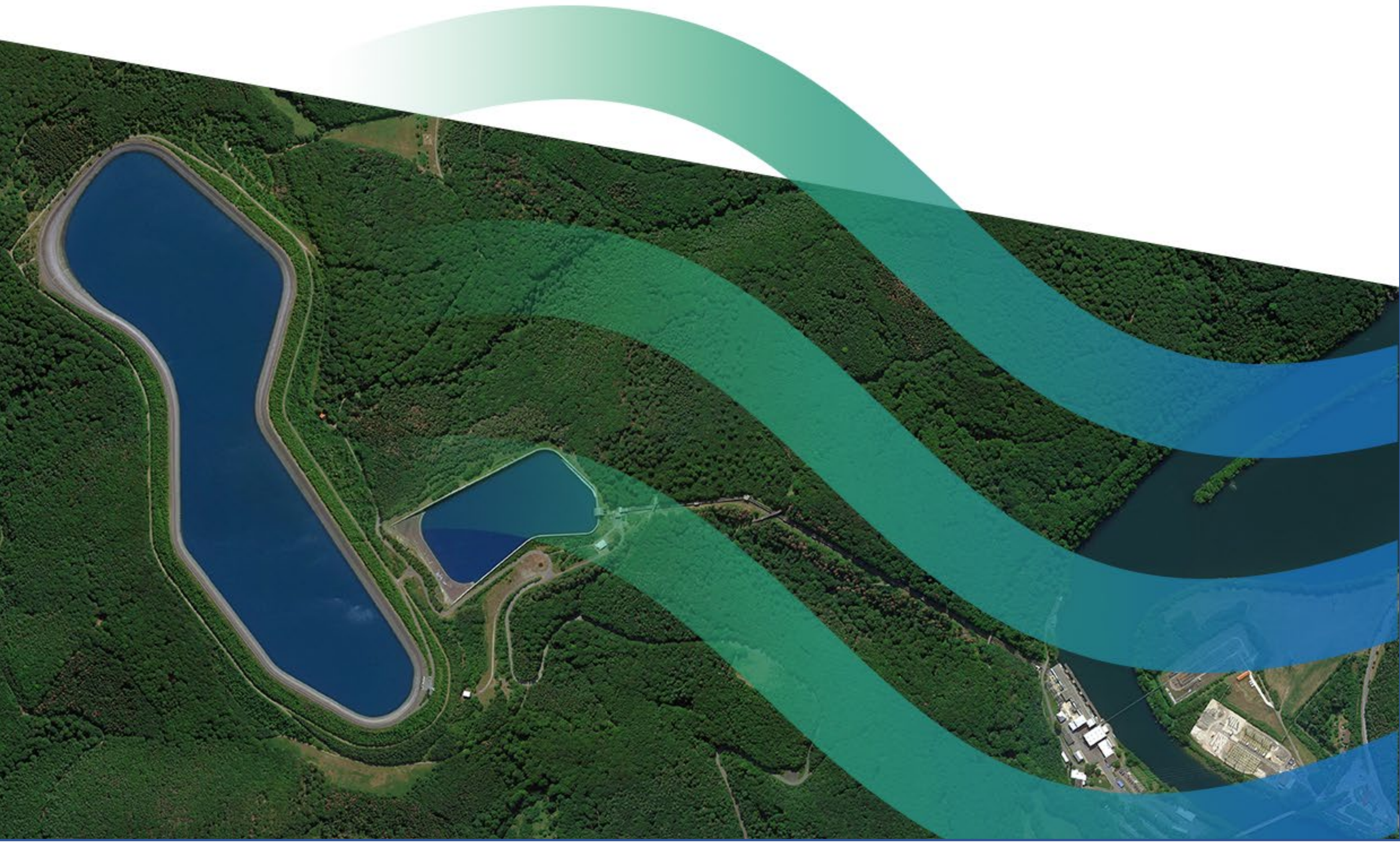
Pumped Storage Hydropower International Forum

Sustainability Working Group

# Working Paper on Sustainability of Pumped Storage Hydropower

## Sustainability Working Group
## September 2021



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## About the International Forum on Pumped Storage Hydropower

Launched in 2020 and jointly chaired by the U.S. Department of Energy and the International Hydropower Association (IHA), the International Forum on Pumped Storage Hydropower (IFPSH) is a multi-stakeholder platform that brings together expertise from governments, the hydropower industry, financial institutions, academia and NGOs to shape and enhance the role of pumped storage hydropower (PSH) in future power systems.

The Steering Committee of the IFPSH, comprised of governments, intergovernmental organisations and multilateral development banks, established three Working Groups (WG) covering 'Policy and Market Frameworks', 'Sustainability', and 'Capabilities, Costs and Innovation' to help address the common challenges facing PSH development.

The Policy & Market Frameworks WG, led by GE Renewable Energy, developed a global position paper to identify the current market and investment barriers and opportunities for PSH development, as well as recommendations to de-risk investment. With thanks to over 20 supporting organisations, country and region-specific recommendations were developed for the U.S., the U.K., Africa, Australia, Brazil, Latin-America and the Caribbean, Europe, Southeast Asia, India and China.

The Sustainability WG, led by EDF, aims to provide guidance and recommendations on mitigating adverse impacts that may occur in the development of PSH to ensure that it can best support the clean energy transition in the most sustainable way.

The Costs, Capabilities and Innovation WG, led by Voith Hydro, seeks to raise awareness on the role of PSH in addressing the needs of future power systems and deepen understanding about its potential, capabilities, costs, and innovation.

## Disclaimer

The inclusion of any technology in the report does not imply endorsement of that technology by editors of the report, International Hydropower Association or participating organisations of the International Forum on Pumped Storage Hydropower. The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of the International Forum on Pumped Storage Hydropower or International Hydropower Association. Neither the International Forum on Pumped Storage Hydropower or International Hydropower Association can guarantee the accuracy of the data included in this study. Neither the International Forum on Pumped Storage Hydropower or International Hydropower Association nor any person acting on their behalf may be held responsible for the use, which may be made of the information contained therein. More information on the International Forum on Pumped Storage Hydropower is available on the Internet (https://pumped-storage-forum.hydropower.org/)

## Acknowledgements

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# EXECUTIVE SUMMARY

The International Forum on Pumped Storage Hydropower (IFPSH) is pleased to publish this Working Paper on the Sustainability of Pumped Storage Hydropower (PSH), which is a culmination of multi-stakeholder collaboration between the hydropower sector, academia and NGOs to share our experiences and deepen our understanding on PSH's sustainability profile and its role in a clean energy future.

## Objective

The overall objective of the Sustainability Working Group was to develop guidance and recommendations on how PSH can best support future power systems in the clean energy transition in the most sustainable way. It thus complements outcomes from Policy and Market Frameworks WG, and Capabilities, Costs and Innovation WG.

As PSH projects are highly site-specific in their performance, costs and impacts, it is important to focus on the processes that lead to sustainable systems, not just on broad PSH performance and cost indicators. Increasingly, energy storage and flexibility solutions will be relied upon to support electricity systems with large amounts of variable renewable energy sources. Therefore system needs should be the point of entry. It will then be necessary to understand the trajectory of the transition towards net zero carbon power systems and then to develop and implement an energy storage (and other forms of system flexibility) strategy leading to that goal.

The general approach for developing sustainable PSH projects can therefore be structured through three major levels:

- **System-level strategic assessment:**

  Determine the storage, flexibility, and ancillary services that a given power system needs and will need, from a long-term planning perspective. Analysis at this level would result in a demonstration of need for energy storage and flexibility;
- **Options assessment:**

  Identify options that would meet energy storage, flexibility and ancillary services needs, based on the characteristics of services that can be provided by available and mature energy storage technologies. Analysis at this level would result in a PSH demonstrated need;
- **Project optimisation:**

  Select project configuration and technical options that would result in the "best" strategic fit of PSH project to avoid, minimise and mitigate social and environmental impacts.

## Guidelines, Tools and Methods

This report provides an overview of existing or in-progress guidelines, tools, initiatives and methods that may be applicable to the sustainability assessment of PSH technology and projects in the 3-level rationale presented above. The main guidelines and other initiatives of interest are:

- **Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP)**, constitute the core requirements for delivering international good practice on material sustainability topics for hydropower and PSH projects. (https://www.hydropower.org/publications/hydropower-sustainability-guidelines)
- **The Climate Bonds Initiative (CBI)** Standard for Hydropower stipulated that hydropower projects must meet the criteria in two assessment tools: the Hydropower Environmental, Social and Governance (HESG) Gap Analysis Tool and G-res Tool can both be used to report the estimated net greenhouse gas (GHG) emissions of a reservoir. (https://www.climatebonds.net/standard/hydropower)
- **The EU Taxonomy on Sustainable Finance** aims to define eligibility conditions to sustainable or green investment, especially in the context of the European Green Deal program.

(https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en)

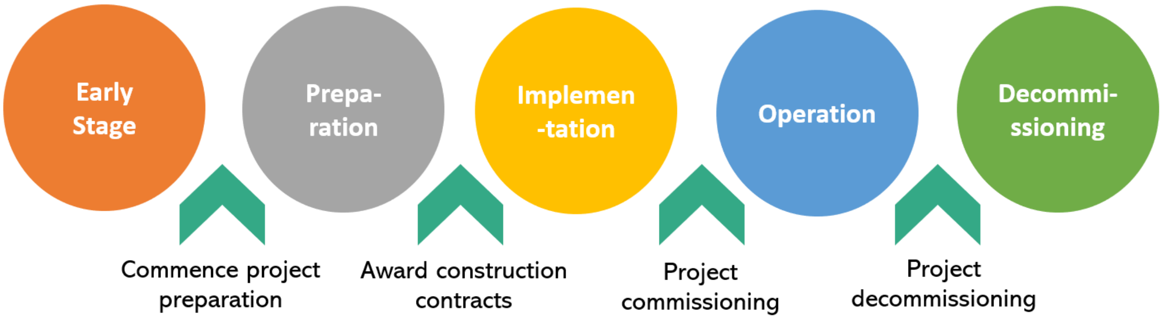
- **The IEA Technology Cooperation Programme** (TCP) on Hydropower (also known as IEA Hydro) mission is "to encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower". (https://www.ieahydro.org/about)

The report also presents analytical tools and their applicability to PSH technology and projects:

- **Hydropower Sustainability Tools** (HST) is an ensemble of three main tools that implement hydropower sustainability assessment principles: HGIIP and HESG, mentioned above, plus the Hydropower Sustainability Assessment Protocol (HSAP). These three tools provide a common language to allow governments, civil society, financial institutions and the hydropower sector to discuss and evaluate sustainability issues for hydropower projects. The HST are fully aligned with **Hydropower Sustainability Standard**, the World Bank Group Environmental and Social Standards (ESS) and the International Finance Corporation (IFC) Performance Standards, and they have well-established governance and quality control procedures.
- **Multi-criteria Analysis** (MCA) is a common but important tool when assessing different options, from whether PSH is the right energy solution, to identifying a preferred site. Key to a successful MCA and identification of a successful and sustainable project is having a clear set of objectives, and measurable criteria (technical and non-technical) to assess the extent to which options can achieve those objectives. MCA can combine technical and non-technical factors of a different nature, as well as global sustainability indicators like the Energy Return On Energy Investment (EROEI).
- **Economic analysis** tools are of high importance for assessing project viability; the related information and issues are covered by Policy and Market Frameworks WG.
- **Life Cycle Analysis** (LCA) is a standardised methodology used to assess the environmental performance of products / services throughout their entire life cycle (raw material acquisition, construction, operation and maintenance, and decommissioning). A LCA can be conducted on any electric power production / storage technology, including any PSH facility, as long as it complies with the ISO 14040-44 standards. As with all LCAs, special attention must be given to the functional unit and boundaries of the analysed system. Its application to PSH is mainly in the research area and it is not yet widely used at the industrial level. Even if LCA can cover several impact categories (GHG resource depletion, ozone etc.), it does not usually cover the full spectrum of environmental impacts that are relevant for hydropower (e.g. ecological continuity, sediment management). Specific attention to the quantification of GHG emissions from reservoirs during the operation phase of a PSH project is provided in this report. Based on the experience, practice and a hydropower sector data on reservoirs' GHG emissions, this issue is not considered to be significantly different from conventional hydropower reservoirs and should be not an issue for the vast majority of reservoirs (usually with a high power density for PSH).

## Tools across PSH project stages

The project stages adopted by the HST have been used to structure the guidance on assessment tools applicable to different stages of PSH projects, to which a fifth stage, Decommissioning, has been added as shown in the following figure:



The milestones separating project stages are in accordance with key decision points in the PSH project's life. Across these stages, various tools and methods may apply, for example, the HSAP may apply to all stages to assess various topics and/or footprint indicators. The HESG, on the other hand, which is used to check for gaps against good practice on relevant environmental, social and governance topics, is not relevant to the Early Stage or Decommissioning. The MCA is well suited for Early Stage and Preparation stages, but may not be used for the implementation and operation stages. LCA may be mainly considered for options assessment in the Early Stage, though its application for PSH is still being developed. Chapter 4 details these aspects.

Various case studies are presented in the report to give a non-exhaustive but illustrative vision of how guidelines, tools and methods can help in the sustainability assessment and optimisation of PSH projects:

- PSHs in Tasmania (Australia)

This case study shows how MCA can be used to progressively narrow down the project selection process. It includes the use of social, environmental, technical and financial criteria. As the site selection process progressed, a tailored ranking approach was taken to enable differentiation of PSH sites based on the attributes of the projects in the top three.

- Kaunertal Expansion Project – Versetz PSH (Austria)

The Kaunertal Expansion Project (KXP) underwent a HSAP assessment in 2016. The objectives of the HSAP assessment of the KXP were to:

- Identify potential gaps in project sustainability
- Identify areas for improvement
- Communicate with NGOs and other stakeholders
- Get an independent, external perspective of the project
- Optimise the proponent's (TIWAG) planning processes and ensure they were comprehensive.

With 18 of the 21 topics assessed scored at levels at or above basic good practice, the findings showed that the project met or exceeded basic good practice across many metrics. The use of HSAP also effectively identified gaps in meeting basic good practice with respect to project affected communities, cost benefit analysis and downstream flow regimes, and further work is required to close these gaps.

- Coire Glas PSH project (Scotland, UK)

Located in the Great Glen, Scotland, Coire Glas is a PSH scheme with a potential capacity of up to 1500 MW and was granted planning consent by the Scottish Government in October 2020 authorities on an Environmental Impact Assessment (EIA) submitted as part of the statutory planning process and review by local and national stakeholders.

Being developed by SSE Renewables, it would be the first PSH scheme to be commissioned in the UK for more than 30 years.

The benefits that the project will bring to the UK electricity network include:

- Providing much needed rotating inertia to help with frequency regulation
- Dynamic fault current injection for fault protection systems
- Fast acting and large scale dynamic load following
- Adding resilience to the system with large 'black start' capacity for re-energisation in times of blackout.

Recognizing the importance of HST tools, SSE intends to have the project assessed using the implementation stage of HSAP. This assessment will be used to benchmark the EIA to the HSAP and identify any gaps that need to be expanded upon for assurance of possible lenders and financiers.

- Grand-Maison PSH adaptation XFLEX Project (France)

Owned and operated by EDF Hydro, Grand-Maison is Europe's largest PSH facility, with an installed capacity of 1,800 MW. Grand-Maison facilities have been chosen to demonstrate the simultaneous use of very high-head pumps and Pelton turbines, and corresponding enhancement of flexibility services for the power system, thanks to an innovative, system integration of hydraulic short circuit technology (simultaneous pumping and partial turbining). This demonstrator is one of the XFLEX HYDRO innovation European projects that aims to demonstrate how more flexible hydro assets can help countries and regions to meet their renewable energy targets.
A HSAP/HESG assessment will be done within the XFLEX HYDRO project by looking at the entire infrastructure in operation.

- LCA synthesis studies for PSHs

A review of LCA studies for regarding analysis of PSH is presented in this report. PSH performs well when looking at construction and decommissioning phases. The synthesis highlights the effect of an electricity generation mix on the Global Warming Potential (GWP) performance of PSH and Li-ion batteries. It also shows that specific attention must be given to the boundaries and functional units of the power system. The issue of GHG emissions from PSH reservoirs does not seem to be significant, and in situations with low power density (e.g. <rates (< 5 W/m$^2$ as used in CBI criteria)), a possible adapted methodology is proposed based on the G-res tool to evaluate the PSH scheme emissions. This proposition requires further work and is under consideration with the IHA.

- CEDREN studies on existing reservoirs retrofit to PSH (Norway)

Within the Centre for Environmental Design of Renewable Energy in Norway (CEDREN), several publications have addressed the potential for retrofitting existing pairs of reservoirs with increased power capacity as well as additional pumping capacity. The major potential environmental impacts from adding increased generation and pumping capacity to hydropower facilities using existing reservoirs, both as lower and upper reservoirs, are discussed. The main conclusion is that effects vary depending on location, operation, and local conditions. The possibility of also improving environmental conditions in heavily impacted existing reservoirs is also highlighted.

- Local benefits of PSH Projects

Benefit sharing is best understood as "a package of deliberate measures taken by hydropower developers that allow local communities to share benefits from a hydropower project, over and above required impact mitigation measures" (www.commdev.org/pdf/publications/Hydro_Benefit_Sharing_Key_Insights_FIN.pdf).

Most of the general experience on benefit sharing and the resulting principles, categories and methods are applicable to PSH projects. As for other hydropower projects, their main objectives and benefits, such as the balancing of the power grid, are regional or even national in scale.

There are a small number of potential benefits that are specific to PSH projects or, conversely, impossible for PSH projects to deliver. In general, as PSH involves two reservoirs, there are more focal areas for potential local impact (both positive and negative), and these and the associated local stakeholders need to be considered systematically. Some PSH projects may be able to provide solutions for pre-existing land use problems, such as those using abandoned open-pit or underground mines, quarries and similar 'brownfield' sites. If combined with variable renewables, small PSH projects may also enable a reliable, independent and sustainable power supply for communities, including on islands or other off-grid situations.

## Main recommendations

a) Massive expansion of storage solutions are needed to meet a net zero carbon future for power systems and PSH projects should be considered a key enabler of this transition, as well as other storage technologies.

b) The sustainability assessment of PSH project should rely on a multi-level approach, including:
   - System-level needs;
   - Options assessment; and
   - Project optimization.

c) PSH projects are very site-specific, and sustainability cannot be defined by a simplistic classification. Some key factors to consider for options assessment and project optimisation are listed in this report in order to integrate associated environmental functions and sensitivity, safety issues and social aspects into a given site configuration with an intent to avoid, minimise and mitigate impacts.

d) Existing hydropower sustainability tools (HST) are adequate for PSH technology and project assessment. A few adaptations arise from the case studies presented in Chapter 5, such as the potential to improve ESG risk screening tools for the Early Stage phase.

e) LCA applications to PSH technology and projects are still quite recent and have been mainly conducted in the research domain. They provide interesting outcomes but specific attention must be given to the boundaries and functional units of the power system to avoid misleading conclusions. There is no evidence to suggest a material difference in GHG emissions from PSH reservoirs compared to those from conventional hydropower reservoirs which, on average, fall between those of wind and solar power.

f) PSH projects, as with many hydropower projects, can generate one-time or permanent local benefits of various kinds, which should be considered in their sustainability profile assessment.

These conclusions and recommendations should be considered alongside those from the other WGs as many sustainability issues like economic viability, financial feasibility, etc. interact with those investigated by the other WGs.

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## Figures and Tables

# Chapter 1

# INTRODUCTION

## 1.1 Objective of Working Group 2 on PSH Sustainability

The overall objective of the Sustainability Working Group (WG.2) was to develop guidance and recommendations on **how PSH can best support future power systems in the clean energy transition and their trajectory towards zero-carbon content in the most sustainable way**. As PSH projects are highly site-specific in their performance, costs and impacts, it was important to focus on the processes that lead to sustainable systems, not just generic PSH performance and cost. Since energy storage and flexibility solutions are principally important in supporting other variable renewable energy sources to maintain the performance of the entire power system, it is important to use system needs as the point of entry.

### 1.1.1 WG.2 focus and connection to other IFPSH working groups

The International Forum on Pumped-Storage Hydropower (IFPSH) coordinated by the International Hydropower Association (IHA), is based on three strategic pillars, each covered by a specific Working Group (WG):

WG.1 on "Policy and Market Frameworks" has developed a position paper that identifies the barriers to PSH development and policy recommendations to provide greater revenue certainty and to de-risk investment (with a strong focus on regional/country recommendations).

WG.2 on "PSH Sustainability" aims at providing the basis and guidelines for planning and implementing power systems that are sustainable, making appropriate use of PSH as an established and evolving technology for grid flexibility and storage. One of the key challenges in developing PSH is environmental and social planning and permitting, and WG.2 work will help define the most appropriate tools and criteria to be used, including sustainability assessment tools.

- A subject in common with WG.1 is economic analysis, as a PSH project cannot be considered sustainable if it is not economically viable in the long term. This is an important component of the 'demonstrated need' that will be discussed in the following sections. Similarly financial viability is crucial. Section 0 of this report briefly covers these aspects.

WG.3 on "Capabilities, Costs & Innovation", aims, among other subjects, to compare PSH costs and capabilities with other energy storage options and power system flexibility services. WG.2 contributes to this by showing how to determine which factors to consider in designing the best set of options at the system level at an early stage of the project development. This should include existing and innovative methodologies for integrated planning and analysis.

### 1.1.2 Importance of system-level approach: trajectory towards clean energy systems

The general approach for developing sustainable PSH projects can be structured through three major levels:
- System-level strategic assessment
- Options assessment
- Project optimisation.

**Importance of system-level strategic approach**

The overall performance of a power system can be described through following attributes:
- Stability
- Reliability
- Cleanliness – in terms of emissions and social-environmental impacts
- Affordability
- Flexibility
- Resilience
- Expandability to enable the development of the system and provide for a major expansion in electrification of all sectors.

The transition to a net zero carbon future must start with an understanding of *the needs of the power system in terms of energy storage, flexibility and ancillary services*, through exploring:

- What are the specific requirements of a particular grid or power system?
- How much storage and in what locations?
- What response times, and what other ancillary services are there for voltage and frequency control?
- At what time in the future expansion of the system will these things be needed?

There should then be an inquiry into the *options to meet those storage and flexibility needs*, including all applicable technologies in addition to PSH. These questions will lead to the *selection of option(s)* and optimising their design in the context of the system needs. This should be done first as part of the Early Stage phase of planning and development, leading to a '**demonstration of need**' for specific sorts of technologies.

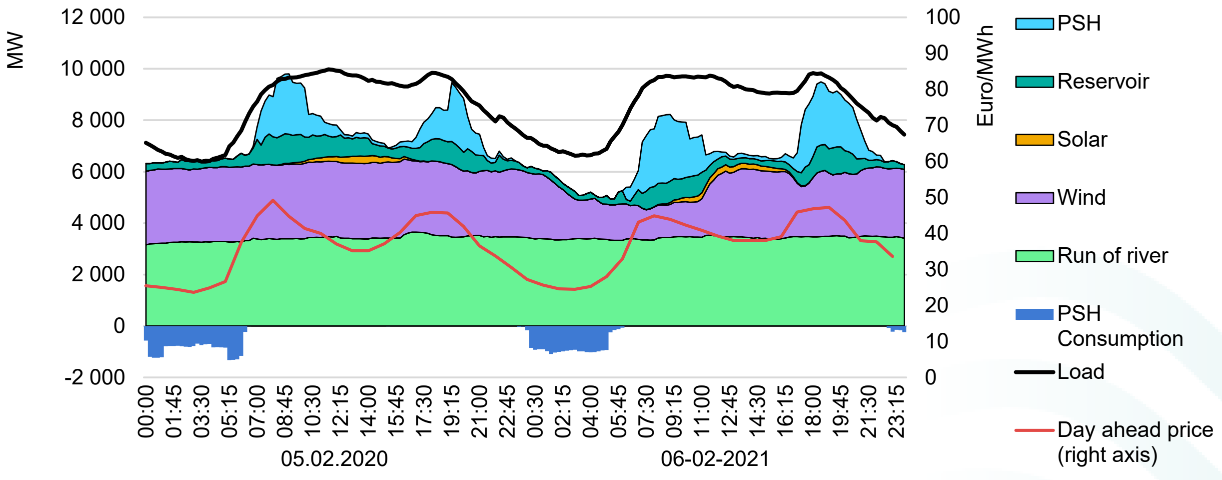
Projects utilising these storage technologies should be identified and prioritised according to current and future needs, development and remuneration models, costs, scheduling, and optimum locations from the perspective of the power system and wider sustainability topics. Projects emerging from this process will have a proven '**strategic fit**' and will be well placed to follow good international industry practice in their preparation, implementation and operation.

### Box 1. Illustrates typical load-generation balance, flexibility needs and the role of PSH in some power systems

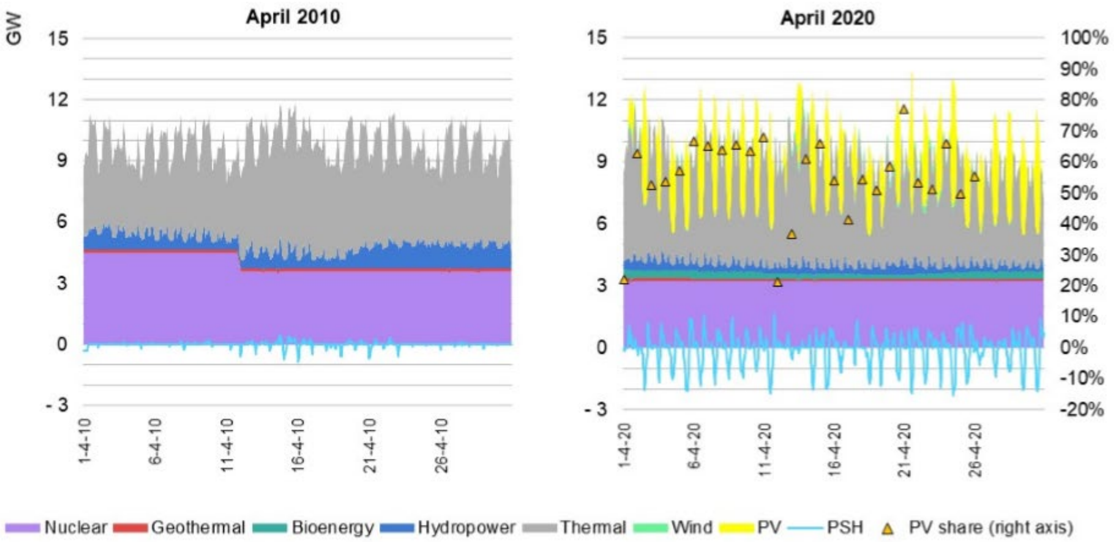
Figure 1 below, from the International Energy Agency (4), illustrates typical load-generation balance, flexibility needs and the role of PSH in some power systems:

- (a) In Austria, the 2-day sequence of 5 - 6 February 2021 shows the role of PSH (both pumping and turbining) to meet the demand and ensure adjustment of variable renewable energy (VRE) generation.
- (b) In Kyushu Island (Japan), figure 1 b shows the comparison of load-generation balance for the month of April between 2010 and 2020, and how PSH is playing a more and more important role to ensure the balance.

Figure 1 Examples of load-generation balance, flexibility needs and role of PSH in some power systems (a) Austria and (b) Kuyshu, Japan. *Source: IEA (2021)*



(a) Austria: 5-6 February 2021 load variations and hydropower generation, including storage



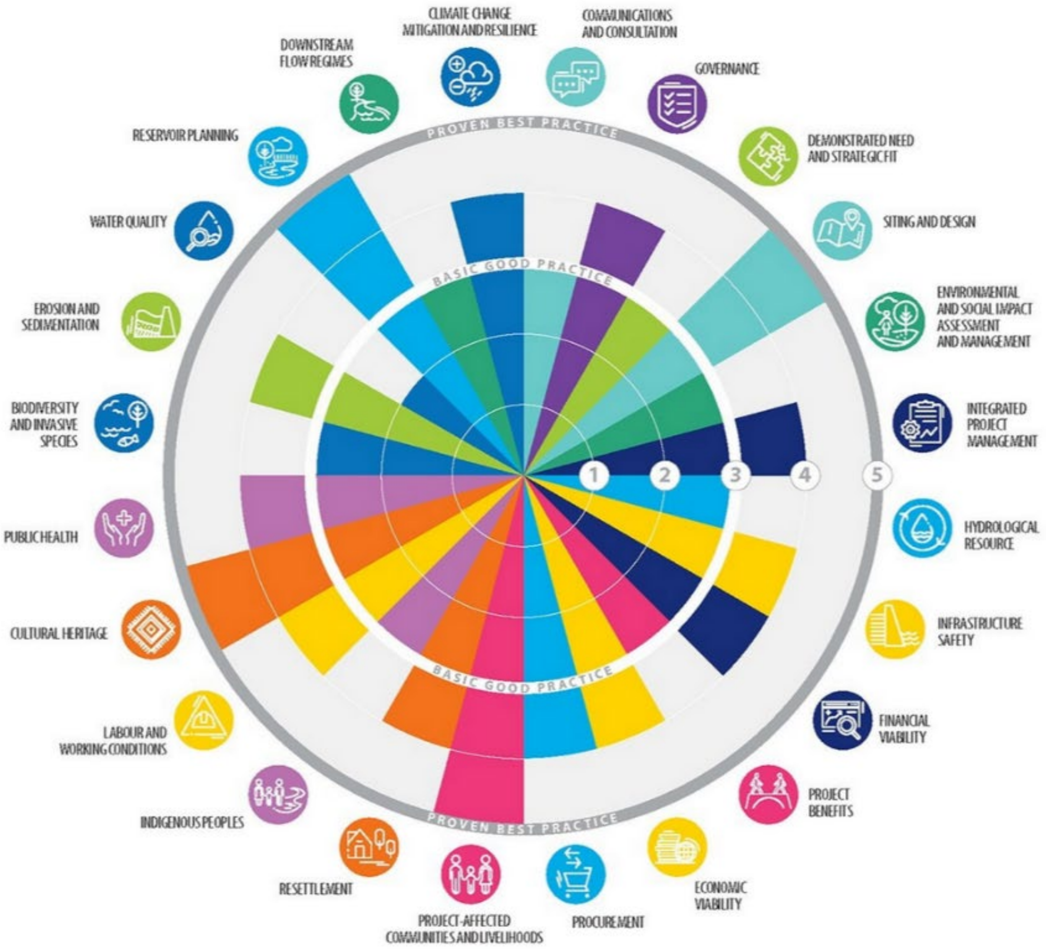
(b) Kyushu, Japan: Comparison of power generation features for the month of April between 2010 and 2020

The structure of this report attempts to follow this overall rationale, as detailed in Chapter 2, which identifies the factors that must be considered for PSH projects from a system-level approach, to options assessment, and then project optimisation. Chapter 2 also gives an overview of existing sustainability guidelines or frameworks that might be used for PSH projects.

The HST and other recognized sustainability tools already exist for hydro powerplants (HPPs) and cover all sustainability aspects to be considered for PSH projects in power systems. This extends beyond just environmental performance, including a range of factors that are well illustrated by the Hydropower Sustainability Assessment Protocol (HSAP) sustainability profile shown in Figure 2.

These tools are presented in detail in Chapter 3. They can be used at different lifecycle stages of project development as shown in Chapter 4. Applications of these tools to actual projects is illustrated through case studies presented in Chapter 5, which show relevancy of the tools and potential areas of adaptation.

Figure 2 Example of a hydropower project sustainability profile as illustrated by HSAP tool



This report is intended for decision-makers and experts of international institutions, financial institutions, government agencies, hydropower professionals, NGO's, and opinion leaders in the energy field and sustainable development/environmental/climate policy frameworks.

# Chapter 2

# SUSTAINABILITY FRAMEWORK

**Summary**

- PSH should adopt a 3-level rationale as its assessment approach.
- First, a system-level strategic assessment is important for understanding the needs of energy storage, flexibility, and ancillary services.
- Second, the assessment should make selection and assessment of technology options early to meet the system needs.
- Third, projects will have a proven ‘strategic fit’ and follow good international industry practice in their preparation.
- Existing guidelines and initiatives assessing Hydropower and PSH include the Hydropower Sustainability Assessment Protocol, Climate Bonds Initiatives eligibility criteria, EU Taxonomy on Sustainable Finance, and IEA Hydropower Guidelines.

## 2.1 Assessment approach: system-level, options assessment, project optimization

The assessment of PSH projects cannot be reduced to a simplistic classification in categories of “good” vs “bad” projects with respect to sustainability. As mentioned in the introduction, it is proposed to adopt a 3-level rationale as follows:

### System-level strategic assessment

Overarching factors should first be considered at a strategic level to identify what needs must be satisfied to support the trajectory/path of the power system for a given region/context towards a clean energy system target.

This identification of needs is generally identified through considering:

- Electrical system service needs, markets characteristics, and strategic orientation to develop renewables generation and reduce the carbon content in the energy mix, sufficient to meet transition targets;
- Characteristics of flexibility and ancillary services that will be needed;
- Economic performance and life duration expectation as revealed by master plan or integrated resource planning analysis;
- Overall socio-environmental integration of the project into a given site configuration with associated environmental functions and sensitivity, safety issues, and social aspects, with an intent to avoid, minimise and mitigate impacts.

Analysis at system-level and strategic scenarios are often conducted with the help of power system and transmission modelling tools (in-house research tools; commercial tools like SDDP[1] for instance - https://www.psr-inc.com/softwares-en).These tools are generally focused on economic indicators and considerations but are increasingly including sustainability considerations. For further information we refer to Palmer (5) as an interesting example on the use of such aa system-level tool to explore the sustainability of storage solutions through Energy Return On investment (EROI) indicators as applied to the Texan ERCOT grid system and which shows the relationship between storage performance and the VRE penetration rate.
The outcome of this strategic consideration is a defined storage/flexibility **demonstrated need**.

### Options assessment

To conclude that PSH is an appropriate and sustainable response to the demonstrated storage/flexibility need, it is essential to examine the range of potential storage technologies with their own performance characteristics and suitability profile to satisfy the storage/flexibility needs. In some situations, another storage technology might be considered as a better solution than PSH, as the different storage technologies do not cover the same domains of services (power level, energy capacity, time response – see WG.3 deliverables and Figure 3).

Figure 3 Overview of domains of service and technical performance

(provisional information extracted from IFPSH WG.3 reports – refer to WG.3 reports for more information)

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[1] Stochastic hydrothermal dispatch with network restrictions Software

| | Comparison metrics / Type of energy storage | Pumped Storage Hydro<br>1000 MW / 10hr | Li-Ion Battery Storage (LFP)<br>100 MW / 10hr | Lead Acid Battery Storage<br>100 MW / 10hr | Vanadium RF Battery Storage<br>100 MW / 10hr | CAES compressed air<br>1000 MW / 10hr | Hydrogen bidirect. with fuel cells<br>100 MW / 10hr |
|---|---|---|---|---|---|---|---|
| Technical Capabilities | Technical readiness level (TRL) | 9 | 9 | 9 | 7 | 7 | 6 |
| | Inertia for grid resilience | Mechanical | Synthetic | Synthetic | Synthetic | Mechanical | no reference |
| | Reactive power control | Yes | Yes | Yes | Yes | Yes | Yes |
| | Black start capability | Yes | Yes | Yes | Yes | Yes | Yes |
| Performance Metrics | Round trip efficiency (%*) | 80% | 86% | 79% | 68% | 52% | 35% |
| | Response time from standstill to full generation / load (s*) | 65...120 / 80...360 | 1...4 | 1...4 | 1...4 | 600 / 240 | < 1 |
| | Number of storage cycles (#*) | 13,870 | 2,000 | 739 | 5,201 | 10,403 | 10.403 |
| | Calendar lifetime (yrs*) | 40 | 10 | 12 | 15 | 30 | 30 |

- Comparison between different energy storage technologies that may meet the specified flexibility and storage requirements, e.g. PSH, batteries, CAES, etc.
- Comparison between PSH projects of a very different nature in their fundamental configuration.

An options assessment can be processed using a combination of different tools and methods like MCA, HST components, LCA, combining technical and non-technical factors. Some sustainability indicators can also help this process, particularly when using MCA.

## Energy Payback

The concept of "energy payback" quantifies how much a system can deliver energy over its total lifespan compared to the energy required to build, operate, maintain and decommission this system. This "energy payback" concept is usually translated into the Energy Return On Energy Investment (EROEI) or Energy Delivered On Energy Invested (EDOEI) indicators. While the concept of energy payback and EROI has been around for over a decade (IHA, 2004), it has been rarely used to assess generation options from a sustainable perspective. Hydropower often exhibits highly favourable energy payback compared to most alternatives for power generation. For example, EROI often exceeds values of 150 to 200 for hydropower, far above others. By comparison, if the consuming part in the energy count of EROI is not considered, most batteries have EROI values around three to ten, depending on the number of cycles per day (7).

## Project optimisation

Once the *demonstrated need of a PSH project* has been established based on the options assessment, particular projects can be designed to optimally meet those needs. The most sustainable PSH projects will then be derived from a more detailed consideration of different project options, including technical, environment, social and economic factors, both in terms of risks and opportunities, such as:

- Underground vs superficial penstock and/or power station
- Proximity of the electricity grid and ease of power exportation
- Ecological functions to be maintained or even improved
- Open-loop vs closed-loop (closed loop schemes may have no or very limited connection to a natural river system)
- Multi-purpose opportunities
- Whether it is possible to use existing reservoirs

- Surface water vs groundwater for reservoir fill
- Whether it is possible to change operation modes of existing assets
- Sensitivity to natural extreme hazards, such as seismic risk, geotechnical risks (landslides) etc., depending on the type of dam
- Opportunities to install collocated combined technologies, including:
  - Other renewable technology e.g. solar PV
  - Colocation with a desalination plant

The project optimisation phase also generally incorporates the EIA/EIS required by almost all relevant regulatory agencies or authorities.

Note that some of these factors may also play a role in the 2nd level of assessment (options assessment), described earlier in this section.

Existing sustainability guidelines, recommendations, tools and methods for the hydropower sector are well designed to support the optimisation process towards the most sustainable PSH during all lifecycle stages of a project. The following sections of Chapter 2 provides a brief overview of these guidelines and tools. Chapters 3, 4 and 5 detail how these tools can be applied.

## 2.2 Overview of key existing or in-progress guidelines and initiatives

### 2.2.1 Hydropower Sustainability Assessment Protocol

The IHA has elaborated and published the **HSAP** with a series of tools and methods. This set of guidelines and **ST** constitute the core instruments for assessing the sustainability of hydropower and PSH projects in the present report. They are described in detail in Chapter 3, and scoping and illustrations on their actual application to PSH projects are presented in detail in Chapters 4 and 5.

### 2.2.2 Climate Bonds Initiative (CBI) eligibility criteria

The Climate Bonds Initiative (CBI) is an international investor-focused not-for-profit organisation working solely to mobilise the US$100 trillion bond market for climate change solutions. To date, worldwide green bond issuances have reached over US$1 trillion.

In addition to hydropower, CBI Climate Bond Criteria have already been developed for solar energy, wind energy, marine renewable energy, geothermal power, low carbon buildings, low carbon transport, water infrastructure and forestry.

The criteria for the Climate Bond Standard for Hydropower stipulates the use of two assessment tools supported by the International Hydropower Association (IHA) and the multi-stakeholder Hydropower Sustainability Council: the ESG Gap Analysis Tool for identifying and addressing gaps against recognised good practice across 12 environmental, social and governance assessment topics; and the G-res Tool for reporting the estimated net greenhouse gas (GHG) emissions of a reservoir.

Under the new CBI criteria, to qualify for a climate bond a hydropower project must:

- Demonstrate it has a high-power density and low emission intensity, recording either a power density of more than 5 W/m² or an emissions intensity of less than 100 $gCO_2e/kWh$ delivered. For new projects, the emission intensity requirement is for less than 50 $gCO_2e/kWh$. The latter can be estimated using the G-res Tool for reporting reservoir emissions.
- Undertake an official assessment using the ESG Gap Analysis Tool (HESG), one of the HSTs. The assessment must be carried out by an accredited assessor, be publicly available, and demonstrate:
  - No more than ten gaps in total against international good practice.

  - No more than two gaps in each section.
  - The majority (>50%) of the gaps must be closed within 12 months and the remaining within 24 months.
- Follow the Free, Prior and Informed Consent (FPIC) consultation process if the project affects Indigenous communities, in line with the UN Declaration on the Rights of Indigenous Peoples.

Projects of all sizes and types (including pumped storage) and in all locations will be eligible, provided they meet the CBI criteria.

Learn more about the CBI climate bond and eligibility requirements:
https://www.climatebonds.net/standard/hydropower

### 2.2.3 EU Taxonomy on Sustainable Finance

The Regulation (EU) 2020/852 ("Taxonomy Regulation")[2] entered into force on 20 July 2020. Based on this regulation, the EU Commission approved and published the First EU Taxonomy Climate Delegated Act on 4 June 2021. It will be followed by a Second Delegated Act in 2022.

This instrument aims at defining eligibility conditions to sustainable or green investment, especially in the context of the European Green Deal program. The hydropower (including PSH) industry is mainly concerned with Objectives 1, 2 and 3:

- Objectives 1 (Climate change mitigation) and 2 (Climate change adaptation) are explored through the definition of "Technical Screening Criteria" for assessing the eligibility of socio-economic sectors as substantially contributing/enabling activities.
- Objective 3 (Climate change adaptation) specifies *Do No Significant Harm* (DNSH) criteria to water and marine ecosystems.

This initiative has followed an iterative process of drafting, consultation and revision. The 4 June version integrates the following changes and statements for the hydropower sector within Section 4.5, *Electricity generation from Hydropower*:

- Run-of-river plants (i.e., no reservoir) or plants with power density above 5 W/m$^2$ will not have to carry out the life-cycle assessment to prove that they comply with the 100 gCO$_2$e/kWh threshold.
- Plants with a reservoir and with a power density below 5 W/m$^2$ will have to confirm that they meet the life cycle based GHG emission intensity threshold of 100 gCO$_2$e/kWh.
- A careful alignment had to be found between the requirements of the Taxonomy Regulation, notably the DNSH requirements, and the requirements of existing law, such as the Water Framework Directive (WFD).

Pumped storage hydropower plants are covered within Section 4.10, *Storage of Electricity,* and no distinction is made to other electricity storage technologies in the technical screening criteria, i.e. no special power density or GHG emission intensity thresholds are defined to be eligible.

The specificities of pumped storage are considered in the DNSH criteria for the sustainable use of water and marine resources. For PSH assets, an EIA must be carried out in accordance with Directive 2011/92/EU and an assessment of the impact on water in accordance with 2000/60/EC. While pumped hydropower storage "not connected to a river body" have to comply with the same DNSH criteria as all other storage technologies, those

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[2] Available information on EU Taxonomy project can be found through following link:
https://ec.europa.eu/info/law/sustainable-finance-taxonomy-regulation-eu-2020-852/amending-and-supplementary-acts/implementing-and-delegated-acts_en

"connected to a river body" have to comply with the by far stricter criteria for Section 4.5 (Electricity production from hydropower).

### 2.2.4 IEA Hydropower programme guidelines

The IEA Technology Cooperation Programme (TCP) on Hydropower (also known as IEA Hydro) has a mission "to encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower". Therefore, sustainability issues have always been a part of the programme and its "Annexes" (Task Forces). (Note that the scope of the programme is broader than just sustainability and PSH.)

- Annex XIII of IEA Hydro, "Hydropower and fish", has a focus on challenges and solutions for fish in hydropower rivers, including a best practice report and guidelines to direct the reader of a "roadmap" towards what the main challenges are and how to find solutions for mitigation measures. Pumped storage is not specifically mentioned.
- Annex XII of IEA Hydro, "Hydropower and the Environment", issued three volumes of guidelines in its first phase: "Guidelines for the Quantitative Analysis of Net GHG Emissions from Reservoirs". The guidelines volumes do not consider pumped hydropower as a separate case.
- Annex IX of IEA Hydro, "Valuing hydropower services", focus on the value of hydropower providing flexibility services to the energy system. One of the reports focuses only on pumped storage. Together with Annex XII, the Annex IX has a joint task on "Climate change services" focusing first on "Hydropower providing flood control and drought management".

More information is available at: https://www.ieahydro.org

# Chapter 3

# EXISTING TOOLS AND METHODS

**Summary**

- There are several tools and methods that provide common standard and process for assessing hydropower projects.
- Hydro Sustainability Tools provides a common language to allow public and private sectors to discuss and evaluate sustainability issues.
- Multi-Criteria Analysis provides structure and rigour to the analysis of options and a transparent decision-making process.
- Economic Analysis ensures project viability from a financial perspective. PSH is recognised today as a good cost-competitive gross energy storage solution.
- Life-Cycle Analysis measures the environmental footprint of the object through a standardised methodology.

## 3.1 Hydro Sustainability Tools (HST)

The HST (https://www.hydrosustainability.org/) define international good and best practice in hydropower development. They provide a common language to allow governments, civil society, financial institutions and the hydropower sector to discuss and evaluate sustainability issues. **The HST have been designed so that they are fully aligned with the Hydropower Sustainability Standard, the World Bank group ESF and IFC's Performance Standard** – particularly HESG measures where there are gaps in compliance against good international industry practice.

The HST can facilitate clients in accessing finance by providing guidance to meet requirements of the World Bank's Environmental and Social Framework and IFC's performance standards.

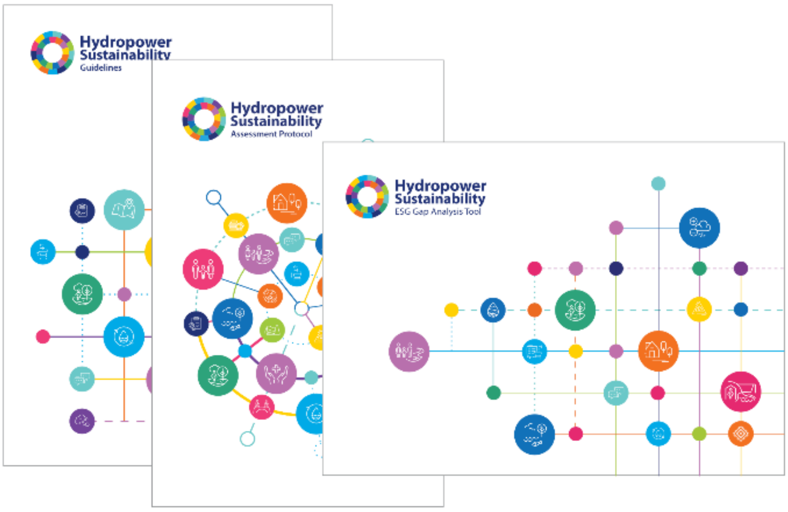
Widely endorsed by industry, governments, financial institutions and social and environmental non-profit organisations, the tools are currently being used by developers and operators around the world to design, build and assess hydropower projects of all types and sizes – including PSH projects.

The HSAP assessment experience described in Section 5 of this document (Case Study 5.3) shows that **the same broad range of sustainability considerations typical for all hydropower projects also apply to PSH projects, and the HST are well suited for sustainability assessment of PSH.**

There are three complementary tools: the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP), the HSAP and the HESG.

1. The **HSAP** measures performance compared to defined basic good practice and proven best practice, enabling projects to benchmark their performance in a comprehensive way. It was the first hydropower-specific protocol for measuring and guiding the performance of hydropower projects against globally applicable criteria for environmental, social, financial and technical sustainability.
2. The **HGIIP** acts as the key document that defines the processes and outcomes that constitute good international industry practice. Performance against the guidelines can be measured through two complementary tools: the HSAP and the HESG.
3. The **HESG** can be used to check for gaps against good practice on relevant environmental, social and governance topics, and includes a gap management plan to improve processes and outcomes.

Figure 4 The three Hydropower Sustainability Tools



The HST offer a way to assess the performance of a hydropower project across more than 20 sustainability topics. The breadth of the topics gives clients a clearer understanding of the overall sustainability of a project, including environmental, social, technical and economic aspects.

For more information, please visit https://www.hydrosustainability.org/ - information on the history and evolution of HST is given in ANNEX B, as well as insights on governance and quality control aspects.

## 3.2 Multi-Criteria Analysis (MCA)

Multi criteria analysis (MCA) is an important and commonly used tool when assessing different options, from whether PSH is the right energy solution to identifying a preferred site. Distinguishing between options is often a complex problem that needs to consider a multifaceted array of issues and information. The MCA process provides structure and rigour to the analysis of options as well as a transparent and a defendable decision-making process. It can ensure that all options are considered in a consistent way, removing bias that may otherwise be introduced.

Key to a successful MCA and identification of a successful and sustainable project is having a clear objective (or set of objectives, coming from system-level needs analysis) and measurable criteria to assess the extent to which options can achieve those objectives. In addition, criteria should be considered across multiple perspectives, e.g. corporate, technical, integrative, environmental and social. If only one perspective is considered, potential key issues which define the success or sustainability of the project may be overlooked. For issues that are not easily measurable, surrogate information can be used to assess the issue (impacts on sediment delivery to a delta can be assessed by considering a combination of reservoir retention time, length of river not impacted and catchment area downstream). It is important that the final criteria chosen do not include those that are not material to the MCA objective(s) or which do not distinguish between options.

Depending on the project stage that an MCA is applied to, the objective, perspectives and criteria used to distinguish between options changes to reflect aspects or issues relevant to the stage. For example, consideration of whether PSH is the right energy solution may use criteria that reflect market need, whereas a MCA to determine the preferred project site may consider engineering feasibility and environmental and social impacts.

Once the objective and criteria are defined, it is also important to consider how the options will be ranked based on how well they satisfy the criteria. Some criteria may be quantitative while other may be qualitative. In addition, some perspective may have multiple criteria. It is therefore important to consider how the criteria are combined to provide an assessment that is not biased towards one aspect or issue, or undervalues other important issues. This may include consideration of weighting the relative importance of criteria and/or normalisation of scores to more readily allow comparison between options. Once ranked, it is also important to review the results of the MCA and conduct a sensitivity analysis to ensure the outcomes are defendable.

Ultimately a MCA should allow scrutiny of the options assessment process at different stages of the project by stakeholders and the broader community during later stages of the project. Having a transparent options assessment process allows stakeholders to comment on, as well as understand, why decisions have been made.

## 3.3 Economic Analysis

### 3.3.1 Ensuring Project Viability from financial perspective

WG1 analysed possible revenue streams, which should be implemented with greater long-term certainty, to ensure project viability:

- Energy payments: arbitrage was once the basis of the business model, but it appears to be no longer sufficient for new build PSH. There is now an evolution of markets towards real-time settlement to balance the grid (e.g., Australia, UK).

- Ancillary (or flexibility) services: PSH can provide a wide range of services to the grid but most of them are rarely or insufficiently remunerated. The WG1 report gives an overview of existing remunerations for ancillary services, how they work, and the gaps to be addressed.
- Availability payments through capacity mechanisms: where are they implemented? What are the conditions? Can they be reformed to work for PSH?
- Other recent schemes: hybrids auctions combining REN + Storage, firming contracts to cover peak periods (e.g. Snowy 2.0 in Australia), PPAs (e.g. 25-year PPA in India).

### 3.3.2 PSH economic value

The WG.1 report also details the economic value of PSH technology; the reader is invited to peruse this report for more details.

PSH is recognized today as a good cost-competitive gross energy storage solution. Even though the capital expenditure (CAPEX) is high, as with any large infrastructure project, PSH has generally one of the lowest costs of production and storage in terms of cost/kWh, thanks to its lifetime and scale. All economic aspects (e.g. costs, economic performance, and revenues mechanisms depending on markets conditions) are detailed in WG.1's report, and complemented on costs aspects by WG.3's report.

## 3.4 Life Cycle Analysis (LCA) tools and methods

### 3.4.1 Why and when to use LCA?

Life-Cycle Analysis (LCA) is a sustainability tool that measures the environmental footprint of a service/product/system through standardized methodology (see next section and ANNEX C) against a set of predefined indicators and metrics.

LCA-based comparison of PSH with other storage options, such as types of batteries, CAES, and power-to-gas is possible but requires caution and presents limitations.

- storage facilities may have very different technical and operational characteristics, and storage/flexibility services may be different and not reflected by a single functional unit.
- The metrics of an environmental footprint assessment do not cover all of impacts of a given technology. Other assessments would be required.

LCA cannot be considered as a self-sufficient tool to select the best storage technology that a system requires, but it can complement a set of tools to highlight some aspects of a technological and environmental footprint.

### 3.4.2 LCA tools and their applicability to PSH technology and projects

**LCA methodology**

Life Cycle Assessment (LCA) is a standardized methodology widely used by the international scientific community and engineering and consultancy businesses to assess_the environmental performances of products / services throughout their entire life cycle. Standardization is through the ISO 14040 and ISO 14044 standards.
LCA is an approach that considers:

- every life cycle stage under analysis, from the raw material acquisition stage through the production of the product / service, its use, end-of-life treatment, recycling and final disposal - this would represent a system boundary of "cradle-to-grave", though this is not the only system boundary available.
- multiple environmental impacts and indicators – see below and ANNEX C for more details.

According to ISO 14040-44 standards, any LCA shall be conducted through four mandatory and interlinked phases as schematized in Figure 9 of ANNEX C (see this Annex for details about LCA methodology).

### Application to PSH technology

So far, application of LCA to PSH technology and projects is mainly in the domain of research, and not yet applied on an industrial decision-making basis. However, the LCA standardised methodology described above can be used as for any product / service according to ISO 14040-44 standard.

For power plants, one common **functional unit** generally considered is 1 kWh provided by the plant, on average, during its entire lifetime, and delivered for customers at a given voltage [3] (e.g. Oliveira et al., 2015; Abdon et al., 2017; Kapila et al., 2019). A functional unit is the unit of production against which all comparisons are made within an LCA. For storage facilities, the functional unit may also be related to the power the facility can deliver (x MW) (e.g. Guo et al., 2020) or to its energy storage capacity (x MWh) (e.g. Immendoerfer et al., 2017; Stougie et al., 2019). Energy storage capacity is by far the most common functional unit used. One difficulty for PSH plants is that they are both a power plant and a storage facility and that there is no single functional unit that relates to both functions.

In regard to **system boundaries**, for any PSH facility, these typically include - otherwise clearly specified and justified: raw material acquisition, construction, operation (which includes energy consumption used for pumping) and maintenance (which include every equipment replacement that will occur during the lifetime of the facility) and decommissioning of the plant. Nevertheless, some studies "omit" certain parts of the life-cycle, which prevent their results from being comparable with those from other studies (e.g. no "operation" in Früger et al., 2018, no "electricity generation for charging" in Stougie et al., 2019).

Finally, there is not a standard set of metrics to be covered by energy storage products or services, as some publications may only explore one **environmental impact category/indicator**, climate change, computed with IPCC calculation factors, which is called: "GWP (Global Warming Potential)", "GHG emissions" or "$CO_2$ footprint" in the publications. Many publications use off-the-shelf LCA calculation methods that provide several indicators. For instance, the ReCiPe method provides several indicators including GWP, cumulative energy demand (CED), fossil fuel, mineral and metals depletion, natural land transformation (NLT) and eutrophication (as in Immendoerfer et al. (2017)). Other limitations identified in review of LCA studies include the lack of comparison of PSH and other technologies like batteries against their respective raw material and natural resource needs (e.g. rare earth metals) and the lack of consideration of hydropower specific issues as LCA impact indicators (e.g. fish, sediment).

## 3.4.3 Addressing the question of GHG emissions from the reservoirs during PSH operation

As shown in Section 2.2, criteria are converging on the use of a 5 W/m² land-use conversion power density rate, above which hydropower projects are not required to conduct a GHG Life Cycle Assessment. As explained in Section 2.2 there is no obvious argument to consider that a different criterion should be specifically used for PSH. The main difference with conventional hydropower would be if construction of the two reservoirs is required, then the sum of the reservoirs' surfaces should be considered. On the contrary, if one of the two reservoirs already exists (retrofitting), only the new reservoir should be taken into account (considering the GHG emissions from the existing reservoir cannot be attributed to the PSH facility).

When the land-use power density is below this criterion, a GHG Life Cycle Assessment may make sense. A part of GHG emissions may come from the reservoirs themselves through alteration and amplification of carbon transformation processes. The evaluation of these emissions is not straight forward. In recent years, the IHA, UNESCO, the World Bank and other stakeholders have developed the G-res tool based on the available literature data (Source: IHA G-res tool website (https://g-res.hydropower.org/scientific-basis), and used a unique framework

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[3] The voltage at which the energy is delivered needs to be clearly stated in the analysis, since it determines whether the transportation and distribution electricity networks are considered or not.

in its attempt to represent only the GHG emissions that are attributable to the reservoir (Prairie et al., 2019). The main drivers of GHG emissions are given in ANNEX E. The G-res tool was not developed with data from PSH and it cannot be directly used for PSH reservoirs as such. However, a tentative approach on how the G-Res tool could be adapted is shown in same ANNEX E. Moreover, a stakeholder working group convened by the IHA is ongoing to refine this first adaptation proposal in order to provide specific guidance for PSH. This may also consider the specific case of PSH schemes with multi-purpose reservoirs.

# Chapter 4

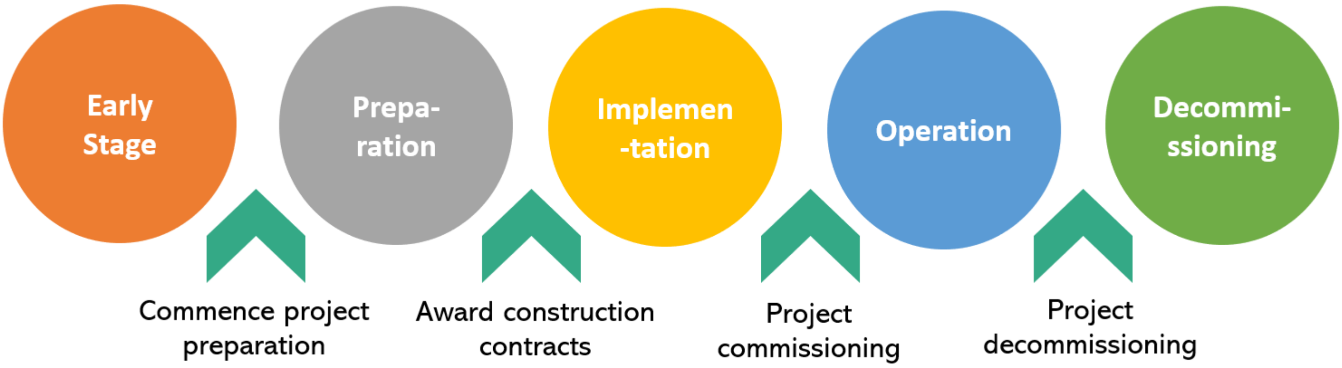
## TOOLS OVER THE LIFECYCLE STAGES OF PSH PROJECTS

### Summary

- PSH projects can be divided into five life-cycle stages.
- Different assessment tools apply to different stages or across all stages of PSH projects.
- The early stage considers the environment and the needs to be met by the project.
- The preparation stage commences when the decision is made to involve investigations, planning, and design.
- The implementation stage starts when the PSH infrastructure begins. Follow by the operation stage and is completed at the decommissioning stage.

The life cycle stages adopted by the HST are used to structure this guidance on which assessment tools are applicable to different stages of PSH projects, to which a fifth stage, Decommissioning, has been added as shown in Figure 5:

Figure 5 Life Cycle Stages of the HST



The milestones separating life cycle stages are in accordance with key decision points in a PSH project's life.

The **Early Stage** focusses on the PSH project concept. This stage considers the strategic environment (markets, regulation, political and social context, etc.) and the needs to be met by a storage project. It must establish the demonstrated need of a PSH project – for instance compared to other potential technologies – and undertakes early identification of risks and opportunities for various project concepts in order to identify the challenges and management responses to proceed with a more detailed project investigation. At this stage, a range of planning approaches, possible siting, and overall design alternative options are assessed without conducting a detailed assessment. Early investigations about project possibilities are often of a confidential nature, especially when developers have not yet decided whether to invest in more detailed studies, or where there is a highly competitive energy market.

The **Preparation** stage of a PSH project commences when the decision is made to progress with technical, environmental, social, and financial studies on a specific PSH project proposal at different levels: feasibility, basic design, detailed or reference design. The preparation stage involves investigations, planning, and design for all aspects of the project. This project stage is normally subject to national regulatory processes, including Environmental and Social Impact Assessment (ESIA) requirements as well as project management and technical regulatory requirements / guidelines (e.g. dam safety). Preparation of the project is typically completed based on issuing of relevant government permits and approvals, such as a construction permit and environmental license.

The **Implementation** stage of a PSH project follows receipt of necessary government approvals prior to construction and issuing of tender documents. During this stage, construction contracts are awarded and construction of the required PSH infrastructure begins, along with implementation of relevant elements of a potentially wide range of environmental and social management plans. The close of the implementation stage is upon commissioning of the first power station unit, noting that further units may continue to be installed and commissioned whilst the first unit(s) are operational.

The **Operation** stage commences with the commissioning of units that enable the project to generate power and earn revenues from electricity sales and the provision of services. This project phase is framed by the conditions incorporated into governmental authorisations, such as in an operating license and environmental permit. Operation of a PSH project will typically extend over many decades, during which time there will be many changes to the context, surroundings, regulatory and market environment, community expectations and values, and will often include relicensing milestones. Decisions made during the operation stage, as the project ages, will consider facility life extension, re-optimisation, and decommissioning.

The **Decommissioning** stage follows an analysis that all other options for the operating facility (see above) are not viable, even with significant adaptation and change of targeted services and benefits. PSH project decommissioning is a specialised area for which there is limited global experience. Particular attention is on economic analyses and risk assessments, plans for safe removal and disposal of project infrastructure, and restoration and rehabilitation of the project site and surrounds (e.g. reservoir sedimentation management, post-emptying river restoration).

Table 1 Suggested sustainability tools across the lifecycle stages of PSH projects

| | EARLY STAGE | PREPARATION | IMPLEMENTATION | OPERATION | DECOMMISSIONING |
|---|---|---|---|---|---|
| **HSAP** | Use as a guide for early identification of risks and opportunities for various PSH concepts.<br>Includes key topics relating to demonstrated needs, options, policy context; the political situation and institutional capacities; and technical, social, environmental, and economic risks & opportunities.<br>Identifies challenges and informs decision to proceed with a detailed PSH investigation. | Can apply when detailed technical, environmental, social and financial feasibility studies are available for a proposed PSH.<br>Assesses 24 topics, including governance, financial, technical, social and environmental perspectives, against international good and best practice criteria.<br>Informs whether all preparatory requirements are met, management plans and commitments in place and ready to implement.<br>An assessment early or midway through the Preparation stage will guide improvements. | Can apply to assess performance on delivery of all construction, resettlement, environmental and other management plans and commitments.<br>Assesses 21 topics, including governance, financial, technical, social and environmental perspectives, against international good and best practice criteria.<br>Results can inform the readiness for, timing and conditions relating to PSH operation. | Can apply to inform the view that the PSH is operating on a sustainable basis with active measures in place towards monitoring, compliance and continuous improvement.<br>Assesses 20 topics, including governance, financial, technical, social and environmental perspectives, against international good and best practice criteria.<br>Assessments may be forward looking (i.e. what activities should be undertaken) or backward looking (reflecting on how well activities were undertaken).<br>The approach is similar to that of ISO 14001, in that the existing condition is taken as the baseline, and risks are assessed against that condition.<br>If the project has any ongoing or emerging issues relating to a topic, assessment, management, compliance and outcomes are evaluated for those issues. | There is no decommissioning stage tool in the HSAP. The Early Stage assessment tool can provide guidance on some important considerations to take into account for decisions relating to decommissioning: keeping or removing the reservoir. All local project benefits have to be considered in the keeping / removing alternative. |

| | EARLY STAGE | PREPARATION | IMPLEMENTATION | OPERATION | DECOMMISSIONING |
|---|---|---|---|---|---|
| **HESG** | (N.A.) | Can apply for more rapid assessment of the international good practice criteria of the Preparation Stage HSAP.<br>Consists of 12 sections addressing environmental, social and governance HSAP topics.<br>Identifies significant gaps against international good practice, and an action plan. | Can apply for more rapid assessment of the international good practice criteria of the Implementation Stage HSAP.<br>Consists of 12 sections addressing environmental, social and governance HSAP topics.<br>Identifies significant gaps against international good practice, and an action plan. | Can apply for more rapid assessment of the international good practice criteria of the Operation Stage HSAP.<br>Consists of 12 sections addressing environmental, social and governance HSAP topics.<br>Identifies significant gaps against international good practice, and an action plan. | |
| **Multi-Criteria Analysis** | Can be used at a strategic level to consider multi-dimensional aspects of the best decision to be made about a power storage / flexibility solution, in a given multi-dimensional context.<br>Indicators used must reflect the factors of consideration at the relevant assessment level of analysis. | Can be used at a preparation level to select best options for a preferred site and preferred project configuration (technical options) with respect to risks and opportunities | (N.A.) | (N.A.) | Can be used at a strategic level to consider multi-dimensional aspects of the best interest between decommissioning and operation extension, potentially associated to minor to major adaptation of the existing project |
| **LCA** | Can be used to provide some environmental footprint indicators between different technologies, and support the demonstrated need of a technology/project. Indicators cover a large spectrum of areas including: $CO_2$eq content per unit of service; water footprint; land use; resources depletion; eutrophication.<br>However, some environmental impacts specific to Hydropower and PSH technology/project, are not always accounted for (e.g. impacts on fish population, fish continuity, sediment management. | Can be applied to optimise a PSH project design and its future operation, against a list of footprint indicators. | Not directly applicable<br>May potentially help specify eco-design solutions and manufacturing eco-processes to contractors | Not directly applicable<br>Can help monitor the environmental footprint of an industrial process, especially at regulatory and/or industrial milestones in the project lifetime, inducing new requirements, new expectations, and thus conducting to possible new operation modes, refurbishment and innovating adaptation. | Can be used to reconsider the relevance and demonstrated need of the project before concluding to a decommissioning phase. |

# Chapter 5

# APPLICATION OF SUSTAINABILITY TOOLS: CASE STUDIES

## Summary

- Applications of the tools have been conducted from different regions around the world.
- Hydro Tasmania applied the MCA tool that prioritised social and environmental criteria.
- The Kaunertal Expansion Project in Austria commenced HSAP assessment to identify potential problems and crucial stakeholders.
- Coire Glas in Scotland will apply HST tools covering environmental and socio-economic perspectives.
- In France new technology under the XFLEX HYDRO project will be demonstrated at the existing Grand’Maison dam. The assessment will apply a lighter version tool using internal assessors.
- LCA can be used to test different technological options comparing their potential impacts on the environment.

## 5.1 MCA applied to PSH projects in Tasmania

### Selection Process for Pumped Storage Hydro Projects in Tasmania – environmental and social ranking (Hydro Tasmania 2021)

Hydro Tasmania commenced a PSH options assessment process in 2017 and selected a single preferred site in 2020. The options assessment progressed through four distinct stages:

1. Top 30 potential sites – concept study
2. Top 14 potential sites – early pre-feasibility study for each site
3. Top 3 potential sites – complete pre-feasibility study, commence feasibility study for each site
4. Preferred site – complete feasibility for preferred site (current)

Social and environmental criteria were prioritised from the earliest stage through final site selection. In Stage 1, three key criteria were used to identify the top 30 sites from a broad range of options:

- Avoidance of high conversation reserved areas (Tasmanian Wilderness World Heritage Areas)
- No new dams on rivers to be built
- Impact to private land avoided or minimised

From Stage 1 onwards, Hydro Tasmania's Integrated Business Risk Management (IBRM) process was applied as an MCA tool to help site selection and includes social, environmental, technical and financial criteria. This internal corporate governance framework guided risk-based project ranking decisions. Sites that exceeded an internal corporate threshold of environmental and social risk (in addition to other risk types) were excluded in the selection of the preferred sites in the early site selection process (Stage 1 and 2 above). In the later stages of selecting the preferred site (Stages 3 and 4 above), the social and environmental risk assessment informed feasibility and design decisions and was less of a factor in the selection of the preferred site as all sites in the top 3 were within the threshold of acceptable social and environmental risk levels. Early screening processes prior to selecting the top 3 sites were most material in excluding sites that were considered unfavourable based on social and environmental criteria. As the site selection process progressed, a tailored ranking approach was taken to enable differentiation of sites based on the attributes of the projects in the top 3. Criteria used in the selection of the preferred site were:

### Mandatory Criteria

- Minimum installed capacity (MW)
- No exceedance of IBRM risk threshold (including social, environmental, technical, and financial risk thresholds)

### Selection Criteria:

- Net present value (NPV) of value and costs
- Risk / certainty of outcome – IBRM risks (including social, environmental, technical, and financial)
- Construction schedule
- Flexibility on key parameters (storage and/or power)

## 5.2 HSAP applied to Versetz PSH in Kaunertal Expansion Project (Austria)

The Kaunertal Expansion Project (KXP)[4] underwent an HSAP assessment in 2016, with application of the HSAP's Preparation Stage tool. The KXP is proposed by TIWAG-Tiroler Wasserkraft AG ("TIWAG"), a vertically integrated energy supply corporation owned by the Austrian Province of Tyrol. As of 2016, the KXP preparation activities were well underway and the project had submitted the necessary regulatory approval documentation to the Authority.

The Kaunertal hydropower project was commissioned in 1964, with the Gepatsch storage reservoir in the Kauner valley and the power station 900 m lower at Prutz in the Inn valley. The central feature of the expansion project is a new PSH project located between the new upper reservoir and the existing lower reservoir. It has a head of approximately 600 m and will generate 400 MW and pump 390 MW. The KXP includes a number of complementary investments to increase the catchment yield and augment the downstream power stations, to use the additional water effectively. The main features of the KXP are summarised in Box 1, and the total new capacity from these additions equals 1,015.5 MW.

### The essential features of the KXP

- Inter-basin transfer of water resources from the Ötztal valley, augmenting the catchment area by 272 km²
- A new upper stage reservoir for pump storage located in the Platzertal, with a catchment area of around 8 km2
- Use of the Gepatsch reservoir as the lower stage reservoir for pump storage
- A new underground PSHP (Versetz PSHP) close to the existing Gepatsch reservoir
- A new second power station (Prutz 2) and tailwater basin in Prutz
- Conversion of the old pressure tunnel as an underground conduit for 220 kV high voltage transmission between the Versetz PSHP and the Prutz substation. A new pressure tunnel between Gepatsch and Prutz, the "Prutz Pressure Shaft project", has already been built as a stand-alone project, as an upgrade was required ahead of the timing of the KXP
- Raising of the Runserau weir system for the storage of additional water supply
- A new second power station (Imst 2) in Imst together with a new pressure tunnel between Runserau and Imst and a tailwater basin
- Addition of a third turbine at Haiming Power Station plus enlargement of the tailwater basin.

TIWAG's hydropower upgrade and development program is in line with the Tyrolean government's energy strategies that aim for reduced $CO_2$ emissions and increased energy efficiency, renewable energy generation, and energy security. TIWAG identified the expansion of the Kaunertal power plant as a potential project in 2004, following an extensive evaluation of options for new generation. During the following years, alternative sites and designs for a new upper reservoir in the area surrounding the existing Gepatsch reservoir were identified and evaluated, with the Platzertal emerging as the preferred upper reservoir location in 2011.

The Permit to be issued by the Tyrol provincial government's Department of Environmental Protection ("the Authority") addresses all authorisations required by the project, including the environmental licence, water rights, construction licence, electricity connection permit, and the concession agreement. The Environmental Impact Statement (EIS) submitted to the Authority in July 2012 includes the results of all feasibility studies and the construction and operational plans for the project, in addition to the environmental and social studies. TIWAG submitted an EIS revision in June 2015 as a response to Authority requests, after which the assessment was put on

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[4] https://www.tiwag.at/en/about-tiwag/power-stations/expansion-of-hydropower/our-power-station-projects/the-kaunertal-expansion-project/ See more introductions on TIWAG website: https://www.tiwag.at/en/about-tiwag/power-stations/expansion-of-hydropower/our-power-station-projects/the-kaunertal-expansion-project/

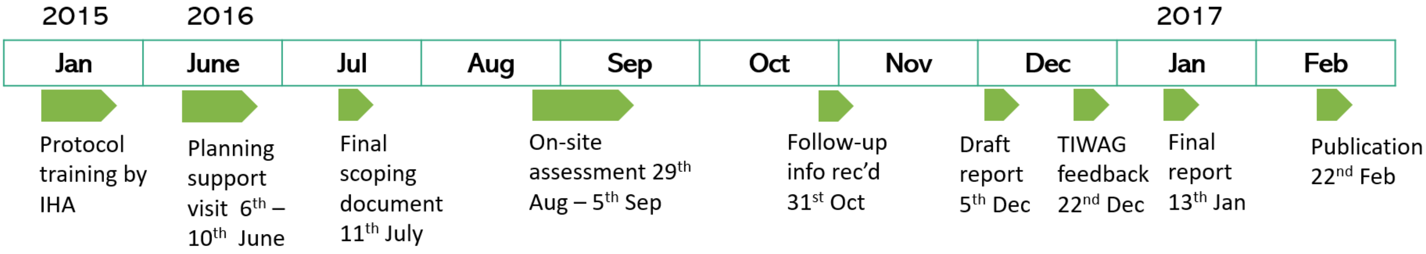
hold while some legal questions relating to water rights in the Ötztal were addressed through the courts. TIWAG commissioned the HSAP assessment during this holding period on the EIS assessment process.

The objectives of the HSAP assessment of the KXP were to:

- identify potential gaps in project sustainability;
- identify areas for improvement;
- communicate with NGOs and other stakeholders;
- get an independent, external perspective of the project; and
- optimise TIWAG planning processes and ensure they are comprehensive.

The assessment was an official assessment according to the Terms & Conditions of Use of the Protocol, with the assessment team members accredited by the Hydropower Sustainability Governance Committee. Leading up to this assessment were two visits, the first to provide an introduction and training on the Protocol to TIWAG (January 2015), and the second to ensure planning activities would be completed in time for the onsite assessment (June 2016). Planning and scoping activities clarified that two of the HSAP topics would be Not Relevant: P-14 Resettlement and P-15 Indigenous Peoples. The assessment timeline is shown in Figure 6.

Figure 6 HSAP assessment timeline for the KXP

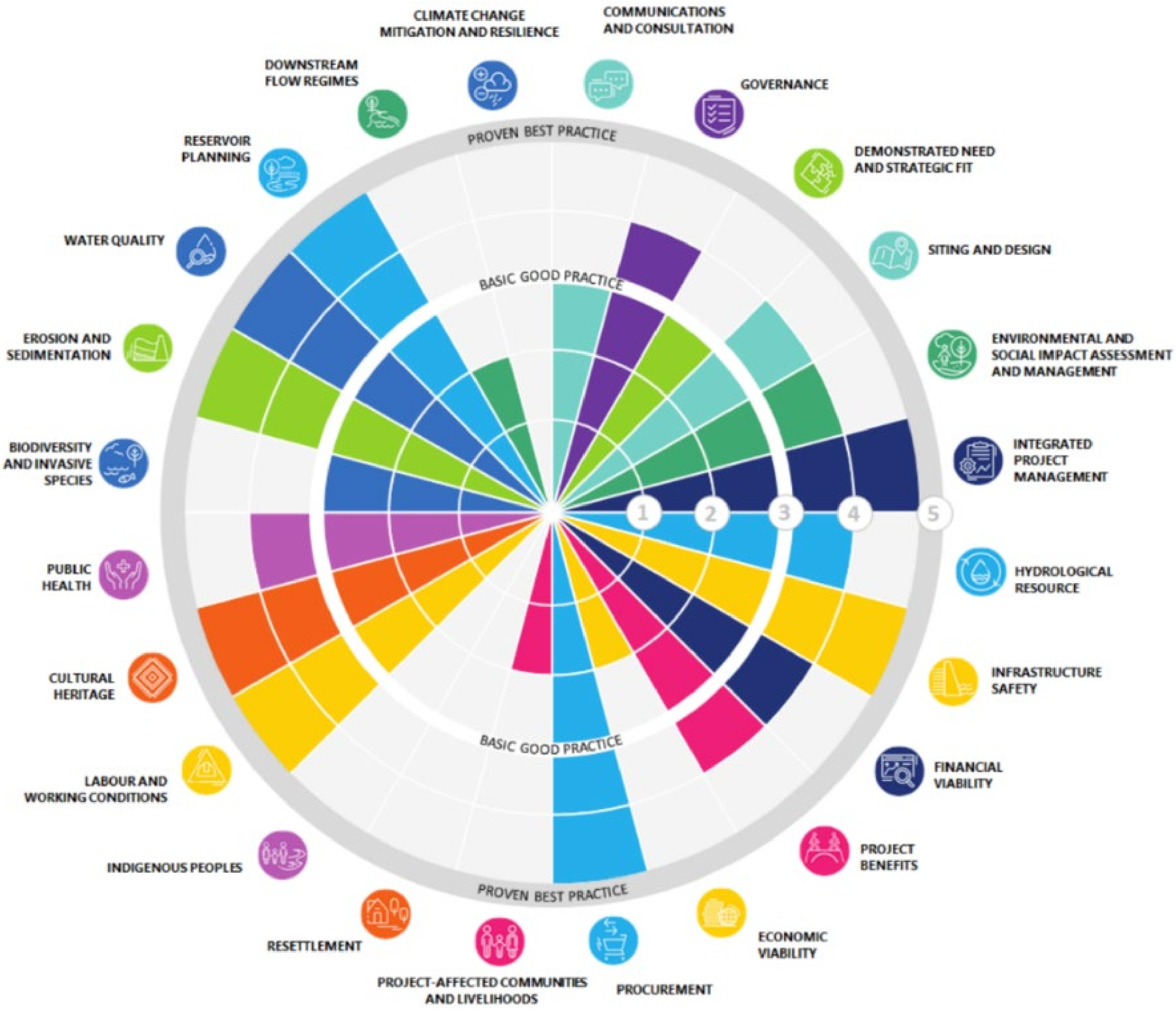


An internet-based document share system was populated with documents relevant to the HSAP topics prior to the arrival of the assessors for the onsite assessment. The assessors also undertook their own internet searches to obtain publicly available information about the project and background issues.

The onsite assessment was undertaken with a team of four Accredited Assessors and one trainee Assessor. The Assessors undertook individual paths of investigations and site visits to ensure the widest coverage in the time available. Interviews and site visits were in Innsbruck, at all locations of project components as well as upstream and downstream locations, in surrounding villages and farming properties, and at locations of some mitigation measures. Interviews were also conducted by phone where face-to-face meetings were not possible. Following the onsite assessment, the assessors submitted 176 questions and document requests relating to issues requiring further clarification. In total, the onsite assessment involved 83 interviews, and 345 items of documentary or web-based evidence were reviewed by the assessors.

With 18 of the 21 topics assessed scored at levels at or above basic good practice, the findings showed that the project met or exceeded basic good practice across many metrics. The use of HSAP also effectively identified gaps in meeting basic good practice with respect to project affected communities, cost benefit analysis and downstream flow regimes, and further work will be required to close these gaps. For a number of topics there was insufficient evidence at this point in time to demonstrate the Outcomes criterion was met.

Figure 7 HSAP assessment outcomes for KXP



18 of the 21 topics assessed scored at levels at or above basic good practice. The project scored highly because TIWAG invested considerably into the preparation of this project, and already had feedback from the Authority on its first EIS submission and via extensive stakeholder engagement.

The three topics scoring below Basic Good Practice were due to:

- Strong opposition to the project amongst some community groups, relevant to topic P-13 Project-Affected Communities and Livelihoods;
- Limitations to the cost-benefit analysis, relevant to topic P-11 Economic Viability; and
- Limitations to information provision to support effective stakeholder engagement regarding Downstream Flow Regimes, topic P-23.

Revised project documentation was submitted to the Authority in December 2017, and a third revision will be submitted in 2021. In the last two years several decisions on water rights have been made by the court, with some still pending. TIWAG aims to start construction of the KXP by the end of 2026; the timing of a final investment decision will depend on market conditions.

The KXP case shows that it may be necessary to also assess system augmentations that may accompany a new PSH proposal. The HSAP assessment shows that the same broad range of sustainability considerations typical for all hydropower projects also apply to pumped storage projects, and the hydropower sustainability tools are well suited for sustainability assessment of PSH.

## 5.3 HSAP applied to Coire Glas PSH (Scotland)

Coire Glas is a proposed PSH scheme with a potential capacity of up to 1500 MW. Being developed by SSE Renewables, it would be the first PSH scheme to be commissioned in the UK for more than 30 years.

Coire Glas, like all PSH schemes, will be a major civil engineering construction project and has an estimated construction time of 5-6 years. A project of this scale has a high initial upfront construction cost but low operational costs and a very long operational life (over 50 years). Of the project's estimated cost of over £1bn more than 70% is in the civil engineering structures. This investment therefore will be spent directly in the UK and specifically in the Scottish Highlands with the associated job and other benefits that will bring.

SSE have been developing the Coire Glas Pumped Storage Project since 2010. In 2020 SSE Renewables was granted planning consent by the Scottish Government in 2021 started engagement with EPC contractors to implement the project.

The project is working on a first base case assumption of a pumped storage hydropower generating facility that will comprise delivery of the following key items:

- A concrete faced rock fill dam 92m high.
- Waterway tunnels of approximately 4km length, approximately 10m diameter (varies).
- Various tunnels to enable plant operation, access, and ventilation.
- A Powerhouse cavern (149m x 24m x 46m) and a transformer cavern (138m x 18m x 24m).
- Four, 50Hz, 360MVA reversible Francis pump turbine units operating at a maximum gross head of 530 m with a rated station discharge (all units) of 331 $m^3/s$ (generating).

The project is to be located in the Great Glen, Scotland, a valley famous for its scenery. Situated 25 km northeast of Fort William, the project would abstract water from Loch Lochy a natural lake (lower reservoir) to a purpose-built upper reservoir, Coire Glas.

### The UK Electricity Market

There are currently four PSH plants in the UK with an installed capacity of 2,800 MW. One of which, Foyers PSH station on Loch Ness, is owned and operated by SSE Renewables. In June 2019, the UK became the first major economy to legislate for a net-zero target for greenhouse gas emissions by 2050. The UK Government is enabling this change and large-scale energy storage is a key enabler of the net-zero target. The Coire Glas project is planned to be one of the enabler projects.

The benefits that the project will bring to the UK electricity network include:

- Providing much needed rotating inertia to help with frequency regulation.
- Dynamic fault current injection for fault protection systems.
- Fast acting and large-scale dynamic load following.

Adding resilience to the system with large 'black start' capacity for re-energization in times of blackout.

## Coire Glas Environmental Impact Assessment

Under Scottish law, SSE Renewables prepared and submitted an Environmental Impact Assessment report for Coire Glas. The core of the EIA assessed the following issues:

| | |
|---|---|
| • Consideration of Alternatives | • Ornithology |
| • Description of Development | • Aquatic Ecology |
| • EIA Approach, Consultation and Scoping | • Fish |
| • Planning Policy | • Geology and Water Environment |
| • Water Management | • Cultural Heritage |
| • Spoil Management | • Traffic and Transport |
| • Landscape Character | • Noise |
| • Visual Amenity | • Air Quality |
| • Terrestrial Ecology | • Land Use and Recreation |
| • Forestry | • Socio-economic |

The primary issues considered by the Scottish Ministers in their decision were:

- Environmental impacts of the proposed development, in particular the landscape and visual impacts, and the impacts of rock removal and the management of spoil on transport and local communities during the construction phase,
- The estimated economic benefits which the proposed development is likely to bring,
- And the extent to which the proposed development accords with and is supported by Scottish Government policy.

The Scottish Ministers concluded positively and granted permission. The Ministers were satisfied that any remaining environmental issues can be appropriately addressed by the mitigation measures set out in the EIA Report and secured by conditions attached to the consent.

## Coire Glas Implementation

SSE Renewables in early 2021 began engaging with contractors and suppliers for implementation of the project. As the HST tools were developed over the period and parallel to the development of this project, the project has not been subject to an HSAP assessment. Recognizing the importance of such tools, SSE Renewables intend to embark on an assessment in accordance with the Implementation stage of the tool's lifecycle. This assessment will be used to benchmark the EIA to the HSAP and identify any gaps needed to be expanded on for assurance of possible lender and financers.

## 5.4 HSAP/HESG applied to Grand'Maison PSH adaptation project (France)

Located in the French Alps, Grand'Maison embankment dam on the Eau d'Olle river is Europe's largest PSH facility, and is owned and operated by EDF Hydro. The dam was constructed between 1978 and 1985 with its power station being commissioned in 1986 with an installed capacity of 1,800 MW. The power station repeats the pumped-storage process as needed and acts as a peaking power plant. The headwater and tailwater reservoirs feature 150 million $m^3$ and 15 million $m^3$ capacity, respectively. In addition to the eight pump turbine units, the station is equipped with four conventional Pelton units, which are being uprated to 170MW (from 150).

Power generation or pumping can be initiated within minutes. On an annual basis, the power station generates 1,420 GWh of electricity and consumes 1,720 GWh in pumping mode.

XFLEX HYDRO is an €18m energy innovation project that aims to demonstrate how more flexible hydro assets can help countries and regions to meet their renewable energy targets. The four-year, EU-funded project involves seven demonstration projects, 19 organisations and will conclude in 2023.

One of these demonstration projects focuses on the Grand'Maison dam. XFLEX HYDRO is an ambitious energy innovation project demonstrating how flexible hydropower technologies can deliver a low-carbon, secure, and resilient power system.

Grand'Maison PSH facilities have been chosen to demonstrate the simultaneous use of very high-head pumps and Pelton turbines, and corresponding enhancement of flexibility services for the power system, thanks to an innovative system integration of hydraulic short circuit technology – an operating mode named 'REVERSE'. According to a fully automatic optimisation algorithm, while the pumped storage plant is globally in pumping mode, a Pelton turbine regulates the overall load based on grid frequency support signal. After 2 years of intensive preparation, REVERSE mode will be commissioned in summer 2021.

It is proposed that the HSAP/HESG assessment should not be limited to the changes, impacts, and spill-over effects of the XFLEX hydro programme and new REVERSE mode. As the external changes to the structure induced by the flexibilization programme are moderate, it would be appropriate to complete the evaluation approach by looking at the entire infrastructure in operation.

It could be especially interesting to assess:

- The monitoring of the resettlement and its legacy years after the construction: if necessary, the consequences of a resettlement carried out according to the lesser criteria of the time of construction;
- Affected activities and communities and their management: on substance (issues and stakes) and form (contract, partnership, agreement, etc.);
- Governance, especially with the economy and tourism stakeholders.

Due to time and resource constraints, we do not necessarily recommend a full formal assessment with an external assessor.

We recommend a lighter version of the assessment tools, using internal assessors. We also propose to focus on only 3 to 5 topics per case study, choosing each time the topics that are most appropriate and representative for each site.

## 5.5 LCA applied to PSH projects: synthesis of case studies

### Conventional LCA

### *Use of LCA at different lifecycle stage of a project*

As seen in section 0, LCAs can be conducted on PSH technologies as long as they comply with the ISO 14040-44 standards. The main differences between these LCAs rely on the quality of the available data for the ISO "inventory" phase of the LCA: the more advanced the project, the more reliable the data and therefore the results.

LCA can be used to test different technological options (among a list of potential technologies adapted to a given service to be provided to the system), to compare their potential impacts on the environment. This can be done at a very early stage of the project. At a later stage of the project, during implementation for instance, LCA can help choose the most environmentally virtuous materials and processes to be used.

### *Literature review on LCA research for PSH*

A synthesis of the main literature research results on PSH LCA is presented in ANNEX D. The list of references is not exhaustive and some additional sound information can be found in other publications, like in Flury & Frischknecht (2012)(1).

Special attention should be given to the hypotheses of each study. In order to be comparable, LCA results should relate to identical functional units, system boundaries, and environmental impact categories and indicators. Since PHS facilities are very site specific, this is seldom the case (for example, PSH storage capabilities and operational characteristics are usually different from one site to another).

This literature review shows that the main parameters influencing PSH LCA results are:

- the electricity mix used for pumping (through its environmental impacts)
- the round-trip efficiency (RTE) of the PSH plant (balance of generation and pumping efficiency) (note that for open loop PSH, the additional input of water from tributaries in the upper reservoir may be considered as an enhancement of the round-trip efficiency)
- the operational hypotheses, mainly the total amount of energy delivered by the storage facility over its lifetime.

The LCA environmental impacts of a PSH facility are basically a combination of the LCA environmental impacts of the construction and decommissioning phases of the facility, and of its operation and maintenance phase, which in particular includes the pumping energy. Depending on the electricity mix used for pumping, the equilibrium between these two components varies. The construction and decommissioning phases of the facility drive most of the environmental impacts when the electricity mix used for pumping comes with little environmental impacts. In that case, civil-engineering materials and electro-mechanical components are the largest factors to consider for the construction phase. The environmental impacts of the operation and maintenance phase are mostly driven by both the environmental characteristics of the electricity mix used for pumping and the round-trip efficiency of the plant.

In a country with many sources of electricity generation with contrasted GHG emissions (low vs high emissions), the use of the "average" mix can be questionable as the pumping can be favoured/focused during periods of low GHG emissions (windy periods for instance, or when taking surplus generation from nuclear power plants during the night). Nevertheless, this level of analysis is generally not considered in ISO 14040-44 standards (average mix is preferred).

### *Comparison to other storage technologies*

As stated above, one must be very cautious when comparing LCA results. As an illustration, Figure 8 shows the influence of the charging mix and the round-trip storage efficiency on LCA results for two storage technologies: PSH and Li-ion batteries (LIB). These results are based on simplified LCA models for two hypothetical but realistic 100 MW storage system, providing 32 GWh each year:

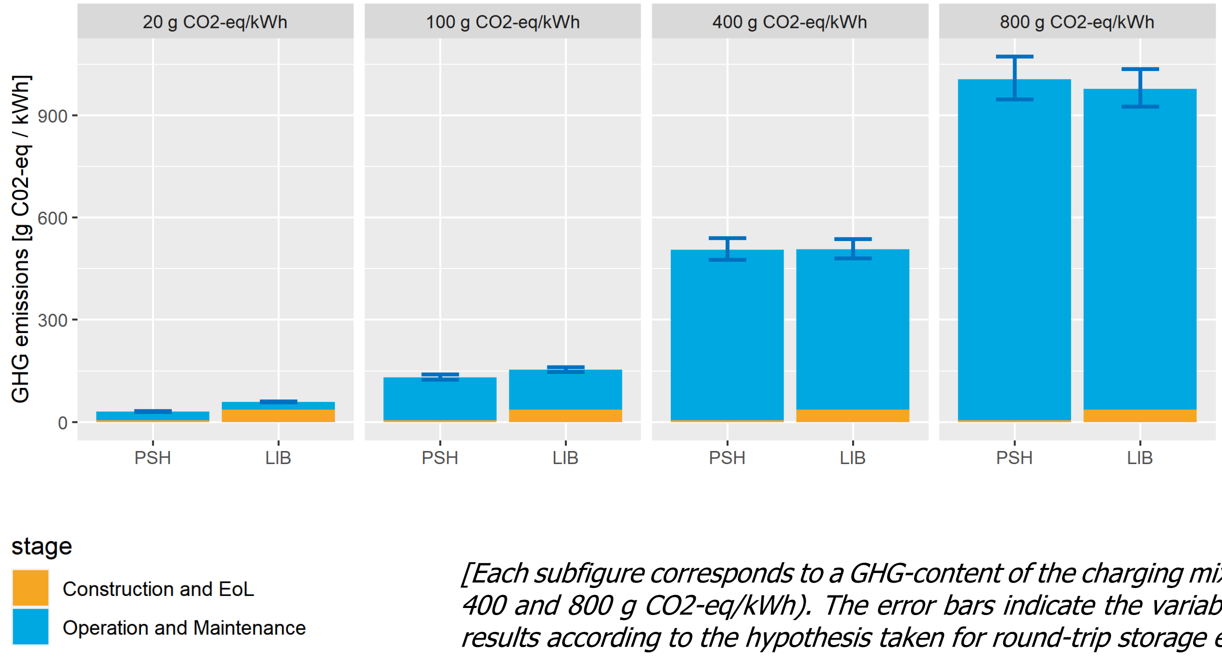
- a PSH model derived from the Ecoinvent database;
- an in-house LIB model based on real data from battery energy storage systems.

On one hand, GHG emissions due to the construction and decommissioning (End of Life, EoL) phases do not depend on the charging mix nor on the system efficiency: they are the same whatever the charging mix considered. These emissions are more important for Li-ion batteries storage systems than for PSH.

On the other hand, GHG emissions due to operation and maintenance strongly depend on the charging mix: the higher the GHG-content of the charging mix, the higher the GHG-emissions of the operation stage and the lower the impacts of the construction and decommissioning stage in proportion. The efficiencies of the storage systems also influence the results as shown by the variability ranges in Figure 8.

This theoretical example illustrates the fact that LCA results, including the comparison between storage systems, depend on assumptions regarding operation. Such analysis can be extrapolated to other storage technologies and to other LCA indicators (such as particulate matter emissions, resource depletion, etc.).

Figure 8 Influence of the GHG-content of the charging mix and of the round-trip storage efficiencies on the life-cycle GHG emissions per kWh generated for 2 storage technologies: PSH and LIB – Source: EDF R&D.



*[Each subfigure corresponds to a GHG-content of the charging mix (20, 100, 400 and 800 g CO2-eq/kWh). The error bars indicate the variability of the results according to the hypothesis taken for round-trip storage efficiencies (75% to 85% for PSH and 80% to 90% for LIB)].*

As discussed above, this theoretical example does not consider potential key differences between storage facilities characteristics and capabilities. It enlightens the fact that LCA could be a very efficient and useful tool to compare several options pre-selected to provide a similar service to the system.

## GHG emissions from reservoirs

**While the hydropower profession has now large experience and database of GHG emissions from conventional hydro reservoirs, there is almost no specific values of GHG specific to PSH reservoirs.** Nevertheless, based on current understanding, we may hypothesise that GHG emissions from PSH reservoirs should not be significantly different from conventional hydropower reservoir.

Some values and ranges from the literature (especially IPCC, AR5) for conventional Hydro Are as follows:

- Emissions of biogenic CH4 result from the degradation of organic carbon primarily in hydropower reservoirs (Tremblay et al., 2005; Barros et al., 2011; Demarty and Bastien, 2011), although some reservoirs act as sinks (Chanudet et al, 2011). Few studies appraise net emissions from freshwater reservoirs, i. e., adjusting for pre-existing natural sources and sinks and unrelated anthropogenic sources (Kumar et al, 2011).

- A recent meta-analysis of 80 reservoirs indicates that $CH_4$ emission factors are log-normally distributed, with the majority of measurements being below 20 $gCO_{2eq}$ / kWh (Hertwich, 2013), but gross emissions of approximately 2 $kgCO_{2eq}$ / kWh coming from a few reservoirs with a large area in relation to electricity production and thus low power intensity (W / m2) (Abril et al., 2005; Kemenes et al., 2007, 2011).
- The global average emission rate was estimated to be 70 $gCO_{2eq}$ / kWh (Maeck et al., 2013).

The median worldwide value for conventional hydropower is around 23-24 $gCO_{2eq}$ / kWh (source: IHA/IPCC). **Due to the high variability among power stations, the average emissions rate is not suitable for the estimation of emissions of individual countries or projects**. The preferred approach is to calculate the power density (W/m²) and use a specific assessment with the G-res tool (guidance to come) for projects with power density below the criteria.

### Main outcomes from LCA approach to PSH

LCA applications to PSH technology and projects are still quite recent and have been mainly conducted in the research domain. They provide interesting outcomes but specific attention must be given to the boundaries and functional units of the power system to avoid misleading conclusions:

- LCA cannot be used as unique self-sufficient sustainability tools to assess sustainability performance of a storage technology and project;
- LCA does not consider some Environmental impact aspects that must be covered by global EIA / ESIA methodology specific to hydro and PSH projects (e.g. impacts on Fish population);
- PSH technology projects do quite well with respect to Construction & Decommissioning phases (LCA GWP scores per kWh generated);
- The environmental impact of consuming energy during storage (pumping) phase: the use of an "average" energy mix must be cautious as the pumping energy can be absorbed during periods of low or high GHG emissions, indeed it is clear that the main driver for new PSH projects is the increased penetration of VRE (see WG.1's report), and as such it is to be expected that they will mainly pump during times of excess VRE generation with correspondingly low GHG emissions;
- GHG emissions from reservoirs of a PSH project should be similar to conventional hydro and the same criteria/tools should be used. In the cases where the power density does not exceed 5 $W/m^2$, a specific evaluation of GHG emissions might be considered.

## 5.6 CEDREN studies on existing reservoirs retrofit to PSH (Norway)

Within the Centre for Environmental Design of Renewable Energy - CEDREN research centre - in Norway (www.cedren.no), several research activities, studies and publications addressed the potential for retrofitting existing pairs of reservoirs with increased power capacity as well as additional pumping capacity. The studies include technical, economical, market, environmental and social aspects of increasing the capacity in Norwegian hydropower with 20GW additional capacity (8). Discussion topics included the major potential environmental impacts from adding increased generation and pumping capacity to hydropower facilities using existing reservoirs both as lower and upper reservoir. New patterns of filling and emptying reservoirs will most likely occur, increasing daily or short-term fluctuations in water level. This may result in altered stratification patterns, i.e. the water temperature pattern, affecting growth of species, life cycles of organisms, water quality and ice cover. Reduced ice cover may have effects on fish behaviour leading to increased energy expenditure and reduced winter survival. Another consequence of the water level fluctuations is increased risk of bank erosion, caused by relatively rapid changes in pore water pressure. However, the main conclusion is that effects may vary depending on location, operation, and local conditions. There is a possibility of also improving the environmental conditions in some reservoirs that are heavily impacted today.

## 5.7 Local benefits of PSH Projects

In recent years, the sharing of benefits with local communities has become an increasingly important issue for hydropower developers and operators. Projects were traditionally justified with economic and technical advantages at the national or power grid levels, without much consideration of advantages for directly affected communities. This approach has come to be seen as not just unfair, in terms of who will benefit and who will bear negative impacts, but also counterproductive as it can cause local opposition, conflicts and delays.

Not all the impacts of construction and operations on local communities can be fully mitigated or compensated. Local acceptance thus requires an intention, commitment and conscious effort at identifying and delivering additional local benefits. Benefit sharing is best understood as "a package of deliberate measures taken by hydro developers that allow local communities to share benefits from a hydro project, over and above required mitigation measures" [5].

There is now a growing number of reference materials and sources on good and best practices as well as case studies for hydropower projects [6]. Local benefits are often quite country- and project-specific, reflecting the wide range of project types and local conditions. Expectations regarding local benefits are likely to increase over time, and developers and operators should understand the available options. These fall into the following categories:

- Financial mechanisms such as taxes, royalties and fees, equity shares and development funds, all leading to revenue sharing or shared ownership
- Helping build capabilities of local institutions
- Workforce training and local employment
- Local procurement
- Livelihoods development
- Social services
- Economic infrastructure
- Electrification and electricity subsidies
- Reservoir use and operational management

Local benefits can be one-time or permanent, and can be built into the original siting, design and operational decisions, or identified at a later stage. Benefits should be commensurate with the scale of impacts and scale of generation and revenue from a project. Directly affected communities should be priority recipients of benefits. No type of hydropower project is going to deliver benefits without deliberate intent, planning, commitments, risk management, and ongoing monitoring to ensure benefit delivery.

Most of the general experience on benefit sharing and the resulting principles, categories, and methods are applicable to PSH projects. As for other hydropower projects, their main objectives and benefits – such as the balancing of the power grid – are regional or even national in scale. Local communities may not even be connected to power grids yet, and even if they are, would only receive a small share of these benefits.

There are a small number of potential benefits that are specific to PSH projects, or impossible for PSH projects to deliver. In general, because PSH involves two reservoirs, there are more focal areas for potential local impact (both positive and negative), and these and the associated local stakeholders need to be very systematically considered.

Closed-loop PSH have very limited ability to provide any secondary benefits from use of the reservoirs. In general, strong water level fluctuations and other operational constraints can limit the value of any PSH reservoirs for other purposes, such as for flood control or recreation. However, there are some cases where PSH reservoirs do have additional benefits. The lower reservoir of the Waldeck I and II PSH projects in Germany, for example, is a protected area because of its value for migratory water birds, as the reservoir does not freeze over in winter. This fact as well

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[5] https://www.commdev.org/pdf/publications/Hydro_Benefit_Sharing_Key_Insights_FIN.pdf

[6] For two recent examples, see https://www.hydropower.org/publications/hydropower-benefit-sharing-how-to-guide and https://www.commdev.org/publications/capturing-hydropowers-promise-case-studies-on-local-benefit-sharing-in-hydropower-projects/

as the cable-car between the lower and upper reservoirs, operated by the Hydropower Company and open to the public, increases the attractiveness of the area, which is strongly dependent on tourism.

Some PSH projects may be able to provide solutions for pre-existing problems. Projects that use abandoned open-pit or underground mines, quarries and similar ‘brownfield’ sites may help a community recover from previous land uses. A number of such PSH projects are already operational (such as the Dinorwig scheme in the UK), and many more are in different planning stages. The conversion of conventional hydropower to PSH, which is being considered for many projects, also offers opportunities. These include in some cases a simple life extension – with the resulting benefits in terms of continued jobs and local taxes, for example – and in other cases an opportunity to re-consider design and operations, to deliver enhanced local benefits.

If combined with variable renewables, small PSH projects may also enable a reliable, independent, and sustainable power supply for communities, including on islands and in other off-grid situations. Also, because of its siting flexibility compared to conventional hydropower and open-loop PSH, closed-loop PSH can reduce the length of transmission lines needed to connect the project to demand centers, thereby reducing local impacts to land use and ecological, cultural, and visual resources.

Pumped Storage Hydropower International Forum

Sustainability Working Group

# Chapter 6

# Recommendation

a) A massive increase in energy storage will be needed to move towards a net zero carbon future, and PSH, along with other storage technologies, should be considered as key enablers of this transition, in the trajectory toward clean energy systems.

b) The determination of PSH project sustainability should rely on a multi-level approach:
   - *System-level needs*: determine what are the storage, flexibility and ancillary services that a given power system needs / will need in a long-term planning perspective;
   - *Options assessment*: identify global options that would meet energy storage, flexibility, and ancillary services, based on the characteristics of services that can be provided by energy storage; combined with system-level assessment, define a **strategic trajectory** of energy storage and PSH development to be implemented depending on needs and storage solutions/technologies possibilities;
   - *Project optimization:* select PSH project configuration and technical options that would result in the "best" sustainable PSH project to avoid, minimise, and mitigate social and environmental impacts.

c) PSH projects are very site-specific, and sustainability cannot be reduced into a simplistic classification. Some key factors to consider for options assessment and project optimisation are listed in this report, to lead to an overall integration of the project into a given site configuration with associated environmental functions and sensitivity, safety issues, and social aspects, with an intent to avoid, minimise, and mitigate impacts.

d) Existing sustainability tools for hydropower (e.g. the HST suite developed by IHA and other stakeholders) are adequate for PSH technology and projects assessment, and are recommended sometimes with few adaptations which can be inspired from case studies given in chapter 5 – for example: the potential to improve HESG risk screening tools for Early Stage phase.

e) LCA applications to PSH technology and projects are still quite recent and have been mainly conducted in the research domain. They provide interesting outcomes but specific attention must be given to the boundaries and functional units of the power system to avoid misleading conclusions. There is no evidence to suggest a material difference in GHG emissions from PSH reservoirs compared to those from conventional hydropower reservoirs which, on average , fall between those of wind and solar power. – see outcomes in Section 0.

f) PSH projects, as many Hydropower projects, can generate one-time or permanent local benefits of various nature, which must be considered, studied and valued in their sustainability profile assessment.

All these conclusions and recommendations have to be articulated with those coming out from WG.1 and WG.3 propositions, probably through an overarching integrated IFPSH report, as many sustainability issues like economic viability, financial feasibility, etc. interact with those investigated by the other WGs.

## SOME REFERENCES & INFORMATION RESOURCES

(1) Flury K., Frischknecht R. (2012). Life-cycle inventories of Hydroelectric Power Generation. ESU-Services Ltd.
(2) Hydropower Sustainability Tools: Guidelines, Protocol, Gap Analysis and How-to-guide - https://www.hydrosustainability.org/
(3) International Energy Agency (2000). Hydropower and the Environment: Present Context and Guidelines for Future Actions, IEA Technical Report,Volume II, Main Report, 172 p.
(4) International Energy Agency (2021). Hydropower Special Market Report.

(5) Palmer, G. (2017). A Framework for Incorporating EROI into Electrical Storage. Biophys Econ Resour Qual 2, 6 (2017). https://doi.org/10.1007/s41247-017-0022-3

(6) IHA G-res tool website (https://g-res.hydropower.org)

(7) Le Varlet T., Schmidt O., Gambhir A., Few S., Steffell I. (2020). Comparative life cycle assessment of lithium-ion battery chemistries for residential storage. The Journal of Energy Storage, April 2020. DOI: 10.1016/j.est.2020.101230

(8) Harby A., Sauterleute J., Korpås M., Killingtveit Å., Solvang E. and Nielsen T. (2013). Pumped storage hydropower. In *Stolten, D. and Sherer, V. (eds) 2013: Transition to Renewable Energy Systems. Wiley-VCH*. Pp 597-618.

See also additional references given in the following Annexes.

# ANNEX A

## Additional information on additional initiatives addressing Hydro and PSH projects sustainability

We provide here a non-exhaustive list of additional regional, national or international initiatives also addressing the issues of sustainability criteria, standards proposition, or equivalent consideration to sustainability appreciation which can be more or less applied to Hydro and/or PSH projects.

**Low Impact Hydropower Institute (LIHI) certification (US)**: https://lowimpacthydro.org/

The Low Impact Hydropower Institute (LIHI) is an independent, non-profit organization in the US that certifies hydro projects on a series of factors, not only restricted by size or specific operational parameters alone, but covering:

- *Ecological flow regimes* that support healthy habitats
- *Water quality* supportive of fish and wildlife resources and human uses
- Safe, timely and effective upstream and downstream fish passage
- Protection, mitigation and enhancement of the soils, vegetation, and ecosystem functions in the watershed
- Protection of *threatened and endangered species*
- Avoidance of impacts on *cultural and historic resources*
- *Recreation access* is provided without fee or charge

The LIHI certification program was established to enable US Hydro projects to be granted and comply with the Renewable Portfolio Standard (RPS) requirements in some US states energy policies. So far, a list of more than 170 Hydro projects have been certified, with a large variety of sizes and configurations (https://lowimpacthydro.org/certified-facilities/).

**HydroWIRES (Water Innovation for a Resilient Electricity System)**

The mission of the HydroWIRES (Water Innovation for a Resilient Electricity System) Initiative is to understand, enable, and improve hydropower's contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. Covering all grid reliability, resilience, and grid integration within WPTO's hydropower portfolio, work conducted under HydroWIRES is organized under four interrelated research areas:

1) Value under Evolving System Conditions
2) Capabilities and Constraints
3) Operations and Planning
4) Technology Innovation.

While WPTO has historically focused on technology solutions to drive down the cost of hydropower development and support the expansion of the sector, HydroWIRES adds a complementary focus on hydropower's role as an integrator of variable renewables. The central hypothesis of HydroWIRES is that, as the electricity system undergoes rapid changes, the U.S. hydropower fleet is well-positioned to take on this new role by offering:

- Additional value streams
- Enhanced flexibility
- New operational strategies
- Innovative technology solutions.

WPTO works closely with a group of DOE National Laboratory researchers to both plan and implement projects under each research area to address hydropower industry challenges.

## Academia and NGO's recommendations and publications (TNC, WWF)

Several recent papers suggest the potential for pumped storage hydropower can be a useful and beneficial part to an integrated renewables-based electricity system. This is because of its ability to provide long-duration energy storage and the importance of energy storage in some geographies for shoring up the intermittency of solar and wind. Like all major infrastructure projects, the environmental and social impacts of a pumped storage hydropower project will be dependent on how a facility is sited, designed, constructed operated and decommissioned. These and other key variables need to be compared with other economically viable storage options. One of these papers emphasizes the importance of evaluating and selecting PSH projects using multiple options assessments at the system-scale:

- Opperman, J., J. Hartmann, M. Lambrides, J.P. Carvallo, E. Chapin, S. Baruch-Mordo, B. Eyler, M. Goichot, J. Harou, J. Hepp, D. Kammen, J. Kiesecker, A. Newsock, R. Schmitt, M. Thieme, A. Wang, and C. Weber, 2019. Connected and flowing: a renewable future for rivers, climate and people. WWF and The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_ConnectedFlowing_Report_WebSpreads.pdf

System scale energy planning involves conducting early assessments to evaluate the potential outcomes of cross-sector and stakeholder values that result from alternative energy development scenarios. This approach compares the results for energy generation, financial performance, and environmental and social values that are affected by different combinations of siting and operations of potential wind, solar, hydropower and energy storage facilities (including pumped storage and battery storage). This approach has been applied in North America, South America, Africa, and Asia to illustrate the opportunities to meet energy needs, generate positive financial performance, and cause the least impacts to people and nature. Examples below illustrate the potential benefits of system-scale energy planning:

- Wu, G.C., E. Leslie, D. Allen, O. Sawyerr, D. Cameron, E. Brand, E. Cohen, B. Ochoa, M. Olson. Power of Place. Land Conservation and Clean Energy Pathways for California, 2019. The Nature Conservancy, Sacramento, CA.
- Opperman, J., G. Grill and J. Hartmann, The Power of Rivers: Finding balance between energy and conservation in hydropower development. 2015. The Nature Conservancy: Washington, D.C. https://www.nature.org/media/freshwater/power-of-rivers-report.pdf
- Opperman, J., J. Hartmann, J. Raepple, H. Angarita, P. Beames. E. Chapin, R. Geressu, G. Grill, J. Harou, A. Hurford, D. Kammen, R. Kelman, E. Martin, T. Martins, R. Peters, C. Rogéliz, and R. Shirley. 2017. The Power of Rivers: A Business Case. The Nature Conservancy: Washington, D.C. https://www.nature.org/content/dam/tnc/nature/en/documents/powerofriversreport_final3.pdf
- The Nature Conservancy, 2020. *A System-Scale Analysis of Hydropower Development Opportunities in the Coatzacoalcos River basin: Applying Hydropower by Design to evaluate trade-offs of alternative development scenarios*. Submitted to the Inter-American Bank as a report of work and products conducted under Contract RG-T2936-P001. The Nature Conservancy, Arlington Virginia, 196 pp. (Can make available on a web site)
- The Nature Conservancy, WWF, and the University of Manchester. 2016. Improving hydropower outcomes through system-scale planning: an example from Myanmar. Prepared for the United Kingdom's Department for International Development. 2016. Arlington, Virginia, USA. https://www.nature.org/content/dam/tnc/nature/en/documents/System-ScalePlanning_Myanmar_Report.pdf

## Project Level Tools

At the project level, there are sources available that have evaluated the potential social and environmental impacts from pump storage facilities. These sources offer tools and approaches for evaluating E&S impacts.

- Saulsbury, B. 2020. A Comparison of the Environmental Effects of Open-Loop and Closed-Loop Pumped Storage Hydropower. Hydrowires. US Department of Energy. PNNL-29157.

https://www.energy.gov/sites/prod/files/2020/04/f73/comparison-of-environmental-effects-open-loop-closed-loop-psh-1.pdf

- Pittock, J. 2019. Pumped-storage hydropower: trading off environmental values? Australian Environment Review. 95-200.
- Normyle, A., Pittock, J. 2019. A review of the impacts of pumped hydro energy storage construction on subalpine and alpine biodiversity: lessons for the Snowy Mountains pumped hydro expansion project, Australian Geographer, DOI:10.1080/00049182.2019.1684625
  https://doi.org/10.1080

**Other investment guidelines (insurance companies)**

Major insurance companies investing into other companies as shareholders have established among their strategic principles the so-called "Corporate Responsibility" Principles and/or signed "the United Nations Principles for Responsible Investment (PRI)" and/or the UNEP "Principles for Sustainable Insurance (PSI)".

In consideration of these principles, they apply Responsible Investment Policies. Their investment decisions by following these principles are a considerable driver for the industry towards the use of sustainable technologies.

# ANNEX B

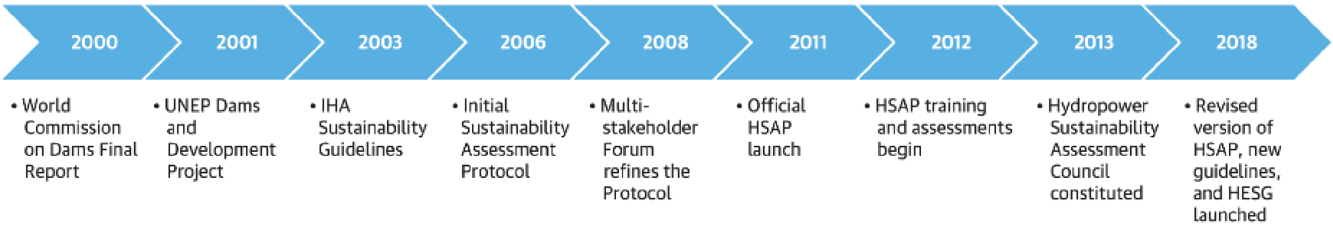
## Information on governance, history, evolution, and quality control of Hydropower Sustainability Tools (HST)

**Reputation, quality, and credibility of HST**

The HST are governed by a multi-stakeholder body, the Hydropower Sustainability Assessment Council (https://www.hydrosustainability.org/council). The Council includes representatives of social, community and environmental organisations, governments, commercial and development banks, and the hydropower sector. This inclusive approach to governance ensures that all stakeholder voices are heard in the shaping of the use of the HST.

The HSAP is the product of a transparent dialogue convened by the multi-stakeholder Hydropower Sustainability Assessment Forum (HSAF) over the course of a decade. The forum was tasked with recommending enhancements to IHA's assessment tool, which had been developed in response to the findings of the World Commission on Dams Report, to provide a standardized means of assessing the sustainability of hydropower projects.

### Evolution of the Hydropower Sustainability Tools



The IHA acts as management entity to the Council and is responsible for overseeing training and accreditation and co-ordinating governance activities.

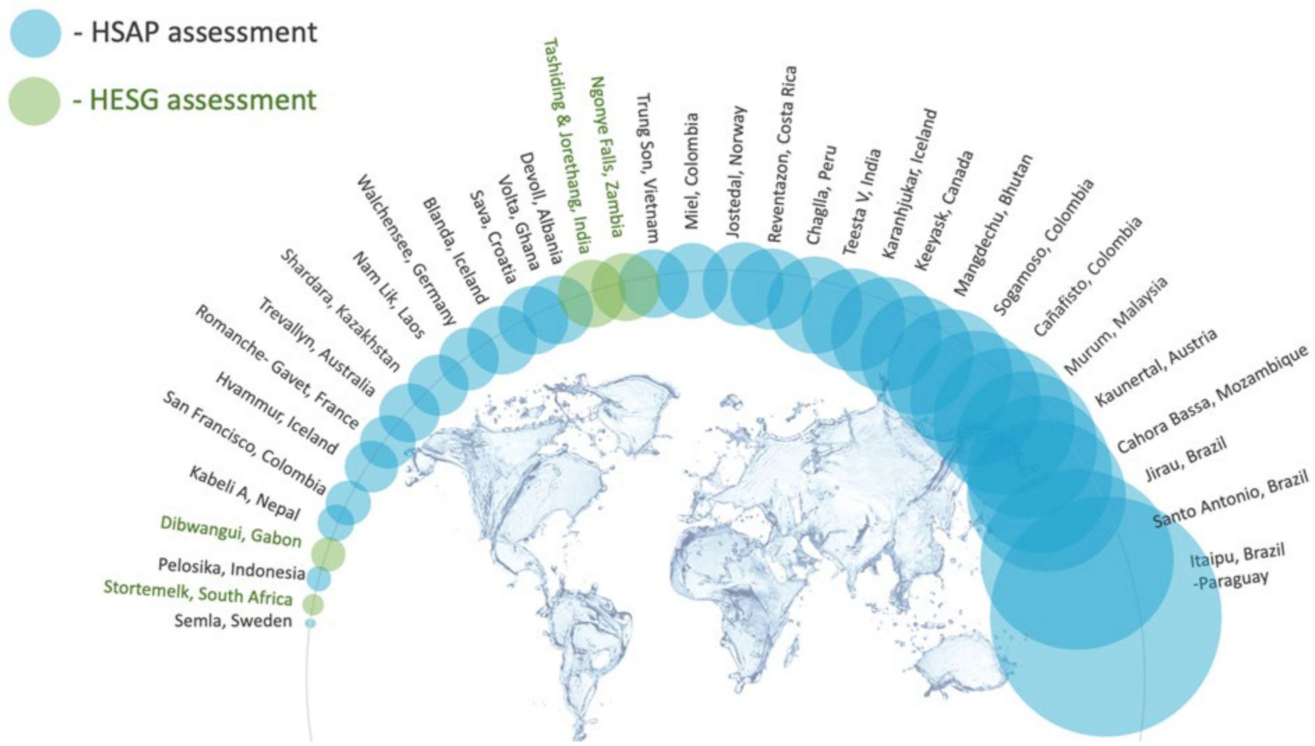
### Hydropower Sustainability Governance Committee

**Assessing a project**

Assessments by accredited "assessors" are independent evaluation of a hydropower project, through a comprehensive and systematic evidence-based approach. In practical terms, objective evidence is collected during an assessment to understand how well a project is performing. Visual, verbal and written evidence is collected by conducting interviews, visiting project location and affected communities and reviewing relevant documentation.

Assessments can examine hydropower projects of any type, and throughout different stages of a project's life-cycle, including: early-stage, preparation, implementation and operation.

Diagram of official assessments



For an overview of an assessment process, please visit the directory of published assessments www.hydrosustainability.org/published-assessments

## Quality control and transparency

Official assessments are exclusively carried out by Accredited Assessors to ensure the highest quality and rigour in the assessment process. Using Accredited Assessors in assessments allows for independent review of a project's performance.

All assessors are accredited by the Hydropower Sustainability Assessment Council. These professionals have significant experience in the hydropower sector and in relevant sustainability issues. Accredited assessors have appropriate auditing qualification in line with ISO 19011, have completed 40 hours of training in EMS, health and safety or social auditing, and have at least six years of auditing experience.

Assessments are undertaken following the principles of independence and transparency. Published assessment reports are required to undergo a 60-day public consultation period during which the general public can make comments on the report. Assessors need to address each comment before submitting the final report.

Official assessments must comply with the requirements in the Terms and Conditions for Use, which can be found on https://www.hydrosustainability.org/sustainability-tools.

# ANNEX C

## Additional information on LCA methodology

### LCA methodology

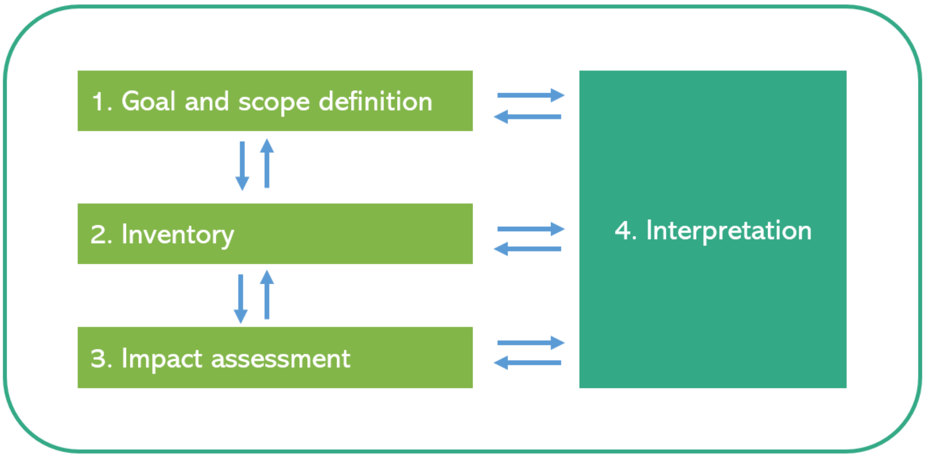
Life Cycle Analysis (LCA) is a standardized methodology (mainly through the ISO 14040 and ISO 14044 standards) widely used by the international scientific community and by engineering and consultancy business units to assess the environmental performances of products / services throughout their entire life cycle.

LCA is a product / service approach that considers:

- Every life cycle stage of the product / service under analysis, from the raw material acquisition stage through the production of the product / service, its use, end-of-life treatment, recycling, and final disposal - therefore the expression "cradle-to-grave" is usually used when including all of these stages in the system boundary. Other system boundaries using fewer stages are also possible.
- Several environmental impacts and indicators – see below for more details.

According to ISO 14040-44 standards any LCA shall be conducted through 4 mandatory and interlinked phases as schematized in Figure 9.

Figure 9 . The four phases for conducting an LCA as specified by the ISO 14040-44 standards



*First phase - Goal and scope definition:* applying the LCA standardized methodology requires to make several important choices regarding the scope of the analysis. Such choices are listed in the standards, but no indication is given as to exactly what to choose, since it depends on the goal of the analysis. Nevertheless, the ISO standards ask practitioners to clearly state and justify their choices. Different choices leading to different LCA results, this first phase of an LCA is therefore of great importance.

In particular, special attention must be given to the following two topics:

- The operational characteristics of the analysed system are defined through its **functional unit**: what service does the system provide? How much? How well? How long?
- The **boundaries** of the considered system need to be clearly stated. Especially, since LCA is supposed to take into account every life cycle stage of the product / service, when something is omitted, this needs to be duly justified.

*Second phase – Inventory:* Data concerning material and energy consumption, emissions into air, water and soils, production of co and by-products which are within the system boundaries need to be collected. Some cut-off rules are generally used to avoid collecting data with little impacts on the results. This LCA phase is generally the most challenging one.

*Third phase – Impact assessment:* Environmental impact indicators are computed, using LCA databases and impact assessment methods. Common environmental impact categories considered in LCA include: climate change, ozone depletion, particulate matter, photochemical ozone formation, acidification, eutrophication, resource depletion, human toxicity, etc. The purpose of an LCA is to obtain insight on the impacts of a product / service with regards to different environmental concerns, since each of them may reveal different valuable information, it is important to consider several environmental impact categories.

*Fourth phase – Interpretation:* The computed values of the environmental impact indicators and the way the different life cycle stages of the product / service, the materials, the energies used… are contributing to these values are analysed in order to determine what are called the "hot spots" of the product / service: the parts / stages that drive most of the environmental impacts of the product / service. Finding ways to decrease the environmental impacts of the "hot spots" of the product / service can be done afterwards within an eco-design process.

**N.B.**: in addition to the ISO 14040-44 standards, some guidelines already exist that can be used for hydroelectricity and PSH LCAs:

- At the European level, the ILCD handbook (https://eplca.jrc.ec.europa.eu/ilcdHandbook.html) offers a set of general documents designed to help companies to compute LCAs on any type of product/service. It was developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC) in co-operation with the Environment DG.
- At the international level, the private environmental product declaration program "the international EPD system" proposes a set of PCR (Product Category Rules[7]) for "Electricity, steam and hot water generation and distribution", where specific recommendations are made for hydroelectricity plants as well as for PSH installations (https://www.environdec.com/product-category-rules-pcr/find-your-pcr). Such guidelines, when used, facilitates the comparison of different power plants LCA results.

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[7] Guidelines for a particular type of product / service are called Product Category Rules (PCR).

# ANNEX D

## Synthesis of some LCA research studies for PSH projects

Table 2 . Synthesis of literature review for some PSH LCA

| Reference | Functional Unit | Boundaries | Type of project<br>Data sources | Size | Efficiency RTE | Power gen. mix (Project location) | **GWP –** Global Warming Potential | Comments |
|---|---|---|---|---|---|---|---|---|
| **Analyses dedicated to electricity production** | | | | | | | | |
| Denholm and Kulcinski, 2004 | 1 GWh | Construction, operation and decommissioning | Based on 9 real installation in the US | 31-2100 MW | 74% | Variable electricity source (from 1 to 1000 t CO2 eq / GWh) | | |
| Oliveira *et al.*, 2015 | 1 kWh | Construction, operation and decommissioning | Simulated project, sourced from dataset adapted to Belgium | 190 GWh | 80% | UCTE 2004<br>Belgium 2011<br>100% PV<br>100% wind | approx. 650 g CO2 eq / kWh<br>approx. 225 g CO2 eq / kWh<br>approx. 100 g CO2 eq / kWh<br><50 g CO2 eq / kWh | *Graphical results (GWP values shown here are derived from the graphs)* |
| Abdon *et al.*, 2017 | 1 kWh | Construction, operation and decommissioning | Simulated project with literature data adjusted to hypotheses | 1 MW<br>100 MW | 78% | Wind and solar electricity<br>Swiss electricity mix | 150 to 475 g CO2 / kWh (depending on hypotheses) | *Graphical results (GWP values shown here are derived from the graphs)* |
| Kapila *et al.*, 2019 | 1 kWh | Construction, operation and decommissioning | Simulated project with literature data adjusted to hypotheses | 118 MW | 77.8% | Canada average<br>Alberta<br>British Columbia<br>Ontario<br>Quebec | 211.1 g CO2 eq / kWh<br>approx. 1050 g CO2 eq / kWh<br><50 g CO2 eq / kWh<br><50 g CO2 eq / kWh<br><50 g CO2 eq / kWh | *Graphical results (GWP values shown here are derived from the graphs)* |
| Mahmund *et al.*, 2020 | 1 kWh | Operation | Data from the ecoinvent database<br>Simulation for 1 kWh of delivered energy | 1 kWh | | US electricity | 1060 g CO2 eq / kWh | |
| **Analyses dedicated to storage** | | | | | | | | |
| Immendoerfer *et al.*, 2017 | 9.6 GWh stored over 80 years | Construction, operation and decommissioning | | 1 GW<br>9,6 GWh | 74,96% | German electricity mix | No values. Only relative comparison between stages and with other storage technologies | |
| Krüger *et al.*, 2018 | | Construction and replacement. Operation stage not included | Values of the project developer | 1.4 GW<br>13.4 GWh | | | 1.1 million t CO2 | |
| Stougie *et al.*, 2019 | 10 kWh stored over 20 years | Construction, maintenance and decommissioning. Electricity for charging not included | Simulated project based on literature data. The PHES is in Norway and the electricity transported via NorNed cable to Delft (Netherlands) | 95 MW | 78% | | 74 g CO2 eq / 10kWh of storage capacity | |
| Guo et al., 2020 | 1 kW | Construction, maintenance and decommissioning | Conventional pumped hydro (CPHES) : based on 7 recent CPHES in China<br>Underground pumped hydro (UPHES): based on a real reservoir + assumption regarding the use as UPHES | 200-1200 MW | 75% | China | CPHES: 314.605 kg CO2 eq / kW<br>UPHES: 658.655 kg CO2 eq / kW | |

# ANNEX E

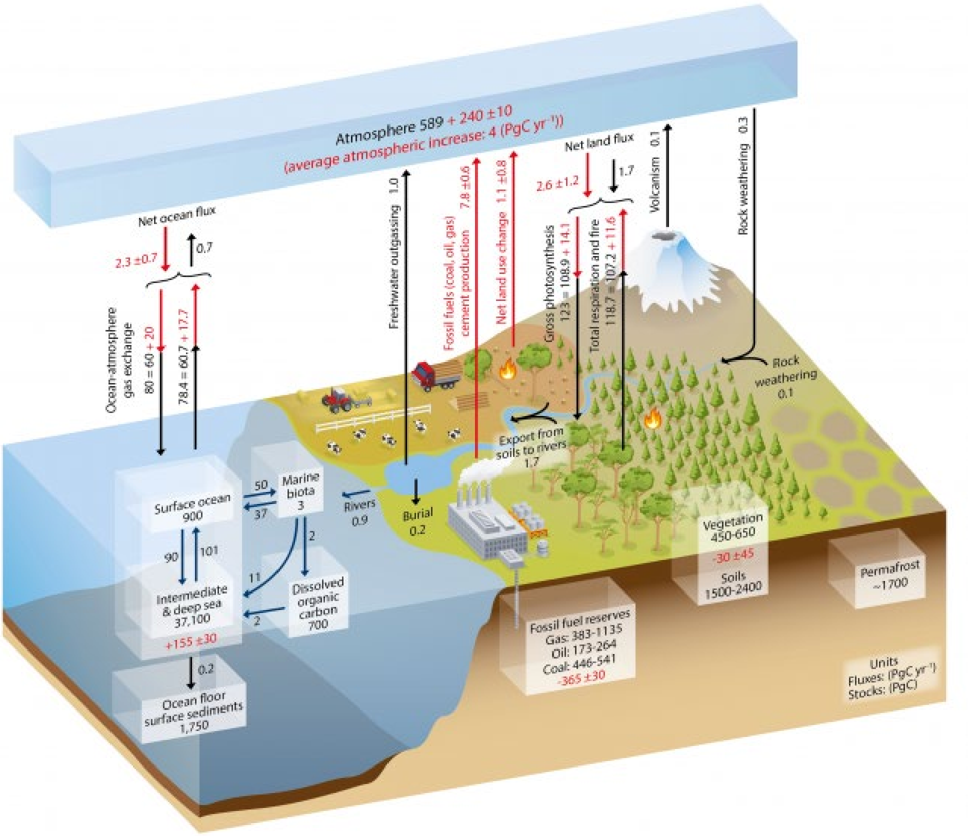
## GHG emissions from PSH reservoirs: applicability of G-Res tool and methodology, and proposition of adaptation

### Context [8]

The global carbon cycle plays a central role in the atmospheric equilibrium, as GHG, particularly carbon dioxide ($CO_2$) and methane ($CH_4$), are important drivers of climate change.

In the current context, understanding the natural and anthropogenic GHG fluxes between the landscape and the atmosphere is essential in order to improve our understanding of future changes.

Figure 10 Global carbon cycle (Source: IPCC 2013)



### Altered carbon cycle of reservoirs

Several carbon transformation processes are altered and amplified following the impoundment of a reservoir. First, the impoundment creates a body of water with a much longer residence time than the river of the pre-impoundment situation.

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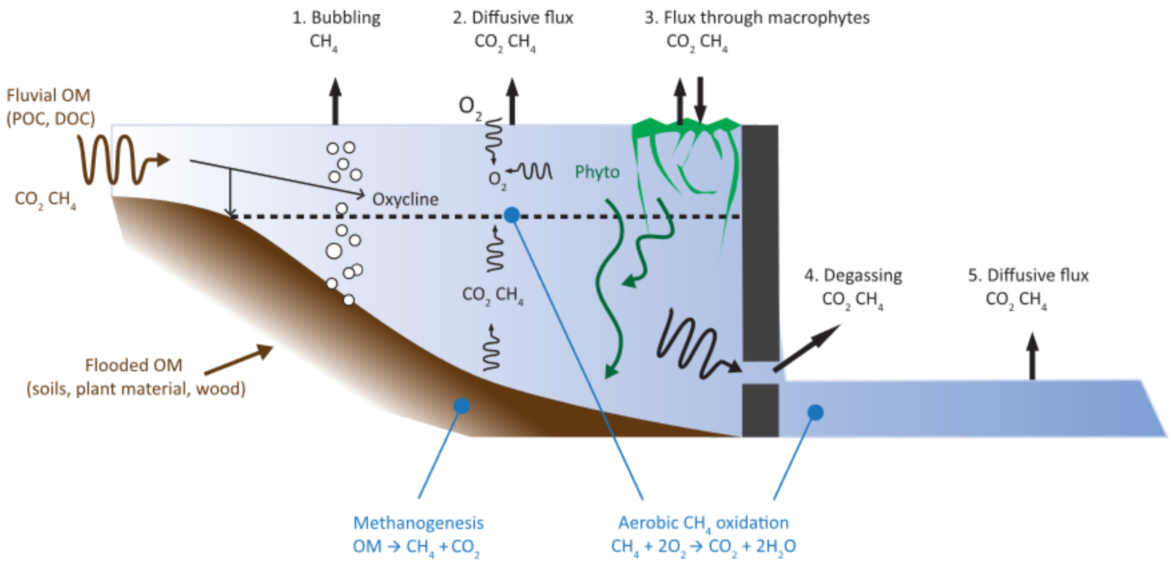
[8] Source: IHA G-res tool website (https://g-res.hydropower.org/scientific-basis/)

This allows more time for biological processes and accumulation of particulate carbon to take place within the reservoir itself, although they may anyway occur elsewhere downstream. Secondly, it changes the physical and chemical environment of the carbon pools. For example, the carbon contained in the soil organic matter and, to a much lesser extent, vegetation can be degraded more rapidly once submerged under water and this increases the stock of GHGs within the waterbody that can then be released to the atmosphere.

In areas devoid of oxygen (e.g. sediments, flooded soils, anoxic water layers), the decomposition of the organic matter often leads to the production of CH4. CH4 dynamics is a highly complex biological phenomenon in aquatic systems. Firstly, it can be produced through different microbial pathways (e.g. acetoclastic, hydrogenotrophic). Secondly, once produced, the $CH_4$ can itself be degraded to $CO_2$ by methane oxidizing bacteria (MOB). Whatever remains as $CH_4$ can then ultimately be released to the atmosphere through different physical pathways of varying efficiencies: (1) bubble fluxes (ebullition) from the shallow water; (2) diffusive fluxes from the water surface of the reservoir; (3) diffusion through plant stems; (4) degassing just downstream of the reservoir outlet(s); and (5) increased diffusive fluxes along the river course downstream (Figure 11) and (6) drawdown emissions.

Figure 11 Carbon dioxide and methane pathways in a freshwater reservoir with an anoxic hypolimnion.

*[ For reservoirs with a well-oxygenated water column, methane emissions through pathways (2), (4) and (5) are reduced (adapted from UNESCO/IHA, 2008, in GHG Measurement Guidelines for Freshwater Reservoirs derived from the UNESCO/IHA GHG Emissions from Freshwater Reservoirs Research Project (2010).)]*



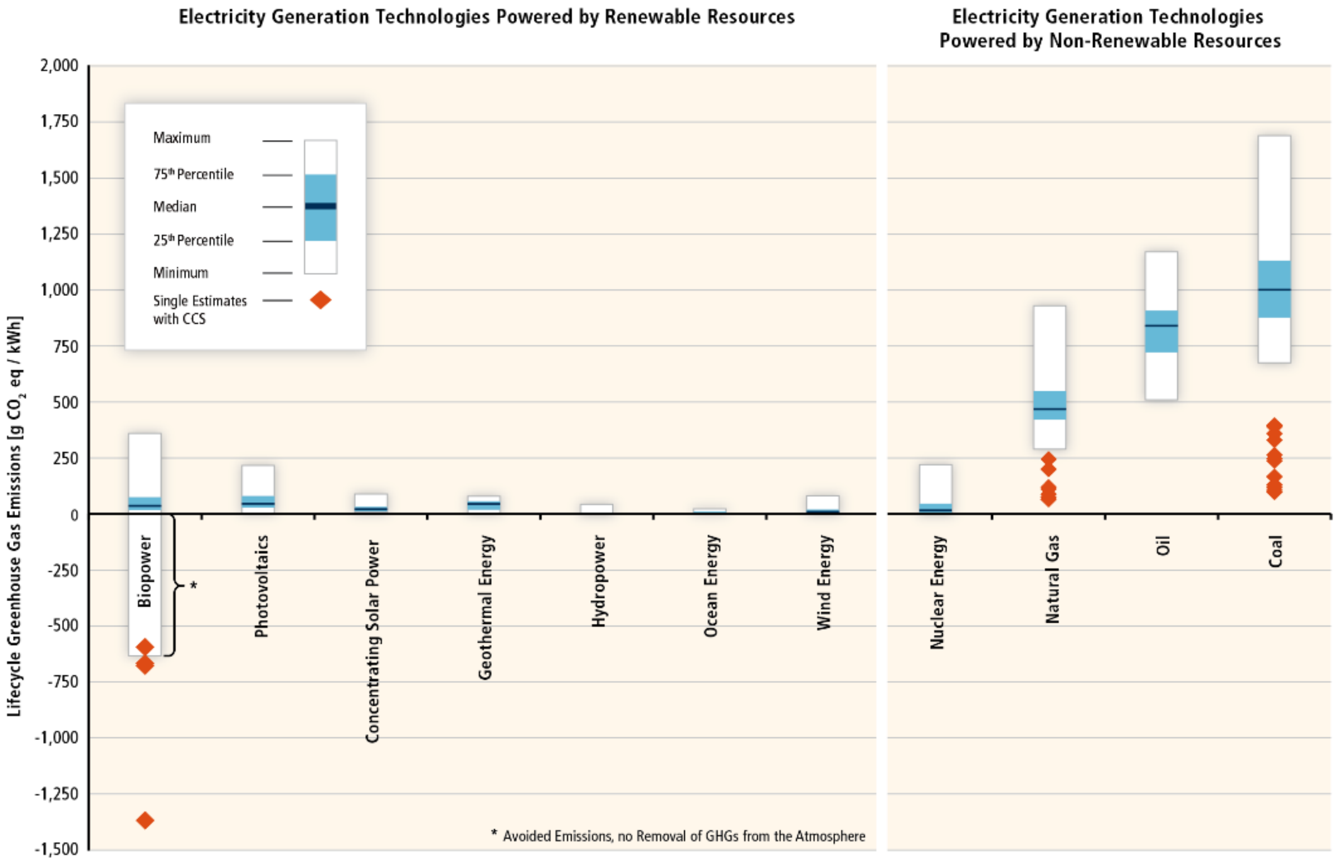
The construction of a dam to retain the water also requires structures (e.g. outlets and spillways) to evacuate the water from the reservoir to regulate water levels. These structures can be located at different reservoir depths depending on their purpose (i.e. emergency flood releases, sediment management, water intake, etc.). In the reservoir water column, the deeper water layers are isolated from the surface and more vulnerable to oxygen depletion and hence may contain high GHG concentrations. If water from anoxic or oxygen-poor depths of the reservoir are released downstream of the reservoir, it can result in a release of important quantities of GHG through a process known as degassing.

With such alterations to the carbon cycling, impoundment will induce new GHG emissions, particularly in the early years following impoundment. The intensity of the emissions, the main emission pathway, the dominant form in which they occur ($CH_4$ or $CO_2$) as well as their evolution through time will depend on the particular climatic, geographic, edaphic and hydrologic settings of the reservoir and its catchment (Prairie et al 2018). Until recent years, there has only been models to predict some emissions pathways, but no model to estimate the changes to the carbon cycle and the quantification of the changes to the GHG fluxes due to the creation of a reservoir.

## GHG emissions values for conventional hydropower [9]

The climate effect of hydropower is very project-specific. The Figure 12 illustrates the range of GHG emissions from hydropower reservoirs. This range is not due to uncertainties (processes, measurement or calculation methodologies) but mainly caused by the diversity of the reservoirs. It explains why a site specific assessment is required to estimate GHG emissions from hydropower reservoirs

Figure 12 Comparative lifecycle GHG emissions (IPCC SRREN, 2011)



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Count of Estimates | 222(+4) | 124 | 42 | 8 | 28 | 10 | 126 | 125 | 83(+7) | 24 | 169(+12) |
| Count of References | 52(+0) | 26 | 13 | 6 | 11 | 5 | 49 | 32 | 36(+4) | 10 | 50(+10) |

Lifecycle emissions from fossil fuel combustion and cement production related to the construction and operation of hydropower schemes reported in the literature fall in the range of up to 40 $gCO_{2eq}$ / kWh for the studies reviewed in the SRREN (Kumar et al, 2011) and 3 – 7 $gCO_{2eq}$ / kWh for studies reviewed in (Dones et al., 2007). Emissions of biogenic CH4 result from the degradation of organic carbon primarily in hydropower reservoirs

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[9] Source: IPCC Assessment Report 5 Climate Change 2014: Mitigation of Climate Change

(Tremblay et al., 2005; Barros et al., 2011; Demarty and Bastien, 2011), although some reservoirs act as sinks (Chanudet et al, 2011). Few studies appraise net emissions from freshwater reservoirs, i. e., adjusting for pre-existing natural sources and sinks and unrelated anthropogenic sources (Kumar et al, 2011). A recent meta-analysis of 80 reservoirs indicates that CH4 emission factors are log-normally distributed, with the majority of measurements being below 20 $gCO_{2eq}$ / kWh (Hertwich, 2013), but gross emissions of approximately 2 $kgCO_{2eq}$ / kWh coming from a few reservoirs with a large area in relation to electricity production and thus low power intensity (W / m2) (Abril et al., 2005; Kemenes et al., 2007, 2011). The global average emission rate was estimated to be 70 gCO2eq / kWh (Maeck et al., 2013). **Due to the high variability among power stations, the average emissions rate is not suitable for the estimation of emissions of individual countries or projects**). The median value is 23-24 $gCO_{2eq}$ / kWh.

**NB: there are no specific values for PSH**

## The G-RES tool [10]

The G-res tool uses a unique framework in its attempt to represent only the GHG emissions that are attributable to the introduction of the reservoir in a catchment. The G-res tool's operating principles require the explicit consideration of:

- The GHG footprint of the landscape prior to impoundment.
- The particular environmental setting of each reservoir (climatic, geographic, edaphic and hydrologic).
- The temporal evolution of the GHG emissions over the lifetime of the reservoir (100 yrs).
- Displaced GHG emissions, i.e. emissions that would have occurred somewhere else in the aquatic network regardless of the presence of a reservoir.
- Emissions increasing the net GHG emission impact of the reservoir, but that are the result of release of nutrients and organic matter by human activity occurring upstream of or within the reservoir (unrelated anthropogenic sources).

Within these principles, we can thus apply a simple conceptual equation to define the net GHG footprint as:

**Net GHG Footprint = [Post-impoundment GHG balance from the catchment after introduction of a reservoir] – [Pre-impoundment GHG balance of the catchment before introduction of a reservoir] – [Emissions from the reservoir due to unrelated anthropogenic sources]**

This net GHG footprint is thus representing a realistic estimation of the actual emissions exclusively attributable to the reservoir impoundment. It also provides a new global approach showing the emissions for the complete lifetime (100 yr) of reservoirs and not for specific yearly emissions as obtained with field measurements. Thus, the G-res was not developed as a tool for validation of the field measurements, but to obtain the complete emissions portrait over a reservoir's lifetime. The G-Res tool also takes into account not to include natural emissions of CO2 that would have been emitted elsewhere (displaced emissions)

In addition to the change in emissions due to the reservoir itself, G-res considers two additional aspects. Firstly, it includes a limited assessment of construction phase emissions, focusing on the key elements of the infrastructure required to establish a reservoir. This is an important consideration since the civil works required can be significant and because the emissions associated with the construction phase occur in the present rather than delayed in to the future. The assessment included in G-res provides an indicative result for the user to judge the relative importance of this source of GHG emissions. Secondly, G-res includes a method to allocate the net GHG footprint to the services that the reservoir provides. This method relies on users specifying the services of the reservoirs so that the G-res divides the GHG emissions between these services, attributing their impact or benefit appropriately.

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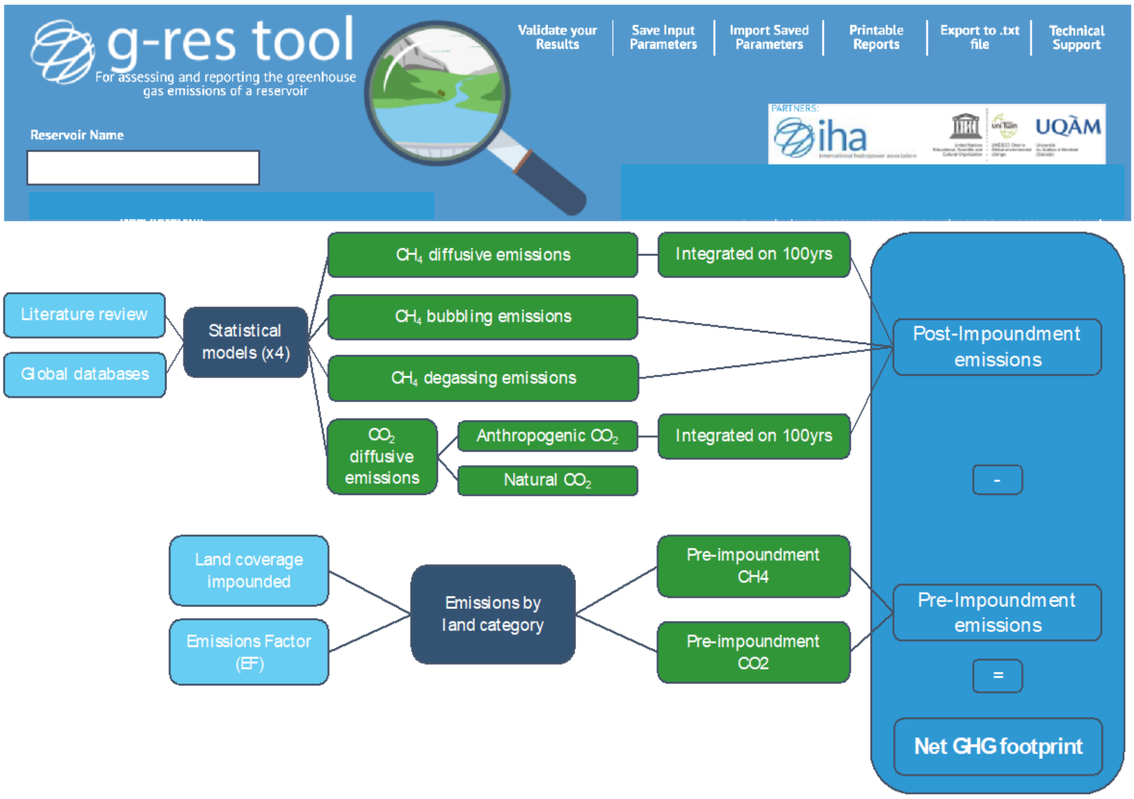
[10] Source: Prairie YT, Alm J, Harby A, Mercier-Blais S, Nahas R. 2017. The GHG Reservoir Tool (Gres) Technical documentation v2.1 (2019-08-21). UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association. 76 pages.

The G-res tool has been implemented as a fully integrated online tool (www.hydropower.org/gres-tool). A complete G-res tool Users Guide is available for download at the same website to accompany and facilitate the step-by-step usage of the tool. The G-res tool online access is available for free, but the user is required to undertake a validation process of results for any official document publication (https://g-res.hydropower.org/results-validation/).

Figure 13 Conceptual design of the G-res tool (Prairie et al., under review)



## Main drivers of GHG emissions from reservoirs

The main drivers of GHG emissions are summarized in the next table. The way these parameters control GHG emissions are not as straightforward as shown in this table. The reality is much more complex with many interactions between these parameters. The purpose here is just to have in mind these factors in order to assess how they can also have a role in controlling GHG emissions in PSH reservoirs.

Table 3 . Main drivers of GHG emissions from reservoirs (simplified)

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| | | | $CO_2$ | $CH_4$ | Rationale |
|---|---|---|---|---|---|
| **Catchment** | Latitude (climatic area) | | ↓ | ↓ | Emissions decrease with latitude (from tropical to boreal zones) due to a decrease of the temperature and of the biomass production |
| | Temperature (opposite to altitude) | | ↑ | ↑ | Emissions increase with the temperature |
| | Organic matter (OM) load (dissolved and particulate) | | ↑ | ↑ | GHG originate from the decomposition of the OM: the larger the input, the larger the OM quantity likely to be transformed into GHG<br>Note that in the G-res tool CO2 emissions from the OM input from the catchment are not considered as it would have been produced somewhere else in the river continuum |
| | Phosphorus load | | ↑ | ↑ | Phosphorus is usually the chemical compounds limiting the growth of the phytoplankton in reservoir and therefore the quantity of autochthonous OM prone to the decomposed into GHG (mostly CH4) |
| **Reservoir** | Land use in the reservoir area | | ↑↓ | ↑↓ | For pre-impoundment emissions, the land use in the reservoir area is considered. If the reservoir floods forested area ($CO_2$ sink), the net $CO_2$ emission will increase. On the contrary in case of wetlands ($CH_4$ source), net CH4 emissions will decrease. |
| | Initial carbon stock in the reservoir | | ↑ | ↑ | GHG originate from the decomposition of the OM: the larger the initial stock, the larger the OM quantity likely to be transformed into GHG. The initial stock is mainly composed by the uppermost 30 cm of soil, and to a lesser extent by the vegetation |
| | Age | | ↓ | ↓ | GHG emissions are known to decrease with the age of the reservoirs |
| | Morphology | Surface area | ↑ | ↓ | In term of emission per surface unit, a larger reservoir favors $CO_2$ emissions hinders $CH_4$ emissions. However, large surface areas are often linked to large littoral zones that positively affect CH4 emissions (see below). Of course, total emissions ($CO_2$ and $CH_4$) are directly related to the surface of the reservoirs |
| | | Shape (% littoral zone) | - | ↑ | Shallow zones favor $CH_4$ emissions |
| | | Depth | ↑ | ↑↓ | The larger the depth, the larger the probability to have an anoxic bottom layer (see the next line). On the other hand, the shallower, the more littoral area and then more $CH_4$ in general |
| | Hydrodynamics | Thermal / O2 stratification | ↑ | ↑ | The thermal stratification usually induces a chemical stratification with the presence of a deep anoxic layer with high CH4 concentration (pelagic production, diffusion from the sediment and no O2 oxidation). GHG may escape/emit through degassing |

| | | | | | |
|---|---|---|---|---|---|
| | | Residence time/dilution | ↑ | ↑ | High residence times favor the primary production process, allow accumulation of GHG and reduce the "dilution" (or renewal) of GHG-rich water in the reservoir with water from the tributaries |
| | Design/operation | Depth of the water intake | ↑ | ↑ | If the water intake is below the oxicline/thermocline depth, the release of GHG –rich bottom water enhances the degassing pathway (in the G-res tool, degassing is considered if water intake is below the thermocline (on/off process)) |
| | | Water level variation | - | ↑ | Bubbling may increase with rapid water level variation, drawdown emissions may also increase |

## GHG emissions from reservoirs: differences between PSH and classical hydropower

The following table briefly summarizes the way the main common drivers for GHG emissions may apply specifically to PSH reservoirs.

Table 4 Main drivers of GHG emissions from PSH (see Figure 5 for definition of Q1 and Q2)

| | | | **Dependent of the PSH type/design/operation mode?** |
|---|---|---|---|
| **Catchment** | Latitude (climatic area) | | It depends only on the location of the PSH. Emissions tends to increase from boreal to tropical climatic areas |
| | Temperature (opposite to altitude) | | |
| | Organic matter (OM) load (dissolved and particulate) | | Open loop PSH ($Q_1$ and/or $Q_2 \neq 0$): the allochthonous OM input from the catchment is the same as in conventional hydro reservoirs<br>Closed loop ($Q_1$ and $Q_2 \approx 0$): no allochthonous OM input except during the initial filling and the successive partial fillings |
| | Phosphorus load (trophic state) | | Open loop PSH ($Q_1$ and/or $Q_2 \neq 0$): the phosphorus input from the catchment is the same as in conventional hydro reservoirs<br>Closed loop ($Q_1$ and $Q_2 \approx 0$): no phosphorous input except during the initial filling, runoff from land in the intermediate catchment(s) (if significant) and the successive partial fillings |
| **Reservoir** | Land use in the reservoirs’ area | | It depends only on the location of the PSH. The size of the reservoirs is nevertheless a key factor |
| | Initial carbon stock in the reservoirs | | It depends only on the location of the PSH<br>But if the bottom of the reservoir is covered with waterproof concrete or membrane (sometimes the case for one of PSH reservoir, for instance for marine PSH), this initial stock is about zero. Moreover, if a thick layer of soil is removed (for civil work, in case of small reservoirs), the new uppermost layer may have lower carbon content (to me measured) |
| | Age | | If one (or two) PSH reservoir(s) is(are) old (> 10-20 years), GHG emissions are much lower than if one (or two) reservoir(s) have to be constructed |
| | Morphology | Surface area | Smaller and shallower reservoirs (water depth < 5 m) are expected to have lower emissions, because no degassing occurring, but, they may be also prone to higher ebullition |
| | | Shape | |
| | | Depth | |
| | Hydrodynamics | Thermal / O2 stratification | For reservoirs with low to very low residence time, the stratification is likely to be virtually absent. Low residence times are excepted when reservoir(s) is (are) small as compared to turbine/pump discharges or/and with daily or weekly operation mode (reservoir(s) is (are) emptied/filled every day/week) |
| | | Residence time/dilution | |
| | Design/operation | Depth of the water intake | Water intakes are usually designed to use the full capacity of the reservoirs and therefore located as deep as possible (favoring degassing and downstream emissions) |
| | | Water level variation | PSH with rapid water level variations are prone to enhance $CH_4$ bubbling fluxes and also potentially drawdown emissions |

## How to estimate GHG emissions from PSH reservoir?

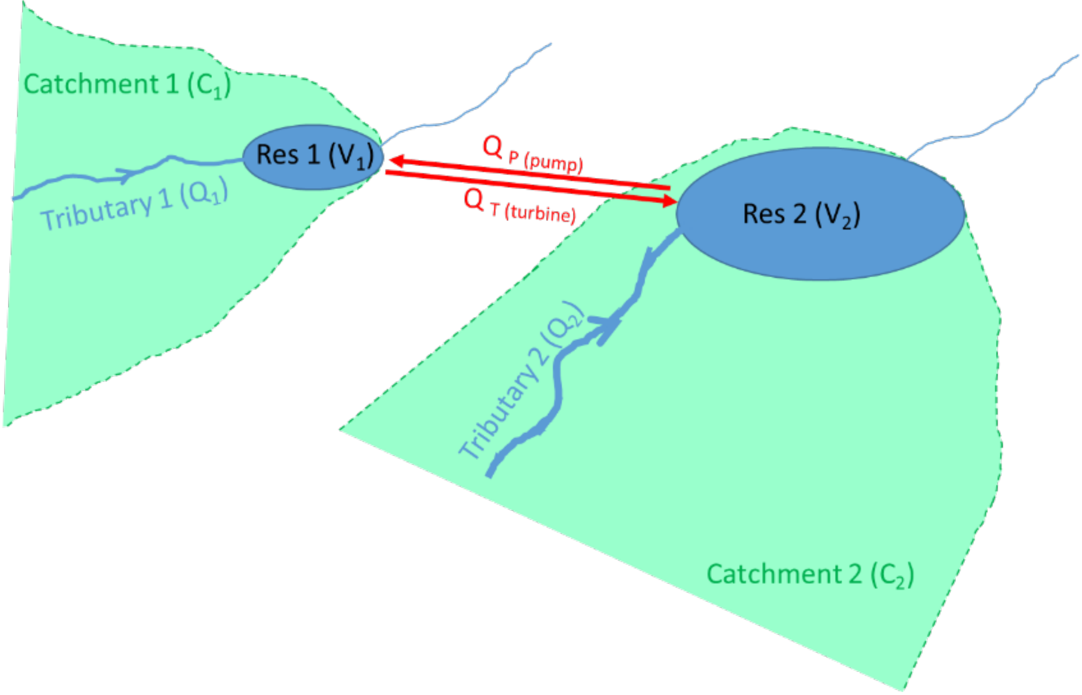
### General principles

The objective of this report is not to develop a new tool for the estimation of GHG emissions but to examine the relevancy of existing tools and suggest adaptations or recommendations for their use. We will discuss here only the emissions due to the reservoirs and not those related to the construction developed elsewhere in the report.

Contrary to conventional hydropower, at least two reservoirs (an upper and a lower) are needed for PSH. As a first and rough approach, the G-res tool could be used on these two reservoirs separately and the emissions added. However, considering the exchanges between these two reservoirs, such a simplified application may be incorrect. Indeed, significant water exchanges occur between these two reservoirs (pump and turbine). As a consequence, the natural catchment of a given reservoir is increased by the catchment of the second reservoir. But the impact of this increase is not a simple mathematical addition of catchment surface/characteristics. The way the reservoirs are effected by the linkage of the two catchments depends primarily on the respective size of the reservoirs and of the turbine/pump discharge capacities.

Figure 14 Schematic representation of a PSH with two reservoirs.

*Res 1 is located at higher altitude than Res 2. Note that for a closed loop, Q1 = Q2 ≈ 0 (no significant tributary)*



**The approach that should be used to get an estimate of GHG emissions is to simulate the two reservoirs separately and to add the net emissions but:**

- **Consider catchment(s) regarding the PSH characteristics and water exchanges between the reservoirs (see Table 5 and Table 6)**
- **Some adaptations for the reservoirs' characteristics as compared to the conventional use of the G-res tool (see Table 6)**

Table 5 Contribution of catchment to consider for simulation of reservoirs 1 and 2 (see Figure 14) with the G-res tool for various configurations

| **PSH characteristics** | | | | **What is the catchment to consider?** |
|---|---|---|---|---|
| **Closed loop** | $Q_1 \approx Q_2 \approx 0$: | | | - Water quality in the reservoir close to that used for the initial reservoir filling + periodic re-filling $\mathbf{C = C_{filling}}$<br>- Note that even without inflow, there will be a modification of the water composition and a production of organic matter in the reservoir (plants and algea may grow, creating a carbon stock and becoming a source of emissions) |
| **Open loop** | $Q_1 = 0$ and $Q_2 > 0$: | | | - Total mixing of the 2 reservoirs : the 2 reservoirs have the same water quality characteristics $\mathbf{C = C_2}$ |
| | $Q_1$ and $Q_2 > 0$ | $V_1 \approx V_2$ | $Q_{P,T} >> Q_1, Q_2$ | - Rapid/efficient mixing of the 2 reservoirs (homogenization of their water quality characteristics),<br>- concerning inputs from the catchments, the two reservoirs can be "merged" with a single catchment $\mathbf{C = C_1 + C_2}$ |
| | | | $Q_{P,T} \approx Q_1 \approx Q_2$ | - 2 distinct catchments,<br>- Concerning inputs from the catchment, the two reservoirs cannot be "merged" and must be considered separately |
| | | | $Q_{P,T} << Q_1 \approx Q_2$ | |
| | | | $Q_{P,T} \approx Q_2 >> Q_1$ | - Concerning inputs from the catchment, the two reservoirs can be "merged" with a single catchment $\mathbf{C = C_2}$ |
| | | $V_1 << V_2$ | $Q_{P,T} >> Q_1, Q_2$ | - Rapid/efficient mixing of the 2 reservoirs (homogenization with final characteristics close to reservoir 2),<br>- Concerning inputs from the catchments, the two reservoirs can be "merged" with a single catchment $\mathbf{C = C_2}$ |
| | | | $Q_{P,T} \approx Q_1 \approx Q_2$ | - 2 distinct catchments,<br>- Concerning inputs from the catchment, the two reservoirs cannot be "merged" and must be considered separately |
| | | | $Q_{P,T} << Q_1 \approx Q_2$ | |
| | | | $Q_{P,T} \approx Q_2 >> Q_1$ | - Concerning inputs from the catchment, the two reservoirs can be "merged" with a single catchment $\mathbf{C = C_2}$ |

## Limitations

**The estimation is only a tentative one as we do not have specific data on PSH reservoir.**

The way degassing and unrelated anthropogenic sources are considered in the G-res tool might be different for PSH.

The closed loop PSH, the evolution with age might be different: the autochtonous carbon may be more and more present (no flushing effect) and emission increase with time (contrary to conventional hydro).

Table 6 List of input parameters required for the G-res tool and changes to consider for PSH as compared to a conventional reservoir case

| | | **Type*** | **Changes vs conventional use of the G-res tool** | **Comments** |
|---|---|---|---|---|
| **Catchment** | Catchment area | 1 | See Table 5 above | |
| | Population in the catchment | 1 | | |
| | Catchment annual runoff | 2 | | |
| | Community wastewater treatment | 2 | | |
| | Release of phosphorus from community sewage | 2 | | |
| | Industrial Wastewater Treatment | 2 | | |
| | Release of phosphorus from industrial sewage | 2 | | |
| | Land cover in the catchment area | 1 | | |
| **Reservoir** | Land cover in the reservoir area | 1 | No | For pre-impoundment emissions |
| | Land use intensity | 2 | No | |
| | Country | 1 | No | |
| | Climate zone | 1 | No | |
| | Impoundment year | 2 | No | Warning: this parameter does not modify the final estimation integrated over 100 years (for instance if the PSH scheme is developed on an old reservoir, the tool will nevertheless give the emissions over 100 years (ie: also the former emissions before the PSH development) |
| | Reservoir area | 1 | No | For conventional hydro, it is suggested to use the surface area occupied by the reservoir at full supply water level. For PSH, even if the two reservoir have the same shape, if a reservoir is full, the second one is empty, we also suggest to use the surface at full supply level |
| | Reservoir volume | 2 | No | |
| | Water level (m asl) | 2 | No | |
| | Maximum depth | 1 | No | Used to estimate littoral area (geometrical approach) |
| | Mean depth | 1 | No | Used to estimate littoral area (geometrical approach) |
| | Littoral area | 3 | No | |
| | Thermocline depth | 3 | Yes/No | For seasonal/annual PSH: No change as compared to conventional hydro |

| | | | | |
|---|---|---|---|---|
| | | | | For daily or weekly PSD: no time to develop a thermal stratification, thermocline depth should be set to 0 m (= no degassing) |
| | Water intake depth | 3 | No | Used to estimate degassing, if applicable (relative depth compared to thermocline) |
| | Water intake elevation | 2 | No | |
| | Soil carbon content | 1 | No | 0 if the soil is covered with concrete or a membrane (or if surface soil removed?) |
| | Wind speed | 1 | No | |
| | Water residence time | 3 | No | |
| | Annual discharge from the reservoir | 1 | Yes | The total discharge must be considered (downstream releases in the river + turbine/pump discharges) |
| | Phosphorous concentration | 3 | No | The evolution of phosphorus concentration in a closed loop scheme is not clear. The impact of the absence of significant import/export during normal operation is complex to evaluate. Nevertheless, using the same calculation as for conventional hydro is probable conservative. |
| | Trophic level | 3 | No | |
| | Mean horizontal radiance | 1 | No | |
| | Mean monthly air temperature | 1 | No | |
| | Mean annual air temperature | 3 | No | |

_*1: the user MUST input data for the calculations, 2: the user may input data for the calculations, 3: automatically calculated by the model Parameter_