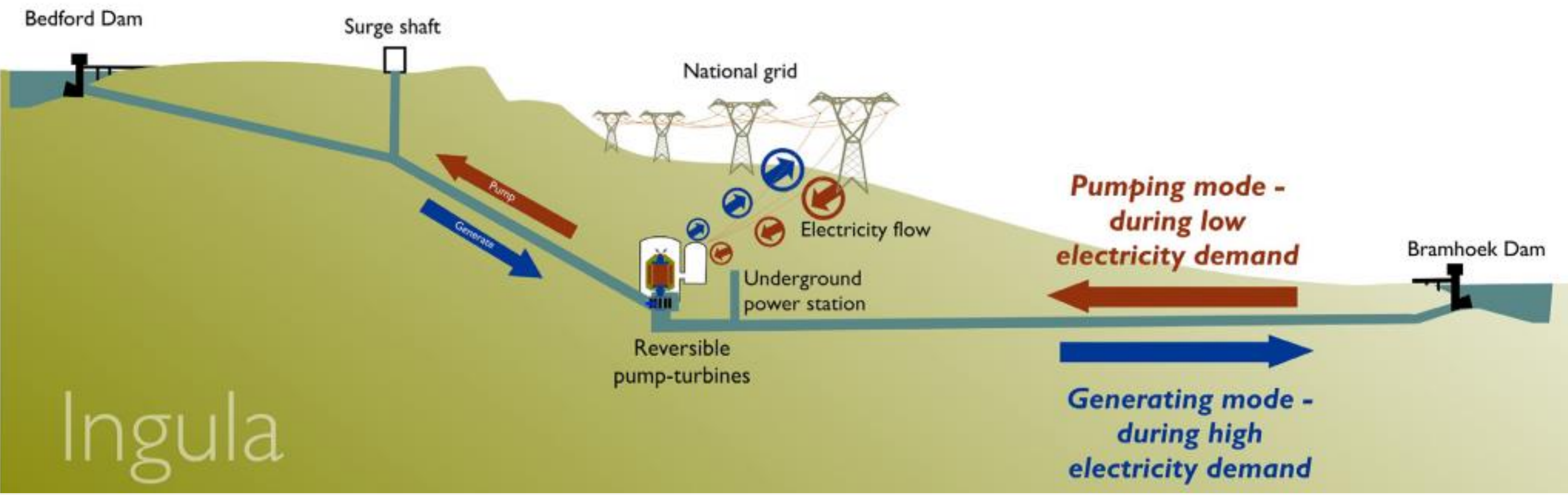

Pumped Storage Hydro

PEIA Energy Breakfast – 19 March 2024

Outline

- What is Pumped Storage Hydro
- Types of PSH
- How to Value PSH
- Recent Experiences (North America)

Pumped Storage Hydro

Presenters

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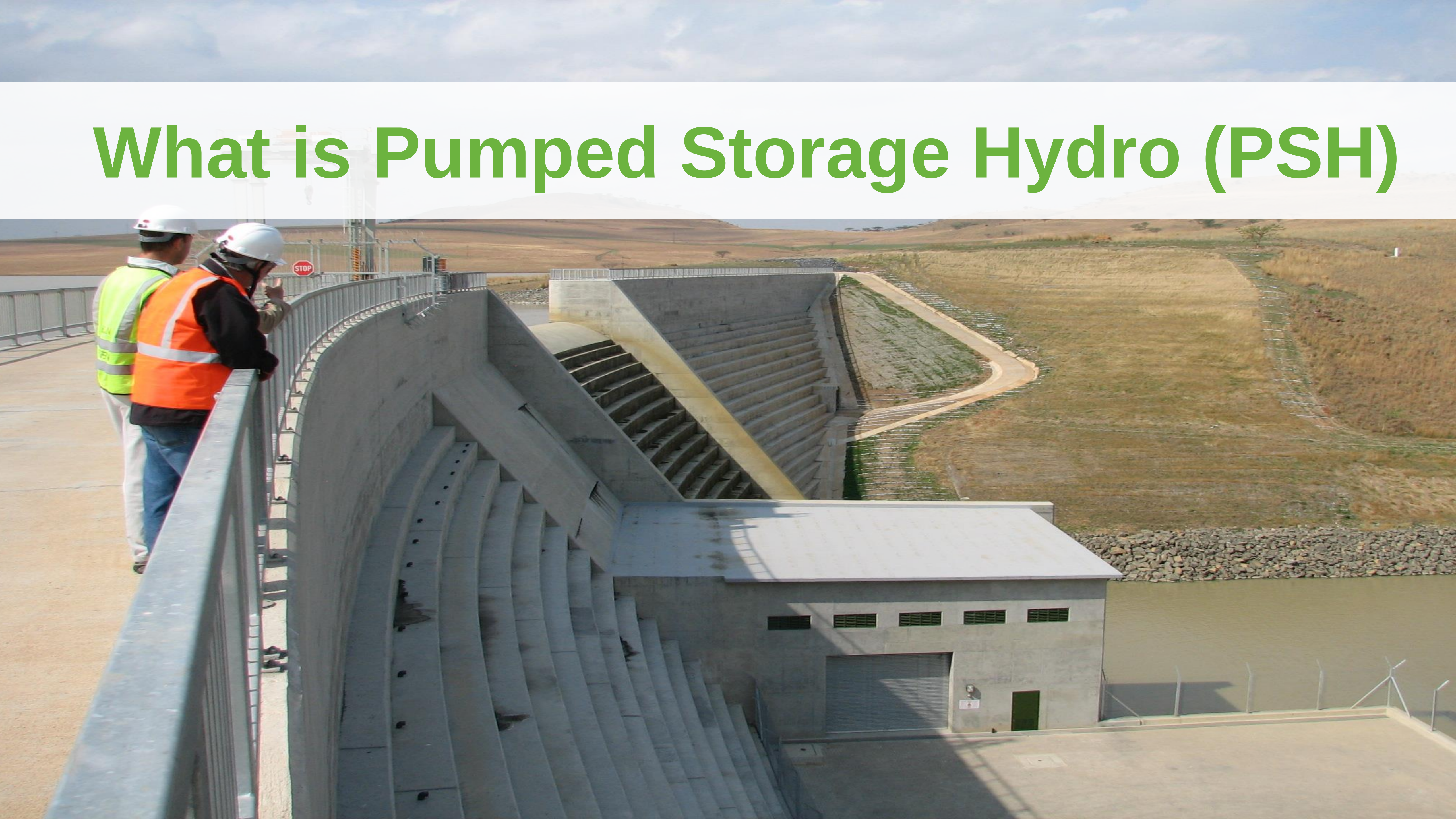
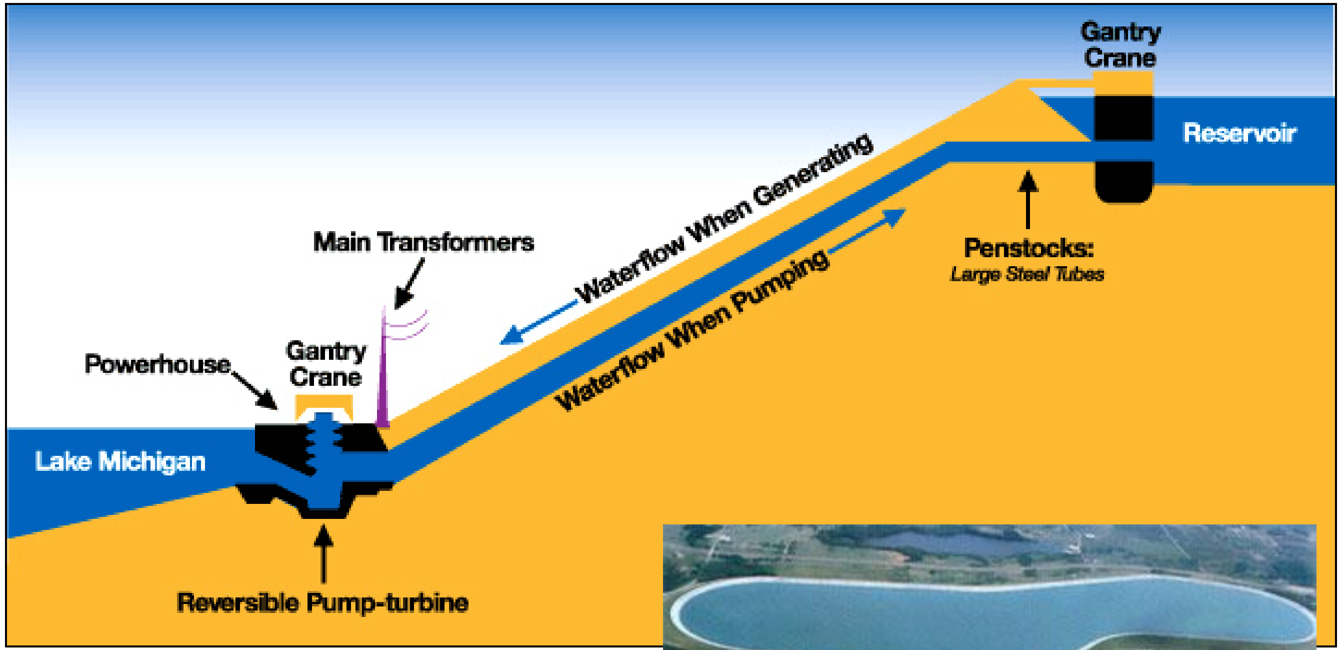
What is Pumped Storage Hydro (PSH)



What is Pumped Storage Hydro (PSH)?

Basics

- A big green battery.
- Transmission asset.
- Tried and tested technology.
- Technology continues to improve to deal with changing system/customer requirements.
- Canada, and especially BC, have some of the best PSH sites in the World.

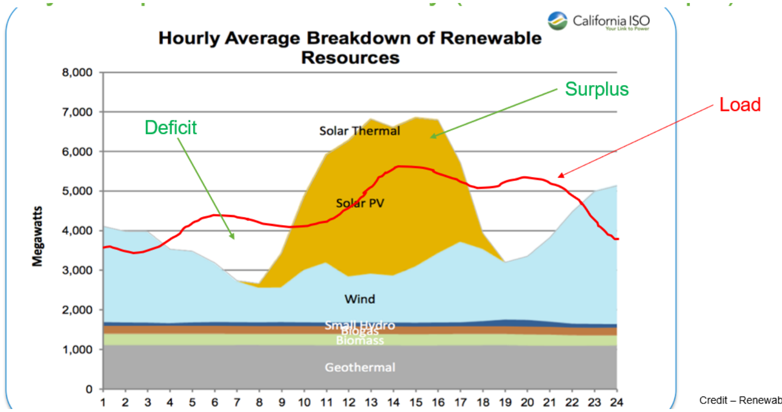


Credit – VisitLudington.com
2,172 MW Ludington Pumped Storage.
Been operating for 50 years (1973).
Recent upgrades to generating units, increasing installed capacity.
Owned by Consumers Energy and Detroit Edison.

What is Pumped Storage Hydro (PSH)

Why do we need energy storage

- Electricity needs to be used immediately it is generated.
- Energy mix has changed and will continue to do so:
  - Addition of more intermittent renewables (i.e. They are now cheaper than most fossil fuels like coal, diesel, etc):
    - Wind
    - Solar
    - Run of River Hydro
  - Government Regulations, Carbon Taxes, etc
  - Climate Agreements



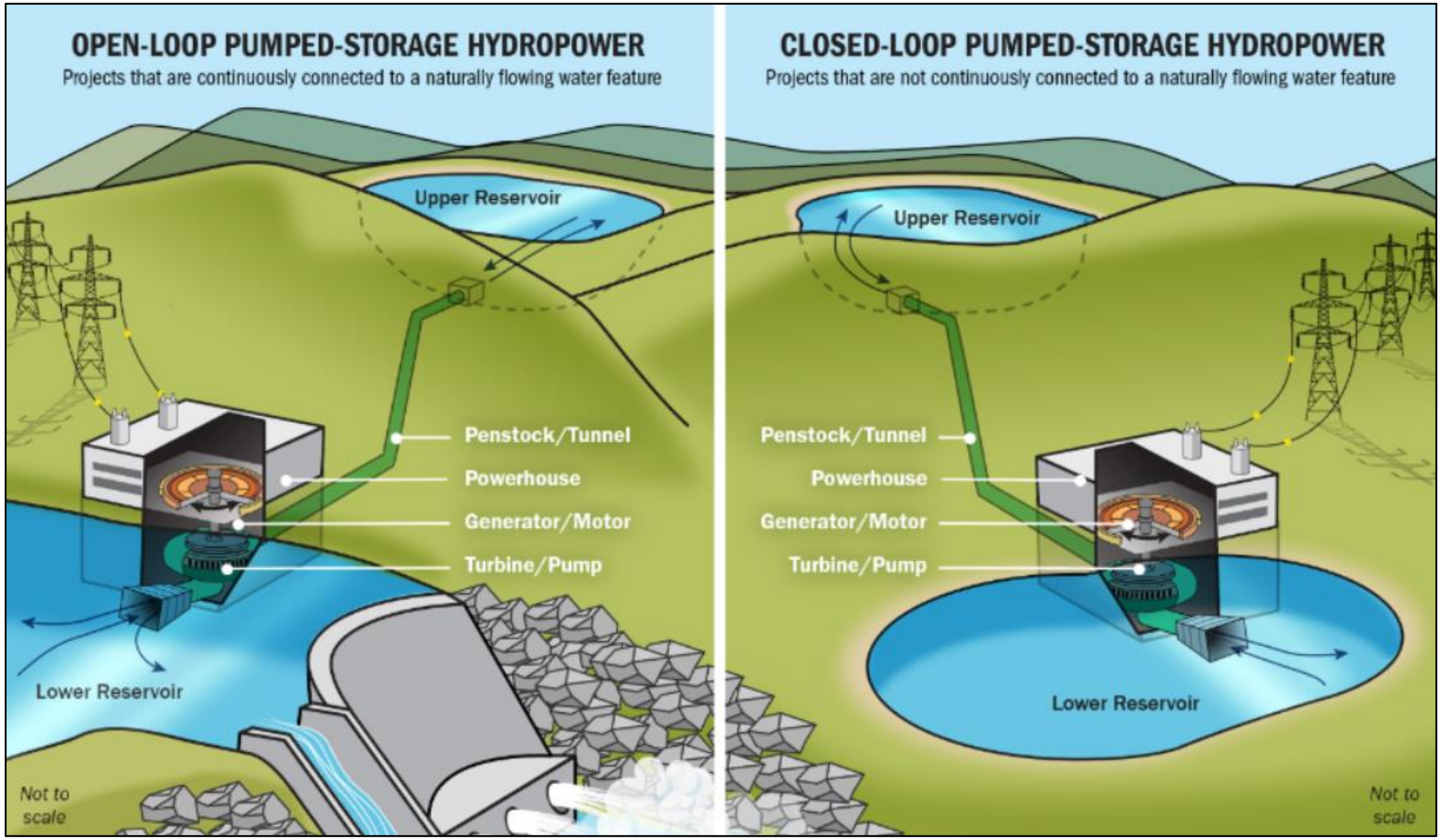
Credit – Renewable Energy World

Types of PSH

Types of Pumped Storage Hydro

Closed Loop versus Open System

- Open Loop PSH:
  - Use existing rivers, dams and/or lakes to lower costs.
  - Can be more difficult to permit.
- Closed Loop PSH
  - Huge flexibility. Not constrained by other water users (i.e. fish, irrigation, recreation, etc).
  - Can be easier to permit.



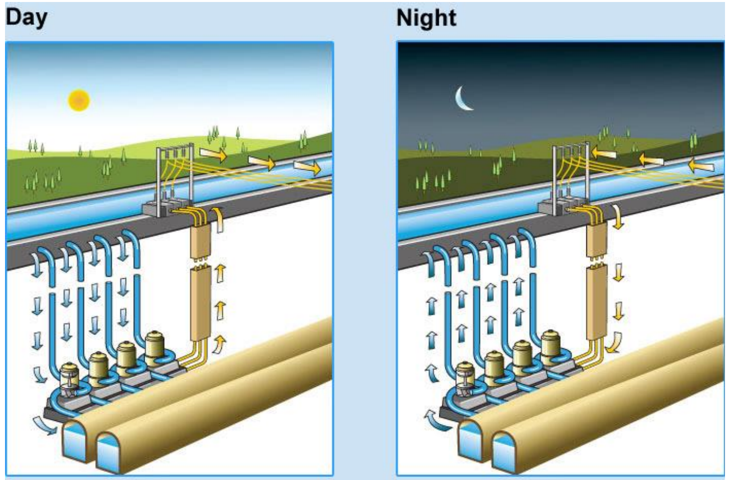
(Source: https://www.pnnl.gov/news-media/open-or-closed-pumped-storage-hydropower-rise)

Types of Pumped Storage Hydro

Hydro at Old Mine Sites

- Brownfield sites.
- Good existing infrastructure.
- Typically closed-loop (i.e. water quality).
- Using old Underground Caverns:
  - Geotech concerns.
- Using old Mine Pits:
  - Can be significant savings.

Source: Riverbank Power - Schematic

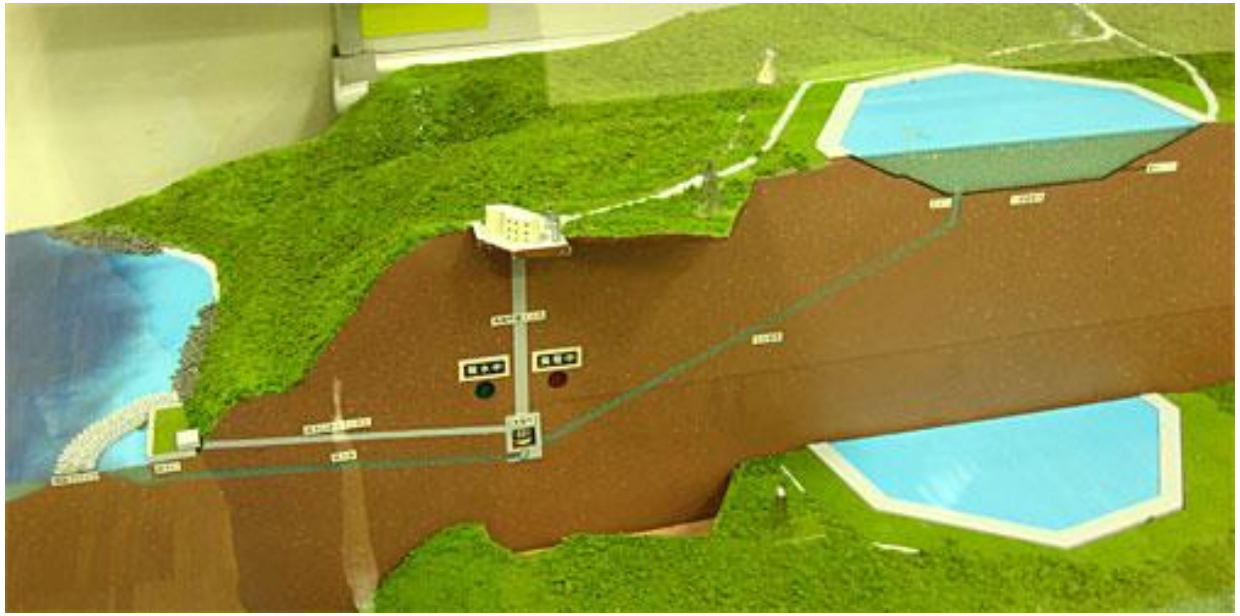


Credit: ONTARIO POWER GENERATION × NORTHLAND POWER

Types of Pumped Storage Hydro

Saltwater Pumped Storage Hydro

- 30 MW Okinawa Seawater Pumped Storage Plant – Japan
- Operated for 15 years. No longer in operation.
- Numerous challenges with Saltwater PSH (i.e. Marine growth, Temperature effects, Saltwater corrosion, Saltwater spray, Groundwater concerns).



Knight Piésold CONSULTING

Types of Pumped Storage Hydro

Daily, Weekly and Seasonal Storage

- Daily Storage 8-10 hours is most common (i.e. 400 MW Swan Lake PSH – 10 hours)
- Weekly Storage (Storage Cycles are also fairly common) (i.e. 1,333 MW Ingula PSH – 7-day cycle)
- Longer term / Seasonal storage is less common (i.e. 2,200 MW Snowy 2.0 PSH – 175 hours)

Credit – Rye Developments / CIP
400 MW Swan Lake Closed Loop PSH
Under development, Oregon, USA

Credit – ESKOM – Knight Piésold
1,333 MW Ingula PSH.Open Loop.
Commissioned 2018, South Africa

Credit – Hydroreview
2,200 MW Snowy 2 Open Loop PSH
Under construction (2029), Australia

Pumped Storage Hydro

Wonderful and Whacky Concepts – Energy Island’s

- North Sea Energy Island – 100 km off Denmark. Energy Hub, Wind Collection, Storage, Power to X
- The Energy Island – Off Netherlands Coast. 2,000 MW PSH + Wind (Kema)

Credit: www.northseaenergyisland.dk

Credit: Kema

Types of Pumped Storage Hydro

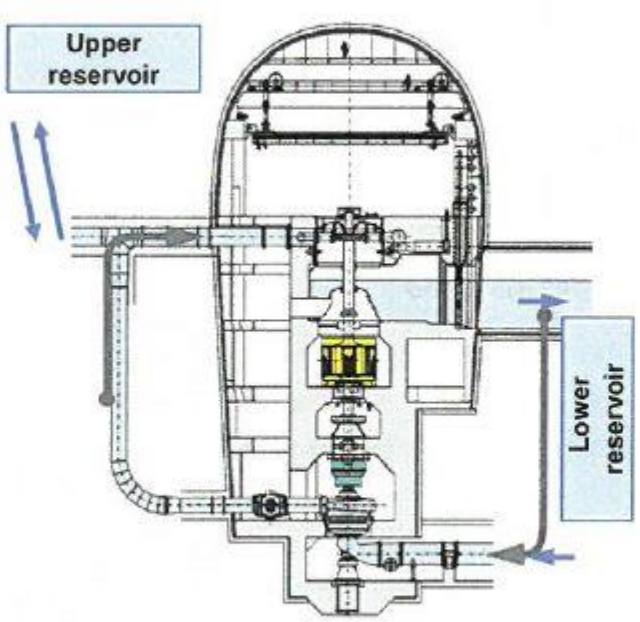
Pump-Turbines Configurations/Types

- Quaternary (4 part) system:

Separate turbine and separate pump

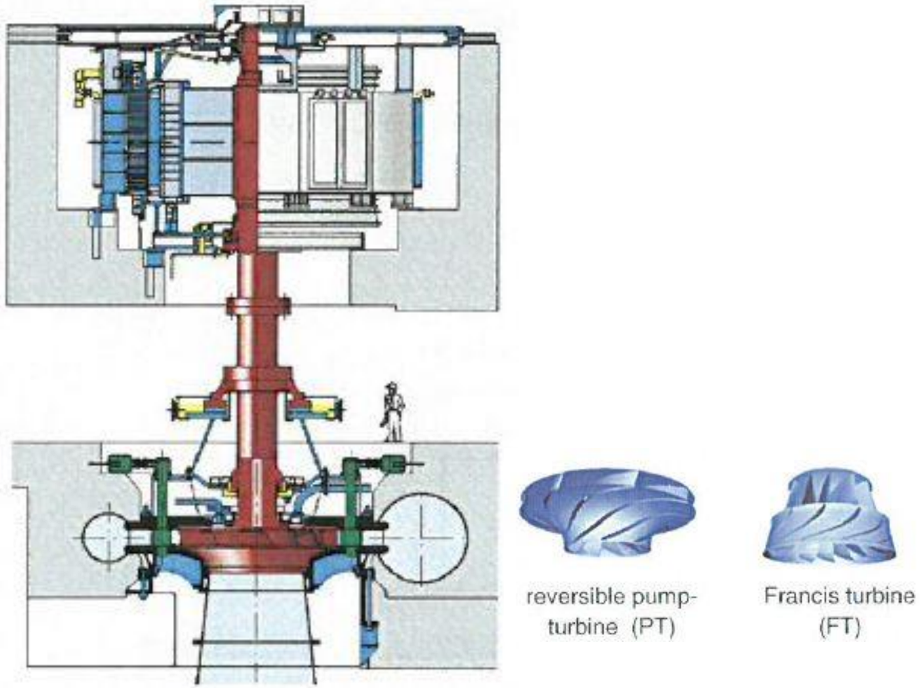
- Ternary (3 part) system:

Separate turbine and separate pump coupled to either side of a common generator



- Reversible Pump-Turbine (2 part)

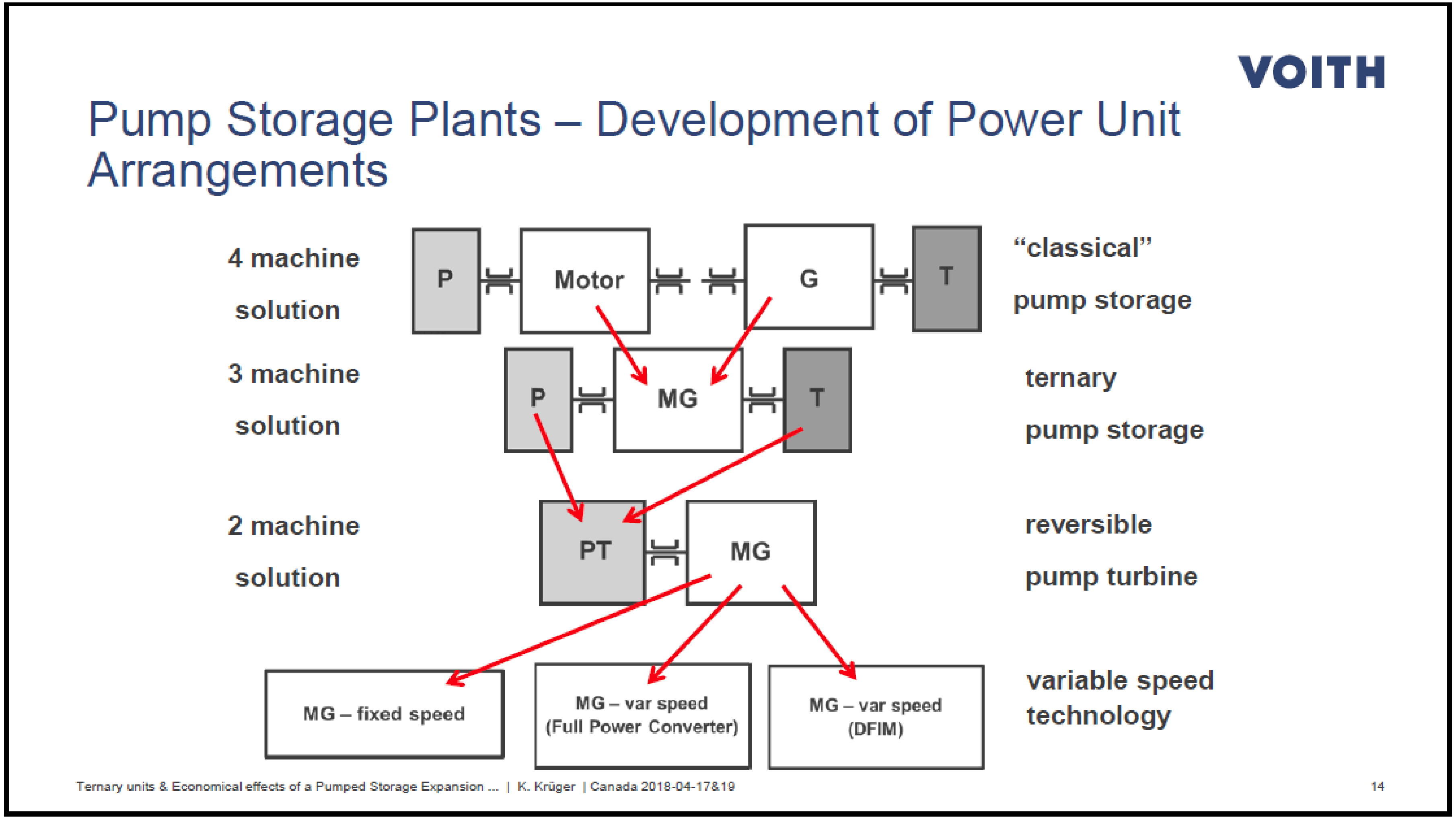
Single unit acts as both pump and turbine.



Credit – Voith Hydro, Andritz Hydro, GE Hydro

Types of Pumped Storage Hydro

Pump-Turbines Configurations/Types



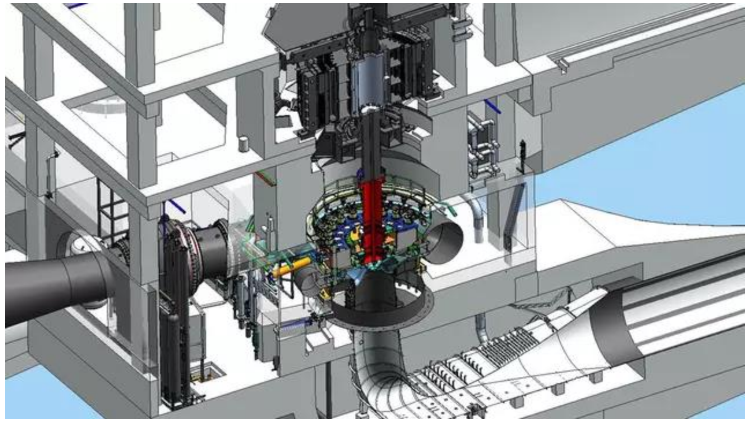
Credit – Voith Hydro

Types of Pumped Storage Hydro

Pump-Turbines – Variable Speed versus Fixed Speed

- Advantages of variable speed units:
  - Can handle larger head variations.
  - Active and reactive power control.
  - Shaping wind. Much more flexibility in pumping mode.
  - Ancillary service markets.
- Disadvantage of variable speed units:
  - Cost.

FIXED SPEED UNIT
Credit – Voith Hydro
1,333 MW Ingula PSH
South Africa



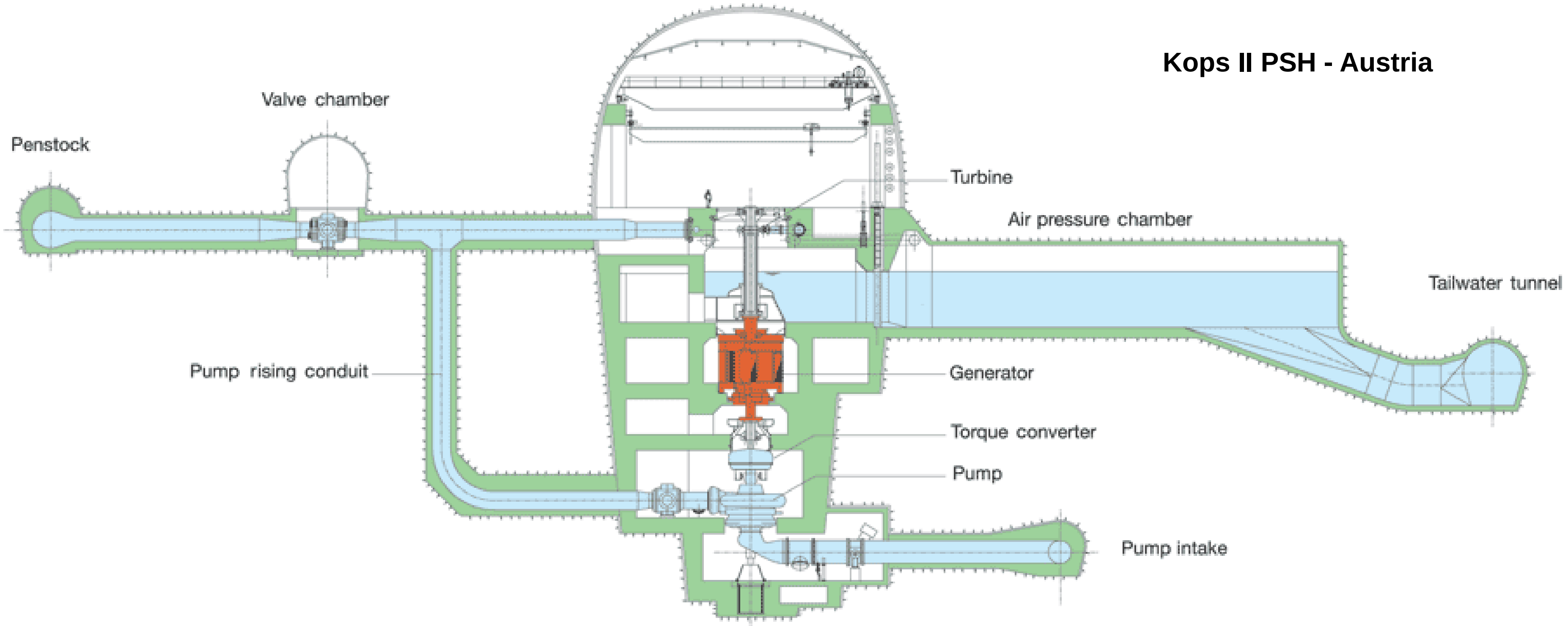
VARIBLE SPEED UNIT
Credit – Voith Hydro
780 MW Frades II PSH
Portugal

Credit – Voith Hydro

Types of Pumped Storage Hydro

Pump-Turbines – Ternary Units & Hydraulic Short Circuit

- Separate Pelton Turbine and Pump, and same shaft.
- Hydraulic Loop (Short Circuit) for fast reaction.



Kops II PSH - Austria

Credit – Voith Hydro & Andritz Hydro

Types of Pumped Storage Hydro

Hydraulic Short Circuit (HSC) Mode

- By using the hydraulic short circuit concept, almost the full power range of the plant is available. Pumping and generation modes. In addition, the hydraulic short circuit helps to control the energy flow into the grid.
- Benefits include:
  - Increased operational flexibility.
  - Power regulation.
  - Load frequency control.
  - Rapid response units.
  - Shorter ramp-up/ramp-down times.

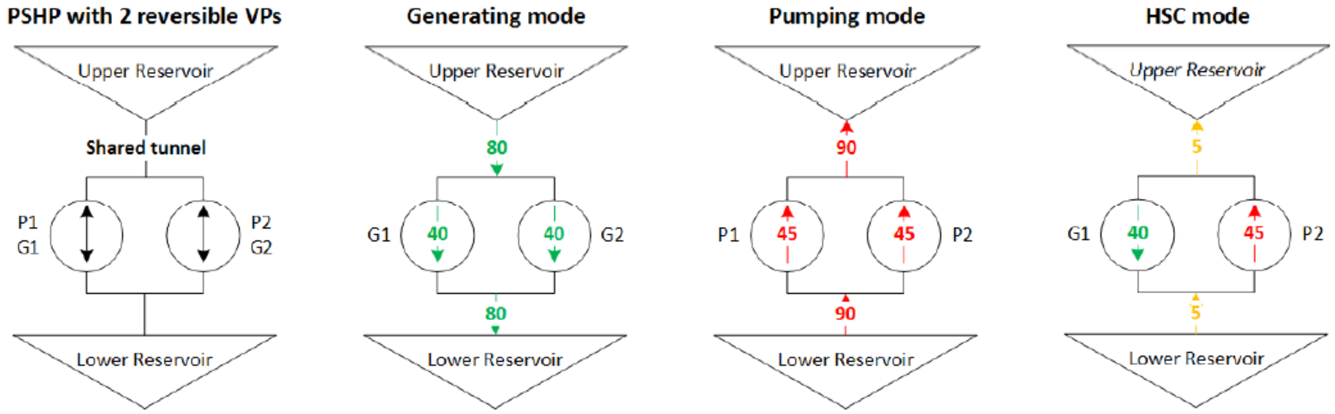


Fig. 1 Three possible operating modes for a PSHP with 2 reversible VPs

Credit – Paper by Skjelbred, Kong, Abgottspon (October 2019)

How to Value PSH

Valuation of PSH

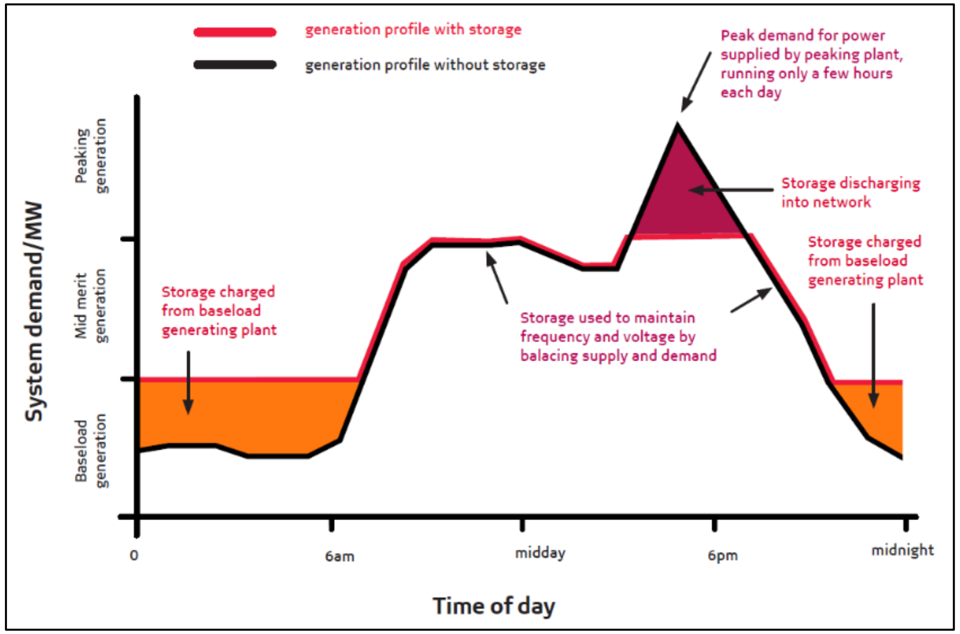
Overview

- Assessing mix of services that PSH provides to the grid
  - Understand revenue streams & estimate annual revenues
  - Input to financial models & project feasibility
  - Help inform engineering design & equipment selection/sizing
- Assessing economic value of services can be challenging
  - Allocate dispatch to several different services
  - Facility operation will vary depending on region and markets

Valuation of PSH

Benefits of PSH

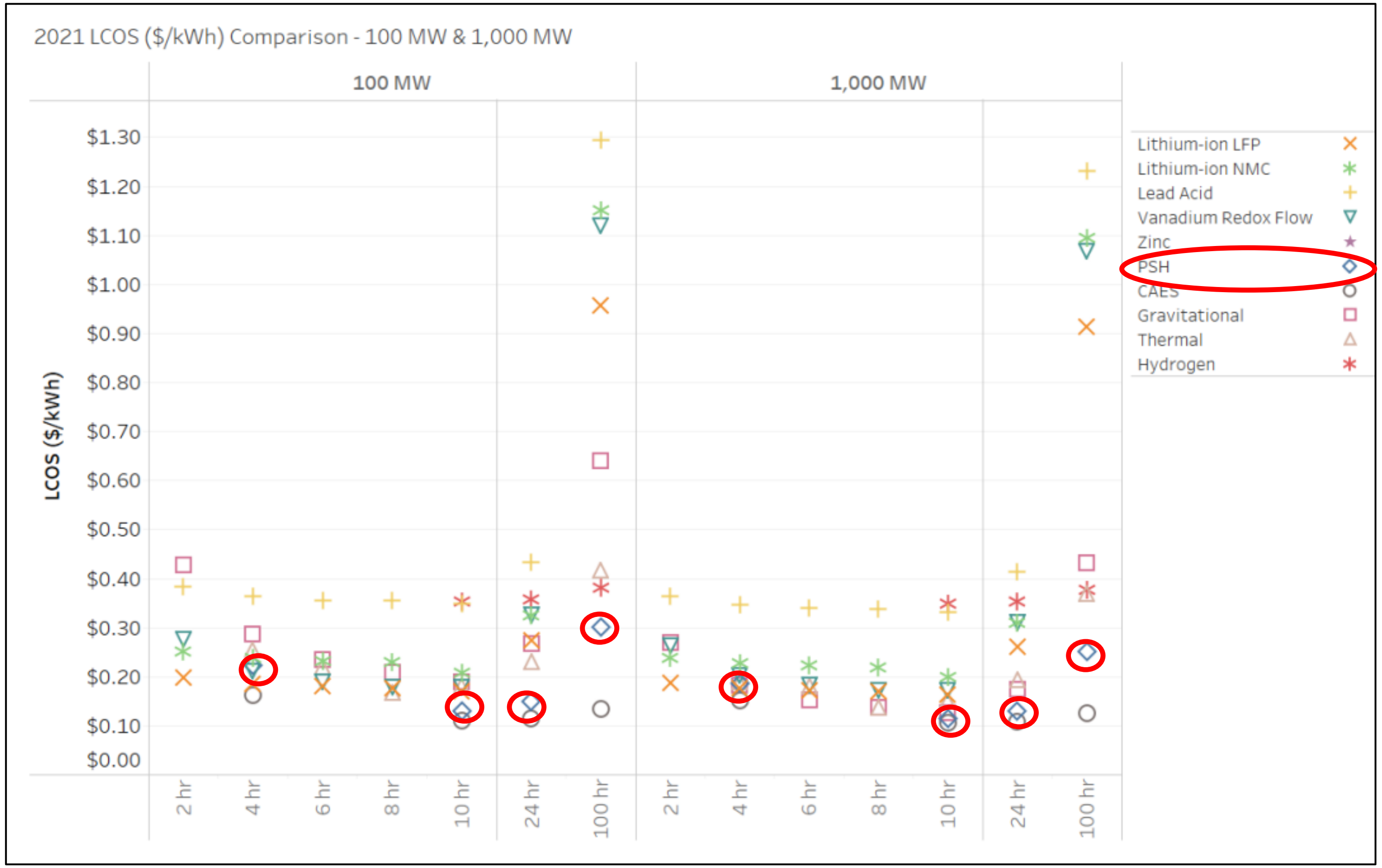
- **Energy balancing** and **peak-load management**:
  - Low demand → Store excess energy
  - Peak demand → Generate energy
- Provide **grid stabilization** and **reliability** by:
  - Flexible operation – can be geared to support grid
  - Quickly switch b/w generation/pumping → Balance supply and demand
- **Longevity and durability**
- Enhance **grid resilience (**backup power and black-start capabilities)
- Facilitates **integration** of variable **renewable energies**
- Etc…



Valuation of PSH

Cost Comparison of EST

- For large size projects (>100 MW), PSH offers very competitive Levelized Cost of Storage (LCOS) metrics
- LCOS analysis accounts for:
  - CAPEX
  - Design life
  - Construction period
  - O&M costs
  - Financial parameters (inflation, debt, etc.)



Energy Storage technology 2021 LCOS Comparison for 100 MW & 1,000 MW (Source: PNNL, 2022)

Valuation of PSH

PSH versus Batteries – Battery Costs and Projections

Cost Projections for Utility-Scale Battery Storage: 2023 Update

Wesley Cole and Akash Karmakar

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-85332
June 2023

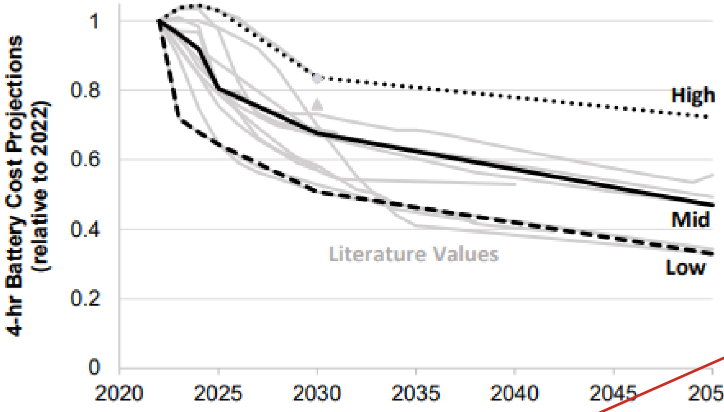


Figure ES-1. Battery cost projections for 4-hour lithium-ion systems, with values normalized relative to 2022. The high, mid, and low cost projections developed in this work are shown as bolded lines.

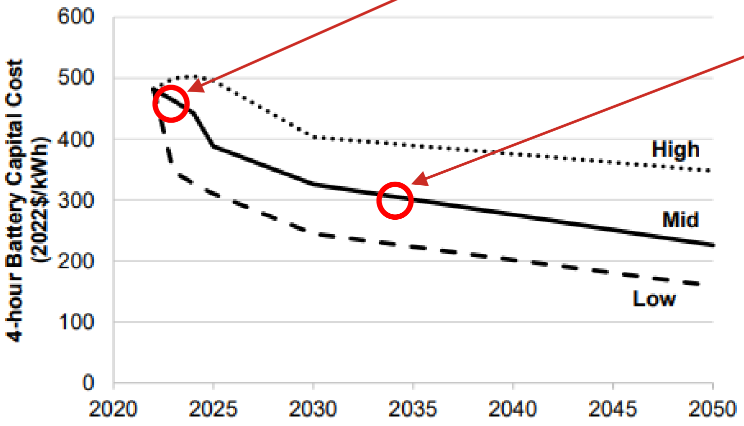


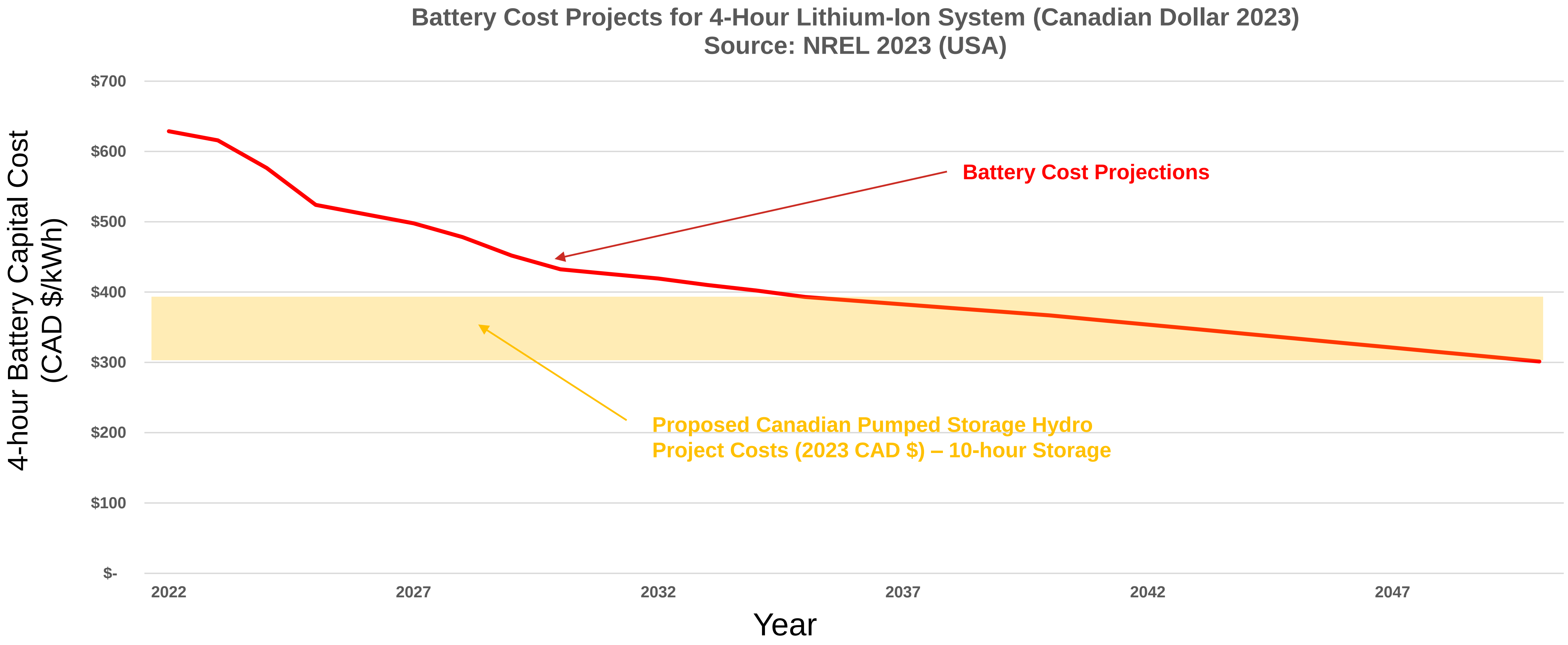
Figure ES-2. Battery cost projections for 4-hour lithium-ion systems.

In 2023 Utility Scale Batteries Cost about US$450/KWh.
(CAD $600/KWh)

By 2035 Utility Scale Batteries are Projected to Cost US$300/KWh.
(CAD $400/KWh)

PSH versus Battery

Proposed Canadian PSH versus Battery Costs



PSH versus Battery

Inertial Mass and Ramp Rates

Inertial Mass

- PSH converts a large volume of water to a stable power source which supplies the distribution network. Response time is slower but inertial mass is greater, resulting in a more stable, less intermittent flow of power which is less susceptible to interference from changes in demand or transmission losses.
- Batteries have a lower inertial mass but faster response time. The lower inertial mass is more suited to delivering short bursts of power in near instantaneous time frames.

Ramp Rate

- Ramp rate = increase/reduction in output per minute.
- PSH equipment can be designed to operate for a range of power generation/consumption levels.
- To ramp up, PSH involves power generators increasing their output, which typically take a few minutes (2+ mins).
- Batteries have a faster ramp rate than PSH but additional reductions in response time are achieved through the use of supplementary super capacitors to help bridge the delay gap between peak demand and peak supply.

PSH versus Battery

O&M Costs and Development Timelines

Operations & Maintenance Costs

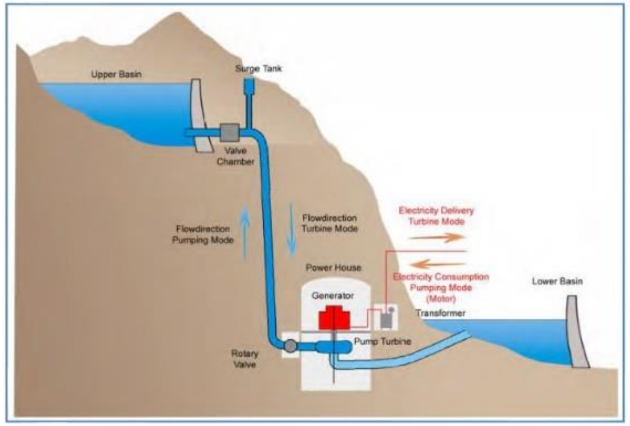
- PSH Facilities generally have low operations and maintenance costs and have life spans extending well beyond 50 years if well maintained.
- Batteries need constant maintenance, with annual replacement of defective cells, which based on feedback from operators results in full battery replacement every 10-15 years.
- Pumped Storage Hydro also operate effectively in all climatic conditions, whereas batteries require insulated and climate controlled buildings that can be expensive in harsh climates.

Development Timeframes

- A utility scale battery facility is generally much quicker to permit and construct than a large scale pumped storage hydro facility.
- A utility scale battery storage facilities life span is however significantly shorter than a pumped storage hydroelectric facility, and the discarded batteries will need to be recycled and/or treated as hazardous waste.

PSH versus Batteries

Pros and Cons (From EDF Presentation)



PHS drawbacks
- Capital intensive
- Site specific
- Environmental impact
- Development costs
- Construction risks

PHS advantages
- Large scale storage
- Duration (up to seasonal)
- Cyclability
- Maturity
- Lifetime
- Multi-usage & local benefits

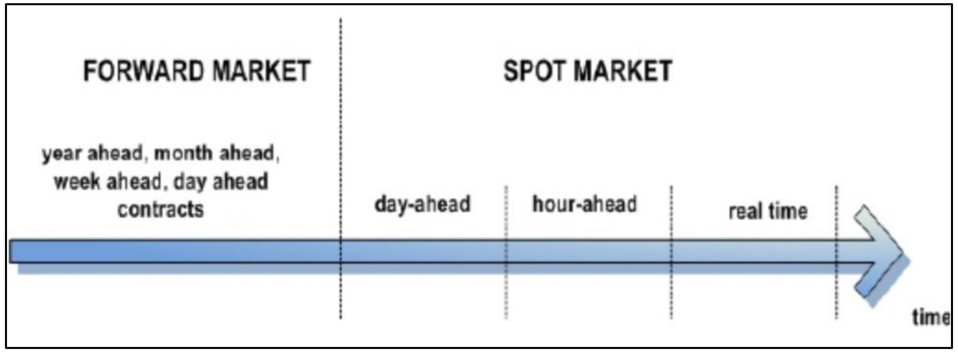
Battery drawbacks
- Lower maturity
- Hazardous materials
- Limited unitary size
- Cycling limits
- Potentially rare materials
- Limited calendar lifetime

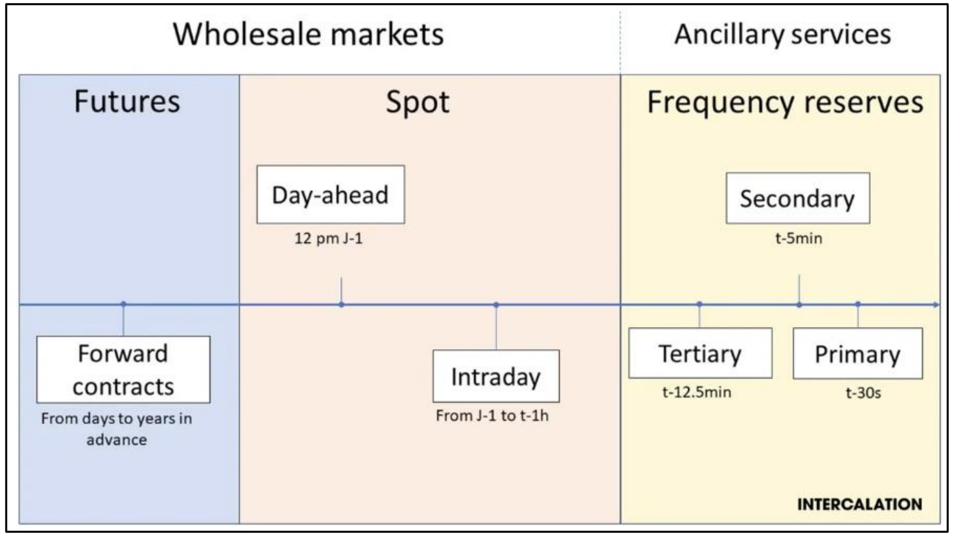
Battery advantages
- Very modular (sizeable)
- Low construction risk
- Limited construction time
- Very small response time
- Potentially mobile storages

Valuation of PSH

Electricity Markets

- Wholesale Market vs Bi-lateral Contracts
- Energy Market (Forward/Spot Markets)
  - Where electricity is bought and sold as a commodity
- Capacity Market
  - Compensates generators for their commitment to provide power during high-demand periods
- Ancillary Services Market
  - Procuring ancillary services to maintain grid stability and enhance reliability.





Valuation of PSH

Revenue Streams – Overview

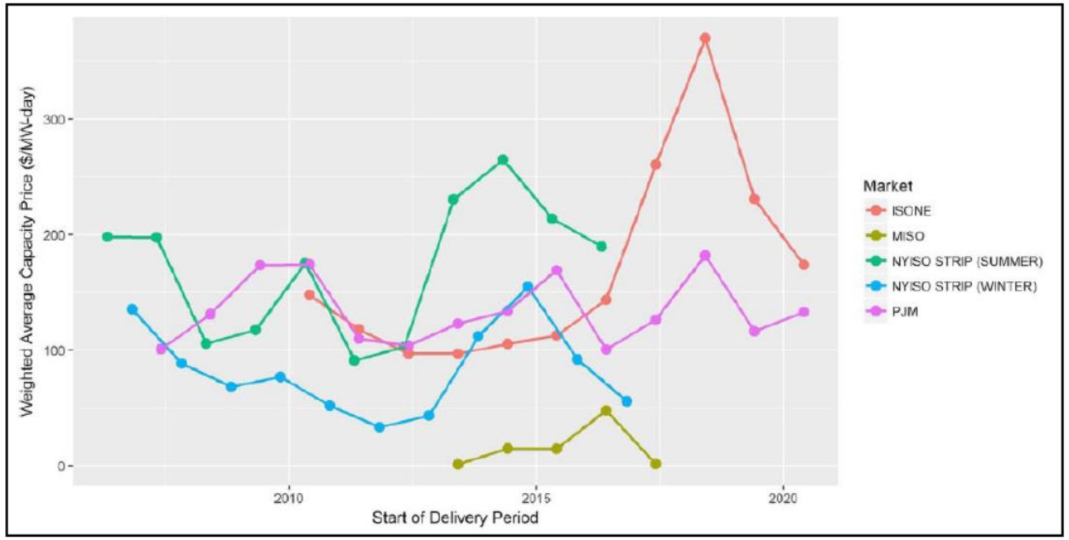
- Energy stored in PSH facility can be dispatched to several operational services
  - Optimize a plant's operations across services to maximize revenue streams
- Transmission Infrastructure Benefits, Power System Benefits, etc.

Category	Sub-Category	Revenue Stream / Services
Operational	**Bulk Energy Services**	Capacity Payments
		Energy Arbitrage
	Ancillary Services	Frequency Regulation
		Spin / Non-Spin Reserves
		Black Start Service
		Voltage Regulation
Other Benefits	**Transmission Infrastructure Benefits**	Transmission Upgrade Deferral
		Transmission Congestion Relief
	Power System Benefits	Reduced electricity generation costs

Valuation of PSH

Revenue Streams – Energy – Capacity Payments

- PSH units are paid for being able to **provide peaking capacity**
  - ISOs Resource Adequacy Programs to increase system reliability
- Value of capacity payments will be based on:
  - Bilateral Contracts
  - Capacity market prices
    - Characteristics of operating region (ISOs),
    - Peaking capacity of the grid system,
    - Percentage of Non-Dispatchable Sources, etc.



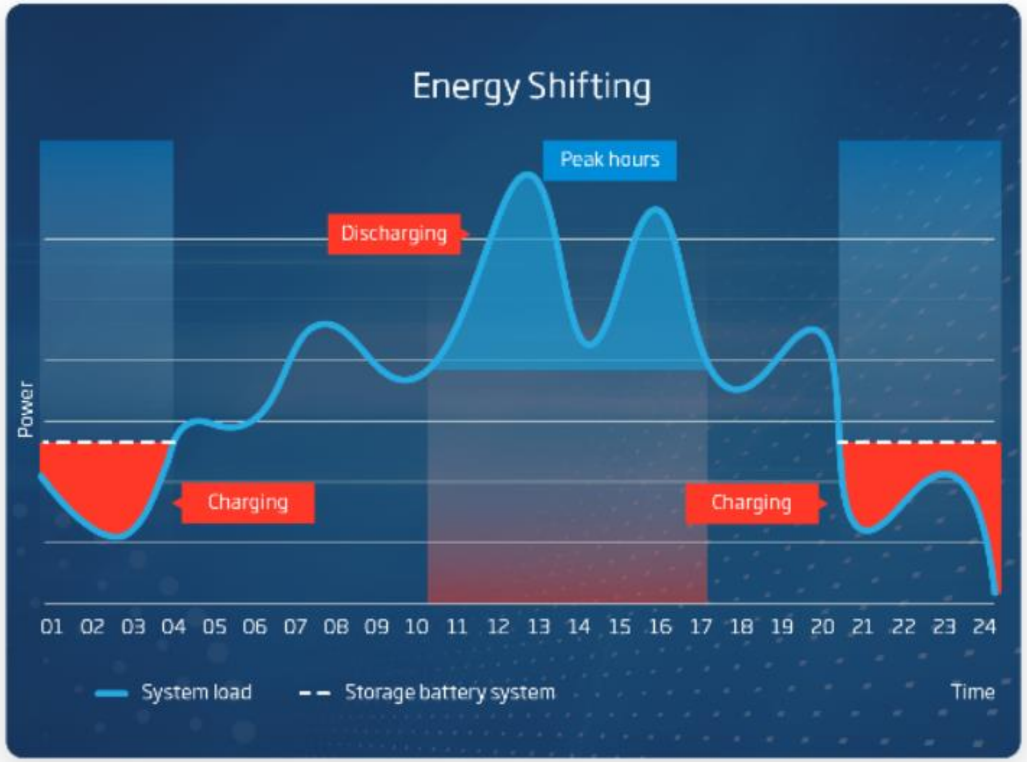
<u>Average capacity payment values for 2022:</u>

CAISO: ~110 $/kW-yr
NYISO: ~60 $/kW-yr
ISO-NE: ~45 $/kW-yr

Valuation of PSH

Revenue Streams – Energy Arbitrage

- Operating principle:
  - **Generation** during peak hours and/or when electricity **prices are high**
  - **Pumping** when demand and/or **prices are low**
- Load-levelling / load-shifting
  - Reduces net system load during peak hours
  - Increases load during off-peak hours
- Facilitates integration of renewables

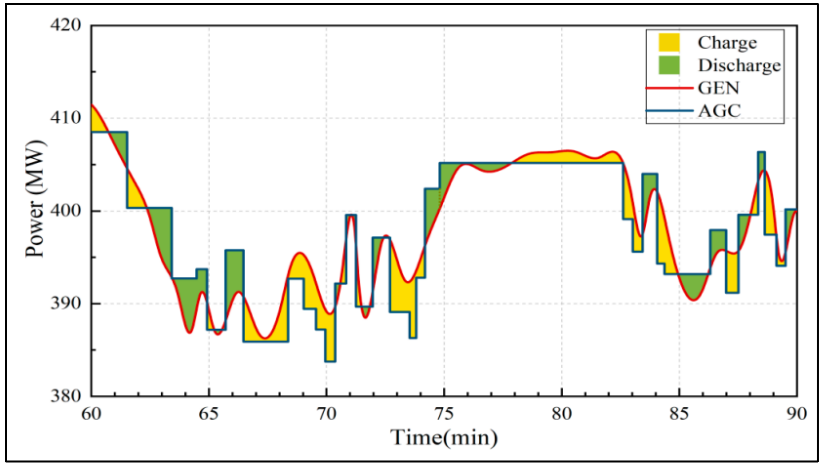


(Load-shifting diagram Source: https://www.trinasolar.com/en-za/trina-storage)

Valuation of PSH

Revenue Streams – Ancillary Services – Grid Stability

- PSH have **ability to quickly vary generation output** to provide ancillary services for grid support
- Grid operators provide payments for ancillary services
  - Frequency Regulation
  - Spinning Reserves
  - Non-Spinning Reserves, etc.
- Ancillary services are not valued for electrical output, but for capability to inject/withdraw electricity over short intervals
- Equipment → Response Time → Type of Freq. Reg.



(Frequency Regulation - Source: Sun et al., 2020)

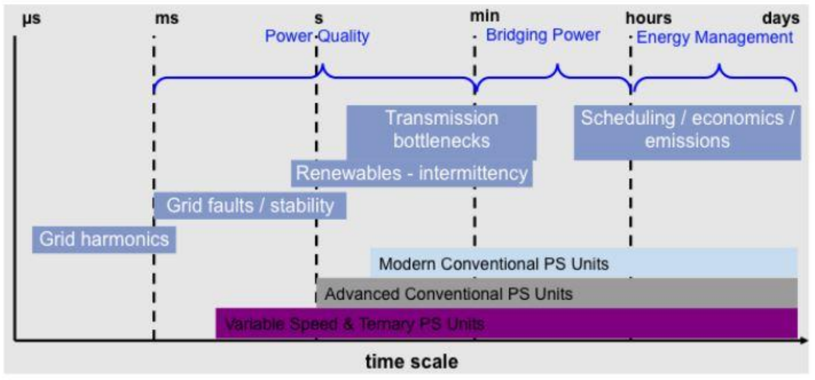


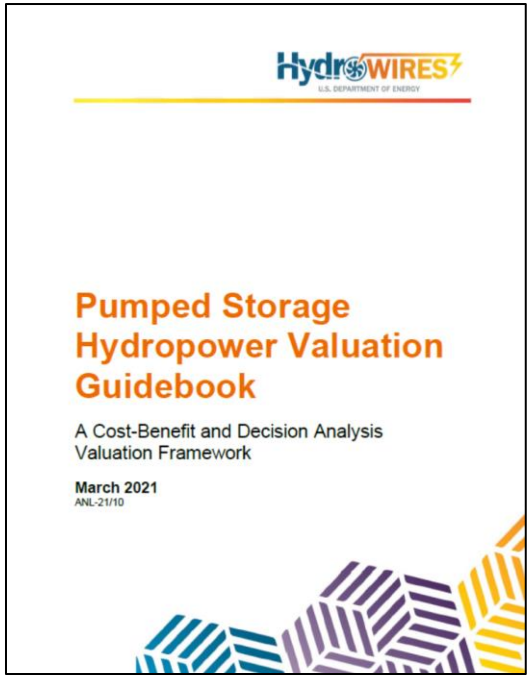
Figure 2-9 Timeframes for modern advanced PS unit regulation

(Source: Fisher et al., 2012)

PSH Valuation Tool

Framework

- In 2021, ANL & PNNL developed a **comprehensive valuation framework** to assess economic value of PSH plants
  - Allow for **consistent and repeatable valuation assessments**
  - **Reduce uncertainty** in valuation results
  - Provide a **better understanding of the true value** that PSH technology brings to the grid
- **PSH Valuation Tool (PSHVT)** developed by ANL & PNNL based on the valuation framework
  - KP supported with reviewing and beta-testing the tool prior to public launch
- PSHVT used to **assess the value of services** provided by PSH plants

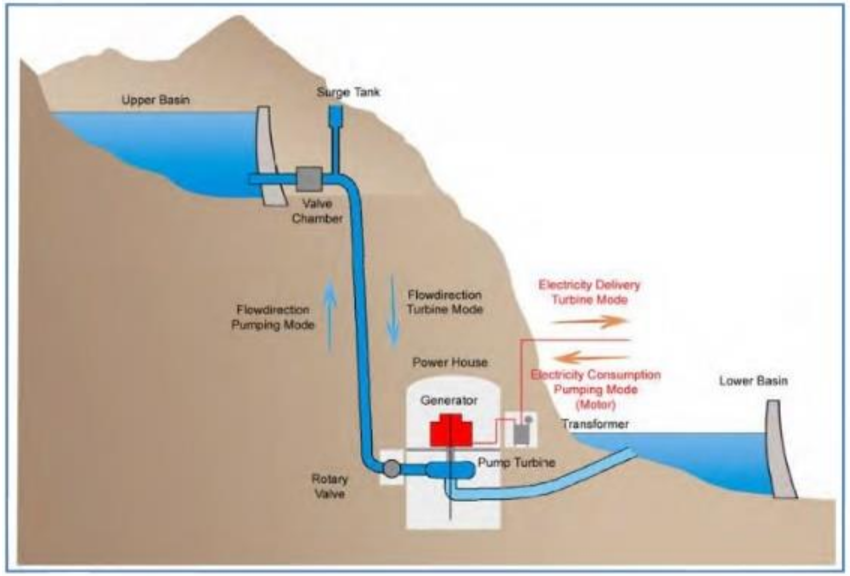


(Source: https://pshvt.egs.anl.gov/)

Case Study

Key Project Characteristics

- Hypothetical project in PNW
- Closed-loop system
- Fixed-Speed Reversible Pump-Turbine Units
  - Hydraulic Short-circuit at Plant Level
- Generating Capacity: 400 MW (2x 200 MW units)
- Pumping Capacity: 390 MW (2x 195 MW units)
- Upper Reservoir Energy Storage: 3600 MWh



PSH Valuation Tool

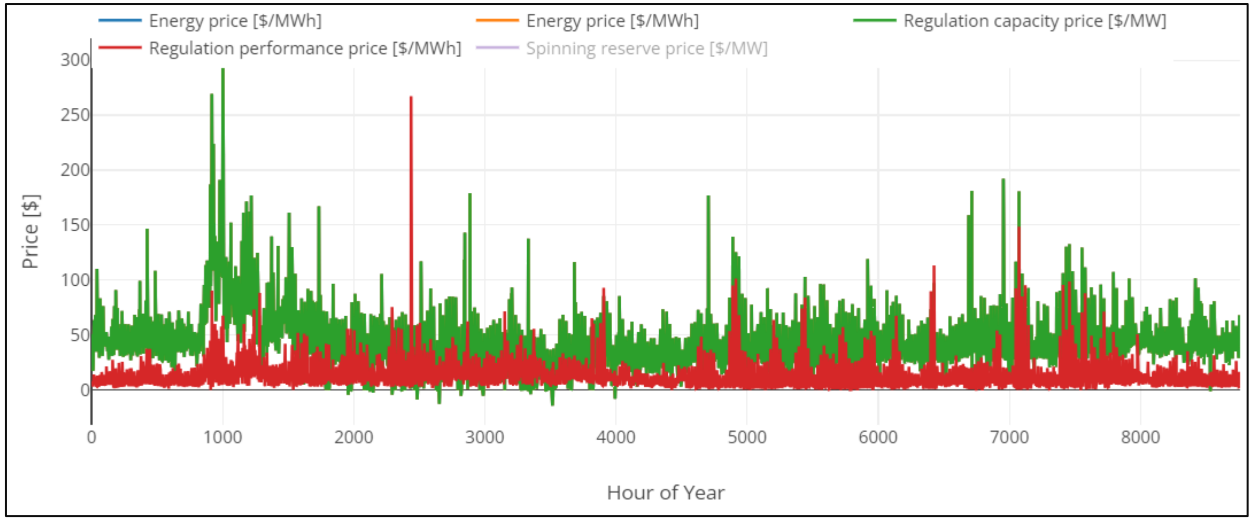
Modelling Approach

- Price-taker
  - Assumes **addition of PSH unit does not significantly affect electrical grid operations** or affect market prices
  - Modelling typically completed based on historical market clearing prices
- Price-influencer
  - **PSH units large enough to affect grid operations** and market prices
  - Need to evaluate how the addition of new plant will impact power system
  - Capacity expansion model of the power system needs to be completed to forecast market clearing prices

PSH Valuation Tool

Price-Taker Model - Inputs

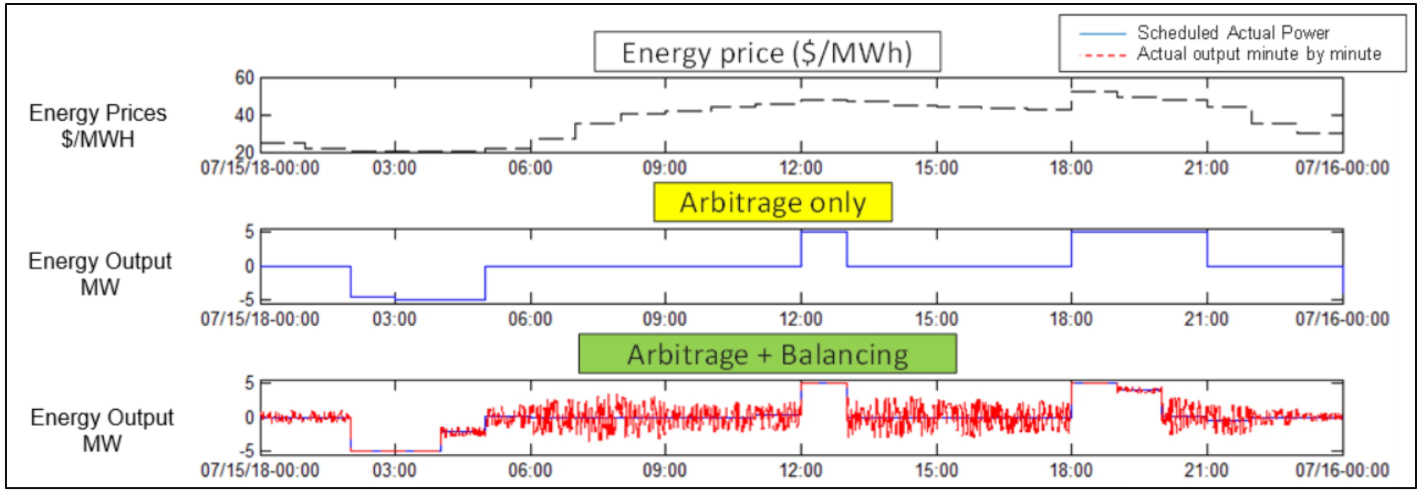
- Type of **electricity market**
- ISO/**Region of operation** (i.e., CAISO, NYISO, etc.)
- **Project characteristics**, design parameters, operational performance and capabilities of the PSH plant
- O&M **Costs**
- **Historical** energy, capacity & ancillary services **market prices**
- **Load** profile



PSH Valuation Tool

Co-optimization

- PSH cannot meet requirements of every service simultaneously
- **Co-optimization necessary when stacking benefits** to avoid double counting
  - Dispatch of energy for one service may limit dispatch for another service
  - Energy dispatched now is not available for dispatch the next hour
- Run on hourly timestep
- Assumes perfect foresight to develop optimal pumping/generating schedule

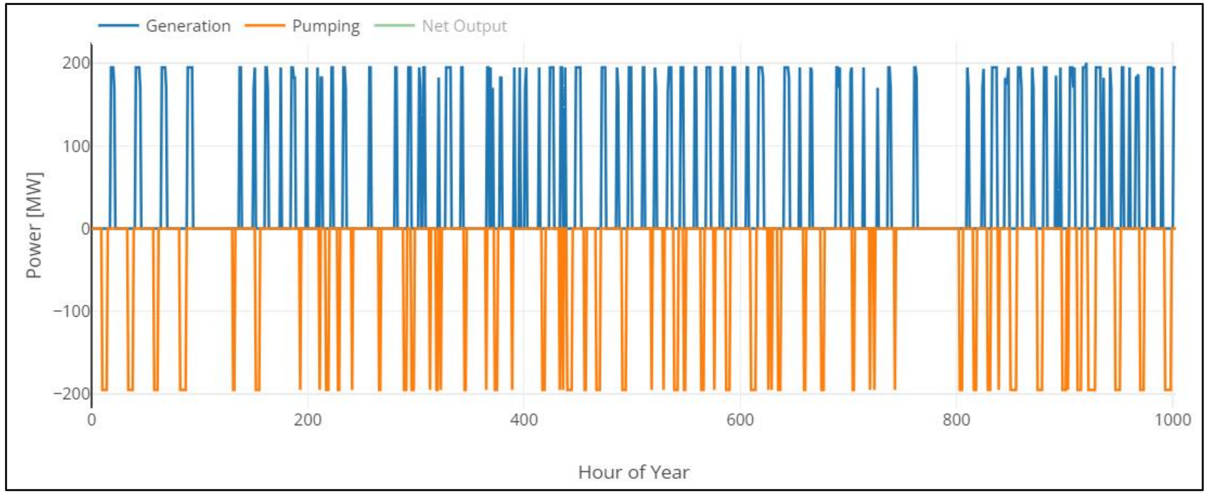


(Source: https://pshvt.egs.anl.gov/)

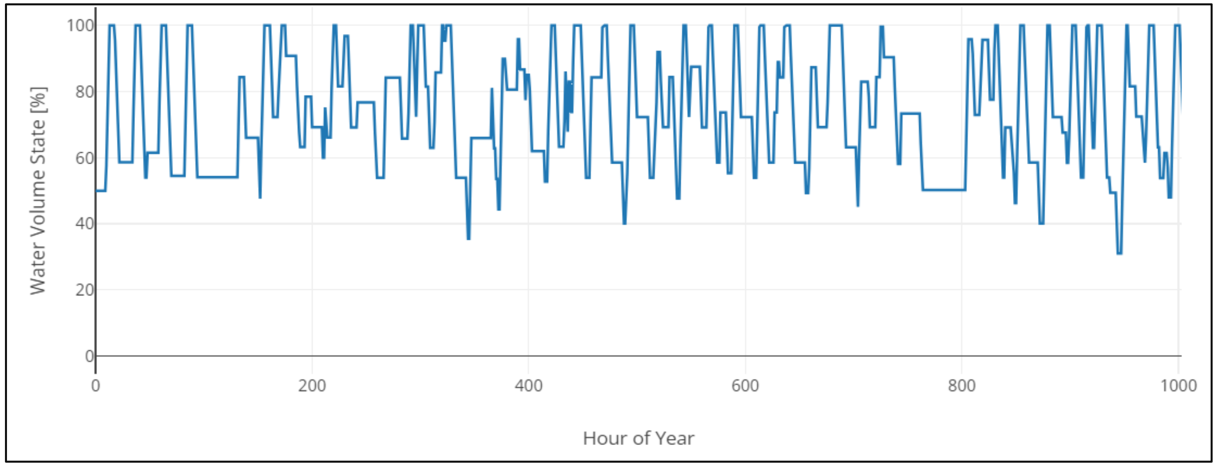
Case Study

Price-Taker Model Results – Schedule

- **Optimal Pumping & Generating Schedule**
  - Unit Level
  - Plant Level



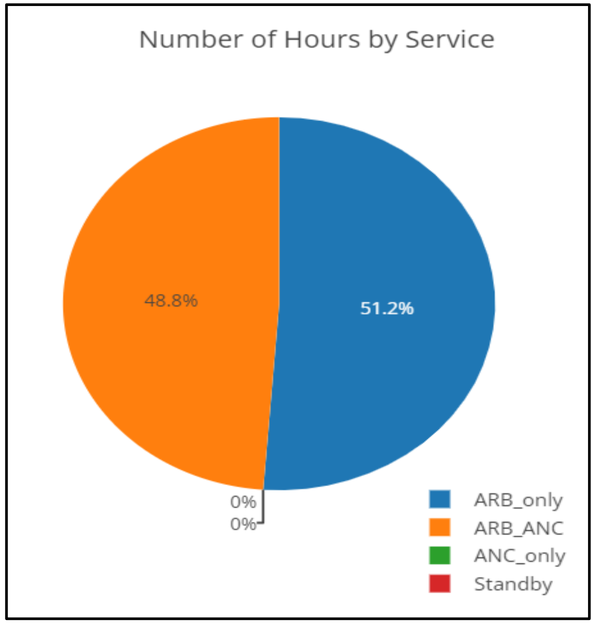
- **Water Volume State**



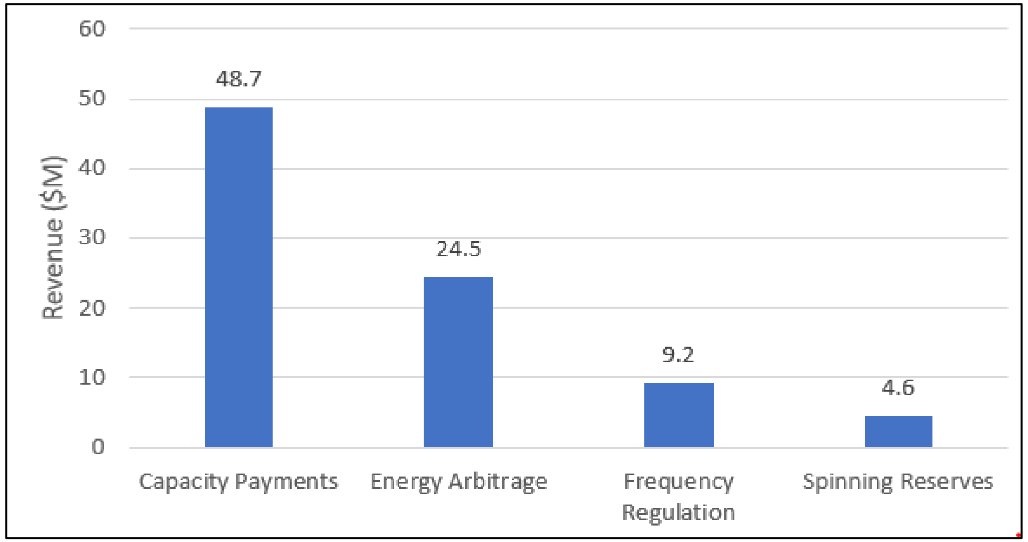
Case Study

Price-Taker Model Results - Revenue

- **Estimated Annual Revenue by Service**
- **Hours by Service (%)**



Service	Estimated Revenue ($/year)
Capacity Payments	$48.7M
Energy Arbitrage	$24.5M
Frequency Regulation	$9.2M
Spinning Reserves	$4.6M
Total	**$87.0M**

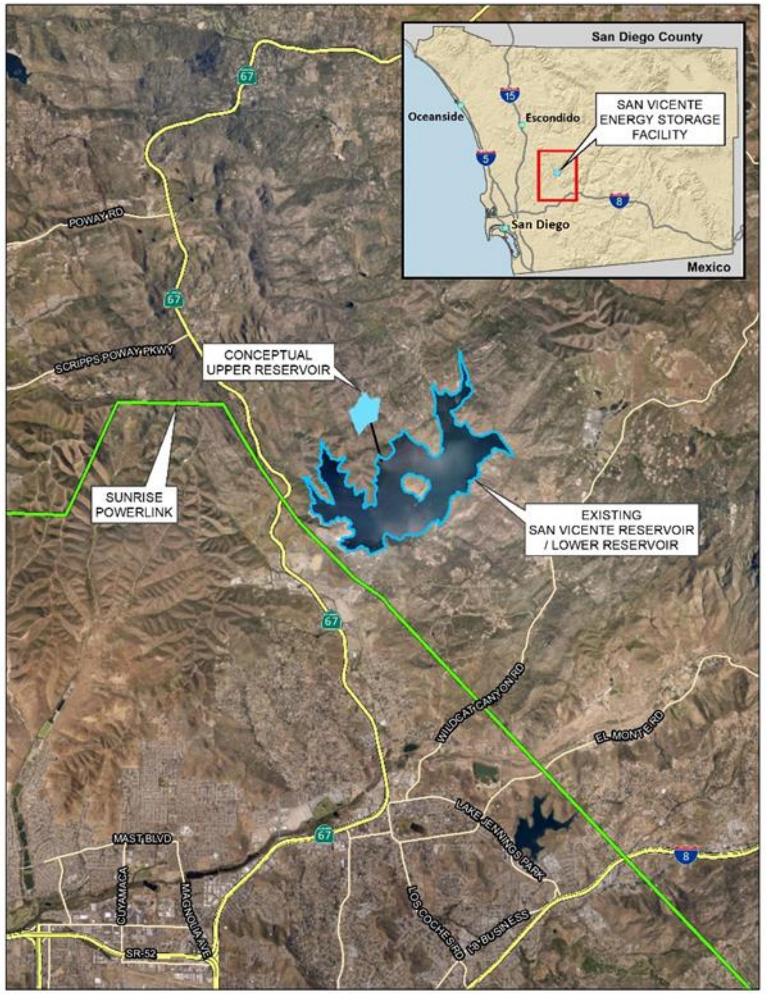


Recent Experiences – PSH (North America)

Recent Experiences (North America)

500 MW San Vicente Pumped Storage Hydro, CA, USA

- 500 MW Pumped Storage Hydro. Open Loop.
- City of San Diego & San Diego County Water Authority
- New Upper Reservoir. “Crows Nest” likely RCC.
- Existing San Vicente Lower Reservoir. Big head variation.
- Constraints: Water use, Ecological, Quagga mussels.
- Power Tunnels & Underground Powerhouse
- 230 kV Transmission and Interconnection



(Credit – San Diego County Water Authority)

Recent Experiences (North America)

400 MW Swan Lake Pumped Storage Hydro, OR, USA

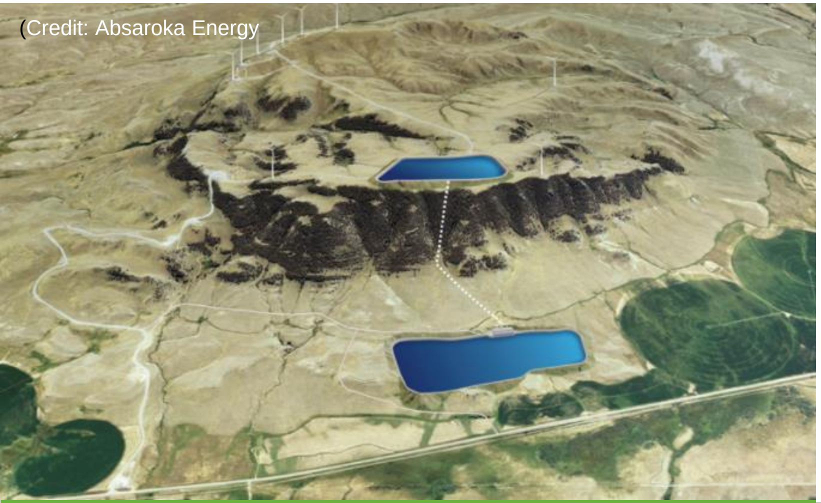
- 400 MW Pumped Storage Hydro. Closed Loop.
- Copenhagen Infrastructure Partners (CIP), Rye Development LLC
- New Upper and Lower Reservoirs. HAC liners.
- Buried Penstock(s). Robust system, minimizing geotechnical risk.
- Surface Powerhouse. Unique topography (Bluffs) allows for surface arrangement.
- Fixed speed reversible pump-turbine-generators. Hydraulic short circuit.


(Credit: Rye Developments

Recent Experiences (North America)

400 MW Gordon Butte Pumped Storage Hydro, MT, USA

- 400 MW Closed Loop Pumped Storage Hydro.
- Developer – Absaroka Energy LLC
- Quaternary – Separate Pumps and Turbines.
- Firming Montana Wind (Coal plants being decommissioned, increased wind).
- Lined Earth Embankment Reservoirs.


(Credit: Absaroka Energy

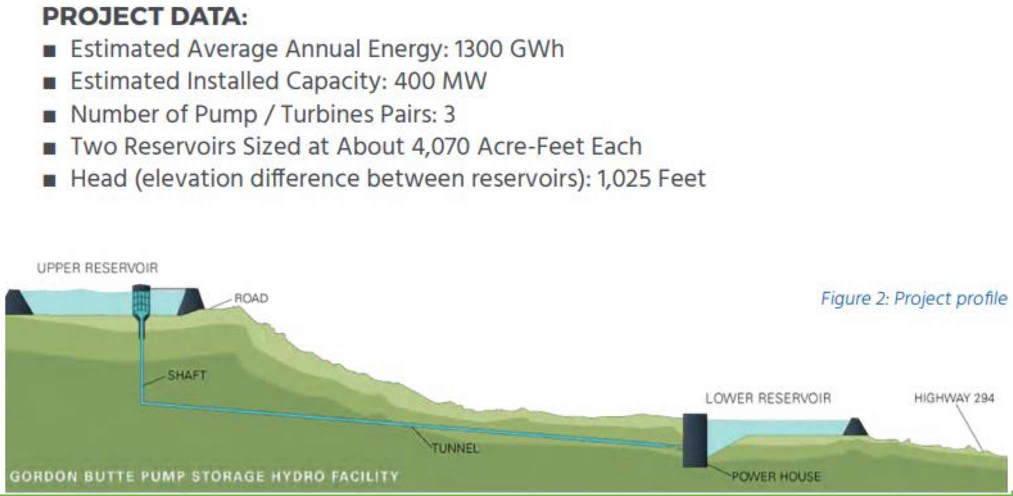
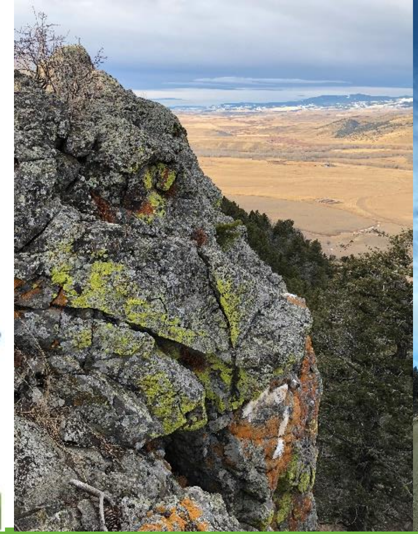


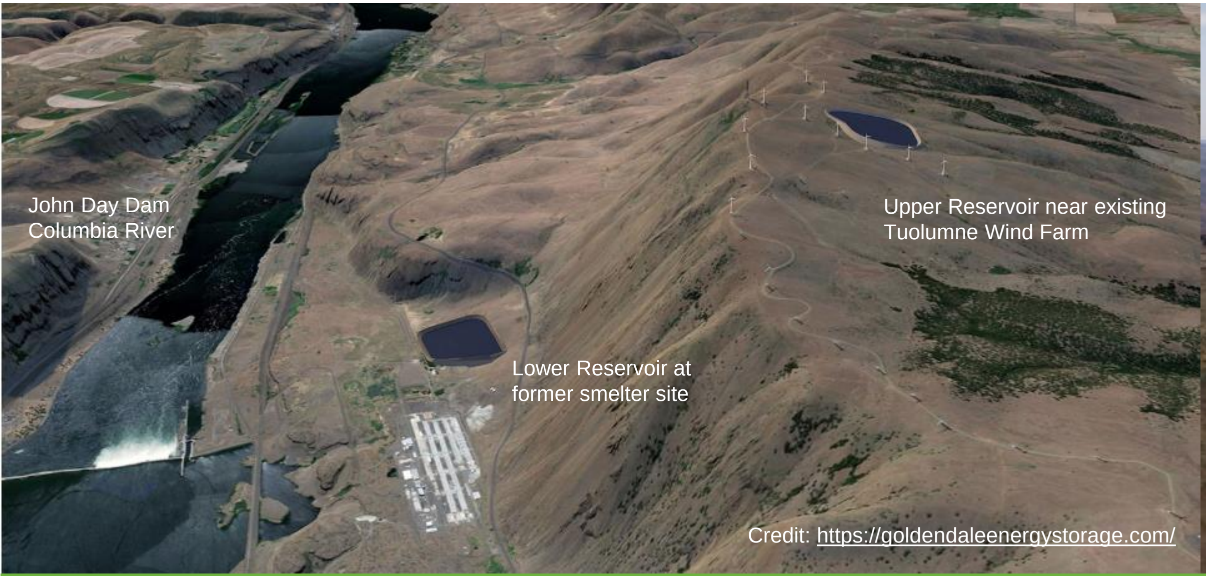
Figure 2: Project profile



Recent Experiences (North America)

1,200 MW Goldendale Pumped Storage Hydro, WA, USA

- 1,200 MW Pumped Storage Hydro. Closed Loop.
- Copenhagen Infrastructure Partners (CIP), Rye Development LLC
- New Upper and Lower Reservoirs
- Brownfields site – Former Columbia Gorge Aluminum Smelter.
- Underground Powerhouse and Water Conveyance Tunnels.

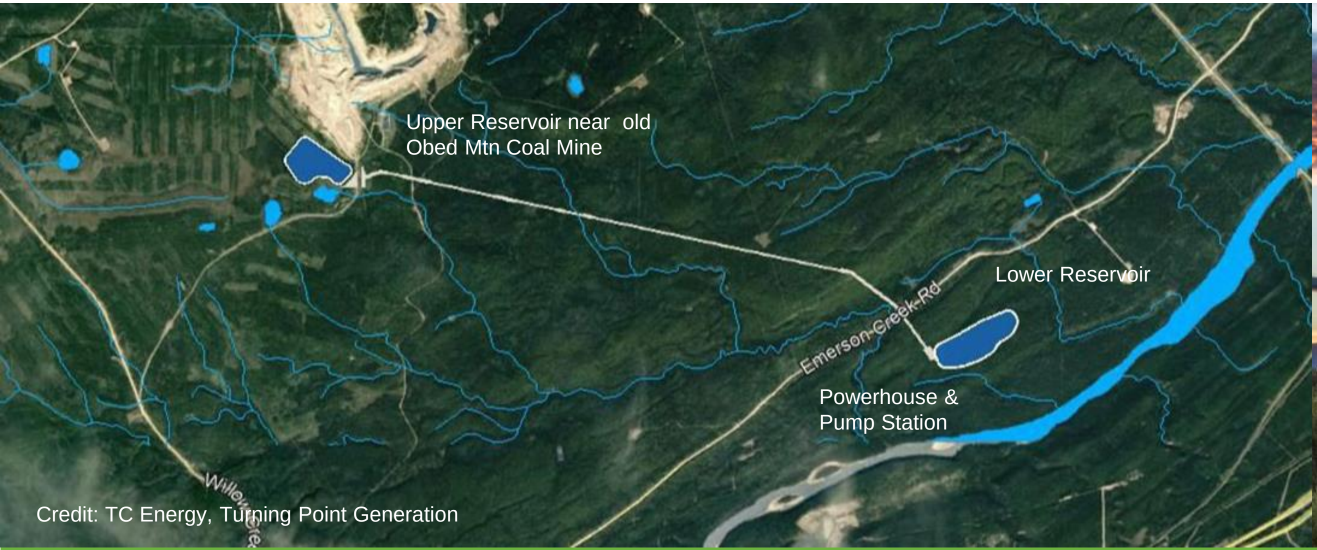


Credit: https://goldendaleenergystorage.com/

Recent Experiences (North America)

75 MW Canyon Creek Pumped Storage Hydro, Alberta

- 75 MW Pumped Storage Hydro. Closed Loop. 37 hours storage.
- Owner – TC Energy. Near Hinton. Traditional territories of the Treaty 6 First Nations.
- Brownfield site – Decommissioned Obed Mountain Coal Mine.
- Quaternary – Separate Pumps and Turbines.
- Buried penstock. 7km long and 2.5m in diameter.



Credit: TC Energy, Turning Point Generation

Recent Experiences (North America)

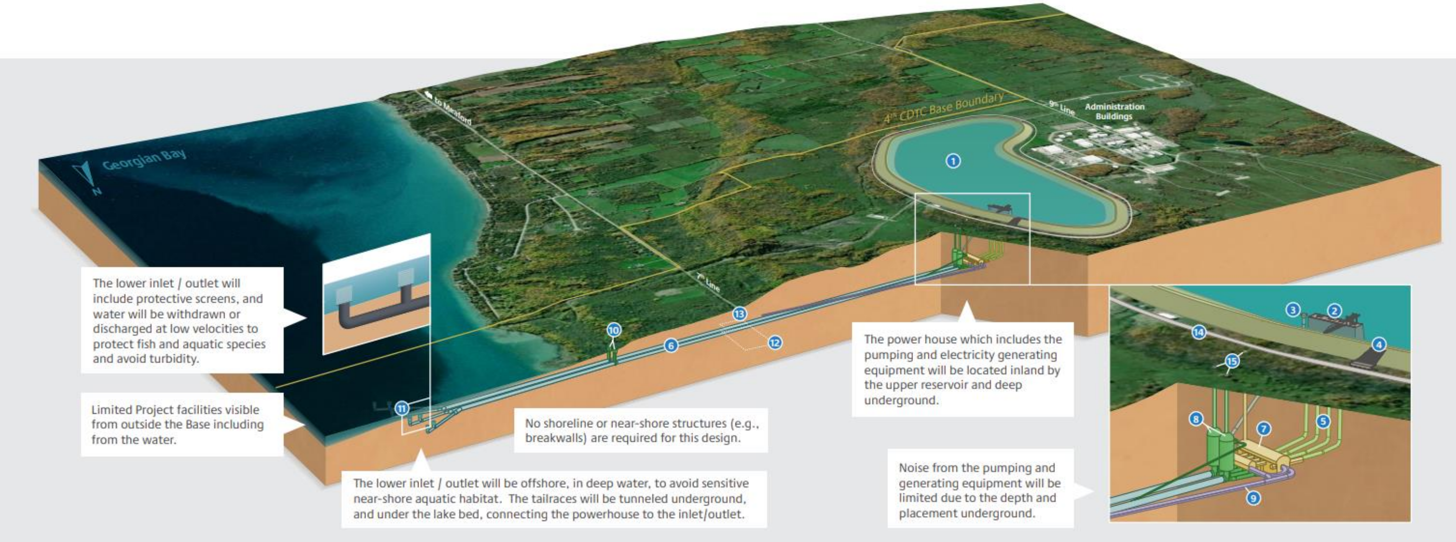
320 MW Tent Mountain Pumped Storage Hydro, Alberta

- 320 MW Pumped Storage Hydro.
- Evolve Power and TransAlta.
  (https://evolvepower.ca/)
- Traditional territories of the Treaty 7 First Nations in Southern Alberta.
- Brownfield site – Old Coal Mine.
- 15 hours storage.
- Approx 300m gross head.

Recent Experiences (North America)

1,000 MW Ontario Pumped Storage Hydro, Ontario

- 1,000 MW Pumped Storage Hydro. Open Loop. 10+ hours storage.
- Owner: TC Energy. (https://www.ontariopumpedstorage.com/)
- Lower Reservoir = Georgian Bay.
- Variable speed reversible pump turbines. Underground powerhouse.
- Located on Meaford Tank Range (DND), Saugeen Ojibway Nation (SON) Traditional Territory



Recent Experiences (North America)

400 MW Mamora Pumped Storage Hydro, Ontario

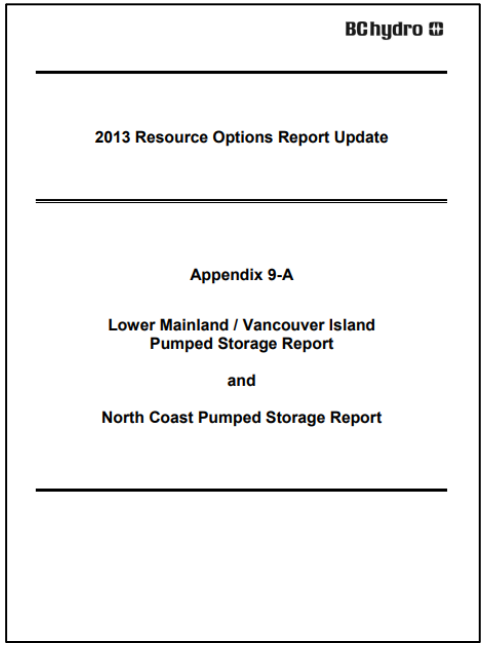
- 400 MW Pumped Storage Hydro. Closed Loop.
- Developers – Northland Power and OPG (https://marmorapumpedstorage.com/)
- Brownfield site – Old Mamora Mine site.
- Alderville First Nation and territory covered by the Williams Treaties First Nations

Credit:

Recent Experiences (North America)

Pumped Storage Hydro in BC?

- BC Hydro Studies, as part of Integrated Resource Plans (IRP).
  (https://www.bchydro.com/toolbar/about/strategies-plans-regulatory/supply-operations/generation-options.html)
- Numerous Privates Sector Pumped Storage Hydro Initiatives (Confidential at this stage).
- Renewables + Pumped Storage Hydro a good option for BC.


BC hydro

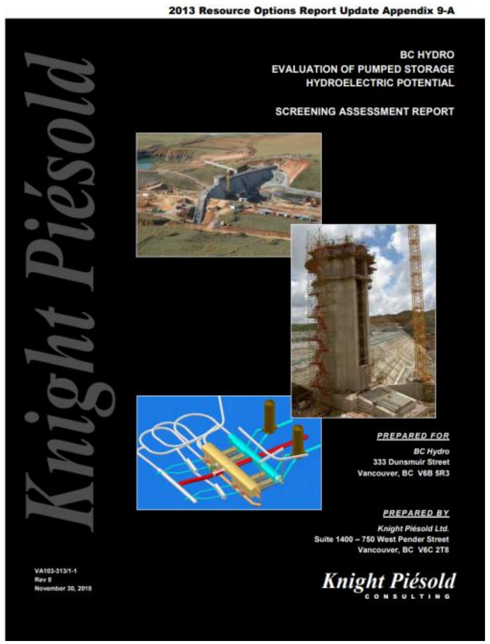
2013 Resource Options Report Update

Appendix 9-A

Lower Mainland / Vancouver Island
Pumped Storage Report

and

North Coast Pumped Storage Report


2013 Resource Options Report Update Appendix 9-A

BC HYDRO
EVALUATION OF PUMPED STORAGE
HYDROELECTRIC POTENTIAL

SCREENING ASSESSMENT REPORT

PREPARED FOR
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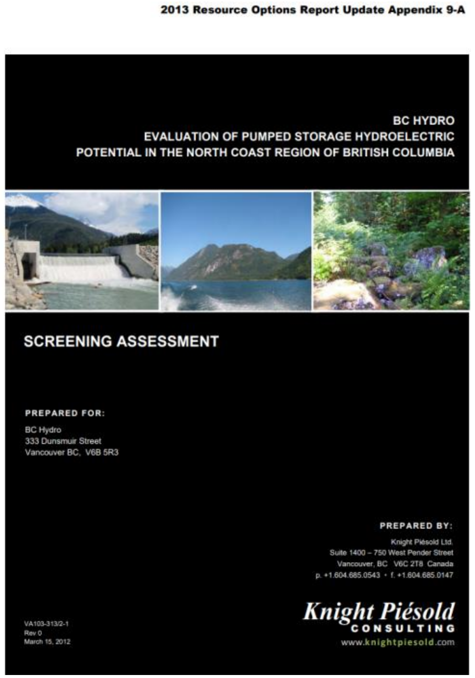
VA103-313/1-1
Rev 0
November 30, 2010

Knight Piésold
CONSULTING


2013 Resource Options Report Update Appendix 9-A

BC HYDRO
EVALUATION OF PUMPED STORAGE HYDROELECTRIC
POTENTIAL IN THE NORTH COAST REGION OF BRITISH COLUMBIA

SCREENING ASSESSMENT

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VA103-313/2-1
Rev 0
March 15, 2012

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2013 Resource Options Report Update Appendix 9-B

HATCH

BC Hydro

Pumped Storage at Mica Generating Station

Preliminary Cost Estimate

H336793, Rev. 0
December 2010

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