the presence of the dam and also that the main use of the dam is power generation, the pumps were constructed at the same time making it difficult to separate the impacts.

Kopswerk II and Bolarque II, semi-open PHES, were both constructed in heavily modified environments and as such have not had significant impacts during operation. Goldisthal, also a semi-open PHES, on the other hand was constructed into a relatively unmodified environment where the lower reservoir was created by impounding a river and the upper reservoir was constructed. This has caused long-term impacts that have to be attributed to operation of Goldisthal.

Turlough Hill, a closed-loop PHES, was sited in a pristine environment. The lower reservoir was an existing lake and the upper reservoir was man-made. As modifications have had to be made for the closed-loop PHES, several long term impacts have to be accounted for during operation.

A summary of the results from the case studies can be found in Table 15.

**Table 15: Summary table of negative impacts during operation highlighted from the case studies**

| | | CAES | Pump-back PHES | Semi-open PHES | | | Closed-loop PHES |
|---|---|---|---|---|---|---|---|
| Potential Issues/EIA terms of reference | | Huntorf | Thissavros | Kopswerk2 | Goldisthal | Bolarque2 | Turlough Hill |
| Human Impact | Population | L | L | L | L | L | L |
| | Traffic | L | L | L | L | L | L |
| | Cultural Heritage | L | L | L | L | L | L |
| | Material Assets | L | L | L | L | L | L |
| Natural and Ecology Systems | Biodiversity | L | H | L | H | L | H |
| | Fisheries | L | H | L | M | L | M |
| | Air and Climate | L-H* | L-H* | L-H* | L-H* | L-H* | L-H* |
| | Landscape and Visuals | L | M | L | M | M | M |
| | Water Resources & Quality | L | H | L | M | L | M |
| **Physical Environment** | Noise & Vibration | L | L | L | L | L | L |
| | Soils, Geology & Sediment Transport | L | H | L | M | L | L |
| | Hydrology & Hydrogeology | L | H | M | H | L | H |

- *Recommended to review each individual case study*
- *Inclusion of combined impacts with existing land uses and pressures*
- *Limited raw data*

## *7.2. Conclusions*

The main benefit of PHES and CAES from an environmental perspective is that storing RES-e will result in a reduction of wind curtailment with consequent reduction in $CO_2$ production. The following sections highlight the main conclusions of the environmental performance during operation of each technology, as determined by the case studies and literature review.


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## CAES

- The case study on the Huntorf CAES facility has highlighted very few environmental impacts during operation. This is partly because the CAES was constructed into a previously modified environment. It is important to note however that there may be further impacts during construction, the analysis of which is beyond the scope of this report.

- The main drawback of the existing CAES is that it is a hybrid system. This means that it is dependent on an external heat source (i.e. natural gas) to replace the heat lost during the compression stage. The required amount is however, one third that of conventional gas turbines. Using biofuel instead may be a way of making CAES carbon neutral, provided that the biofuel is itself carbon neutral. Advanced Adiabatic CAES systems, which are currently under research, would eliminate the required external heat source.

## Open-system (pump-back) PHES

- Thissavros pump-back PHES has a lot of environmental impacts associated with it, mainly because the dam and PHES facility were constructed simultaneously into a relatively unmodified environment. Since most of the long-term impacts are associated with the initial construction of the dam, a more benign solution would be to retrofit an already existing hydropower scheme with pumps. The receiving environment in such a case would already be heavily modified, resulting in a significantly lower environmental impact of the PHES. Although retrofitting has a lower environmental impact, it is not always an option as some countries or regions may require new developments.

- The construction of a dam for hydro generation results in alteration of the natural flow regime of the river. The flow is controlled primarily to meet electricity demands with little consideration for the environmental needs of the downstream river system. This regulation ultimately reduces or eliminates natural peak flood events and low flow events. While minimum flows are normally maintained, this does not guarantee that the environmental needs are met. The operating regime of the facility could be managed, by means of environmental flow, so as to simulate natural flow conditions. In this way the environmental impact could be mitigated but it should be noted that environmental flow is not a substitute for natural flow. Changing operating regimes may also incur a trade-off in reduced operational flexibility and ability to provide fast reserve to accommodate variable RE.

- Rivers transport a vast amount of sediment and nutrients to their lower reaches and coastal areas. The presence of a dam on a river will hinder this process by allowing sediment to accumulate behind it instead. Reduced sediment transport to the downstream environment causes a reduced accretion rate that may be detrimental to the coastal and delta areas and ultimately to the flora and fauna that inhabit these.

- Changing a river environment into a lake environment will likely result in thermal stratification. As extraction of water from the lower thermal layers is the norm when operating the turbines the downstream river is affected by colder water and higher salt concentrations from the discharge. A direct result of changing water temperature, velocity and nutrient levels is that the species abundance and diversity can change. Native species may be outcompeted by non-native species that are more adapted to the new conditions.

- Fluctuating water levels, resulting from the operating regime, will cause frequent inundation and draw down of shoreline, isolation of spawning areas, loss of habitat and limited regeneration both upstream and downstream. Natural fluctuations vary in magnitude on a seasonal basis whereas operational fluctuations vary on a daily basis at a relatively constant magnitude.


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- The presence of a dam hinders both upstream and downstream fish migration. This can be detrimental to fish populations as it can prevent movement between spawning and feeding areas. For upstream migration fish passes may be an option for smaller dams, but for larger dams such as Thissavros the only feasible option is to transport them by trucks or fish lifts. Downstream migration will generally occur via turbines or spillways. Both upstream and downstream migration by artificial means is not fully effective and will result in some fish mortality.

## Semi-open PHES

- Kopswerk II and Bolarque II were constructed in heavily modified environments resulting in low environmental impact during operation. Goldisthal on the other hand was constructed in a less modified environment which has resulted in a greater environmental impact. Therefore potential PHES sites in already modified environments should be considered where available.

- As with the pump-back PHES fluctuating water levels, resulting from the operating regime, will cause frequent inundation and draw down of shoreline, isolation of spawning areas, loss of habitat and limited regeneration both upstream and downstream.

## Closed-loop PHES

- Turlough Hill was specifically designed for peak operation which means that the water level fluctuates through its full active range on a daily basis. This regular mass movement of water inhibits the natural lake processes within the lower lake.

- The shoreline vegetation communities associated with oligotrophic lakes, which are listed on Annex I of the Habitats Directive, is an important characteristic. The artificial modification of the natural water level can reduce the diversity of typical soft water species present. It is unlikely that the natural vegetation of the Lough Nahanagan shoreline can tolerate the artificial lowering of the lake levels and the regular lowering and raising of lake levels associated with the daily operation of the plant.

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