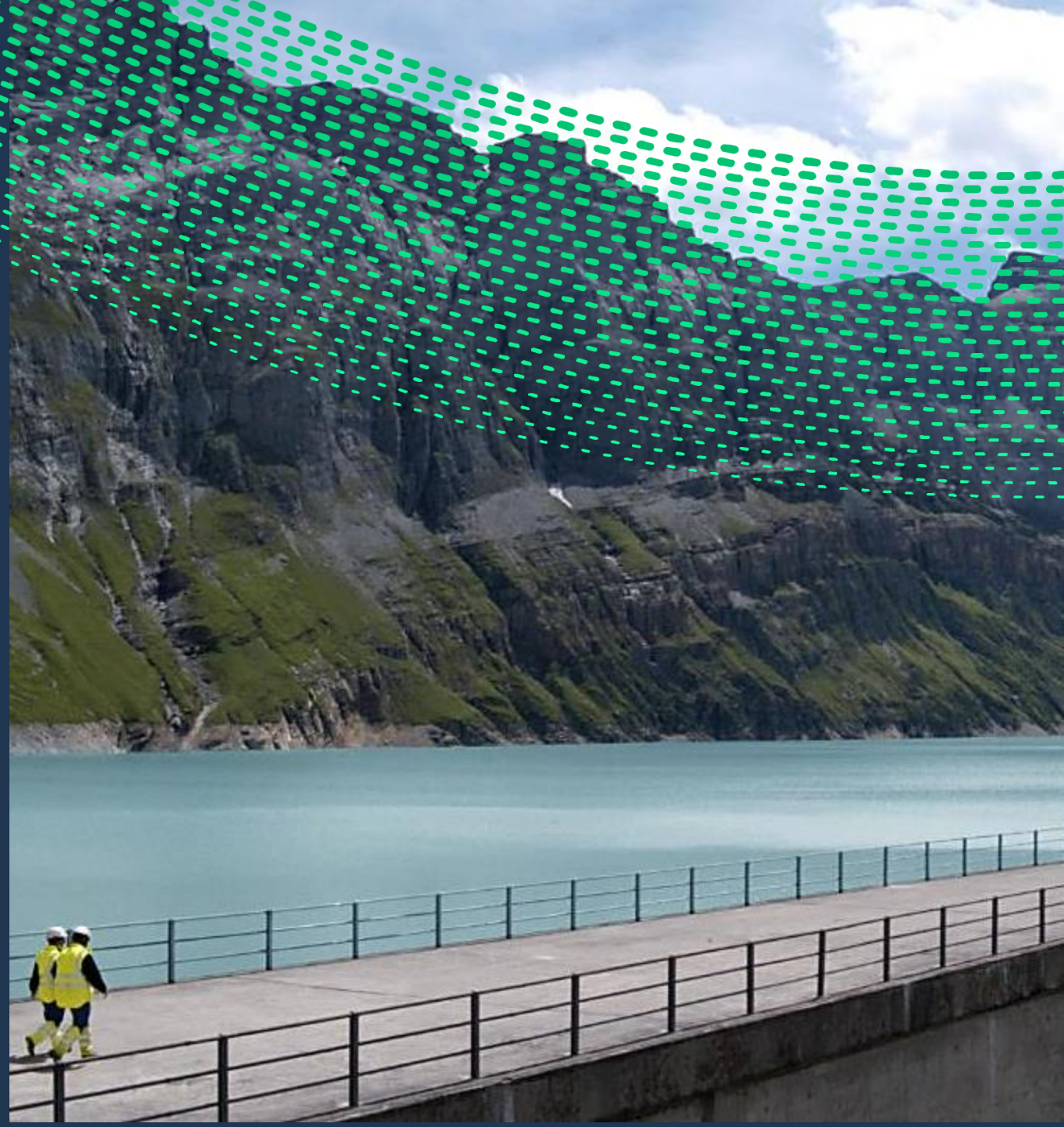
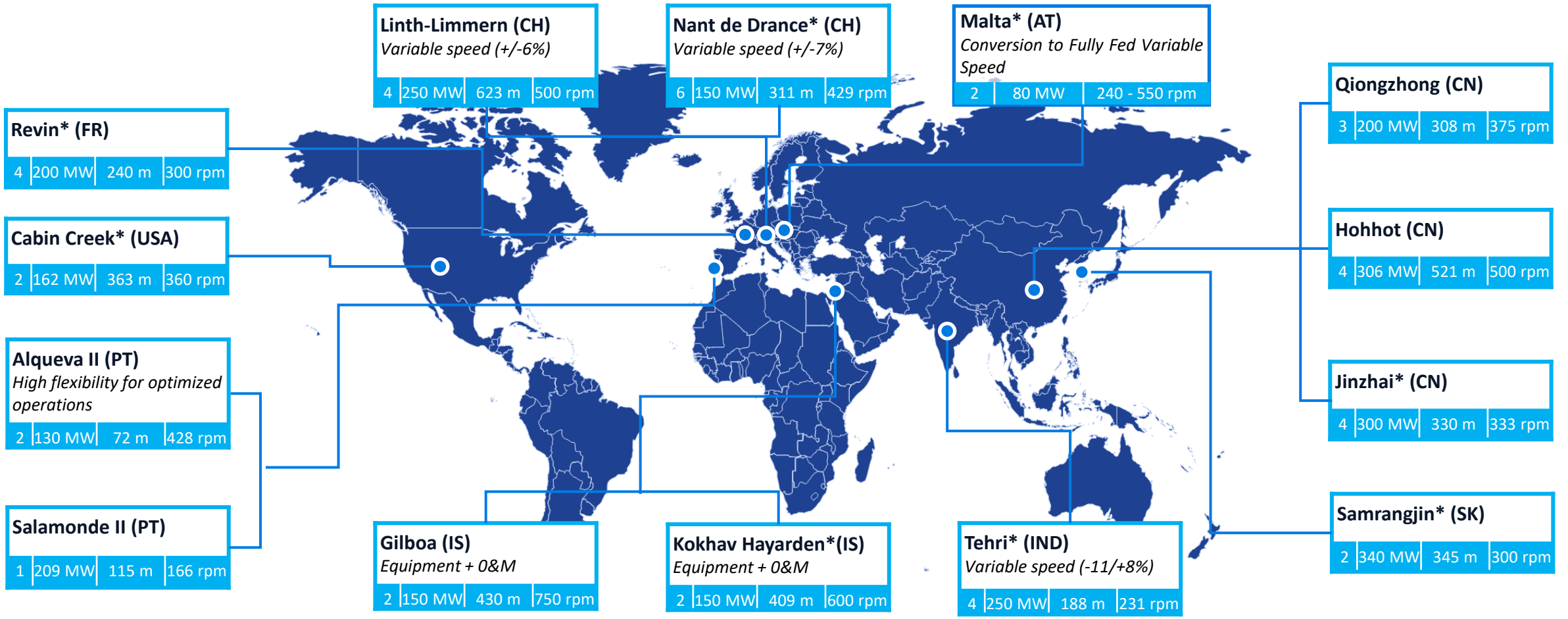
Pumped Hydro Storage
Enabler to reliable renewable energy



References throughout the world

Currently adding ~4 GW of GE's hydro storage projects - incl ~2 GW with variable speed technology



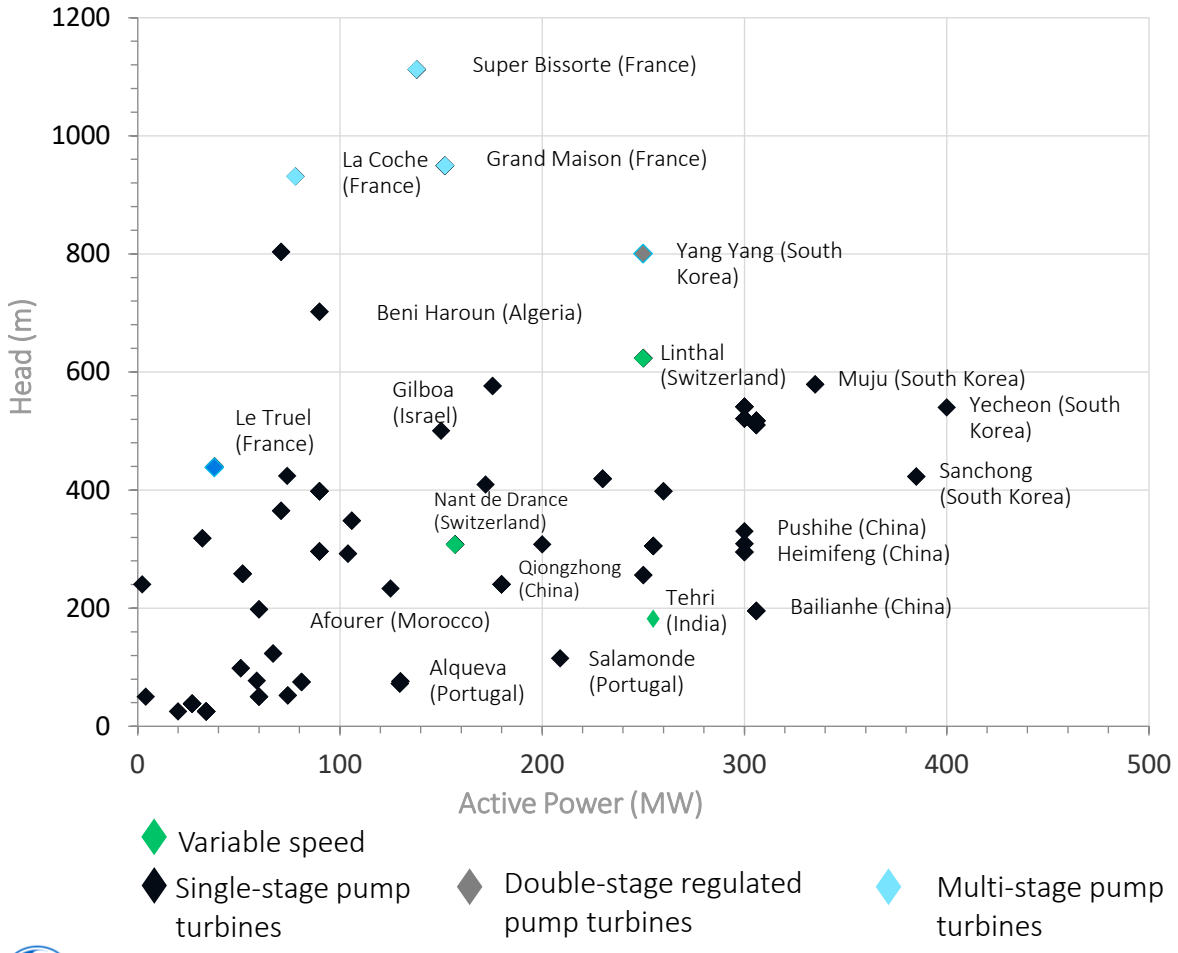
** Projects under construction*

GE Renewable Energy

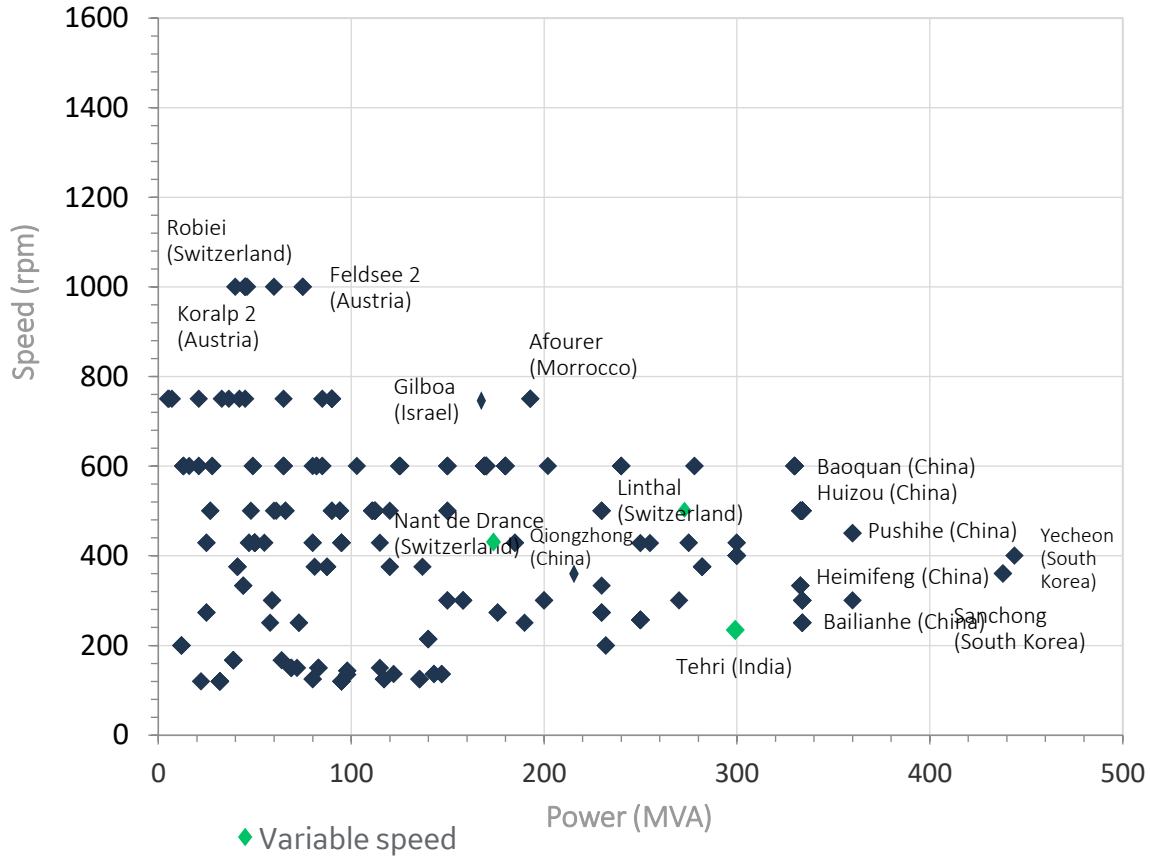
Large range of expertise and experience

30+% of hydro storage plants equipped with GE technology

Range of Pump Turbine Experience

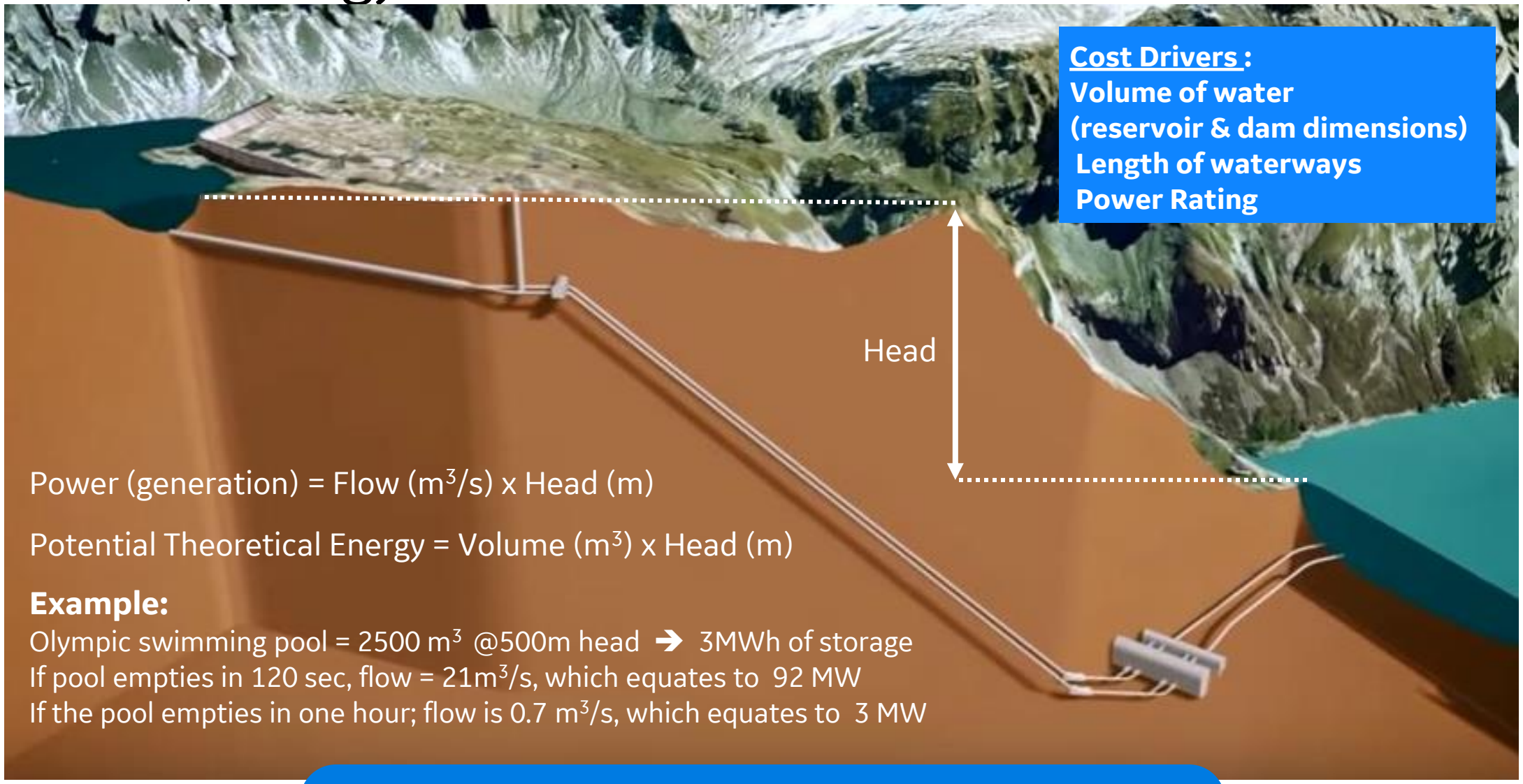


Range of Generator Experience



GE Renewable Energy

Power, Energy & Influence of Site Parametres

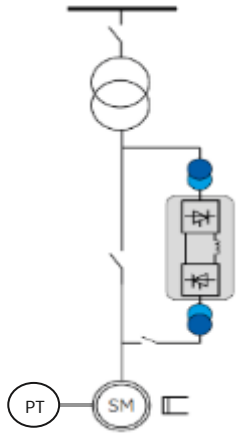


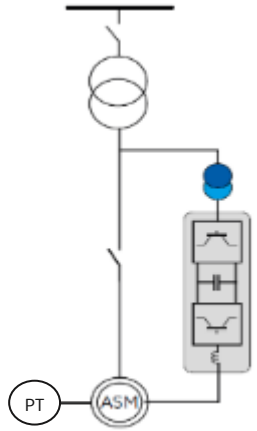
GE Renewable Energy

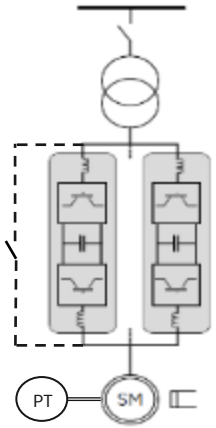
Round trip efficiency above 80% … over whole plant lifetime

Pumped Hydro Storage Technologies

Costs and benefits



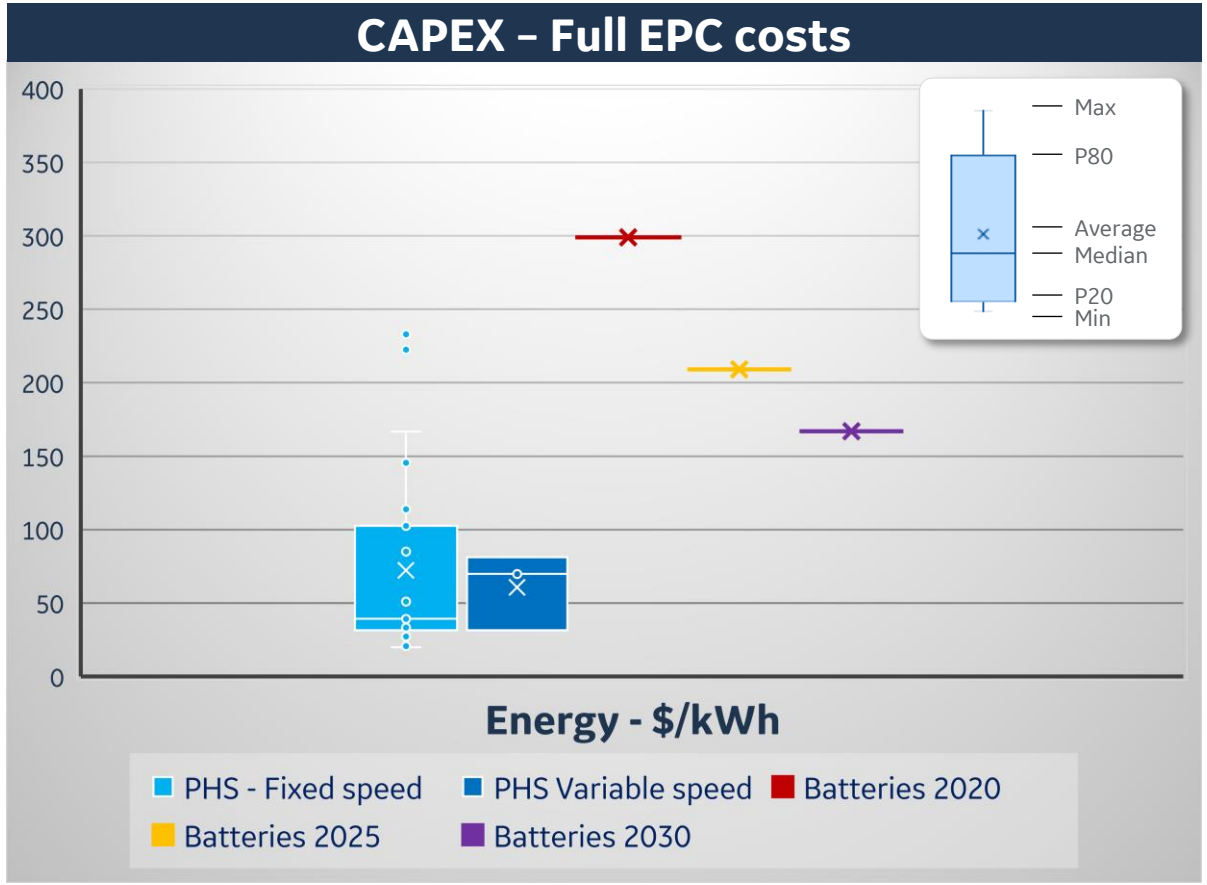




		Reversible Fixed Speed 0-500MW	Variable Speed Doubly Fed 100-400MW	Variable Speed Fully Fed 0-100MW
Costs	Integration & equipment	**$**	**$$**	**$$**
	Civil (Powerhouse/ submergency)	**$/$$**	**$$/$$**	**$$/$$**
	Maintenance	**$**	**$$**	**$$**
Revenue	Arbitrage	**+++**	**+++**	**+++**
	Capacity	**-/+** with HSC*	**++** with HSC*	**++** with HSC*
	Ancillary services	Turbine mode only	**+++**	**+++**
Main interests	Flexibility	+50…+100% (T) and -100% (P) better with HSC*	0…+100%(T) and -100…-20% (P) -100%…+100% with HSC*	0…+100%(T) and -100…-20% (P) -100%…+100% with HSC*
	Reactivity	Seconds	Milliseconds	Milliseconds

*HSC: hydraulic short circuit (with minimum of 2 units)

Capital costs per kWh



Source : GE RE Marketing, BNEF 2020 (4-hour duration Li-ion batteries)

- PHS CAPEX vary widely due to **site-specific costs**; ~20-30% of total CAPEX linked to Electro-mechanical equipment.
  Median price for PHS fixed speed ~25% lower than PHS Variable speed
- Broad range of batteries costs linked to **capacity sizing** (from 30 min up to 4+ hours)
- Prices for energy storage systems vary a lot depending on the **power-to-energy ratio**: large-scale storage capacity of PHS has positive impact on $/kWh whereas more limited storage capacity of batteries negatively impact $/kWh

PHS' large-scale effect ensures competitiveness for long durations

GE Renewable Energy

Understanding Pumped Hydro Capex

Key considerations for developers and investors

Site Selection Considerations

- **Water**: ideally use one or more existing storages
- **Head**: ideally 200-600m (~the higher the better)
- **Waterway**: ideally length <10x the head (the lower the better)
- **Grid Connection**: ideally <20km from transmission (the lower the better)
- **Site Access**: ideally <20km from roads (the lower the better)
- **Land use**: environmental and cultural considerations

Project Design Considerations

Mainly OEMs

- What **type of equipment** should be used? Fixed vs variable speed, etc
- Over **how many units** should the capacity be spread?
- What should **capacity and duration** be?
- What should the **powerhouse position** along the waterway be?
- Overland vs underground **waterway**?
- What should the **powerhouse type** be (shaft vs cavern)?
- What is the optimal **siting and shape** of the reservoirs?

Mainly Civils

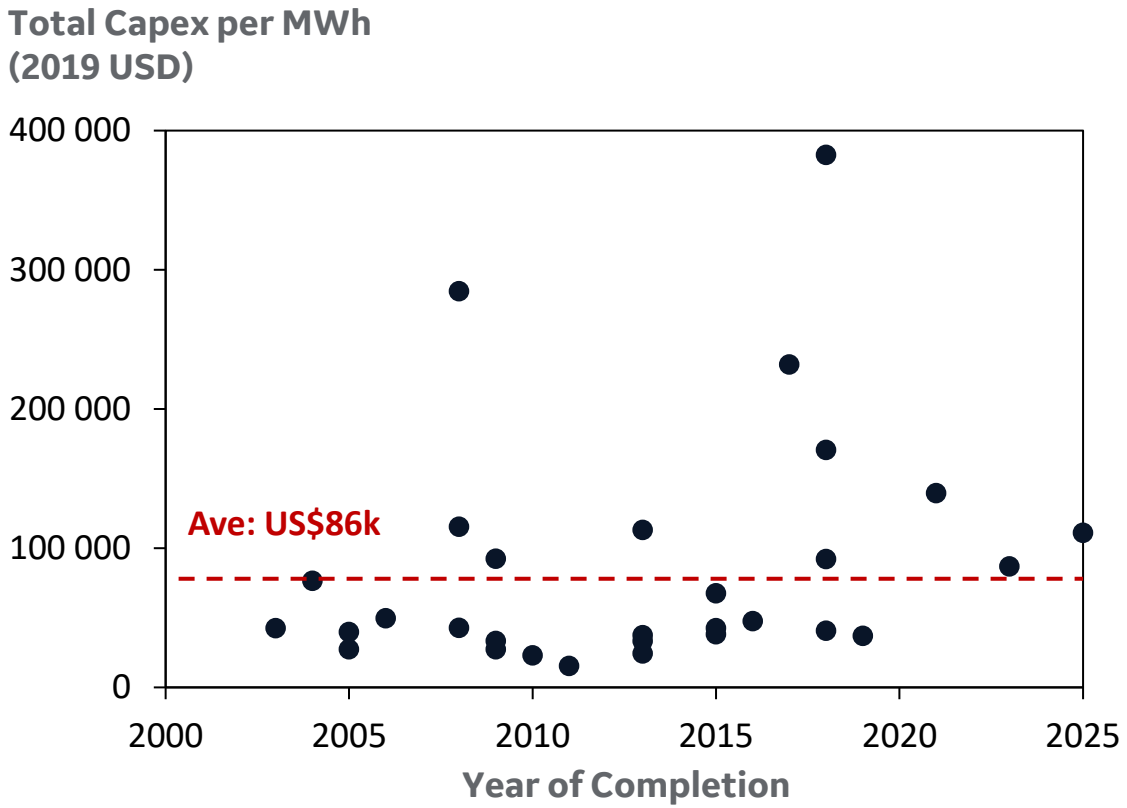
Source: GE Hydro Analysis

GE Renewable Energy

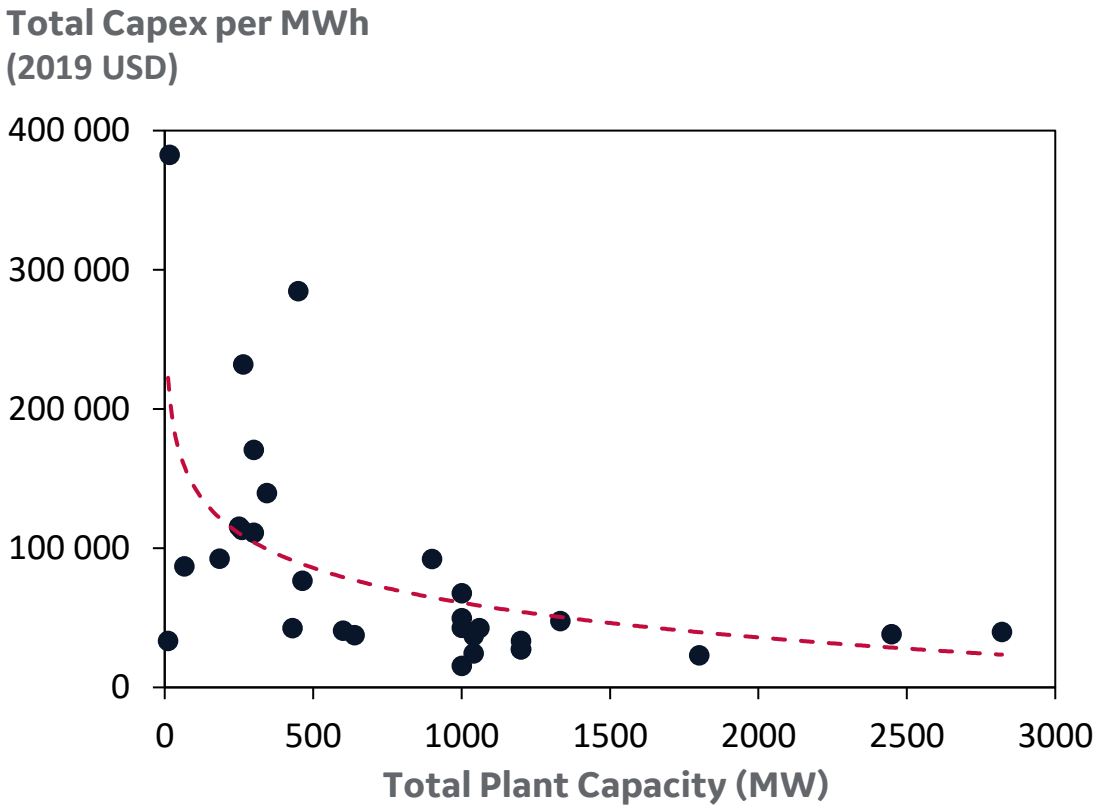
Understanding Pumped Hydro Capex

Capital costs of pumped hydro projects around the world

Capex by Year of Completion



Capex vs Total Plant Capacity



Source: GE Marketing, GlobalData
Notes: Active, Under Construction or Announced projects; Prices escalated according to inflation; 31 projects with available data

GE Renewable Energy

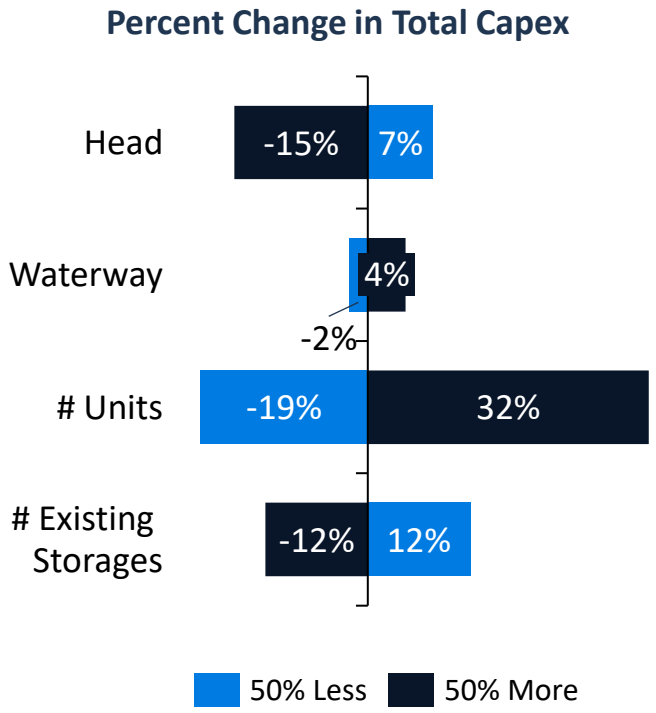
Understanding Pumped Hydro Capex

A worked example

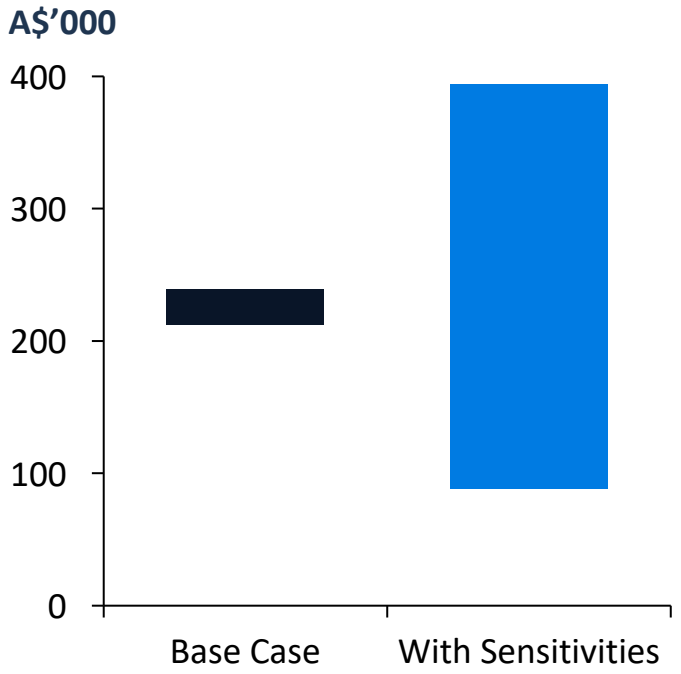
Hypothetical Project Data

Capacity	2x 125MW
Duration	10 hours
Head	250m
Waterway	1250m
Upper Res	Turkey Nest
Lower Res	Existing reservoir

Key Sensitivities



Est. Total Capex per MWh Installed



Source: GE Hydro – Pumped Hydro Capex Model

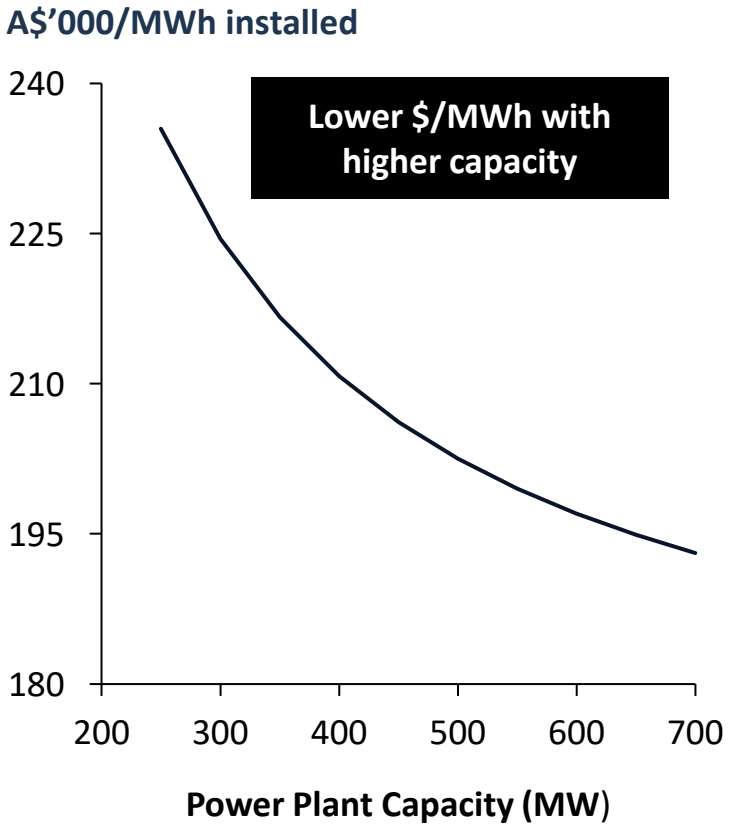
Site fundamentals (and hence site selection) is key!!!

GE Renewable Energy

Understanding Pumped Hydro Capex

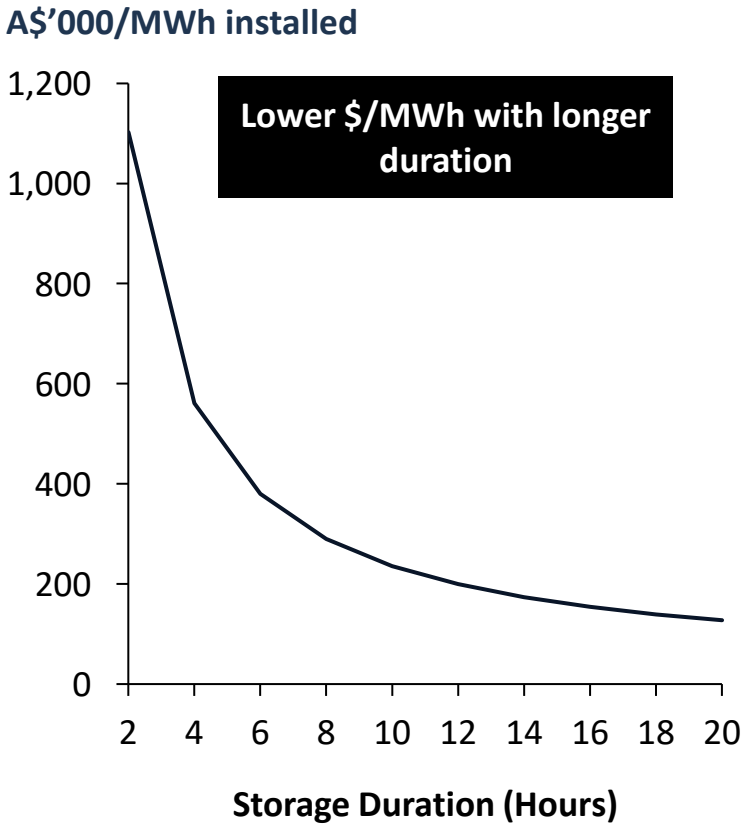
Economies of scale, duration and head

Capex per MWh vs Plant Capacity

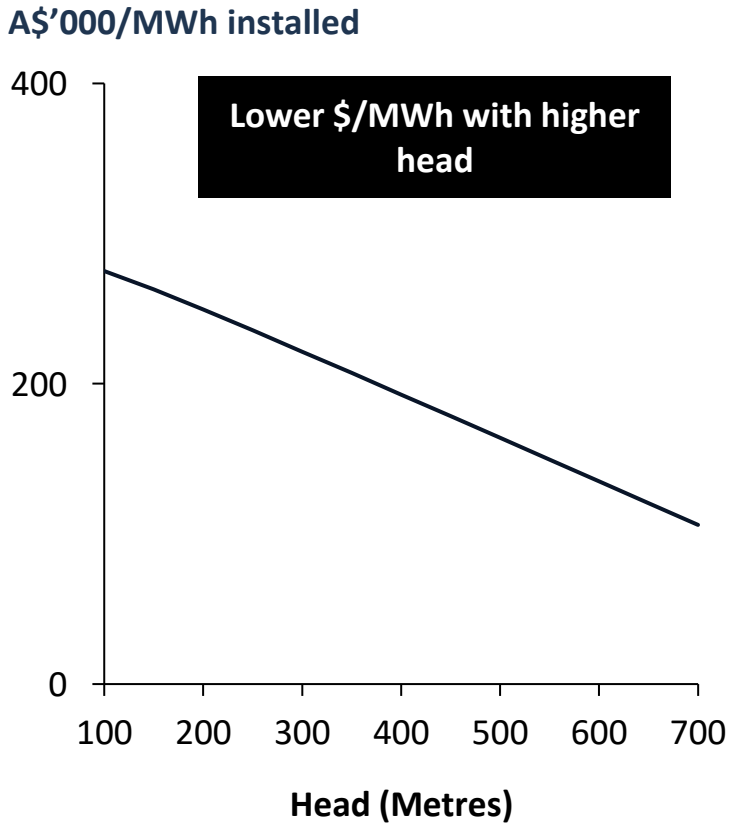


Source: GE Hydro – Pumped Hydro Capex Model

Capex per MWh vs Duration



Capex per MWh vs Head

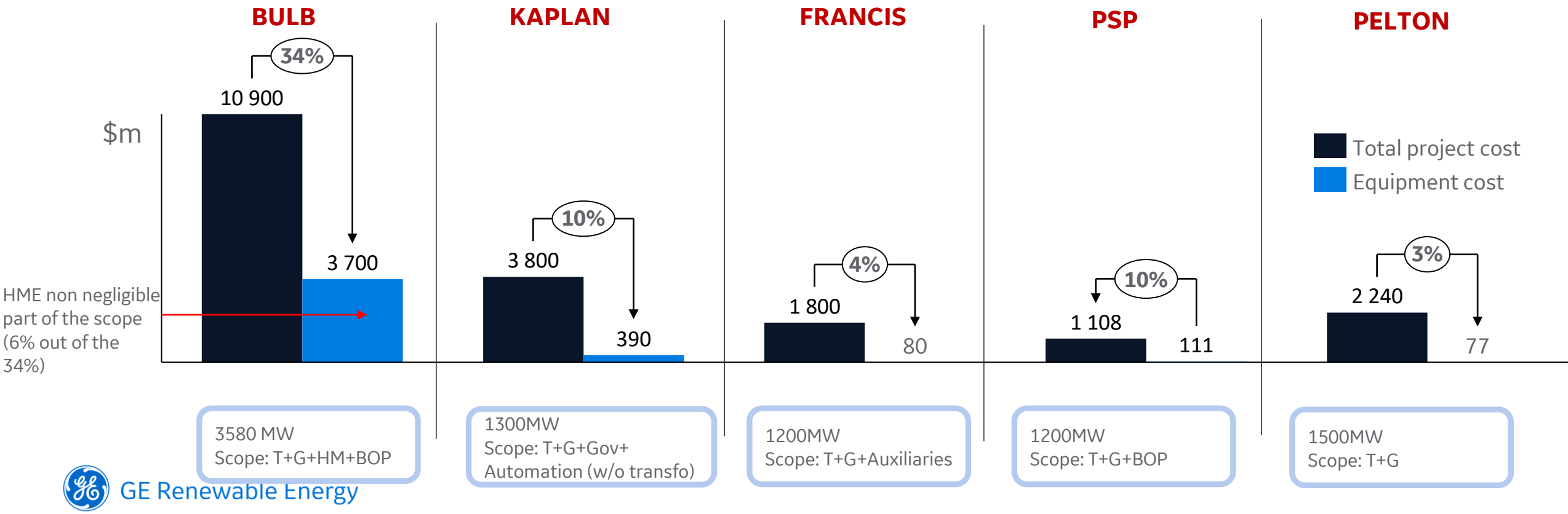


GE Renewable Energy

Electro-Mechanical vs Overall Cost
(New Hydro Project)

From low head run-of-river plants…

…to medium & high head plants

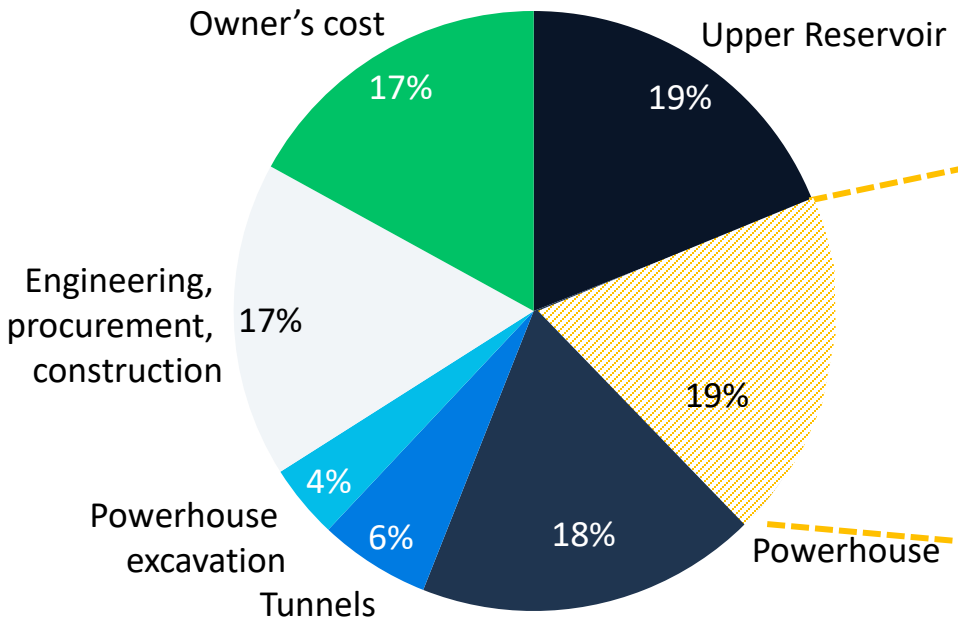


GE Renewable Energy

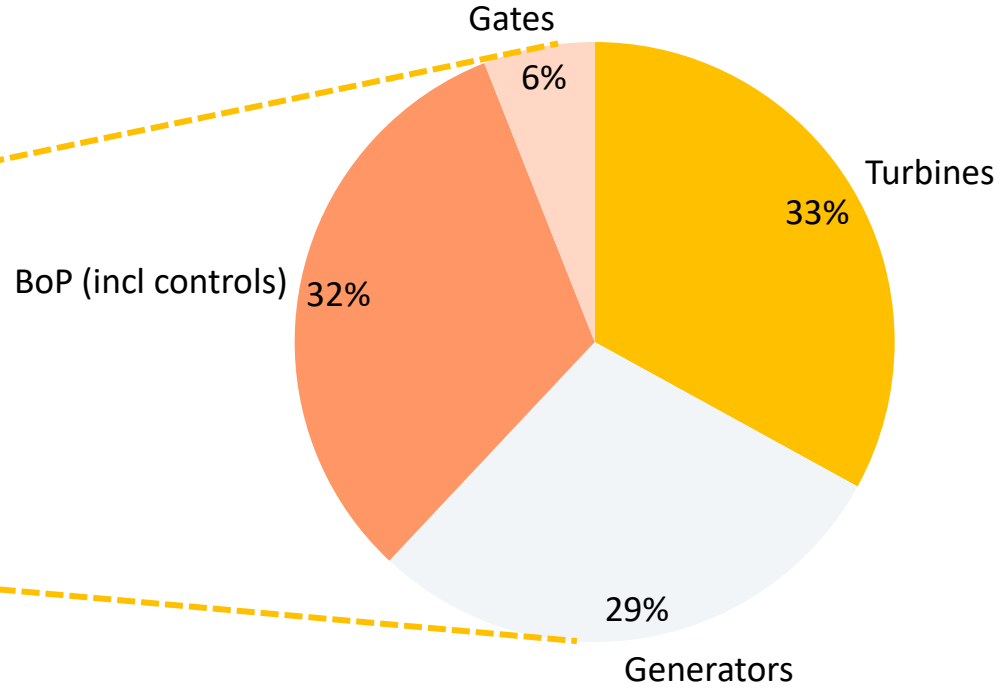
Illustrative Cost Breakdown

Overall Project Capital Cost1

Total: $2,230 / kW +50%



Powerhouse (Electromechanical) Capital Cost[2]



500MW, 5000MWh, 1 existing reservoir, 242m head, L:H ratio of 2.5

Sources : 1 Black & Veatch NREL report, 2011; 2 GE Project Experience

GE Renewable Energy

Third Party Assessments

Pumped Storage Hydro
2020 & 2030 Cost & Performance Estimates

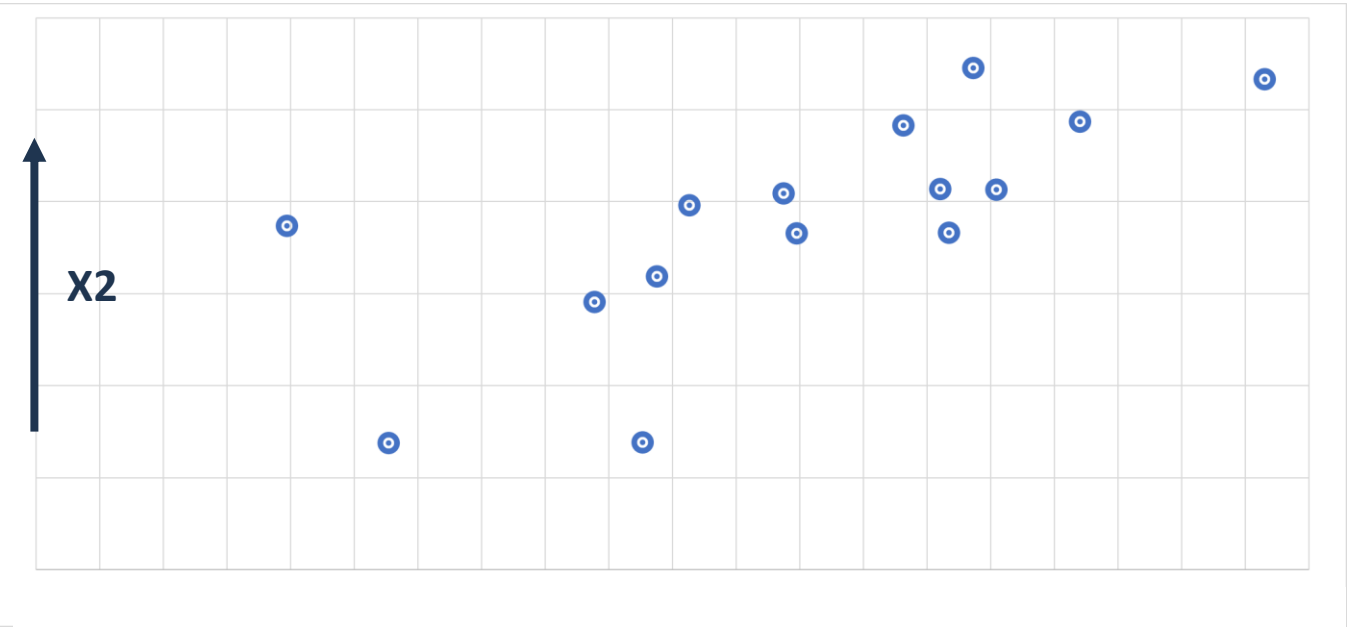
	Parameter	Units	100 MW				1,000 MW			
			4 hr		10 hr		4 hr		10 hr	
			2020	2030	2020	2030	2020	2030	2020	2030
ESS Cost	Reservoir Construction & Infrastructure	$/kWh	[73 - 89] 81		[68 - 83] 76		[61 - 75] 68		[57 - 70] 64	
ESS Cost	Powerhouse Construction & Infrastructure	$/kW	[321 - 817] 742		[321 - 817] 742		[270 - 686] 623		[270 - 686] 623	
ESS Cost	Electro-mechanical	$/kW	[420 - 513] 467		[420 - 513] 467		[353 - 431] 392		[353 - 431] 392	
	Total ESS Installed Cost*	**$/kW**	[1034 - 1688] $1,534		[1424 - 2164] $1,967		[868 - 1417] $1,288		[1195 - 1817] $1,651	
		$/kWh	[259 - 422] $384		[142 - 216] $197		[217 - 354] $322		[120 - 182] $165	
	Total ESS Installed Cost + Contingency Fee*	**$/kW**	[1301 - 2250] $2,046		[1792 - 2885] $2,623		[1093 - 1889] $1,717		[1504 - 2422] $2,202	
		$/kWh	[325 - 563] $511		[179 - 289] $262		[273 - 472] $429		[150 - 242] $220	

Source: 2020 Grid Energy Storage Technology Cost and Performance Assessment
https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf

Equipment Value, selected projects 2012-18

Pump-Turbine

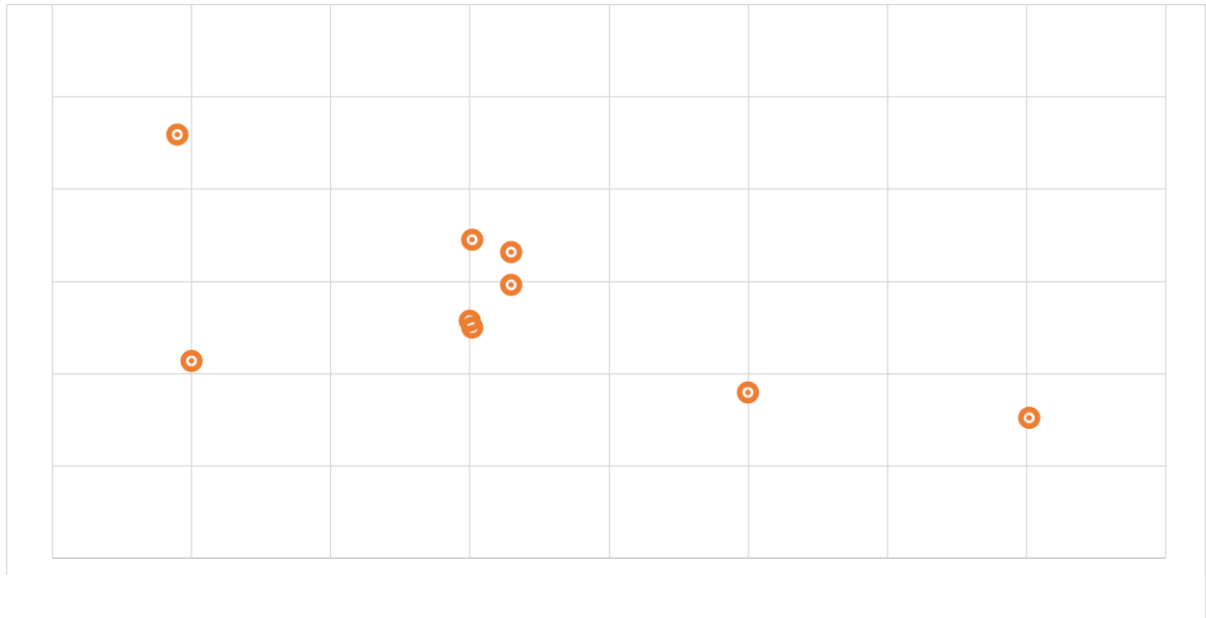
$



Increasing diameter

Motor-Generator

$

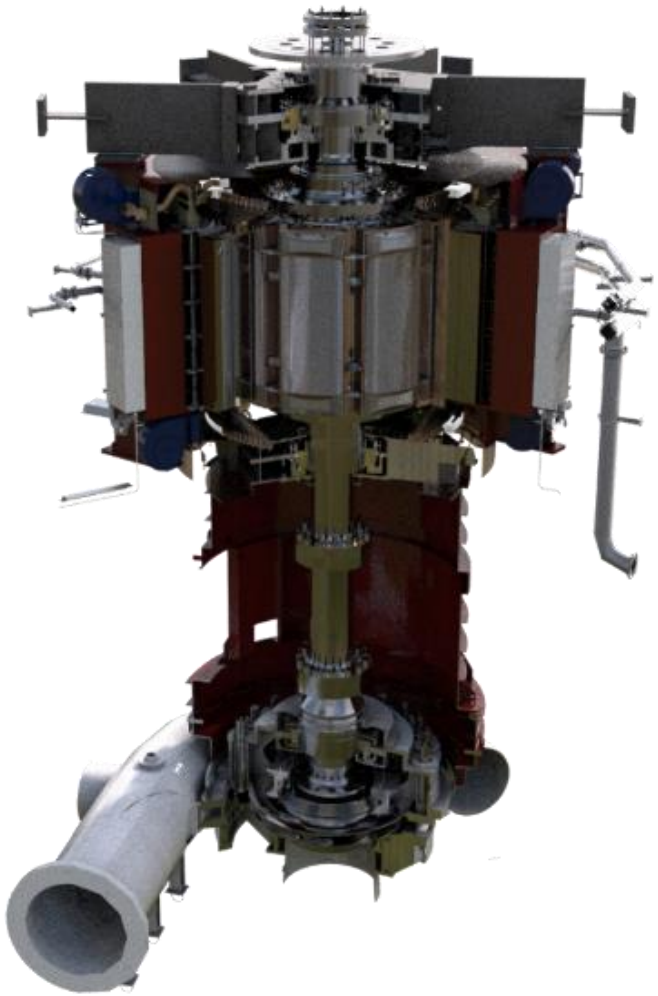


Increasing Power/**speed**

GE Renewable Energy

Dimensioning a PSP Unit

(excluding efficiency)



GE Renewable Energy

MOTOR-GENERATOR

Overspeed speed (rpm)
Inertia / GD²
Power Factor (cos phi)
Grid Frequency 50/60Hz

PUMP-TURBINE

Flow (Discharge) m3/s
Maximum Head (m)
Specific speed (ns/nq)
Circuit
Hump

BOTH

Power (MW / unit)*
Nominal speed (rpm)
N° / position of bearings
Plant Layout
Lifetime

* Influenced by number of units

Optimizing investment through PHS extensions

PHS extension since 2000:

50+ units **10+ GW**

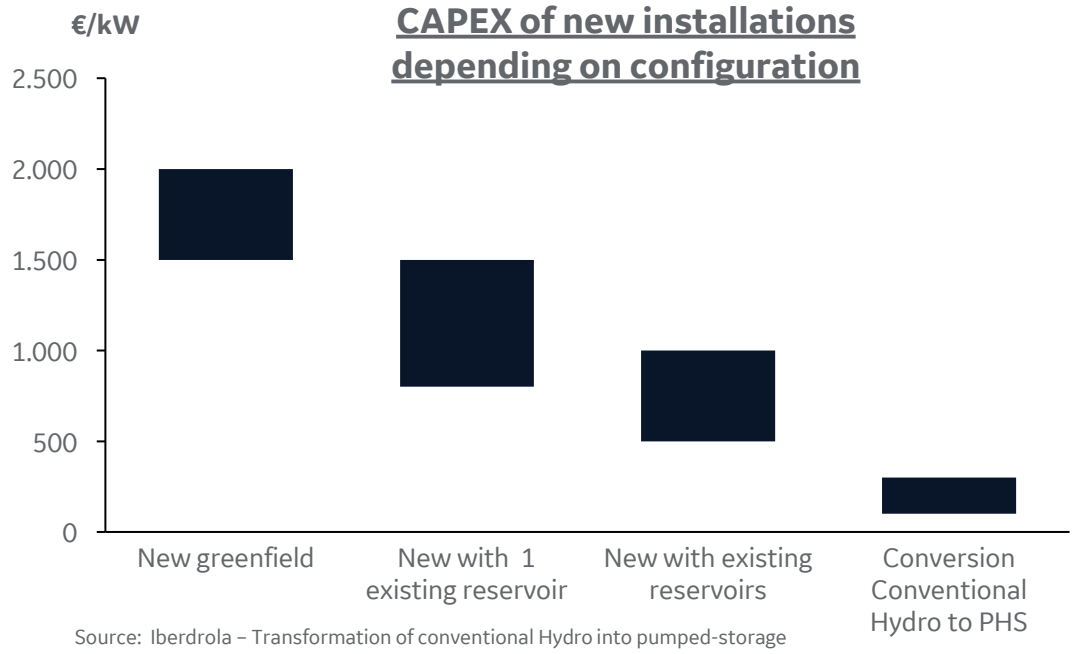
Mainly located in : Europe / China / APAC

KEY ADVANTAGES

- **Shorter delivery time**
- **Lower CAPEX**
- **Limited environmental impact**
- **Simplified permitting process**
- **Performance / efficiency optimization**

Several configurations

- New units in existing power plant /
  New power plant utilizing existing reservoir(s)
- Similar configuration to existing units /
  Adding PHS to conventional units



Source: Iberdrola – Transformation of conventional Hydro into pumped-storage

GE Renewable Energy

Pumped Hydro Storage
Enabling the energy transition

GE can support with:

- **100+ years experience** with **45+ GW** installed base
- **Advanced technology** for higher flexibility (# of cycles, partial load), reactivity, efficiency, stability
- **Fast transition** time machines (**standstill to 100% power in < 70 sec**)
- **3 GW of variable speed technology** installed or under construction with complete integration with GE converter, motor generator, pump turbine, protection and control
- Solution for **short delivery time** (**down to 36 months**)
- **Global and local** organization

Thank you

GE Renewable Energy