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Pumped Storage Hydropower for Sustainable and Low-Carbon Electricity Grids in Pacific Rim Economies

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Abstract: Because generating electricity significantly contributes to global greenhouse gas emissions, meeting the 2015 Paris Agreement and 2021 Glasgow Climate Pact requires rapidly transitioning to zero or low-emissions electricity grids. Though the installation of renewables-based generators—predominantly wind and solar-based systems—is accelerating worldwide, electrical energy storage systems, such as pumped storage hydropower, are needed to balance their weather-dependent output. The authors of this paper are the first to examine the status and potential for pumped storage hydropower development in 24 Pacific Rim economies (the 21 member economies of the Asia Pacific Economic Cooperation plus Cambodia, Lao PDR, and Myanmar). We show that there is 195 times the pumped storage hydropower potential in the 24 target economies as would be required to support 100% renewables-based electricity grids. Further to the electrical energy storage potential, we show that pumped storage hydropower is a low-cost, low-greenhouse-gas-emitting electrical energy storage technology that can be sited and designed to have minimal negative (or in some cases positive) social impacts (e.g., requirements for re-settlement as well as impacts on farming and livelihood practices) and environmental impacts (e.g., impacts on water quality and biodiversity). Because of the high potential for pumped storage hydropower-based electrical energy storage, only sites with low negative (or positive) social and environmental impacts such as brownfield sites and closed-loop PSH developments (where water is moved back and forth between two reservoirs, thus minimally disturbing natural hydrology) need be developed to support the transition to zero or low-carbon electricity grids. In this way, the advantages of well-designed and -sited pumped storage hydropower can effectively address ongoing conflict around the social and environmental impacts of conventional hydropower developments. Noting the International Hydropower Association advocacy for pumped storage hydropower, we make recommendations for how pumped storage hydropower can sustainably reduce electricity-sector greenhouse gas emissions, including through market reforms to encourage investment and the application of standards to avoid and mitigate environmental and social impacts.

Keywords: pumped storage hydropower; renewable energy; low-carbon electricity grids; sustainable development; pacific rim; environmental and social impact

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1. Introduction

In 2020, there was a global shift towards renewable-based electricity generation, including 12% growth in wind generation, 23% growth in solar-based generation, and a 3% fall in non-renewables-based electricity generation [1]. Growth in renewables-based electricity generation is driven by two key factors. First is its declining cost, with onshore wind power already cheaper than the cheapest fossil-fuel based generation and the cost of renewably generated electricity continuing to decline while fossil-fuel based generation costs remain static [2]. The second factor is global concern about carbon dioxide (CO_2) emissions, which are resulting in policies designed to limit CO_2 emissions, with a strong focus on electricity generation. For example, the decarbonization of developed country electricity systems is targeted to be completed by 2035, with the global decarbonization of electricity systems to be complete by 2040 [3]. At a regional level, in recognition of the importance of addressing power sector emissions [4], the Asia Pacific Economic Cooperation (APEC, a group of 21 Pacific Rim economies) announced a target in 2014 to double the renewables-based electricity generating capacity across the 21 APEC economies by 2030 [5].

The primary renewables-based generators are wind and solar systems [6]. These are classed as variable renewable energy (VRE) generators because their outputs cannot be synchronized to match demand due to their weather dependence. There are variety of strategies that can be employed to deal with VRE generators being unable to vary their output based on the demand load. These strategies include:

(i) Geographically spreading VRE generators (such as by spacing solar arrays in an east–west direction means that when night has fallen on arrays further to the east, the arrays further west can still produce power).
(ii) Implementing policies that encourage consumers to use electricity when weather conditions are favorable for generation (e.g., adjusting tariffs based on time of day).
(iii) Selecting a range of VRE generators (e.g., in some locations. wind may generally be prevalent at night when solar generators do not generate power).
(iv) Importing electricity from neighboring grids when demand is high.
(v) Employing smart-grid capabilities (e.g., technologies that allow electricity to be drawn from parked electrical vehicles to meet spot demands).

However, even using all these strategies, there remains a significant need for investments in electrical energy storage (EES), especially as the proportion of VRE sources in the energy mix grows [7].

There are a variety of EES technologies, each with different characteristics that make them suitable for different roles in an electricity grid. In light of this, the authors of this paper provide an overview of the characteristics of different grid-suitable EES technologies and argue that pumped storage hydropower (PSH) has key advantages [8] that make it a highly suitable grid-scale EES technology.

The purposes of this paper are two-fold. Firstly, we examine the status and potential for PSH usage in 24 Pacific Rim economies (the 21 APEC economies plus Cambodia, Lao PDR, and Myanmar) as a means of enabling a transition to zero/low-carbon grids on the Pacific Rim. Secondly, we provide recommendations for implementing PSH developments in accordance with sustainability principles in order to ensure that social and environmental impacts are minimized during the transition to low and zero-carbon electricity grids.

2. Methods

This research into the status and potential for PSH system usage in the 24 target economies was based on three distinct research techniques. Firstly, we conducted desk-based research of academic and grey literature on PSH. Because PSH (or any EES system) needs to be developed within a broader technical and policy context, the desk-based research also covered the following areas in the target economies:

(i) Renewable energy policies and policy trends.
(ii) Existing and planned electrical energy storage.
(iii) Existing and planned PSH.
(iv) Dispatchable power generation capacity.

This first phase of the research was conducted using a snow-balling literature search because the diversity of economies and situations, and the need to draw on extensive grey literature precluded reliance on a systematic keyword search in academic databases.

Secondly, we explored potential for PSH development in the target economies. This research drew on a global PSH atlas developed by a team at the Australian National University [9]. The atlas identifies potential PSH sites globally based on geographic suitability with some exclusions, such as existing developments and protected areas that are included in the world database on protected areas [10]. The atlas shows a total of more than

600,000 closed-loop reservoir pairs capable of storing 23,000,000 gigawatt hours (GWh) of electricity. Each pair-mapped reservoir includes key information including a simplified cost estimate for development, available head, separation between the reservoirs, storage capacity (measured in GWh), and storage time (measured in hours).

The literature review and data from the PSH atlas were enhanced via a three-day workshop on PSH that was attended by 85 energy specialists from 15 of the 24 target economies plus Italy and the United Kingdom. During the workshop, the draft findings from this research were presented, and participants provided feedback to enhance the accuracy and applicability of the findings. The participants came from government energy ministries and utilities, non-government organizations and universities, and multi- and bi-lateral development agencies.

To add depth to the analysis, environmental and social concerns were assessed in six case studies of PSH facilities. The six selected case studies were all prominent PSH projects cited by both PSH critics and proponents globally, and they have been included in our analysis to explore the range of sustainability costs and benefits that can be associated with PSH developments.

3. Theory

3.1. Overview of Electrical Energy Storage Technologies

3.1.1. Different EES Technologies and Their Characteristics

There are many different EES technologies, with each having different characteristics making them suitable for different roles in the grid (Figure 1).

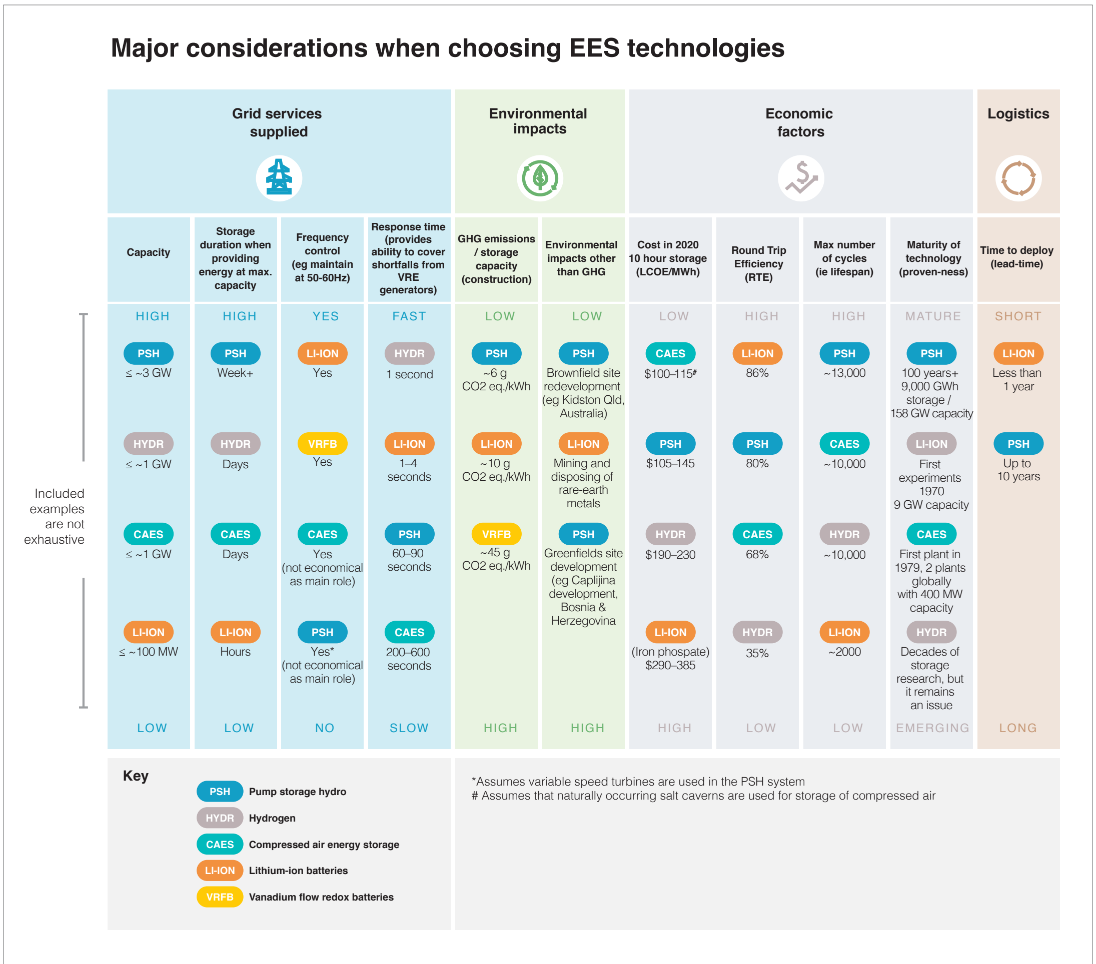

Figure 1. Major EES technology choice considerations (Source: authors, data from [11–25]).

In general terms, as the proportion of VRE generators in a grid grows, the requirement for EES grows as well [7]. However, as individual grids exist in their own particular geographic, governance, and political circumstances, EES requirements need to be assessed on a grid-by-grid basis while considering the different characteristics of the different available EES technologies. Figure 1 shows some of the major considerations that grid managers and electrical energy storage providers need to consider when selecting EES technologies for individual grids.

While there are a wide range of EES technologies, the grid-suitable options are: (i) PSH, (ii) compressed-air energy storage (CAES), (iii) vanadium redox flow batteries (VRFB), and (to a lesser extent) (iv) sodium sulfur (Na-S) and lithium-ion (Li-ion) batteries [18,26]. Another promising EES technology is hydrogen energy storage [27], although the storage of hydrogen remains a challenge [15].

The levelized cost of energy (LCOE) considers all major cost elements for each technology over the technology lifetime, showing that PSH is currently the second cheapest grid-suitable EES technology after conventional CAES, where naturally occurring salt caverns are used for the storage of the compressed air [16]. However, conventional CAES systems burn natural gas to release the stored energy, causing high greenhouse gas (GHG) emissions [11]. CAES GHG emissions can be lowered by (i) storing the heat lost when the air is compressed (this technology remains under development) or (ii) burning low-emission hydrogen produced from renewably generated electricity instead of natural gas in order to release the stored energy [16]. However, both these options add complexity and costs to the system, thus driving up the LCOE for CAES.

Thus, for large-scale EES applications, taking cost and GHG emissions into account, PSH is the most attractive option. Furthermore, Figure 1 highlights that where a particular electricity grid requires (i) large-scale electricity storage, (ii) high instantaneous supply capacity, (iii) low (or positive) environmental and socio-economic impacts, and (iv) a low LCOE with (v) good round trip efficiencies, then PSH should be seriously considered. In addition to these characteristics, PSH systems can also supply valuable ancillary services, such as covering shortfalls in VRE-supplied electricity, as well as possessing the ability to begin supplying electricity in the case of grid-wide blackout [17]. PSH does have some constraints such as long lead times and PSH sites needing to meet a number of physical criteria (as detailed in Section 3.2.1). However, these constraints are well-understood, with PSH being the most mature and technically proven EES technology [20,22].

PSH has a number of other key advantages in cases where there are suitably located PSH sites. In particular, PSH systems:

(i) Have storage capacity flexibility through adjustments to the size of the upper reservoir.
(ii) Have a long operational life-span of up to at least 80 years [28].
(iii) Supply low-cost electricity [16].
(iv) Have low greenhouse gas emissions per unit of energy stored [11] (with some exceptions [29], as discussed below).
(v) Can have low (or positive) social and environmental impacts (e.g., through re-purposing brownfield sites [30]).
(vi) Can be located to use the sea or ocean as the lower reservoir [31].
(vii) Are able to be co-located with VRE generators, such as floating solar arrays installed on reservoirs [32] and/or wind generators [8,31].
(viii) Involve a high proportion of local expenditure for development, thus enhancing local socio-economic benefits [17].
(ix) Have effectively unlimited charge–discharge cycles (assuming appropriate maintenance/refurbishment).
(x) The decommissioning of PSH is well-understood and does not require dealing with environmentally damaging materials.

3.1.2. The Need for Sustainable Development Trajectories in Southeast Asia

There is an urgent need to move away from fossil-fuel based electricity generators to avoid the harm they cause to the environment, as well as to population health and well-being, due to, e.g., greenhouse gas, particulate, and volatile organic emissions [33–35]. In recognition of this, it was globally agreed to phase down the use of unabated coal-fired electricity generators in the 2021 Glasgow Climate Pact [36]. Despite this, the use of coal-fired power stations is growing in countries around the Pacific Rim, such as in Southeast Asia. For example, Viet Nam, Cambodia, and Malaysia have all been rapidly installing new coal-fired power stations [37]. With the growing use of fossil-fuel fired electricity generation, along with the knowledge of the associated environmental and health-related impacts, it is unsurprising that there have been significant studies linking electricity generation and economic growth in Southeast Asia to the need for sustainable development pathways where greenhouse gas, particulates, and other emissions are rapidly curtailed [34,37,38].

Some have argued that hydropower is the low-emission technology that will drive the achievement of global net zero emissions by 2050 [39]. However, hydropower development generates negative environmental and social impacts, undermining its applicability for driving sustainable development. For example, hydropower dam construction and operation in Cambodia, Lao PDR, Thailand, and China are impacting fish migrations, river hydrology, and sediment transfers, with these impacts negatively affecting communities up to a thousand kilometers away from dam sites [40]. A further example of the damage associated with hydropower developments is that 40 million people globally had been directly displaced by dam construction works up to 2010, with ten times this number of downstream river-dependent people impacted by changes in natural river-flows and the loss of ecosystem services [41]. This is particularly concerning, with around 80% of the world's population already exposed to threats to their water security in 2010 [42] and 100,000 freshwater species also relying on healthy aquatic ecosystems [43]. In contrast, PSH systems can be sited and designed in ways that result in minimal negative (or even positive) environmental and social effects (Section 3.2.2). This can be achieved, for example, by designing off-river PSH—particularly when the PSH systems are located in decommissioned mines and other brownfield sites [30].

3.2. Pumped Storage Hydropower

3.2.1. What Is Pumped Storage Hydropower?

PSH systems store electricity by pumping water from a lower to an upper reservoir when there is an excess of electricity (e.g., from solar generators during a sunny day). When electricity demand is high, the water is allowed to fall to the lower reservoir through an electricity-producing turbine [20].

The main types of PSH are closed-loop and open-loop systems. A closed-loop PSH system has two self-contained reservoirs, meaning neither is permanently connected to naturally flowing water. Because closed-loop PSH systems are not regularly connected to flowing water, their environmental impacts tend to be lower than those of open-loop PSH systems [44–46], which are connected to naturally flowing water (normally via the lower reservoir). An open-loop PSH system could consist of a barrage in a river (creating the lower reservoir), with the upper reservoir being a small dam built on a nearby hill [45]. In some cases, existing conventional hydropower systems have been reconfigured as PSH systems, such as with the existing conventional hydropower dam forming the barrage in the river [47]. This is similar in nature to developing PSH in a brownfield site, as most of the negative environmental and social impacts associated with this type of PSH development have already occurred. In these cases, the reconfiguration can be an opportunity to improve environmental performance. Improving environmental performance could be achieved, for example, by adding thermal pollution control devices, enabling the release of environmental flows, and putting mechanisms in place to better regulate silt build-up and to avoid and manage vegetation entering (and decomposing) in the reservoir.

Whether designed as open or closed-loop, PSH systems need to be [48]:

- Linked to a water source (e.g., a lake, river, sub-surface water, or the ocean) that provides sufficient water for moving between the reservoirs.
- Connected to an electricity grid.
- Located where the two reservoirs have a sufficient height difference so that falling water can drive the turbines.

One assessment identified around 600,000 potential closed-loop reservoir pair sites globally, all together capable of storing around 23,000,000 GWh of electricity [44].

3.2.2. Pumped Storage Hydropower and Sustainability

Regardless of whether there is an overall benefit or cost to the environment, PSH development will impact flora, fauna, landscapes, and ecosystem services (e.g., water filtration and fisheries) and will create some greenhouse gas emissions. Normyle and Pittock [49] characterized the main PSH activities that affect the environment as follows:

- Dam construction.
- Road construction.
- Human presence (e.g., accommodation and sanitation facilities for workforce).
- Vegetation clearing.
- Construction of transmission lines.
- Spoil disposal (e.g., linked to reservoir works, tunnel construction).
- Land inundation.
- Facilitating access for invasive species.

There are also GHG emissions relating to the construction of pump/turbine units, manufacturing of cement and steel, transport of materials and personnel, flooding of forested landscapes, and clearing of vegetation for roads [11,50,51].

Overall, PSH systems tend to result in relatively small environmental impacts compared to conventional hydropower [52,53]. This is because PSH reservoirs are much smaller in scale and—particularly in the case of closed-loop systems—tend to have significantly lower impacts on natural hydrology. PSH reservoirs also have a small surface area in comparison to renewables-based electricity generators. For example, if EES (for a 100% renewables-based electricity grid) for one million people is mostly provided by PSH, then reservoirs of around 2–5 km^2 surface area will be required, whereas the land area required for wind/solar installations providing electricity for the same population would be around ten times that [9]. Because of their small size and (often) off-river locations, PSH reservoirs are also much less prone to trapping silt and organic material than conventional, large-scale hydropower [53]. The decomposition of organic material in hydropower reservoirs results in GHG emissions [54], further enhancing the advantages of PSH (particularly off-river PSH).

In terms of social impacts relating to PSH development, there is only a small body of literature available. Generally, PSH impacts will be much smaller in scale than impacts relating to conventional hydropower, but they will occur in similar ways. The three main social impact areas relate to: (i) construction work accommodation, (ii) agriculture production losses, and (iii) population displacement and resettlement [55].

Re-purposing brownfield sites, such as decommissioned mines or existing hydropower facilities, may result in the lowest social and environmental impacts among different PSH types because these sites are generally already degraded. In fact, in some cases where abandoned mines have been re-purposed, PSH developments have been shown to have positive social and environmental outcomes [30]. Because of the lower negative (or positive) impacts for these developments, environmental and social impact assessment processes tend to be smoother, including having fewer objections from local communities and non-government organizations. For example, the Kidston PSH facility being developed in north Queensland, Australia has had greatly simplified impact assessment approval processes because of its limited impacts in comparison to green field site development [17]. The Supplementary Materials of this paper provides details on the Kidston PSH facility, as well as five other PSH case studies. Existing and abandoned reservoirs may also be re-configured for use as PSH in some cases [30]; this relies on a suitable nearby elevated location for the upper reservoir, as illustrated by the Lake Cethana (Australia) and Lamtakong (Thailand) case studies described in the Supplementary Materials.

4. Results

Our results build on a technical paper published by the Asia Pacific Economic Community [17].

Table 1 describes the status of renewables-based electricity generation and EES in each of the target economies, details the transmission linkages between nations/economies, and shows the status and potential for PSH in the target economies.

Table 1 shows that 17 of the 24 target economies (excluding two economies that include conventional hydropower within their targets) are fostering renewables-based generation. In addition, many states in the United States have adopted renewable portfolio standards (RPSs) to drive growth in renewables. For example, California's RPS targets 100% renewables-based generation of electricity by 2045 [56].

The 24 target economies can be roughly split into three groups in relation to PSH development: (i) those that have already invested in PSH, (ii) those that are planning and/or building PSH installations, and (iii) those where there is no evidence of either existing or planned PSH (Figure 2). In the first group are countries, including the People's Republic of China (PRC), Japan and the United States, that have the most significant existing investments in PSH, with the PRC planning extensive expansion. The second group includes some economies from the first group, as well as economies with no existing PSH such as Canada and the Philippines (where PSH projects are currently under construction), as well as Viet Nam and Chile (with PSH systems in planning stages). The third group includes three economies where PSH is not geographically viable (Brunei, Singapore and Hong Kong), economies where electricity system planning is focused on fossil-fuel-powered generators rather than VRE and storage (such as Cambodia), and economies with terrain well-suited to PSH development such as New Zealand and Peru.

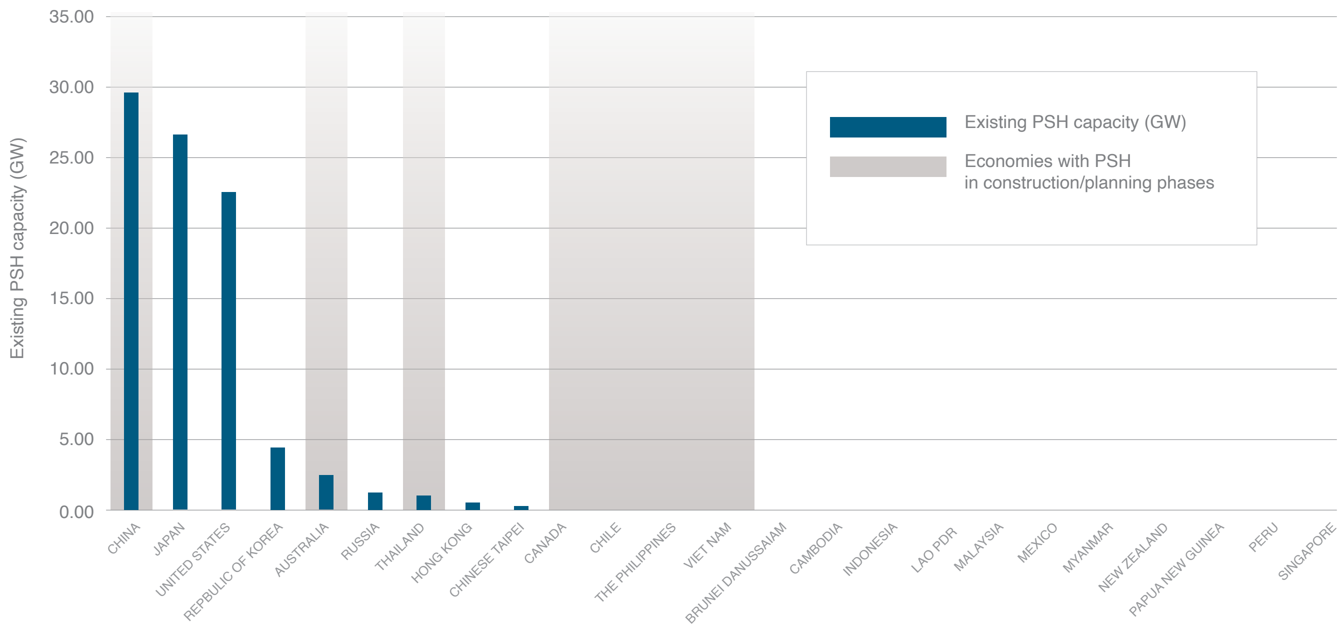

Figure 2. Existing PSH capacity (GW) plus economies with PSH in development (Source: authors).

Table 1. Renewables-based generation, EES, status, and potential of PSH in target economies.

ECONOMY	Current Renewable Energy Generation ‡		Renewable Energy Target	Energy Storage Existence (Yes/No)	Energy Storage Planned (Yes/No)	Grid Reliability Issues (Yes/No)	Cross-Border Electricity Transmission Grids (Yes/No/Planned)	Existing PSH Capacity (GW)	Planned PSH (Yes/No) #	Potential PSH * (No. of Sites)	Potential PSH * (GWh)
	TOTAL	PERCENTAGE									
Australia	40,927 GWh (2019)	18% of generation	33,000 GWh by 2030	Yes	Yes	Lack of investment in flexible electricity generation	Planned—Singapore	2.5	yes	3996	176,506
Brunei Darussalam	1.2 MW (2019)	0.08% of capacity	30% by 2035	No	No	No	Planned—Malaysia and the Philippines	-	no evidence	nil	nil
Cambodia	155 MW (2019)	~9% of capacity	415 MW by 2022	No	Yes	Yes	Yes—Lao PDR, Thailand, Viet Nam	-	no evidence	190	8005
Canada	20 GW (2018)	7.2% of capacity	No data	Yes	Yes	No	Yes—United States	2	yes	23,427	869,828
Chile	5.8 GW (2018)	24% of capacity	60% by 2035	Yes	Yes	Yes	Yes—Argentina; Planned—Andean economies	-	yes	11,780	456,939
Chinese Taipei	2.5 GW (2015)	1.7% of capacity	20% by 2025	Yes	Yes	Yes	No	0.0026	no evidence	550	9248
Hong Kong, China	52 MW (2017)	0.42% of capacity	N/A	Yes	No	No	Yes—China	0.6005 ^	no evidence	nil	nil
Indonesia	9 GW (2017)	14.5% of capacity	45 GW by 2025	No	No	Yes	Planned—Malaysia	-	no evidence	26,025	821,351
Japan	~181,300 GWh (2017)	18% of generation	24% of generation by 2030	Yes	Yes	No	No	27	no evidence	2413	52,657
Lao PDR	41 MW (2016)	0.656% of capacity	951 MW by 2025	No	No	Yes	Yes—Cambodia, Myanmar, People's Republic of China, Thailand, Viet Nam	-	no evidence	5605	188,156

Table 1. *Cont.*

ECONOMY	Current Renewable Energy Generation ‡		Renewable Energy Target	Energy Storage Existence (Yes/No)	Energy Storage Planned (Yes/No)	Grid Reliability Issues (Yes/No)	Cross-Border Electricity Transmission Grids (Yes/No/Planned)	Existing PSH Capacity (GW)	Planned PSH (Yes/No) #	Potential PSH * (No. of Sites)	Potential PSH * (GWh)
	TOTAL	PERCENTAGE									
Malaysia	0.57 GW (2016)	23% of capacity	31% by 2025 40% by 2050	Yes	Yes	No	Yes—Thailand, Indonesia and Singapore	-	no evidence	3756	119,842
Mexico	22,543 GWh (2018)	6.7% of generation	40% of generation by 2036	No	No	No data	Yes—United States	-	no evidence	30,838	1,071,158
Myanmar	173 MW (2019)	3% of capacity	12% by 2025	No	Yes	Yes	Yes—Lao PDR and possibly Thailand	-	no evidence	13,163	435,176
New Zealand	~10,300 GWh (2017)	24% of generation	100% (including hydropower) by 2030	Yes	Yes	Possible	No	-	no evidence	1356	40,486
Papua New Guinea	0.075 GW (2018)	8.6% of capacity	100% (including hydropower) by 2030	No	No	Yes	No	-	no evidence	13,556	391,848
People's Republic of China	415 GW (2019)	21% of capacity	35% of generation by 2030	Yes	Yes	Possible	Yes—Hong Kong SAR, Myanmar, Lao PDR, Vietnam, and Russia Planned—ROK	30	yes	115,871	3,766,868
Peru	2252 GWh (2018)	4.1% of generation	5% of generation by 2013	No	No	No data	Yes—Ecuador	4.7	no evidence	1045	36,479
Republic of Korea	~6 GW, including hydropower (2019)	5% of generation	20% by 2030	No	No	No	Planned—HVDC link to China	-	no evidence	18,892	552,555

Table 1. *Cont.*

ECONOMY	Current Renewable Energy Generation ‡		Renewable Energy Target	Energy Storage Existence (Yes/No)	Energy Storage Planned (Yes/No)	Grid Reliability Issues (Yes/No)	Cross-Border Electricity Transmission Grids (Yes/No/Planned)	Existing PSH Capacity (GW)	Planned PSH (Yes/No) #	Potential PSH * (No. of Sites)	Potential PSH * (GWh)
	TOTAL	PERCENTAGE									
Russia	3 GW (2020)	1.2% of capacity	4.5% of generation by 2030	Under construction	Yes	Yes	Yes—CIS † economies, Finland, Lithuania, China and Mongolia	1.3	no evidence	20,168	871,802
Singapore	~160 MW (2018)	0.18% of capacity	8% of generation by 2030	Under construction	Yes	No	Yes—Malaysia Planned—Australia	-	no evidence	Nil	nil
Thailand	21,402 GWh (2019)	10.1% of generation	20.77 GW by 2037 (26.9%)	Yes	Yes	None evident	Yes—Lao PDR, Cambodia, Myanmar, Malaysia	1	yes	2120	62,590
The Philippines	13,578 GWh (2018)	14.4% of generation	15 GW by 2030	Yes	Yes	Likely	Planned—Malaysia	-	yes	5311	160,911
United States	2.5 million GWh (2019)	8.6% of generation	State by state basis	Yes	Yes	No	Yes—Canada, Mexico	22.9	no evidence	34,820	1,415,472
Viet Nam	No data	No data	12.5% by 2025 21% by 2030	No	Yes	Yes	Yes—Lao PDR	-	yes	6233	202,518

NOTES: ‡ Based on most recent data available; † Commonwealth of Independent States (CIS) economies are: Russia, Ukraine, Belarus, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia, and Moldova; Except where otherwise noted, the data in this table is sourced from Gilfillan & Pittock [17]; ^ Hong Kong's PSH capacity includes an installation located in the People's Republic of China; # Planned PSH to the extent known after a literature review, workshop with experts, and APEC consultation with authorities in their 21 member economies. Additional, planned PSH projects may not have been located; * PSH potential data comes from RE100 Group [9].

In addition to the analysis of the status of and potential for PSH in the 24 target economies, Table 2 summarizes six case studies of PSH facilities that were selected based on prominent projects globally cited by PSH critics and proponents to explore the range of sustainability costs and benefits. These case studies range from a project completed in 1979 to projects that are in construction and planning phases. Additional details for each of the case studies are included in the Supplementary Materials.

Table 2. Six case studies of PSH projects (Source: authors).

No.	Project Name	Description
1	Platzertal extension to Gepatsch hydropower facility, Austria	Status: Planned. Impacts: Will flood a pristine alpine river valley that is home to protected meadows and grasslands, as well as animals such as alpine marmots, which are under threat because of loss of habitat.
2	Snowy 2.0 scheme, Australia	Status: Under construction. Impacts: Is likely to transfer invasive predatory fish and a virus and negatively impact at least two threatened fish species. Clearing of a transmission line easement is also expected to create large environmental impacts.
3	Lamtakong PSH facility, Thailand	Status: Completed December 2019 Impacts: The PSH facility is an add-on to an existing irrigation reservoir. The new reservoir is a turkey's nest dam on a hill-top, and the system is linked to VRE generators. The water regime will not be significantly affected.
4	Lake Cethana, Australia	Status: Scoping to investment-ready stage Impacts: Upper reservoir will be less than 5% of the volume of the existing lower reservoir, so there is unlikely to be any significant impact on water quality, volumes, or freshwater biodiversity. The biodiversity value of the new upper reservoir site has not yet been publicly assessed, but the site is not located in a protected area.
5	Kidston PSH facility, Australia	Status: Under construction Impacts: Being developed on a decommissioned mine site, the environmental impacts of concern relate to water discharges following large rainfall events. These impacts are easily managed, and the project is creating jobs, reducing dependency on fossil-fuel generators, and will continue to maintain and improve the degraded mine area.
6	Čapljina PSH facility, Bosnia and Herzegovina	Status: Completed 1979 Impacts: This project is located in an area characterized by complex and poorly understood underground water flows. The project has reduced water flows into the Hutovo wetlands and significantly disturbed the flows in the Trebišnjica river that is linked to the upper reservoir.

5. Discussion

5.1. PSH Potential in APEC +3 Economies

Modelling conducted by the RE100 Group [9] showed that a good first approximation for EES requirements for a 100% renewables-based electricity grid is 20 GWh per million people. The combined population of the 24 target economies is just over 3 billion people or 3000 million people [57]. Thus, the EES required for these economies will be of the order of:

$$EES_{required} = 3 \times 10^{9}\text{people} \times \frac{20\text{ GWh}}{1 \times 10^{6}} = 60,000\text{ GWh}$$

Based on this approximation, 60,000 GWh of EES capacity would enable 100% renewables-based electricity generation in the target economies. In comparison, the Global PSH Atlas identifies over 340,000 potential PSH sites among the target economies, with a combined potential EES capacity of over 11,700,000 GWh [9], or 195 times the estimated 60,000 GWh of required EES. These 340,000 sites do not include brownfield sites, such as existing reservoirs or decommissioned mines, due to limited information on their shapes and volumes [9], meaning there are additional possibilities for PSH siting across the target economies.

Many of the 340,000 identified sites will not be suitable for development because of ecological and social values, land ownership issues, or commercial unviability [9]. Thus, further ground-based assessments are needed to: (i) expand on the atlas' simplified cost calculations; (ii) determine actual geological, hydrological, environmental, and cultural/heritage situations; (iii) determine land tenure and right to use land; and (iv) satisfy environmental, social, and developmental approval processes [9]. Addressing environmental and social impacts is discussed in Section 5.3.

5.2. Regulatory Frameworks for Encouraging Investment in PSH

A major challenge for PSH is that development requires large up-front capital expenditure. This can be exacerbated because financing institutions generally apply a 40-year discounting period [16], despite PSH lifespans expected to be double this or more [28]. There are a number of developer- and government-driven strategies that can be used to address the large up-front costs. Experience from Australia highlights that PSH developers can [17]:

(i) Lease their PSH facility to a utility to provide a known income stream.
(ii) Invest in complimentary shorter-term income-generating investments (e.g., solar farms) alongside their PSH development.

Governments can support PSH development by ensuring that national energy markets are structured to value all the services that PSH supplies. These services include the ability to:

(i) Rapidly respond to demand changes (e.g., when another generator goes offline without warning).
(ii) Stabilize the voltage, current, and frequency of electricity in the grid.
(iii) Begin providing electricity when an entire electricity grid is blacked out.
(iv) Fill a supply gap when VRE generators produce less than forecast.
(v) Store VRE produced electricity so it can be supplied to consumers at times of high demand.

Because PSH can provide a variety of grid services in addition to bulk energy storage, there are many ways that PSH developments can be financed, including through grants and loans from governments, bi- and multi-lateral development agencies and banks, and private banks and credit agencies [58].

5.3. PSH Evaluation and Sustainability

Planning for PSH should be a part of broader strategic planning for transitioning to low-carbon electricity grids. The strategic planning should include evaluating EES requirements for the grid in terms of both storage and other ancillary services. Once grid requirements are known, each PSH development will need to be individually assessed in four key areas:

(i) Commercial viability.
(ii) Environmental impacts.

(iii) Social impacts.
(iv) The role PSH projects will play in the grid (see Section 5.2).

Commercial viability will be assessed through a business case for the development. To support this, there are both simplified cost estimator tools [59] and detailed EES performance and cost-estimate analyses [16].

Assessing social and environmental impacts is important because they can range from beneficial to unacceptably high. Figure 3 highlights that PSH is neither inherently beneficial nor inherently damaging to the environment, with the six case studies referred to in the figure spanning the full spectrum of impacts. More details on the case studies in Figure 3 are provided in the Supplementary Materials.

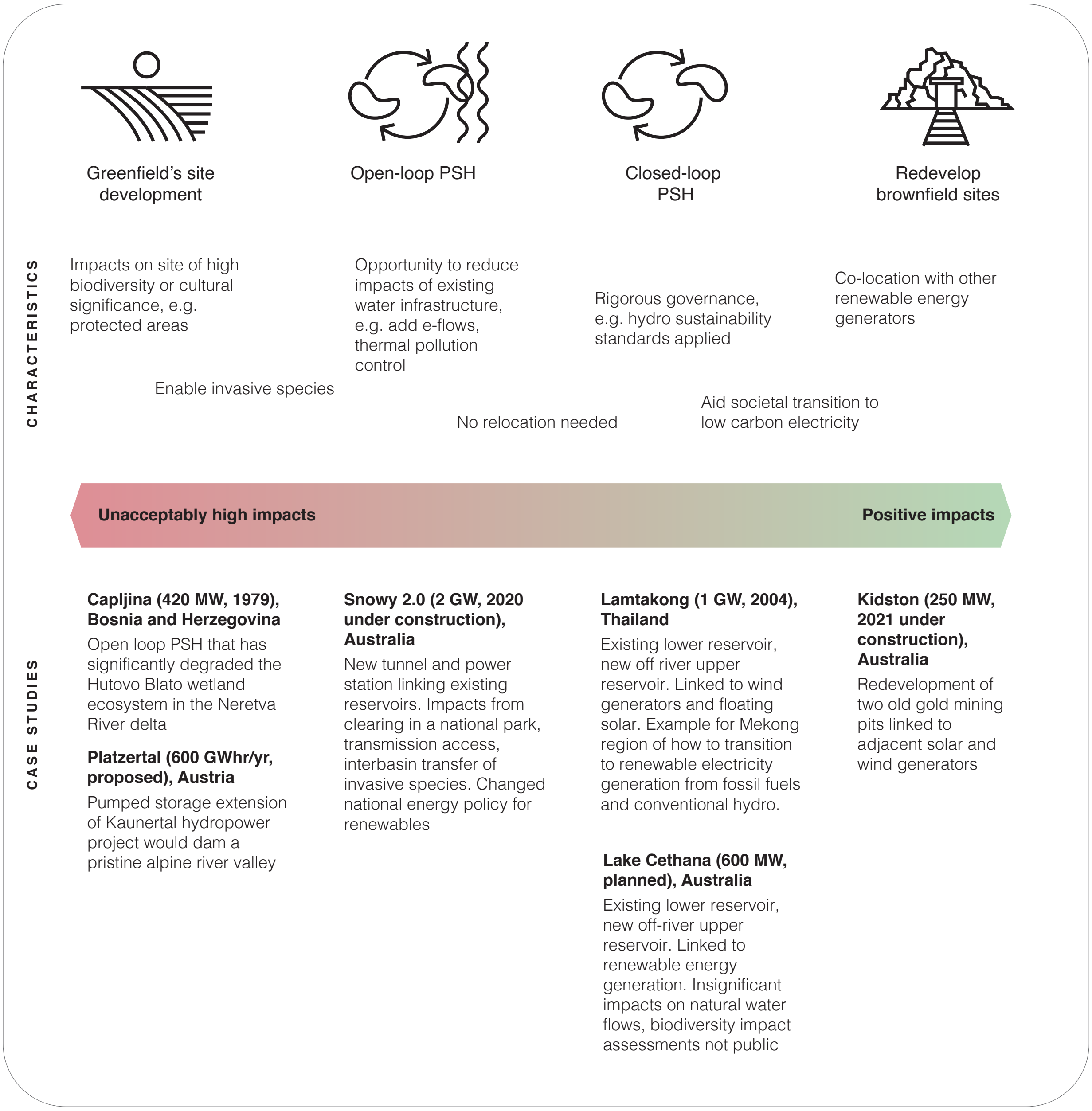

Figure 3. Spectrum of environmental impacts of potential pumped storage hydropower developments (Source: authors).

The two key factors that favor the development of PSH projects at the positive end of the spectrum are (i) siting projects at brownfield sites rather than on-river developments in pristine environments and (ii) applying environmental and social protocols from the earliest scoping and planning phases, as well as during construction and operation.

To support socio-economic and environmental impact assessments during the scoping and planning phases, there are a variety of tools and manuals that are compatible with the International Finance Corporation's (IFC's) Environmental and Social Performance Standards [60]. For example, the International Hydropower Association has developed a suite of standards and guidelines for managing environmental and social affects related to hydropower development [61], and with IFC support, Nepal has developed a Hydropower Environmental Impact Assessment Manual [54]. Independent organizations have also developed tools for assessing hydropower developments. For example, International Rivers, an organization established to protect rivers and the rights of dependent communities, recently launched a set of interlinked assessment tools [62]. The use of tools like those outlined here can ensure that PSH is only developed on sites where impacts will be either positive or minimal and where any negative impacts are able be well-managed and mitigated.

Because developing just 0.6% of potential PSH capacity in the target economies would provide enough storage to support 100% renewables grids around the Pacific Rim, only sites where development would result in minimal (or positive) environmental and social impacts should be considered for development.

6. Conclusions and Recommendations

Because of the weather-dependent nature of the main renewables-based electricity generators (e.g., wind and solar based generators), EES is needed to help electricity systems transition to zero-carbon generation. For individual grids, a strategic process should be used to establish EES requirements and to determine the optimum mix of EES technologies for that grid based on the services it requires. PSH is a well-established technology that can fill many key EES roles in the grid, although it does have geographic constraints and high total upfront capital costs.

The Global PSH Atlas is one tool that aids pre-scoping for PSH sites, and it shows that there is 195 times as much PSH storage potential across Pacific Rim economies as they would need in order to transition to 100% renewables-based grids. This means that PSH development need only be considered for sites where there will be minimal (or positive) environmental and social impacts.

If well-sited and managed, PSH development can create environmental and social benefits, thereby addressing existing conflict and concerns around ongoing conventional hydropower development. To help ensure better practice in siting and design, there are tools for assessing the sustainability of proposed developments. The development of PSH should:

- Be limited to sites with minimal or positive social and environmental impacts. For example, the re-development of brownfield sites (e.g., decommissioned mines) has the potential to create positive environmental and social effects.
- Prioritize off-river closed-loop developments, as these developments tend to have the lowest impacts on natural hydrology.
- Link, where feasible, to renewable energy generation projects, which could take the form of floating solar arrays or nearby wind or solar farms. Hybrid projects such as these allow for any excess renewably generated electricity to be stored and used and times of high demand.
- Avoid tropical sites where significant quantities of vegetation may be inundated or where there is likely to be significant inflows of organic matter in order to limit greenhouse gas emissions.
- Consider options to improve environmental performance where the PSH development will involve retro-fitting existing on-river infrastructure.

Using these measures builds on the International Hydropower Association's advocacy for PSH in ways that will ensure that developments are sustainable, not just in terms of GHG emissions but also in terms of broader environmental and social impacts.

With the growing need for EES as the world transitions to low-carbon electricity grids, countries in the Asia–Pacific region should actively encourage investments in EES to meet their renewable energy policy commitments. This should include supporting low-impact PSH projects through valuing ancillary services provided and linking developers with suitable financing organizations for long-term investments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15093139/s1, Supplementary material: Case-studies of PSH developments (planned and existing). References [63–84] are cited in the supplementary materials.

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Abbreviations

APEC	Asia Pacific Economic Cooperation
CAES	Compressed-Air Energy Storage
CIS	Commonwealth of Independent States
EES	Electrical Energy Storage
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt Hours
Hong Kong SAR	Hong Kong Special Administrative Region
HVDC	High Voltage Direct Current
IFC	International Finance Corporation
Lao PDR	Lao People's Democratic Republic
LCOE	Levelized Cost of Energy
PRC	People's Republic of China
PSH	Pumped Storage Hydropower
ROK	Republic of Korea
RPS	Renewable Portfolio Standards
VRE	Variable Renewable Energy
VRFB	Vanadium Redox Flow Battery

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