Supplementary material: Case-studies of PSH developments (planned and existing)

Case Study 1 – Kaunertal Expansion Project (Austria)

Name: Kaunertal pumped-storage hydropower expansion project

Location: Platzer Valley (Platzertal) in southwestern Austria

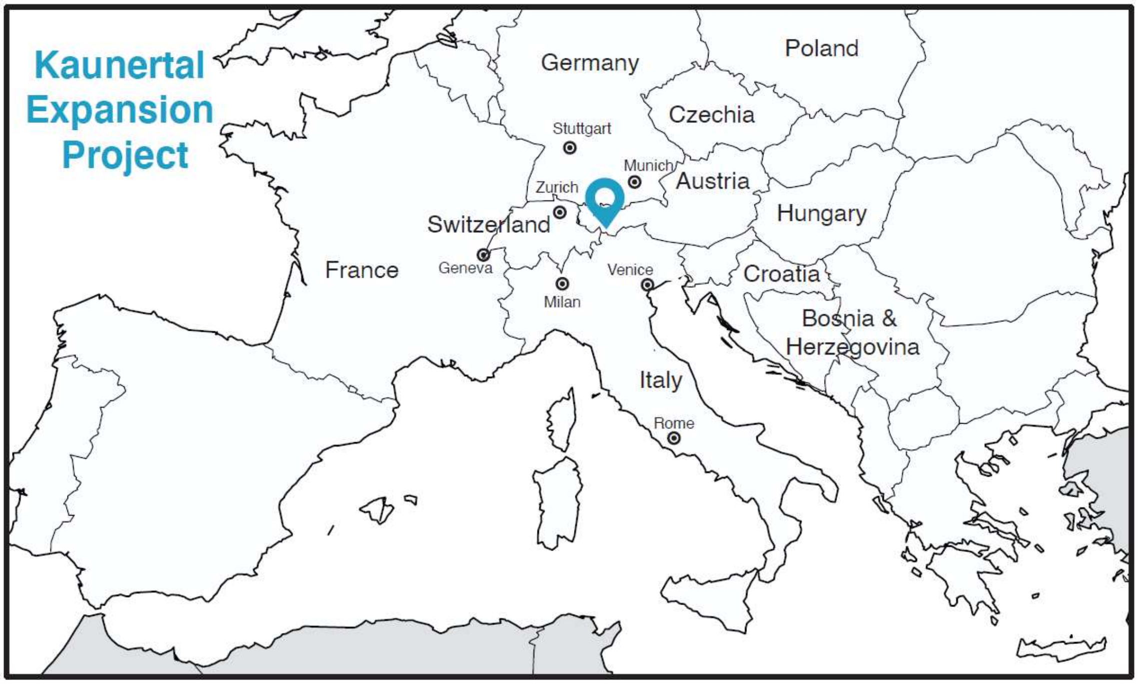

Figure S1: Approximate location of proposed Kaunertal Expansion project (base map courtesy of NASA)

Operating date/status: Planned completion 2028 [1]

Type: Open-loop (lower reservoir is the existing Gepatsch hydropower facility) [1], [2]

		Notes
Power rating	1,076 MW	
Capacity	152 GWh	Will be able to supply 1,076 MW continuously for nearly 6 days
Construction cost	€1.25 billion	Budgeted cost. The project is projected to save generation costs of around €40 million per year. It is described as a highly efficient project financially and technically [1].

Carbon emissions

This PSH project is designed to reduce the need for fossil-fuel powered electricity generation, thus contributing to achieving national/regional climate and energy policy targets in line with EU policies [1]

Conflict related elements

There is substantial conflict over this project, in particular because of the damage that will occur to the pristine Platzertal alpine river valley as a result of the proposed Platzertal PSH facility that is a part of the overall project plan. The Platzertal valley has high ecological value, and was classified as a river-sanctuary in 1998 by the Austrian Government. The valley contains untouched grasslands and alpine meadows, which are protected under European Habitat Directives, and which are among the most threatened habitats in the European Alps. The 119 m high and 450 m wide dam wall will flood an area that is an important refuge for alpine species such as the rock ptarmigan and the Alpine marmot. [2] In contrast, the International Hydropower Association (IHA) recently assessed the Kaunertal Expansion project (including the Platerzal PSH facility), arguing that the project 'met or exceeded basic good practice' across 18 of 21 topics in the IHA's Hydropower Sustainability Assessment Protocol (HSAP) [3, p. 35]. The assessment presented does highlight that the project does not meet downstream environmental flows requirements and that there are gaps in meeting good practice with respect to project-affected communities. The 18 topics where the project was assessed to be meeting or exceeding basic good practice requirements included both *Environmental and Social Impact Assessment and Management*, and *Biodiversity and Invasive Species*. Given that the Platzertal PSH facility threatens protected areas and will inundate important wildlife refuges, this suggests that the findings presented in [3] span a broad set of sub-projects and have thus missed some critical elements in the PSH project element.

Case Study 2 – Snowy 2.0 scheme (NSW, Australia)

Name: Snowy 2.0[1]

Location: New South Wales, Australia

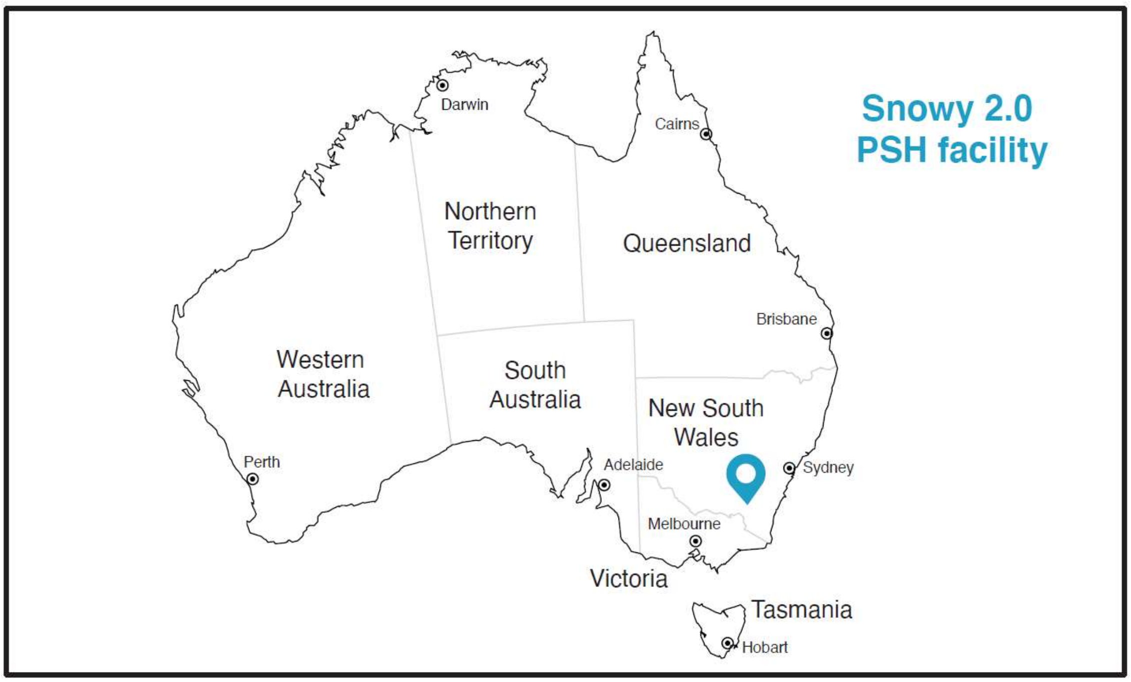

Figure S2: Approximate location of proposed Snowy 2.0 PSH facility (Base map courtesy of NASA)

Status: Under construction, due to be commissioned in 2025 [4]

Type: Open-loop – upper and lower reservoirs

		Notes
Power rating	2,000 MW	
Capacity	350 GWh	Will be able to supply 2,000 MW continuously for over a week
Construction cost	AU$5.2 billion	Budgeted cost. Transmission line upgrades (which service the broader grid) will be an additional cost. The proponent argues that the AU$5.2 billion cost is less than half that of alternative investment in natural gas peaking plants paired with commercial scale batteries.

[1] https://www.snowyhydro.com.au/snowy-20/

Carbon emissions

The operator already has contracts with over 1 GW of solar and wind generators to firm electricity supply. The project will be able to generate continuously for over a week providing capacity to manage a VRE drought. Snowy 2.0 is at a central location in the eastern Australian grid, near renewable energy development zones for solar and wind, and midway between the country's two biggest cities. Australia's National Electricity Market is projected to need to increase utility-scale dispatchable generating capacity by between 6 and 19 GW by 2040 to firm likely VRE generators. As the project has been enabled by Australia's conservative Federal Government, it has substantially undercut arguments by influential climate change sceptics that more investment is needed into fossil fuel generations for reliable electricity supply.

Conflict related elements

The project has generated conflict. Snowy 2.0 is being built in the 690,000-hectare Kosciuszko National Park that covers the highest portion of the Australian Alps. The Park was progressively designated from 1944 in part to conserve the damaged mountain catchments in which the Snowy Mountains Hydroelectric Scheme was constructed. Snowy 2.0 is open loop and increases the generating capacity of the existing scheme by ~50% by linking two large, on river reservoirs (Tantangara (254 GL) and Talbingo (921 GL)) with 27 km of tunnels and an underground power station. Construction of the scheme will use around 900 hectares of the protected area, with 400 hectares being permanently altered. Much of this land comprises a former mine site and infilling two areas of artificial reservoirs with the vast quantity of tunnel spoil that the project is generating.

The hydrology is not significantly changed as the project circulates water between the two existing reservoirs and does not change existing environmental flow releases. By recirculating water, the project will reduce the vulnerability of the Snowy Scheme to water losses from drought and climate change. However, this inter-basin project is likely to transfer invasive predatory fish and a virus that are expected to negatively impact at least two threatened fish species. These impacts are unlikely to be ameliorated by over A$100 million in conservation off-set projects.

A large environmental impact is expected from clearing for the proposed 8 km x 200 m above ground transmission line easement through remote parts of the National Park to link Snowy 2.0 to the existing electricity grid.

Case Study 3 – Lamtakong PSH facility (Thailand)

Name: Lamtakong pumped-storage hydropower project

Location: Between Sikhio District and Pak Chong District, in Nakhon Ratchasima Province, Thailand

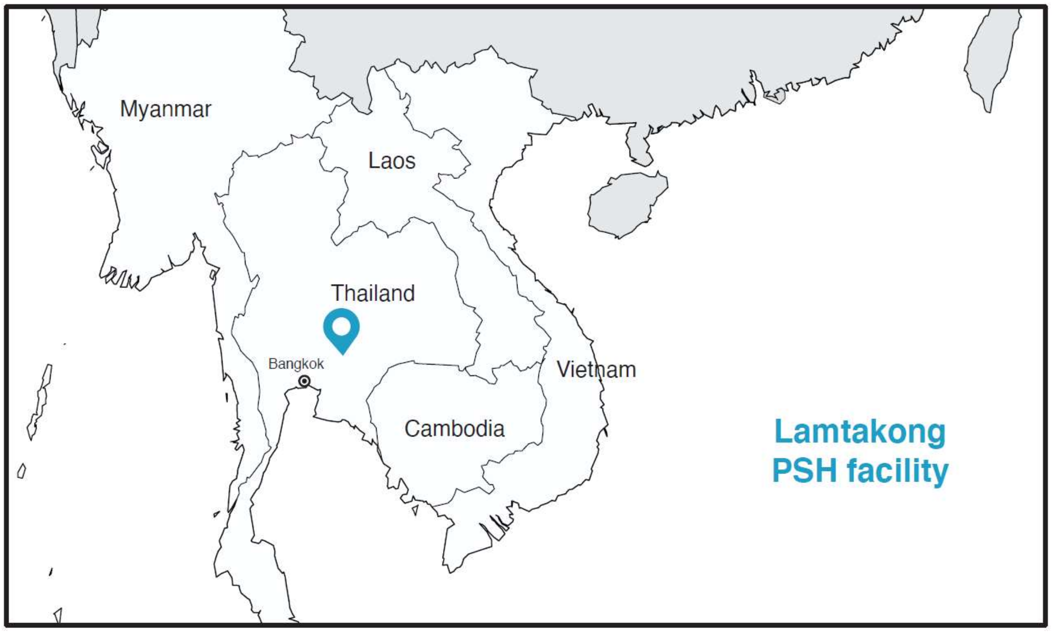

Figure S3: Approximate location of Lamtakong PSH facility (Base map courtesy of NASA)

Operating date/status: Phase II (installation of turbines 3 & 4) operational on December 30, 2019.

Type: Open-loop (lower reservoir is the existing irrigation dam that was constructed on the Lam Ta Khong river in 1974) [5].

		Notes
Power rating	1,000 MW	4 x 250 MW turbines
Capacity	152 GWh	Able to supply 1,000 MW continuously for over 6 days
Construction cost	No data	

Carbon emissions

According to the Electricity Generating Authority of Thailand, the Lamtakong PSH facility will help to meet Thailand's peak electricity loads while also enhancing the power system stability. They further describe the Lamtakong Pumped-storage Hydropower Plant as an eco-friendly power source because it circulates water from the existing Lamtakong Reservoir. The facility is also linked to a 26.5 MW wind farm [6], [7].

Conflict related elements

Blasting of rock during construction of the upper reservoir of the Lamtakong PSH facility caused significant concerns to local residents, including raised incidence of asthma type symptoms [8].

Conservation value of area:

The facility is located in an area that the Mekong River Commission labels as requiring forestry or other maintenance because of high elevation and slopes, and which contains protected forests [9], [10]. The environmental impact assessment for the project assessed that despite the need to maintain forest cover in the area (as it is a part of a drinking water catchment), the project would not have any significant impacts on wildlife or terrestrial ecology impacts, with any impacts being of a short-term nature during the construction phase.

In relation to fisheries in the lower reservoir, the PSH facility was assessed as likely to impact on fish populations, largely because of reduced phytoplankton biomass. To mitigate this, the pumping operations were to be adjusted, particularly during dry periods where the water level in the lower reservoir were lower [9]. The Lamtakong irrigation reservoir stores 310 GL [11], compared to the upper reservoir's capacity of 10.3 GL [6], meaning that cycling of water between the reservoirs is unlikely to have a significant impact on water volumes, water quality, or downstream flows from the irrigation reservoir.

The Lamtakong PSH system is an example of a low-impact PSH system that utilises one of the many existing reservoirs in the Mekong region. It provides a positive example in the Mekong region of how to transition to renewable electricity generation from fossil fuels and conventional hydropower.

Case Study 4 – Lake Cethana (Tasmania, Australia)

Name: Lake Cethana

Location: Tasmania, Australia

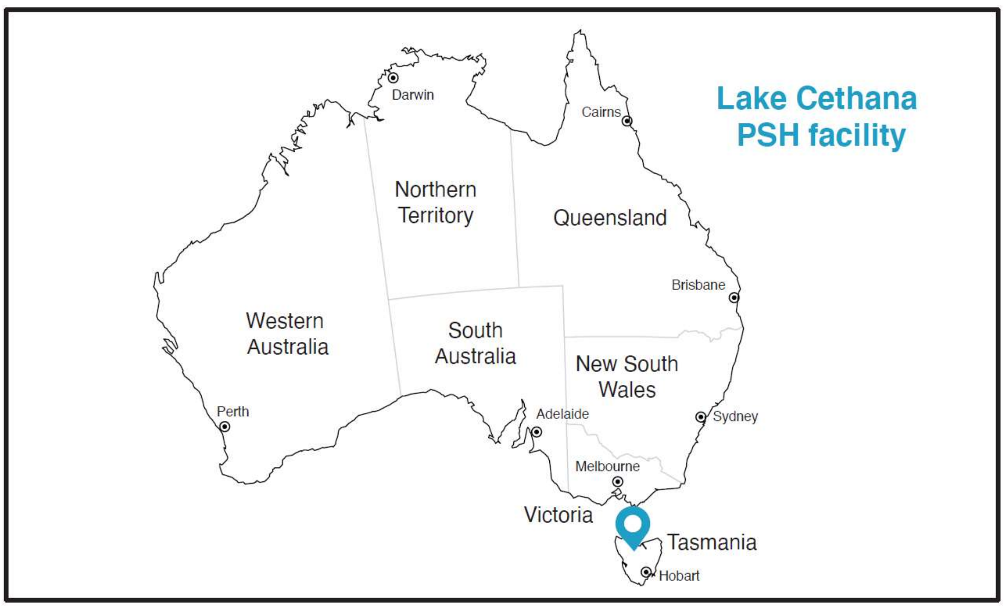

Figure S4: Approximate location of proposed Lake Cethana PSH facility (Base map courtesy of NASA)

Status: Scoping to investment-ready stage

Type: Open-loop, existing lower reservoir Lake Cethana, new off-river upper reservoir

		Notes
Power rating	600 MW	
Capacity	6.6 GWh	Will be able to supply 600 MW continuously for 11 hours
Construction cost	AU$900 million	Budgeted cost. Hydro Tasmania claim that repurposing existing conventional hydro infrastructure results in delivered electricity that is 15% cheaper than five other scenarios with mixtures of batteries, gas and new pumped hydro. Hydro Tasmania want to develop long duration storage to manage challenges such as wind droughts during large low-pressure zones, days of low solar with large cloud bands, and extended transmission or supply asset outages.

Table information source: [12]

Carbon emissions:

Tasmania seeks to benefit from the transition of the Australian electricity market from coal baseload power to renewables. The Tasmanian Government has set a renewable energy target of producing 200% of its current needs by 2040 [13]. It aims to progressively develop an additional 1.5 GW of deep storage and a new interconnecting cable to export power to mainland Australia. The Australian Energy Market Operator in its 2018 Integrated System Plan forecast that up to 17 GW of pumped hydro and utility-scale battery storage will need to be developed as part of a least-cost transition of the electricity sector [14]. This is almost 20 times the current level of EES.

From August 2017, the Australian Renewable Energy Agency (ARENA) and Hydro Tasmania funded an assessment of 2,000 potential pumped hydro sites in Tasmania with over 4.8 GW of storage capacity in Tasmania. This assessment excluded projects that involved construction of new on-stream dams or were located within the Tasmanian Wilderness World Heritage Area. It focussed on options for redeveloping existing schemes into pumped hydro projects, linking existing Hydro Tasmania storages, or using existing storages as either upper or lower reservoirs. This resulted in 14 potential pumped hydro options being selected [15].

From August 2019, ARENA and Hydro Tasmania funded feasibility assessment of three possible PSH developments using a multi-criteria analysis that considered technical, environmental, social and economic factors. In December 2020, Lake Cethana was announced as the preferred pumped hydro project site.

Conflict related elements

Tasmania has had a long history of conflict over conventional hydropower development. This project would involve a new off-river upper storage on the western side of Lake Cethana. The new upper reservoir would cover only 50-70 hectares, and with a wall of up to 25 metres high would hold about 5 GL of water [12]. This land is publicly owned state forest, and while not a protected area, the biodiversity value is yet to be publicly assessed. There would be 3.5 km of underground tunnels and power station. It is not clear where the spoil would be placed. A new transmission line connection would be needed which may use an existing easement. The upper reservoir site is near a main road.

Lake Cethana is the current upper reservoir on a cascade of hydropower dams on the River Forth. As the lake holds 112 GL and the proposed upper storage would hold around 5 GL, the cycling of water between the two reservoirs is unlikely to have any significant impact on water volumes, quality or freshwater biodiversity.

Hydro Tasmania say that they applied the International Hydropower Association Hydropower Sustainability Assessment Protocol to assess environmental, social, technical and economic aspects in selecting Lake Cethana ‘at an early stage.’

Case Study 5 – Kidston PSH facility (Queensland, Australia)

Name: Kidston pumped-storage hydropower project

Location: Kidston, approximately 250km west and north of Townsville in Queensland, Australia

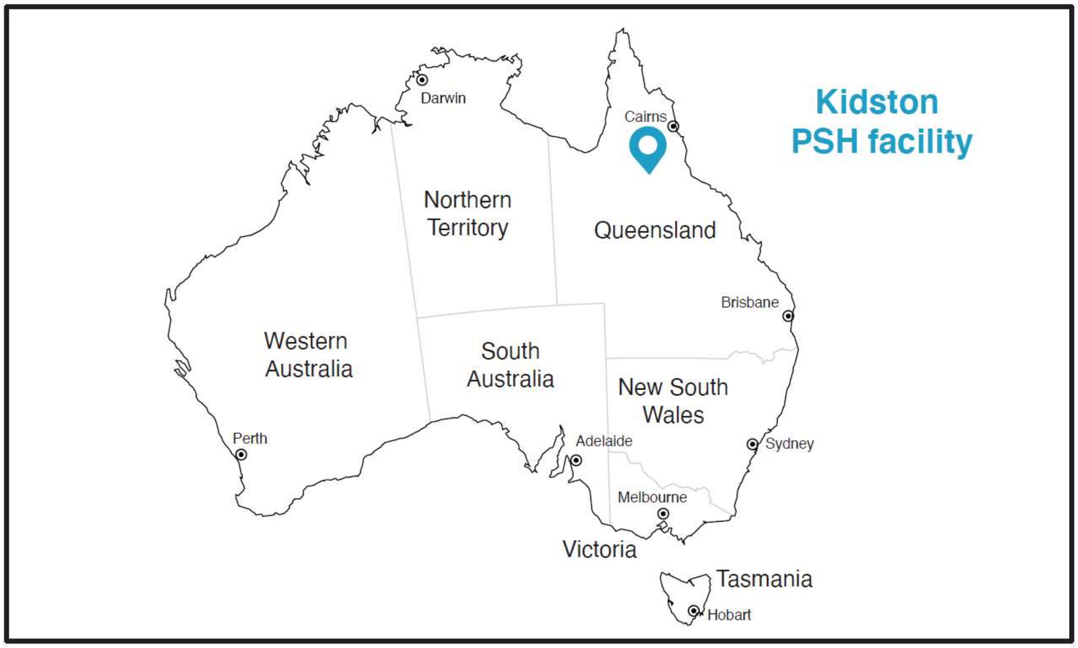

Figure S5: Approximate location of Kidston PSH facility (Base map courtesy of NASA)

Operating date/status: Planned to be operational in 2022 [16].

Type: Brownfields site closed-loop re-development [17]. The Kidston PSH system is being constructed using two existing pits from an abandoned gold mine as the reservoirs.

		Notes
Power rating	250 MW	2 x 125 MW reversible turbines
Capacity	2 GWh	Will be able to supply 250 MW continuously for eight hours
Construction cost	AU$330 million	

Table information source: [16]

Carbon emissions:

The project will store electricity generated from a neighbouring 270 MW solar farm.

Through its direct connection to Australia's national electricity market (NEM), and its co-location with a 270MW solar PV generation system, the Kidston pumped storage hydropower facility, in northern Queensland, Australia, will allow solar energy to be stored and harnessed as baseload power on demand. This is an innovative use of the old Kidston mine infrastructure for the purpose of developing a regional renewable energy industry.

Conflict related elements:

Conservation value of area:

Selection of the Kidston site was made by Genex Power by considering thousands of possible brownfields sites, and then using criteria like secure access to water, access to transmission links, good geology in order to remove less feasible options.

The project is located in a remote area, approximately 250 km from Townsville, in northern Queensland, Australia. Being so remote, the project has been socially acceptable because it has generated local employment.

The project will act as a natural battery storage, allowing energy to be stored and harnessed on demand and includes the following components:

- An upper reservoir formed by a 20 metre high dam around the existing Wises Pit,
- A lower reservoir utilising the existing Eldridge Pit,
- A powerhouse cavern with the capacity to generate 250 megawatts,
- A tailrace allowing water to pass from the powerhouse to the reservoirs, and
- A spillway from the upper reservoir to the Copperfield River.

By selecting Kidston as a brownfields site, the project is being developed in an environment that was already severely degraded due to the gold mining operations in the area. In recognition of this, the Queensland Government did not require an environmental impact statement process for the project, as these are only required in the case that the project will have significant environmental or social effects [18], [19].

The subsequent, and less involved impact assessment report (IAR) for the project notes that

> *[t]he primary activity for which an approval is being sought […] is for the water discharges as a result of excess water following significant rainfall events during operation, and to allow the lowering of water levels to facilitate construction of the Project [20, p. i]*

In addition, the environmental approval for the project included consideration of the change in land use in the project area, and dam failure impact assessment.

The main environmental concerns related to water discharge were the levels of zinc in the water, potential for erosion, impact on fish and other aquatic organisms such as macroinvertebrates. The project undertook baseline assessments of the Copperfield River, as well as making assessments for how the local environment will be impacted during construction and operation. Water discharges will be released at a maximum ration of 1 part release water to 200 parts receiving water, with dilution modelled to be complete within 625 m of the release point. There are no significant impacts projected from the project.

The project will provide substantial environmental benefits in terms of supporting the transition to a low-carbon grid, and reducing the need for gas powered turbines for electricity generation that are currently the main peaking generators in Queensland.

The project is a 'first in the world' example of using disused mine pits for PSH. The project takes over responsibility from the Queensland Government for maintaining and improving a (previously) redundant mine site. As such, the successful implementation of the project will provide a model for re-purposing more of the 11,000 abandoned/closed mines across the state [20].

As the local environmental impacts of the project are minor in scale and able to be easily managed, and the broader environmental and social benefits of the project are large (reduced greenhouse gas emissions, model for future similar developments, construction and operation jobs), the project is considered to be environmentally and socially beneficial.

Case Study 6 – Čapljina PSH facility, Bosnia and Herzegovina

Name: Čapljina PSH facility.

Location: Neretva river catchment, Herzegovina region, Federation of Bosnia and Herzegovina, Bosna and Herzegovina.

Figure S6: Approximate location of Čapljina PSH facility location (Base map courtesy of NASA)

Operating date/status: In operation since 1979.

Type: Open-loop involving underground water hydrology.

		Notes
Power rating	420 MW	Supplies peaking demand electricity
Capacity	No data	The system is operated as a peaking plant, and runs for around 1,500 hours each year, generating around 620,000 MWh of electricity
Construction cost	No data	As a 42-year old PSH system, all construction costs have been paid off.

Carbon emissions:

Reduces water in the Hutovo Blato wetlands, which allows release of additional CO_2 from the area.

Conflict related elements:

The Čapljina PSH system's lower reservoir is located on the Hutovo wetland on the former Matica River, with the powerhouse located underground near the Svitava, in the Hutovo Blato area. The upper reservoir is located approximately 8 km from the Svitava Dam, at the lower surface (above ground) end of the Trebišnjica River. The Trebišnjica River is a complex system of both above and below ground streams that is not well understood. Environmental impacts on the Trebišnjica River system from the Čapljina PSH system are also not well understood because of limited knowledge of water circulation in the complex and largely unknown underground connections. However, there are observable impacts, with reduced water in the Ramsar protected Hutovo Blato wetland. Where, previously the Trebišnjica River used to sink underground and, through underground connections, feed Hutovo Blato with water, the Čapljina hydropower plant development included coating 65 kilometres of the Trebišnjica River bed with concrete [21], [22], cutting off Popovo Polje sinkholes and severely affecting the hydrology of Hutovo Blato, which is included in the Ramsar List of wetlands of international importance [22].

In the upper plateau the same concrete coating created an artificial water regime along the Trebišnjica River's Popovo Polje. A polje is a karst field, which is characterized by soluble underground rock with water travelling along underground channels that have been dissolved in the rock see e.g. , [23], [24].

There has been significant damage to high conservation value areas as a result of the Čapljina PSH system construction and operation. Because several hydropower plants have been built on the Trebišnjica River basin, it is challenging to attribute particular impacts to the Čapljina PSH system. However, the combination of hydropower projects has dramatically altered the Hutovo Blato wetland ecosystem. For example, the original natural Svitava wetland is now the the Čapljina pumped-storage hydropower plant's reservoir with the construction of a dam and several embankments on the former Matica River. Since construction of the Čapljina PSH system, the Derane area, in Hutovo Blato, has lost 5 m^3/s of its summer freshwater flows, which amounts to 50% of the total water flowing into the only remaining natural wetland in the Neretva delta. This has resulted in numerous environmental impacts including increased sedimentation due to water loss. Consequently, the bottom of Lake Derane has risen, and over the last 40 years, the area around Boljun Kuk in the Hutovo Blato wetland is as much as one metre higher than it was previously [22].

Not only has the land level risen, but the minimum water levels in the Krupa River in Hutovo Blato dropped significantly from 1979 when the Čapljina PSH system was completed. These significant changes to the natural water cycle have degraded Hutovo Blato's wetland habitats. For example, habitat loss has resulted in a significant loss of biodiversity. For example, the number of known bird species has decreased by 31%, and endemic fish populations are being replaced by introduced fish species. A variety of endemic plants are in danger of extinction. All this damage has taken place in an area that, thanks to its extraordinary biodiversity, was recognized as the Hutovo Blato Ramsar Wetland of International Importance in 2001. On top of its outstanding biodiversity, the wetland also provides the eco-system service of clean water flows to the lower portion of the Neretva River [22].

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