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Voith at a Glance Nordics

Lars Thoren | 2018-11-06

Voith in figures

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In more than **60** countries

19 000 employees

5 markets

R&D ratio **5.3 %**

Family-owned since **1867**

Sales **€4.22 Billion**

As of: 2016/17

Voith Group

Four Divisions – a well positioned company

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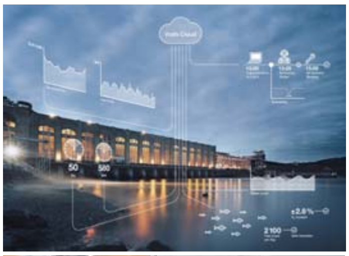

Voith Digital Ventures

Solutions for the internet of things: networking and digitalization

Voith Hydro

Full-line supplier for hydro power plant equipment

Voith Paper

Partner and pioneer in the paper industry

Voith Turbo

Intelligent drive systems and solutions

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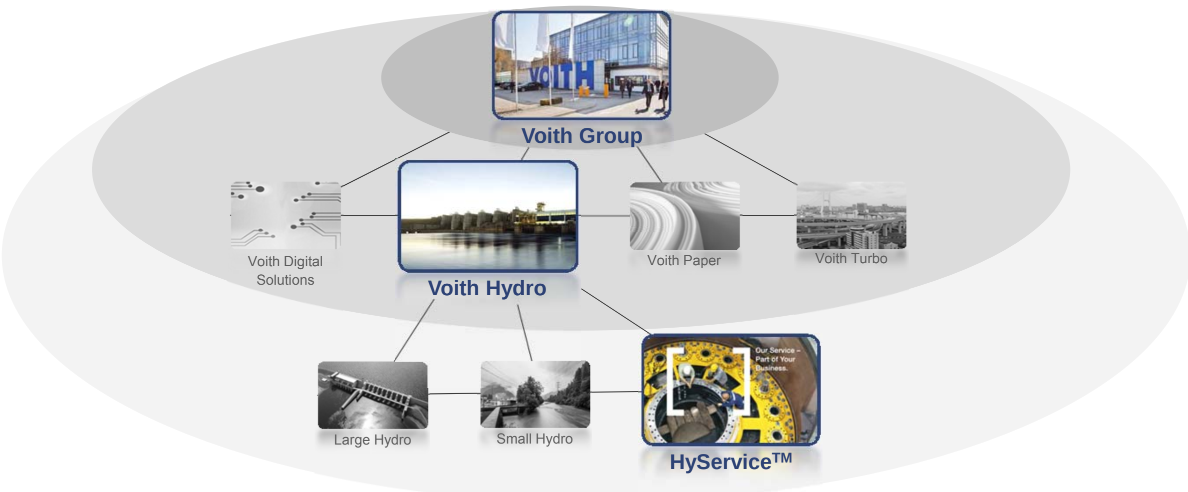
Voith Divisions

Hydro Business Units



Voith Hydro – HyService Nordics
A full-line supplier for Hydro Power Plants

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We offer full-line plant supply for new and also for modernization projects.
From spare parts to turnkey projects, Voith provides individually planned and designed solutions for large high head, low head and run-of-the-river plants.

We also offer stand-alone solutions for **plant automation** as well as **lifetime services for all types of hydro equipment.**

Voith HyService Nordic locations

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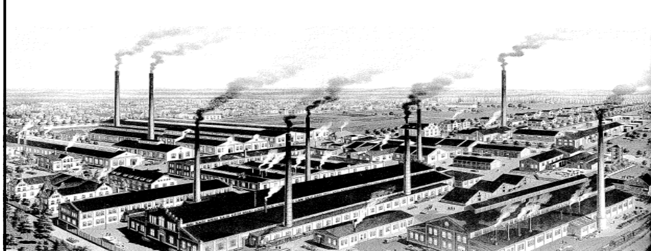
Voith Hydro AB headquarter is located in a historic industrial area in Västerås Sweden with long traditions in manufacturing of electrical machines

- **Västerås**, Generator & Automation
- Kristinehamn, Turbine & Automation
- Östersund, Service Office
- Jokkmokk, Service Office
- **Oslo**, Turbine & Automation
- Fredrikstad, Production and WS
- Trondheim, Automation



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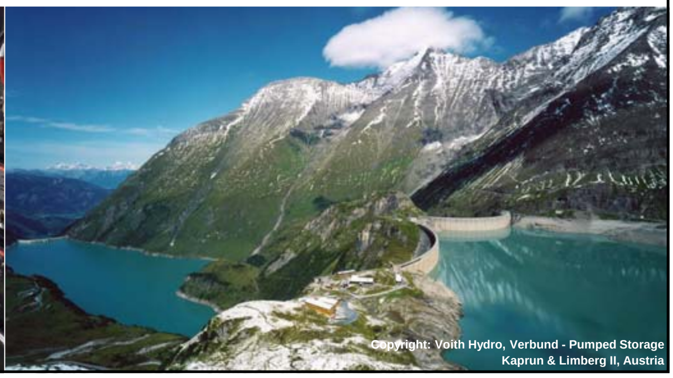
Li-Ion Battery versus Pumped Storage
A comparison of raw material, investment costs and CO_2 footprints

Dr. Klaus Krüger | Västerbergslagens Ingeniörsklubb, Ludvika, Sweden | 2018-11-06



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Introduction

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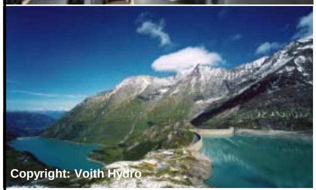

- In recent times, battery storage has experienced a tremendous ‘hype’ in public debate due to technological innovation and a significant decrease in costs
- As a result, several new stationary battery storage schemes in the order of magnitude of several hundreds of megawatt hours have been constructed worldwide during the last decade
- However, the question remains whether the falling costs of a stationary battery storage can be competitive with well-established technologies, such as pumped hydro storages

→ Focus of this webinar will be the comparison of a stationary Li-Ion battery storage system (BSS) to a pumped storage plant (PSP)

→ The results are the outcome of a scientific analysis executed by Voith Hydro with the Institute of Power Systems and Power Economics (IAEW) of the RWTH Aachen University in Germany. For details, please refer to the full paper presented during the HydroVision conference 2018 in Charlotte, N.C., US.

Major characteristics for PSP and BSS

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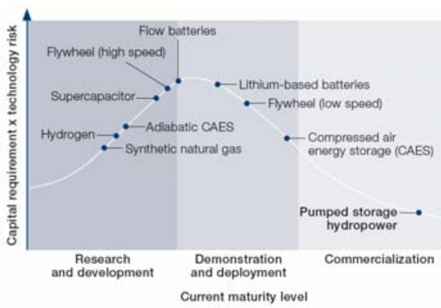

- Pumped storage and hydro storage plants are the only proven bulk-energy storage solutions for the last 110 years.
  BSS: larger industrial applications since 10 years for Li-Ion, 30 years for lead batteries
- PSP: Durable and extremely cycle-proof: 60-100 years of lifetime with designs > 50,000 storage cycles; no restriction on depth of discharge
  BSS with Li-Ion technology: have a calendar lifetime of 15 - 20 years with < 5,000 storage cycles; both depends on depth of discharge (DoD)
- PSP efficiency of 78% - 82% and very low storage energy costs (PSP Atdorf 12 €/kWh for CAPEX, BSS: 85% and > 500 €/kWh)
- 99% of the global "storage capacity" is provided by pump storage (146 GW) 1% by chemical batteries, compressed air and other technologies

Energy Stored on Energy Investment (ESOI) for different kinds of energy storage technologies

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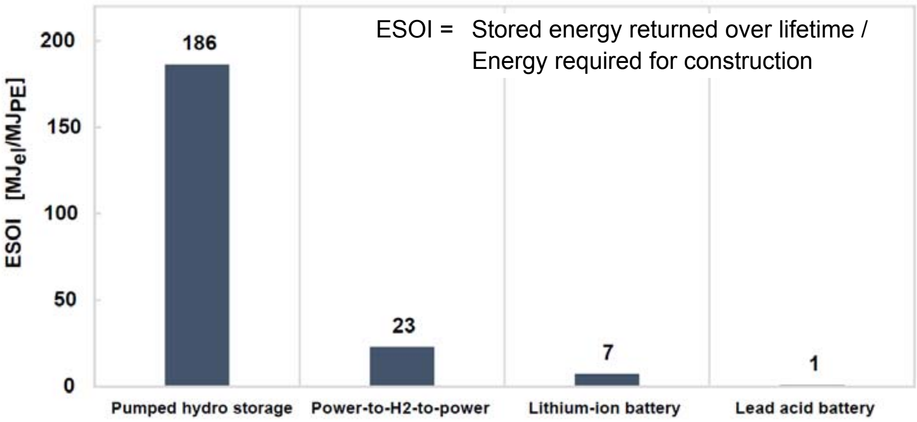

Source: https://www.satw.ch/fileadmin/user_upload/documents/02_Themen/05_Energie/SATW-Energy-Performance-Switzerland-Report-EN.pdf

Battery energy storage system (BSS)

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Copyright: #3

Copyright: #2

- **Cells**

Battery energy storage system (BSS)

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Copyright: #4


Copyright: #5


Copyright: #6


Copyright: #7


Copyright: #8

- Cells
- Modules

Battery energy storage system (BSS)

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Copyright: #10


Copyright: #9


Copyright: #10

- Cells
- Modules
- Battery Management System
- Battery Pack / Tray

Battery energy storage system (BSS)

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- **Cells**
- **Modules**
- **Battery Management System**
- **Battery Pack / Tray**
- **Cabling**
- **Battery electronics**
- **Cubicles / Storage Racks**

complete storage part

Battery energy storage system (BSS)

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site specific

- **DC-AC-Inverters**
- **Transformers, house load**
- **Switchyard**
- **Land property, Civil works**
- **HVAC (T = const.)**
- **Permits**
- **Grid connection**

- **Cells**
- **Modules**
- **Battery Management System**
- **Battery Pack / Tray**
- **Cabling**
- **Battery electronics**
- **Cubicles / Storage Racks**

Stationary BSS

Basic data of the WEMAG battery storage system (BSS) Schwerin in Germany

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Copyright: WEMAG, Batteriespeicher Schwerin


Copyright: WEMAG, Batteriespeicher Schwerin

- Power & storage capacity today: 5MW / 5 MWh expandable to 6 MW / 6MWh (6/6 used for scaling up)
- 25,600 lithium manganic oxide cells (Samsung SDI)
- 20 years of warranty on the cells if T = const. = 17°C 24/7/365
- Transformers: 5 x 1MW (480/20 kV) + 1 transf. for house load
- 10 DC/AC inverters
- Surface consumption of the building: 400m^2 (340m^2 used for scaling up)
- Costs: €6.7M including €1.3M subsidies from the German ministry BMUB

Basic data of the Atdorf pumped storage plant (PSP) in Germany

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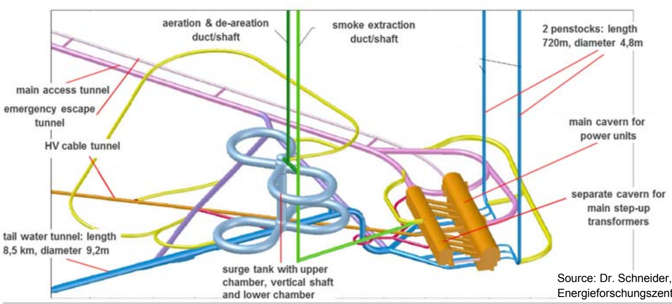
- Planned power & storage capacity: 1.4 GW & 13.4 GWh
- Lifetime: 100 years with replacement of the runners and motor generator sets every 40 years
- Cost: €1.6 bn

3D underground arrangement




Artist impression of upper and lower reservoir

Source: Dr. Schneider, Schluchseewerke. Tagung „Unkonventionelle Pumpspeicher", Energieforschungszentrum Niedersachsen, Goslar, 21./22.11.2013

Scaled up raw material needs for the BSS

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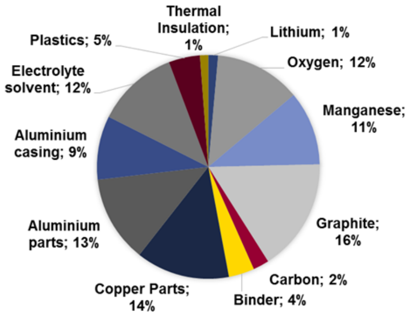

Material breakdown with a share above or equal 1% of mass for Lithium-Ion batteries

Material	Usage	Tonnage for Schwerin 5 MW / 5MWh	Scaled up for 1.4GW / 1.4GWh	Scaled up for 13.4 GW / 13.4 GWh
Steel	Fundament, support, racks, ceiling, battery module	90.01	21,004	201,042
Concrete	Fundament	960	224,000	2,144,000
Copper	Racks	6	1,665	15,944
Plastic	Racks and battery module	1.89	529	5,069
Lithium	Battery module	0.51	141	1,357
Manganese	Battery module	3.87	1,084	10,376
Graphite	Battery module	5.90	1,651	15,806
Mercury	Battery module	0.00000326	0.001	0.01
Cadmium	Battery module	0.0000832	0.02	0.22
Lead	Battery module	0.000029	0.01	0.08
Carbon	Battery module	0.83	233	2,230
Aluminum	Battery module	7.85	2,198	21,043
Rock wool	Battery module	0.43	121	1,163
Electrolytic solvent	Battery module	4.27	1,195	11,442
Binder	Battery module	1.34	374.7	3,588

Considered raw material costs for BSS & PSP

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Raw material	Costs in EUR/t
Diesel fuel	790
Explosives	3,000
Steel	430
Concrete	8
Copper	5,070
Plastic	1,444
Lithium	8,000
Manganese	1,760
Graphite	5,000
Mercury	37,640
Cadmium	1,912
Lead	1,862
Carbon	48
Aluminium	1,682
Rock wool	2,650
Electrolytic solvent	21,010
Binder	54,200
Crude Oil	299

Considered raw materials for PSP (Diesel fuel to Copper)

Considered raw materials for BSS installation (Steel to Crude Oil)

Comparison of raw materials cost required for the initial installation (13.4 GWh)

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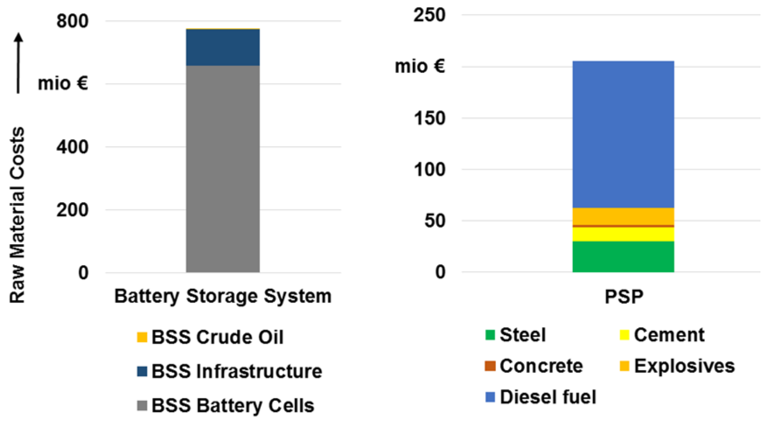
Raw material cost



- The BSS is about 3.7 times more cost intensive considering the raw materials needs
- The dominant cost driver for BSS are the raw materials for the battery cells
- The dominant cost driver for PSP are the costs for diesel fuel during the construction process

Comparison of raw material costs during the assumed lifetime of 100 years (13.4 GWh)

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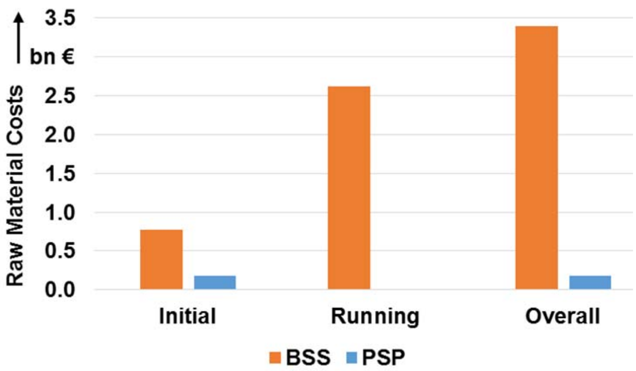
Raw material cost



Assumptions for the comparison:

- The battery cells need to be replaced 4 times within 100 years (every 20 years)
- The runners and the motor-generator sets have to be replaced 2 times (every 40 years)

→ The running raw material costs (excluding initial raw materials) of BSS is about 357 times more cost intensive over 100 years.

→ Conclusion: over 100 years, the raw material requirements of BSS are approximately 18 times more cost intensive than PSP.

Comparison of capital and operational expenditures

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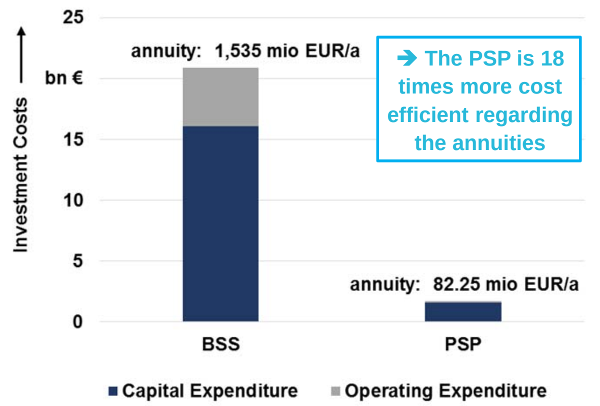
Raw material cost



Assumptions PSP:

- Invest: 1.6 bn EUR for 1.4 GW & 13.4 GWh
- Fixed costs: 2.86 EUR / (kW a)
- Variable costs: 0.56 EUR/MWh and an annual generation of 2.5 TWh
- Interest rate: 4%
- Depreciation period: 40 years

Assumptions BSS:

- Invest: 6 mio EUR for 5 MW & 5 MWh
- Operating costs: 116,000 EUR / a
- Inflation rate of op. costs: 1.5%
- Interest rate: 4%
- Depreciation period: 20 years

CO_2 footprint of both technologies

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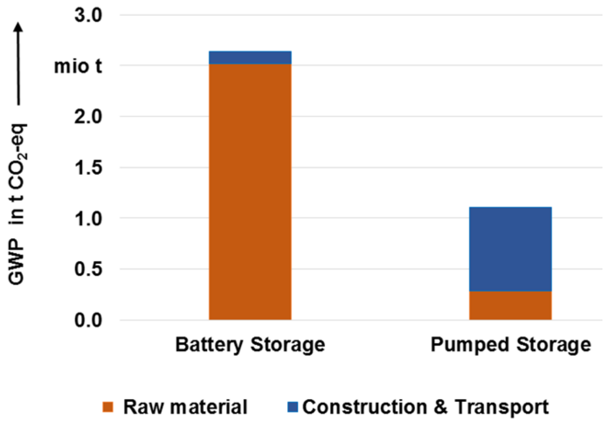
CO_2 footprint

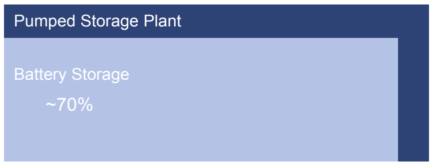


The CO_2 footprint regarding the PSP includes not only the raw materials but also the emissions during construction.

For the BSS the CO_2 footprint contributions for the air-conditioned transport, storage and installation of the battery cells have been considered.

→ The CO_2 footprint of the BSS is about twice the footprint of the PSP

Land use, welfare (added value to the national economy), raw material recycling rate



1. The PSP Atdorf requires an area of 1.086 km² and the BSS an area of 0.759 km², meaning that the land use of the BSS is about 30% lower compared to the PSP. However these calculations are limited to the land use in Germany.

   When expanding the geographical scope to a global level, it becomes especially obvious that the battery storage needs huge land areas for the mining process of the required raw materials. This is not taken into consideration in the figure above.

2. The added value for a PSP in Germany is 80% and the added value of a BSS with imported cells is only 20%.

3. Raw material recycling rate for a PSP is > 80% (copper, steel, concrete). For new BSS with Li-Ion technology this rate is much lower and in some cases not even available yet.

Summary of the comparison

- BSS and PSP have completely different needs for raw materials. A PSP predominantly requires large amounts of steel and concrete, which are relatively cheap. The battery cells of BSS need a huge number of different raw materials, e.g. graphite and manganese, which are highly cost intensive.
- Main consequence: The overall raw material costs for the initial installation for BSS scaled to the same energy storage capacity of the PSP are about 3.7 times higher.
- Over a lifetime of 100 years the overall raw material costs are about 18 times higher for the BSS.
- The capital investment and operating costs of the BSS are 18 times higher than for the PSP.
- The land use requirement of BSS is 70% compared with PSP at the installation site. When expanding the geographical scope to a global level the comparison result would be opposite, due to the mining process needed for the BSS raw materials.
- The CO_2 footprint of the BSS turns out to be twice the footprint of the PSP.

Remarks for BSS and PSS

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- The Power-to-Energy factor for a BSS depends on the type of chemical battery:
  - Li-Ion: 1/3 ... 1/0.5,
  - Lead: 1/6 ... 1/3,
  - NaS: 1/7, ...
- For a PSP this factor can be designed according to the individual project needs, assuming a geological suitable location. Typical values for PSPs are ≤ 1/7. The factor for PSP Atdorf is 1/9.6.
- For bulk energy storage (e.g. ≥ 1 GWh, with Power to Energy factors ≤ 1/7) chemical batteries are far too expensive compared with PSP. In addition, the battery storage needs some oversizing in order to compensate the capacity deterioration of Li-Ion over the lifetime. These additional costs have been not considered.
- The advantage of BSS is a high inherent Power-to-Energy ratio. BSS are ideally suited to fast and short (< 1 ... 1.5h) applications like UPS, peak shaving, governor response, HV grid booster, energy buffer for wind parks or for EV charging stations, ...

Power & energy trading opportunities for batteries & pumped storage in Europe

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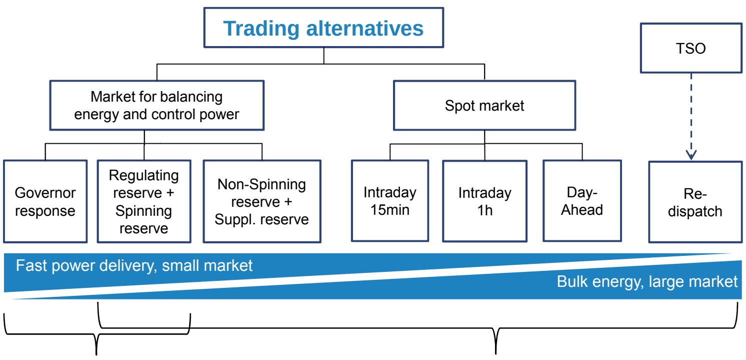

BSS

Copyright: WEMAG, Batteriespeicher Schwerin

PSP

Copyright: Voith Hydro

The TSO expenses for redispatch in Germany only were > 1.4 bn € for 2017 with an energy volume of 20.4 TWh and 5.5 TWh curtailment !

Redispatch = necessary grid stabilization measures due to unexpected weather conditions, very often due to North-South HV grid congestions, ...

Examples for integration of new chemical batteries in or near the switchyard of existing pumped storage plants in Germany

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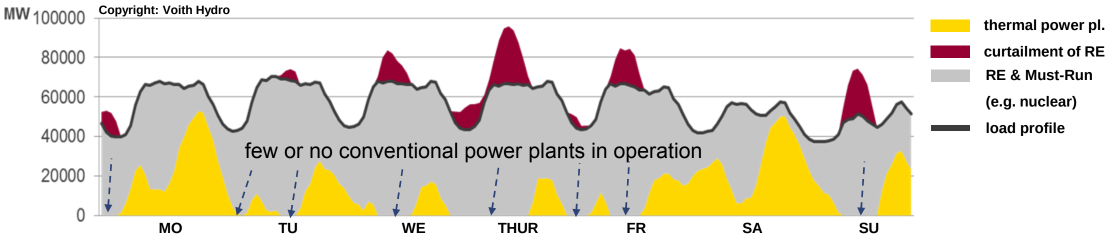

Background: In the past conventional power plants were usually supplying primary frequency control (PFC; US terminology: Governor Response), but these power plants had to be shut down several times per day or week. This was to integrate solar and wind generation; therefore conventional power plants cannot guarantee anymore an uninterrupted provision of this ancillary service for one week.

→ New business case for chemical batteries integrated in existing PSP switchyards, since conventional PSP cannot provide PFC in stand-still conditions (win-win).

Basic data of the new chemical battery storage system at the existing Reisach / Tanzmühle PSP in Germany

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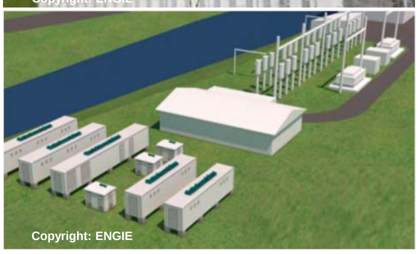

PSP Reisach (1954/1961) and Tanzmühle (1959)

- Volume upper reservoir: 1.5 Mio m³
- Power pump mode: 1*25MW, 3*28MW
- Power generation mode: 1*35 MW, 3*35 MW
- Efficiency up to 80%

Battery

completed in Dec 2017, Supplier: Siemens

- Investment > 12 mio €
- 12.5 MW / 13 MWh
- Battery system is integrated in the existing PSP switchyard of Reisach
- Supplies additional primary frequency control / pooling mode with the PSP which already provides primary frequency control (US: governor response) in hydraulic short circuit and secondary frequency control power (US: regulating reserve + spinning reserve)

Basic data of the new chemical battery storage system at the existing Herdecke PSP in Germany

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*** https://www.windkraft-journal.de/2018/02/06/belectric-realisiert-batteriespeicher-fuer-rwe-in-herdecke/116807

PSP Herdecke
- In operation since 1989
- Energy storage capacity: 590 MWh
- Power pump mode: 153.6 MW
- Power generation mode: 153 MW
- Startup time: 60s
- Efficiency 80%

Battery
- In operation since Feb 2018, Provider: Belectric
- 552 car battery modules with 100 lithium cells each
- 7 MW / 7 MWh, Invest: 6 mio €
- Supplies primary frequency control (US: governor response)
- Battery system is integrated in the existing PSP switchyard

MIT study: The $2.5 trillion reason we can't rely on batteries to clean up the grid in US

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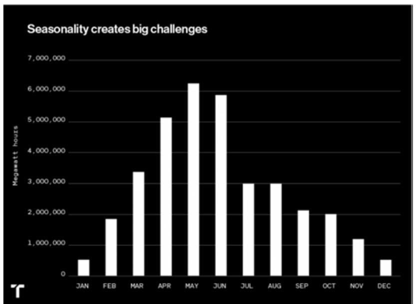

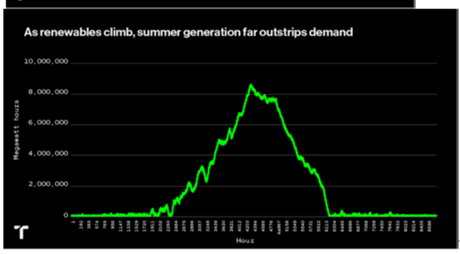

„If renewables provided 80 percent of California electricity – half wind, half solar – generation would fall precipitously beginning in the late summer.“

„Reaching the 80% mark for renewables in California would mean massive amounts of surplus generation during the summer months, requiring 9.6 TWh of energy storage. Achieving 100 % would require 36.3 TWh (current storage capacity is 0.15 TWh only; mainly pumped hydro).“

"Meeting 80 percent of US electricity demand with wind and solar would require either a nationwide high-speed transmission system, which can balance renewable generation over hundreds of miles, or 12 hours of electricity storage for the whole system. At current prices, a battery storage system of that size would cost more than $2.5 trillion."

source. https://www.technologyreview.com/s/611683/the-25-trillion-reason-we-cant-rely-on-batteries-to-clean-up-the-grid/

MIT Study: Energy supply cost rise sharply for different shares of renewables penetration

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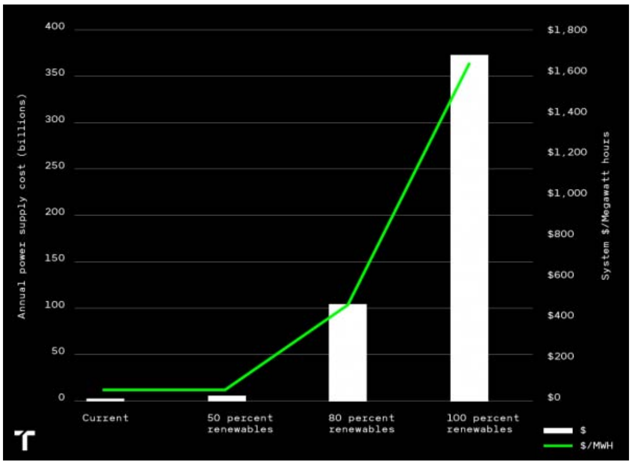

"Building the level of renewable generation and storage necessary to reach the Californian state's goals would drive up costs exponentially, from $49 / MWh for generation & storage at 50% renewable share to $1,612 / MWh at 100 %."

"And that's assuming lithium-ion batteries will cost roughly a third what they do now."

„Today's battery storage technology works best in a limited role, as a substitute for "peaking" power plants (e.g. gas turbines)."

source. https://www.technologyreview.com/s/611683/the-25-trillion-reason-we-cant-rely-on-batteries-to-clean-up-the-grid/

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Development of power outputs for Francis and Pumpturbines

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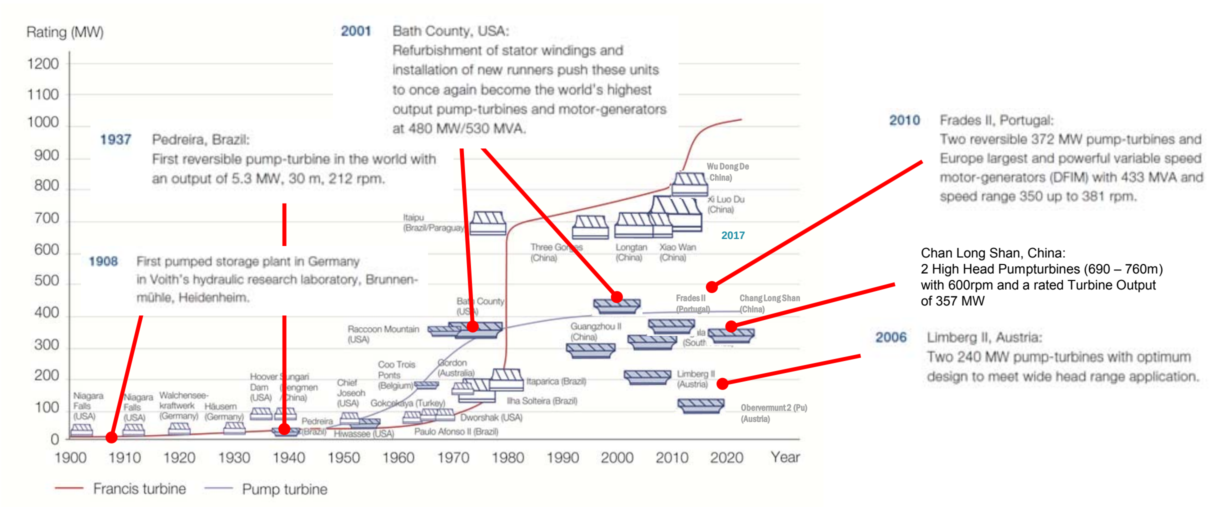

History of Generators and Motor-Generators at Voith Hydro

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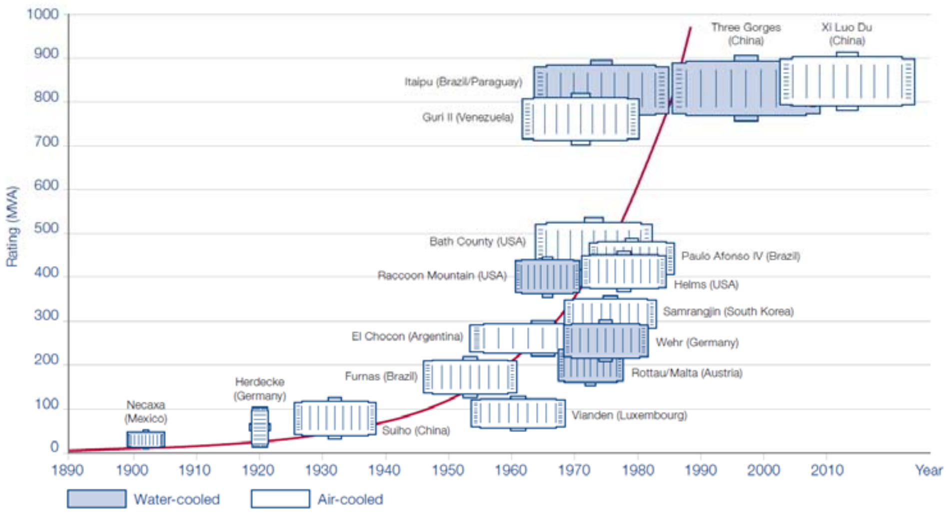

Pump Storage Plants – Development of Power Unit Arrangements

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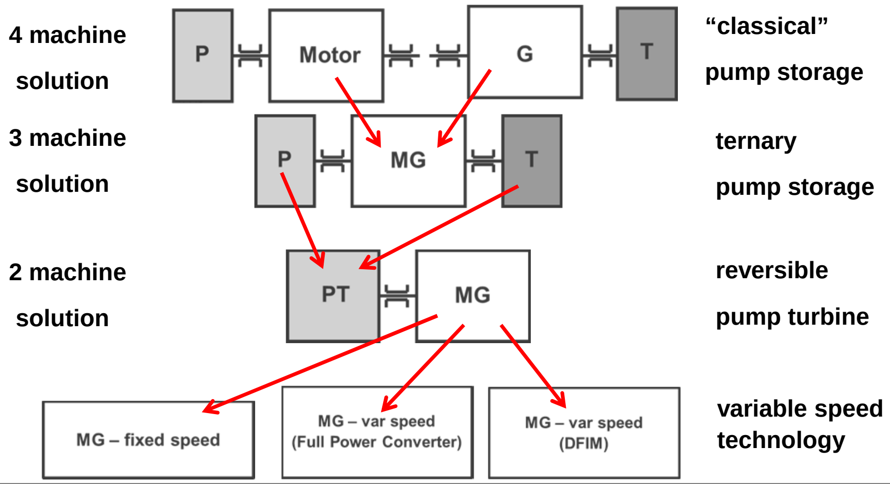

Energy conversion

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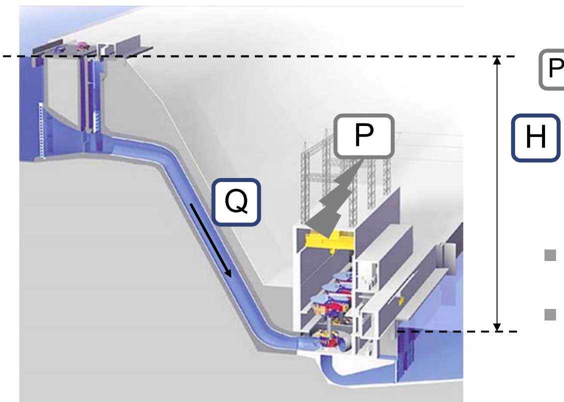

Power ~ Head x Discharge

- Discharge Q drives size of the plant
- Head H drives type of plant and hydraulic machine type

Examples of vertical arrangements for pumped storage units

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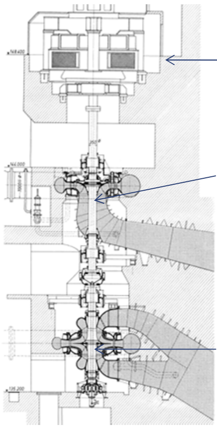
one rotating direction



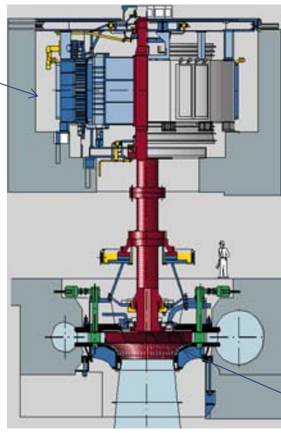
motor-generator

single stage Francis turbine runner

single stage pump runner with two inflows

ternary set: separate pump & turbine

two rotating directions



reversible pump-turbine

single stage reversible pump-turbine runner

Pumped storage application areas of different solutions for the hydraulic machine with respect to head and power

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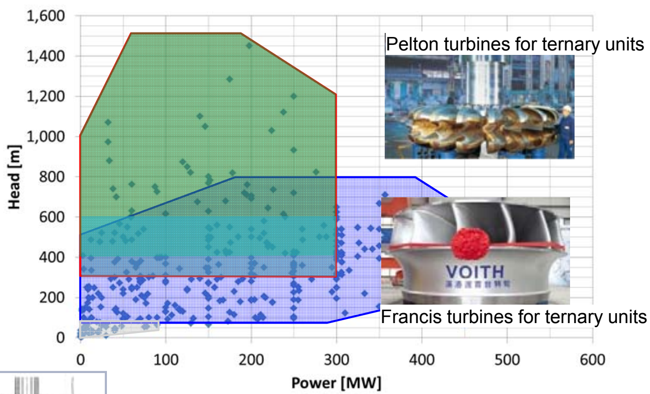
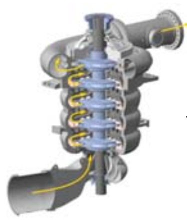
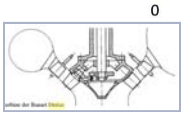




multi stage pumps for ternary units

single stage reversible pump-turbines



source: Voith Hydro – PSP Market Overview

Power unit concepts

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P: pump Pe: Pelton turbine MG: motor-generator FT: Francis turbine PT: pump-turbine	MG – fixed speed	MG – var speed (Full Power Converter)	MG – var speed (DFIM)
P – MG – Pe up to 1500m or more	application for high heads / fast mode changes	-	-
P – MG – FT up to 600m	fast mode changes	-	-
PT – MG up to 800m	most common application in the past	mainly for grid stabilization (low power < 100MW)	mainly for grid stabilization (high power > 100MW)

Overview of pumped storage variants depending on grid needs

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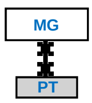
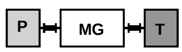
- Conventional reversible unit (PT + MG, fixed speed)
- Conventional units in short circuit arrangement (PT + MG, fixed speed)
- Variable speed reversible unit (PT + MG)

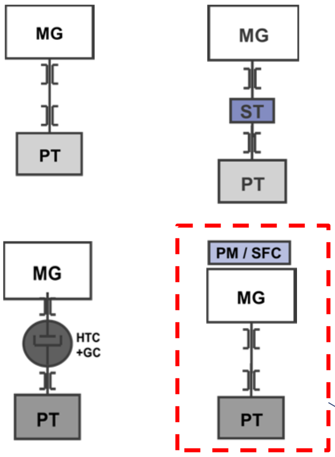


- Ternary unit arrangement (P + MG + T, fixed speed)



Possible configurations for reversible units

VOITH



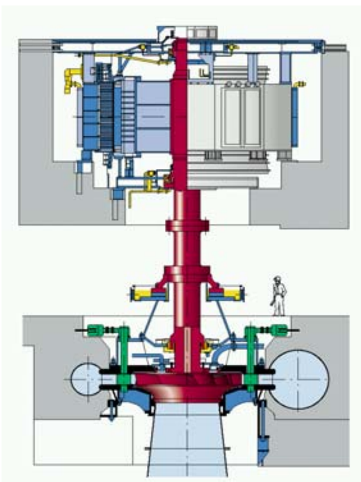
MG	Motor-Generator	
GC	Gear Coupling	starting options of the pump
ST	Starting Turbine	starting options of the pump
HTC	Hydralic Torque Converter	starting options of the pump
PM	Pony Motor	starting options of the pump
SFC	Static Frequency Converter	starting options of the pump
PT	Pump Turbine	

all configurations can be built horizontally and vertically

most common configuration in operation

Conventional Reversible Unit (PT + MG)

VOITH

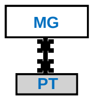


- Typical arrangement for the existing fleet worldwide (proven technology, lowest cost ➔ many being built today worldwide)
- Two rotating directions, fixed speed
- Power control in turbine mode only (consumed motor power can not be controlled in pump mode)
- Load range for generation: 40% - 100% rated power
- A reversible pump-turbine is a pump with design feature to be operational in turbine mode
- Hydraulic circuit possible in case of 2 units (1 unit operates as pump 1 unit operates as turbine)

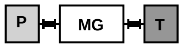
Overview of pumped storage variants depending on Regulation responsiveness and Grid Needs

VOITH

- Conventional reversible unit (PT + MG, fixed speed)
- Conventional units in short circuit arrangement (PT + MG, fixed speed)
- Variable speed reversible unit (PT + MG)



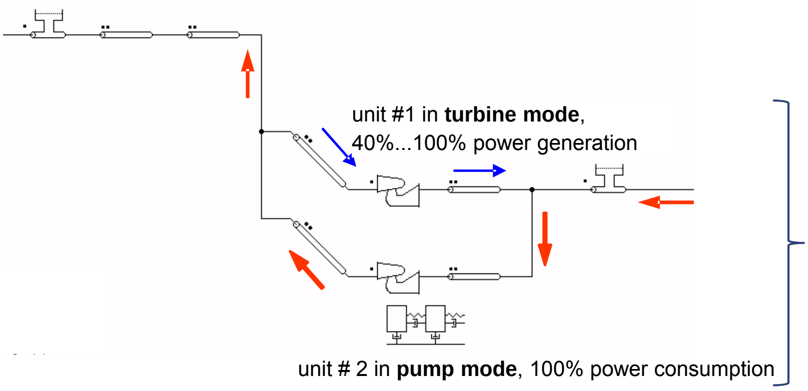
- Ternary unit arrangement (P + MG + T, fixed speed)



Two conventional units in Hydraulic Short Circuit Arrangement

VOITH

Operation of the plant in an asynchronous balanced mode enables better control of the power consumption from the grid (two reversible units in operation with a controlled re-circulation).

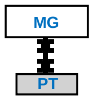


resulting total power consumption control range for both units is **0% ... 60%**

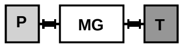
Overview of pumped storage variants depending on Regulation responsiveness and Grid Needs

VOITH

- Conventional reversible unit (PT + MG, fixed speed)
- Conventional units in short circuit arrangement (PT + MG, fixed speed)
- Variable speed reversible unit (PT + MG)

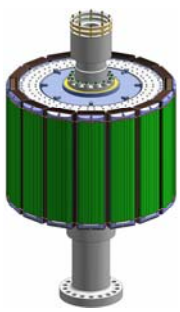


- Ternary unit arrangement (P + MG + T, fixed speed)

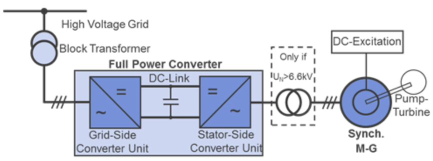


Options for variable speed units

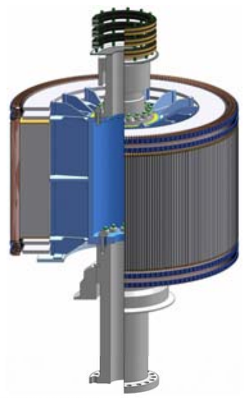
VOITH

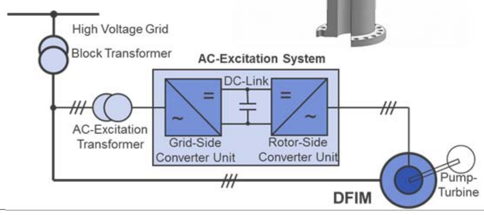


SM: Synchronous motor-generator with a full power convertor between grid and stator



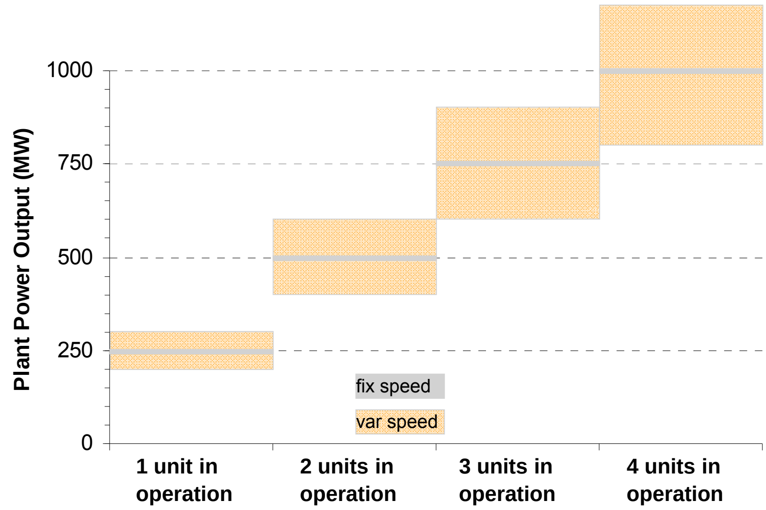
DFIM: Double Feed Induction Machine with AC-Excitation for the rotor





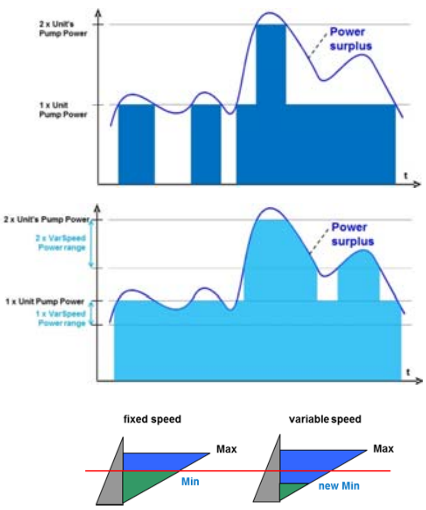
Power control range in pump mode

VOITH



Advantages of variable speed units

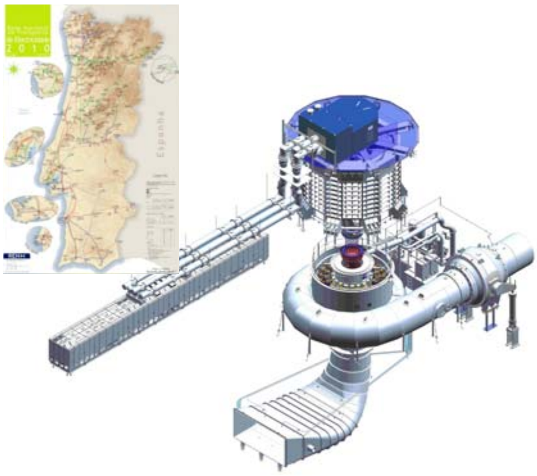
VOITH



- Possibility to control the consumed motor power in pump mode (e.g. in order to compensate the wind volatility and to offer higher flexibility to the grid network operator). This increases also the total number of pump utilization hours in a year.
- Larger head range variations are possible, i.e. better utilization of the reservoir volumes (important for low head applications or deep & narrow reservoirs). Fixed speed: max./min head ratio < 1.25. Variable speed max./min head ratio < 1.45.
- Larger control band in turbine mode due to lower part load (down to 25%) and with higher efficiency can be achieved.
- Faster load ramping in pump and in turbine mode utilizing the AC excitation system for active & reactive power control. This applies also for offering important ancillary services to the grid such as primary and secondary frequency control reserves additionally in both modes.
- Potential to improve the grid stability in case of grid faults (e.g. LVRT) by injecting fast active and reactive power in both modes (pump & turbine mode).

Voith Hydro reference Frades II for DFIM in Portugal

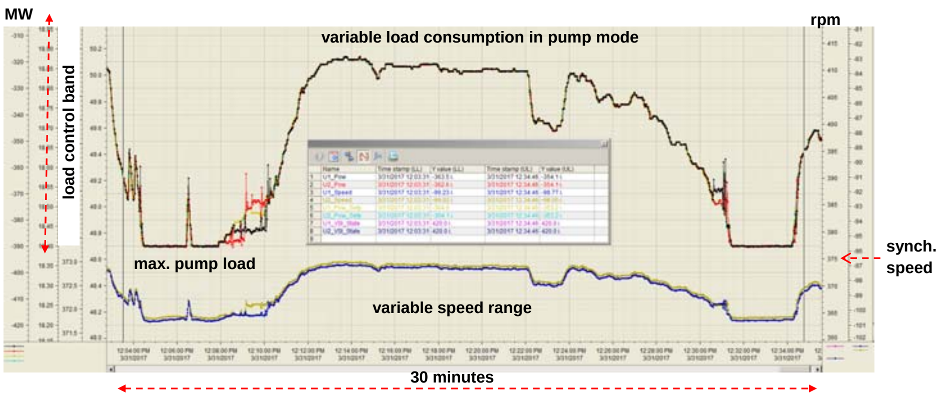
VOITH



- The two largest asynchronous motor-generators for pumped storage in Europe, each with 380MW/420 MVA, have been designed and delivered by VH (erection and commissioning done 2017).
- The power in pump mode varies between + 5% (+18 MW) and - 9% (-68 MW) in order to absorb volatility of the wind.
- With regard to the volume of electrical machines it is the largest in the world due to the low synchronous speed of 375rpm.
- Modeling of the HV grid of Portugal was pre-requisite for the numerical investigation.
- All load cases had to be investigated in the offer stage for both pump and turbine mode including symmetrical and asymmetrical faults.

Operation charts from Frades II in pump mode

VOITH

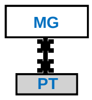


The variable speed feature is being utilized frequently by TSO dispatcher.

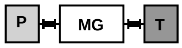
Overview of pumped storage variants depending on Regulation responsiveness and Grid Needs

VOITH

- Conventional reversible unit (PT + MG, fixed speed)
- Conventional units in short circuit arrangement (PT + MG, fixed speed)
- Variable speed reversible unit (PT + MG)

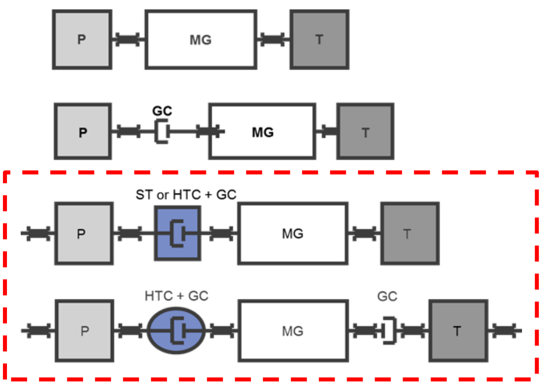


- Ternary unit arrangement (P + MG + T, fixed speed)



Possible configurations for ternary units

VOITH



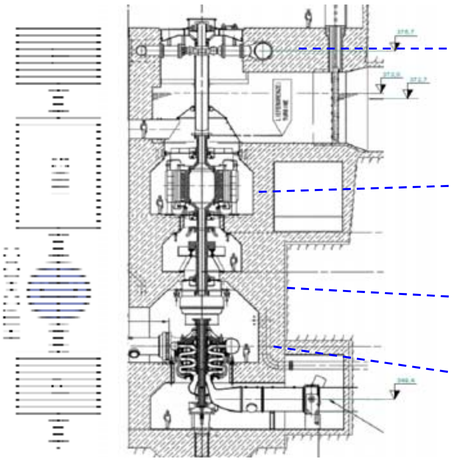
MG	Motor-Generator
GC	Gear Coupling
ST	Starting Turbine
HTC	Hydraulic Torque Converter

all configurations can be built horizontally and vertically

most common configurations in operation

Main components of a vertical ternary unit with a Pelton turbine and a three-stage pump (Kops II, Austria)

VOITH



Pelton turbine
(2 bar air-pressurized)

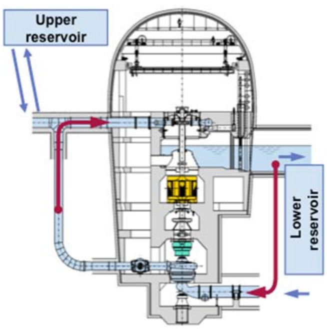
Motor Generator

Hydraulic torque converter

multistage pump (3-stage)
head variation: 726m...836m

Technical driving factors for flexibility of ternary configurations

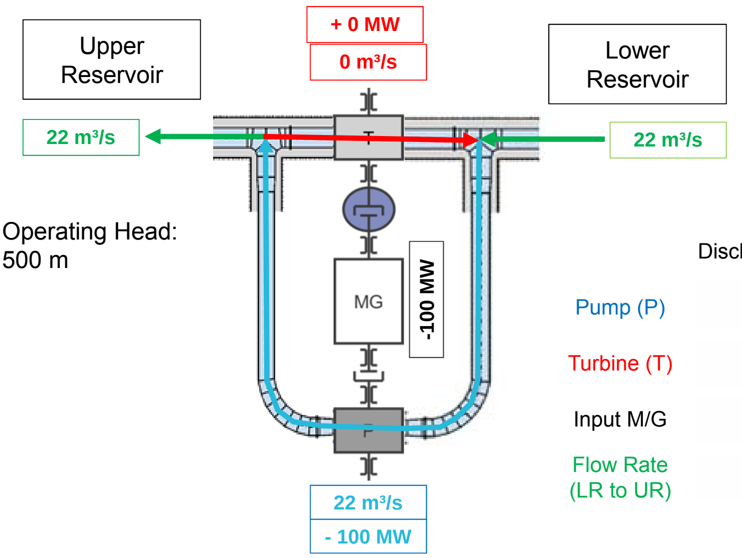
VOITH



- Turbine + Generator + Torque Converter + Multistage pump
- Kops II: 3 x 175 MW in turbine mode,
  3 x 150 MW in pump mode
- Each unit **can be operated individually in hydraulic short circuit**
- Such a ternary flexible arrangement is characterized:
  - **No change of rotation direction in pump or turbine mode** !
    Therefore no phase reversal switch necessary, motor generator stay always connected to the grid, no air blow down system necessary.
  - **Enables steepest load ramps**
  - **Quickest mode changes**
  - Low losses

Hydraulic Short Circuit Operation

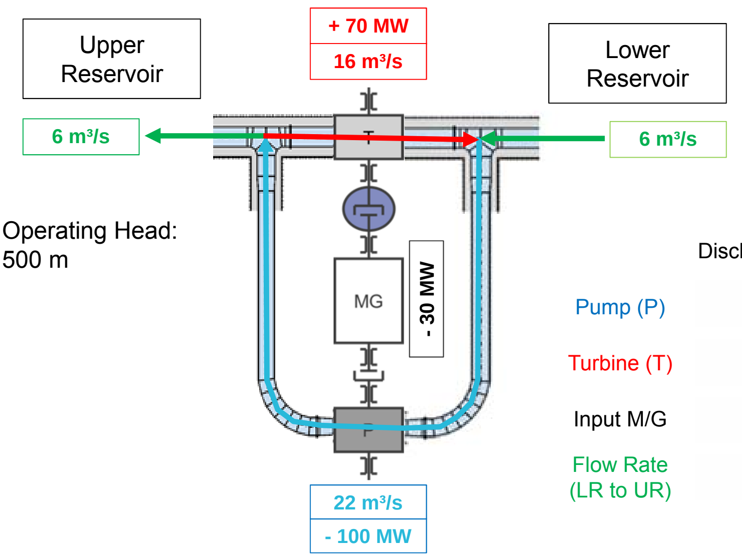
VOITH



	Discharge	Power
Pump (P)		
Turbine (T)		
Input M/G		
Flow Rate (LR to UR)		

Hydraulic Short Circuit Operation

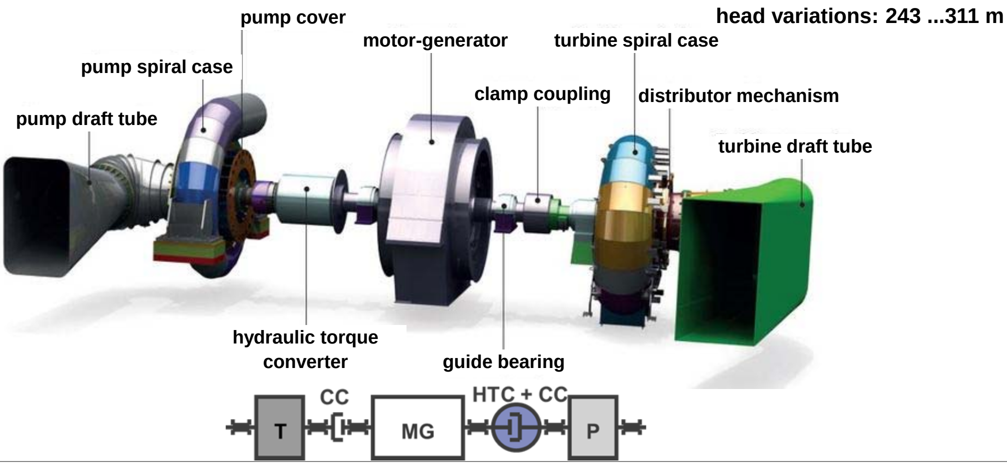
VOITH



	Discharge	Power
Pump (P)		
Turbine (T)		
Input M/G		
Flow Rate (LR to UR)		

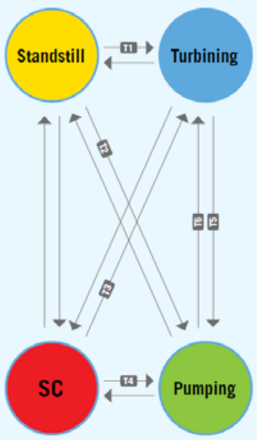
Main components of the two horizontal ternary units of Obervermuntwerk II (2 x 160 MW pumps, 2 x 180 MW turbines)

VOITH



Flexibility is significantly influenced by mode change times

VOITH



Pump-turbine				Time [seconds]				
T	Mode change			A	B	C	D	E
1	Standstill	→	Turbining	90	75	90	90	65
2	Standstill	→	Pumping	340	160	230	85	80
3	SC-Mode	→	Turbining	70	20	60	40	20
4	SC-Mode	→	Pumping	70	50	70	30	25
5	Turbining	→	Pumping	420	300	470	45	25
6	Pumping	→	Turbining	190	90	280	60	25

Ternary sets

- start-up flexibility from stand still
- providing very fast balancing power for grid stabilization & fast load gradients

Reversible pump-turbine
A - advanced conventional (2012)
B - extra fast response conventional
C - variable-speed, DFIM

Remark: These are only examples. In new projects the transition times may have higher values (e.g. depending on the inertia of the waterways and on the design of auxiliary systems involved).

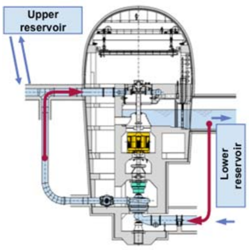
Ternary set
D - with hydraulic torque converter + hydraulic short circuit, horizontal, with Francis turbine
E - same as E but vertical with Pelton turbine

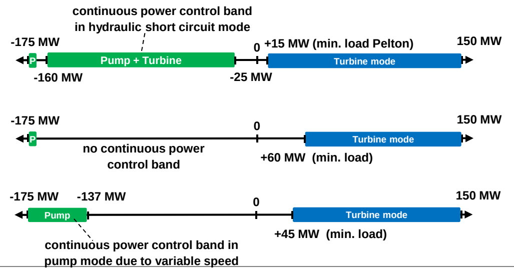
SC = synchronous condenser

Technical driving factors for flexibility of ternary configurations

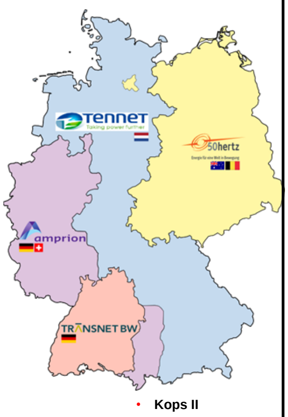
VOITH

- All units **can be operated individually in hydraulic short circuit and can be marketed / rented one by one to TSOs.**
- The **power control band in pump mode can be extended** for this fixed-speed unit.
- Kops II units are running up to 3000h per year in hydraulic short circuit condition
- In this mode efficiency and storage business like arbitrage are not relevant at all, since frequency stability in the grid has the highest priority.



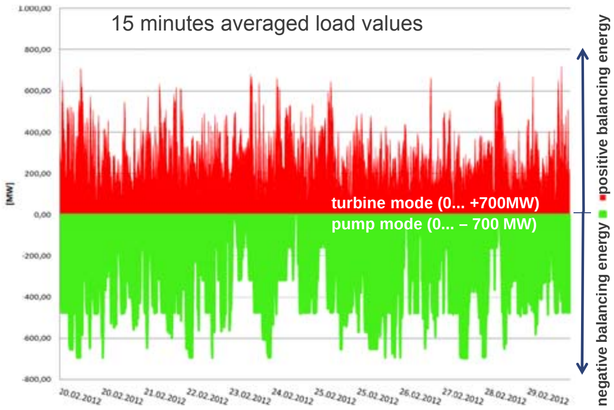


4 TSOs in Germany: Tennet, 50 Hz, Amprion and Transnet BW



9 day load regime of a PSP complex compensating the volatility of wind & solar and their forecast errors

VOITH



Source: Peter Matt, Vorarlberger Illwerke AG: Defining the role of hydropower in the European energy mix. Conference paper during the Hydropower Development, Porto, 17th-18th September 2014.

➔ **Batteries or Demand Side Management cannot endure or comply with these frequent and short cycles**

➔ **Pumped storage (PSP) is the only mature and feasible technology to provide such cycle-intensive services for the high voltage grid stability !**

Owner: Vorarlbeger Illwerke AG in Austria. Name of pumped storage complex: **Werksgruppe Obere Ill – Lünersee:**

- Obervermuntwerk (29 MW)
- Obervermuntwerk II (360 MW) 2 x ternary units
- Vermuntwerk (156 MW)
- Kopswerk I (247 MW)
- Kopswerk II (525 MW) 3 x ternary units
- Lünerseewerk (232 MW)
- Rodundwerk I (198 MW)
- Rodundwerk II (276 MW)

Arrangement of machines: comparison ternary unit with reversible pump-turbine unit

VOITH

Type of machine	P – MG – T	MG / PT
Investments	–	+
Space requirements	–	+
Efficiency	+	–
Setting	+	–
Transition time: P ⇒ T / T ⇒ P	+ (with HTC)	–
Individual hydraulic short circuit	+	–
High heads	+	–
Operation costs	–	+
Technical risks	–	+
Maintenance efforts	–	+

Dr. Klaus Krüger
Head of Plant & Product Safety and Innovation Management
Voith Hydro Holding – VHZ-hpi
Heidenheim, Germany
klaus.krueger@voith.com

Coauthors for the comparison BSS with PSP:

Pierre Mann, M.Sc., Niklas van Bracht, M.Sc.,
Research Group Market & System Analyses and
Prof. Albert Moser, Professor of Institute of Power
Systems and Power Economics (IAEW), RWTH
Aachen University, Germany

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