National Workshop on Pumped Storage Hydropower Projects

8th & 9th February 2018
Energy Management Centre
Thiruvananthapuram

Compendium of Presentations

Day 2

INDEX

Son La HPP, Vietnam

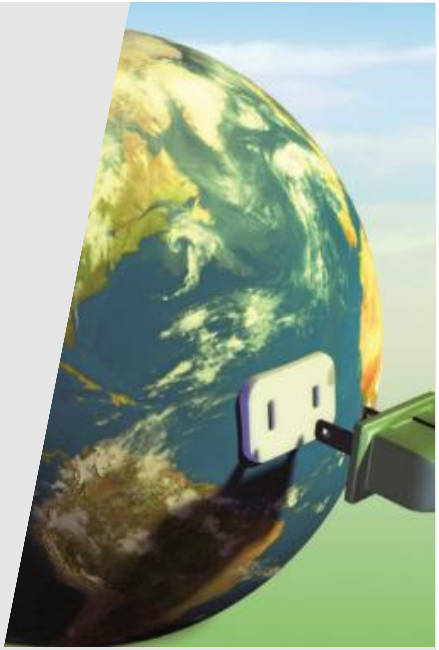
National Workshop on Pumped Storage Hydropower Projects
8-9 February, 2018/Thiruvananthapuram/India

ÅF’s Experience in Pumped Storage Hydro Power

Dr. Dieter Mueller
Vice President, Head of Hydro Power
ÅF – Energy Division

AGENDA

- **ÅF Group**
  - Facts at a glance
  - The business sectors
- **ÅF in Energy**
  - Our services
  - ÅF in the market
- **ÅF in Hydro Power**
  - Competences and services
  - A selection of recent projects
- **ÅF in Pumped Storage Hydro Power**
  - Why PSPP?
  - Examples for Potential Studies – Concept/Feasibility Studies - Design and Construction



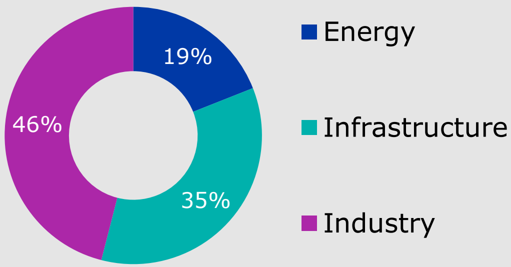
Facts at a glance

Key figures and profile in 2016

- **Headquarter** Stockholm, Sweden
- Stock Listed at **Nasdaq OMX**
- Active in **over 100 Countries:** On four continents; Europe, Asia, South America and Africa
- **Number of assignments:** ÅF performs over **30,000 assignments** for more than **10,000 clients**

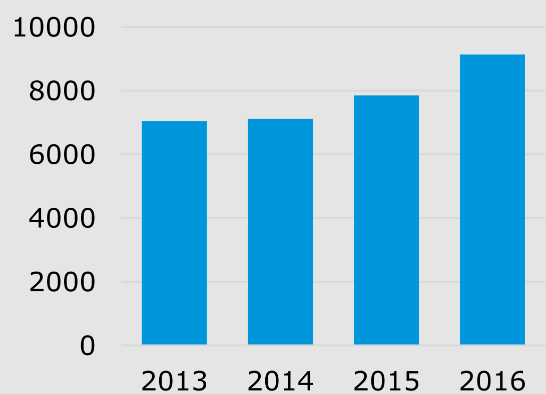
Our business

Contribution to Group sales



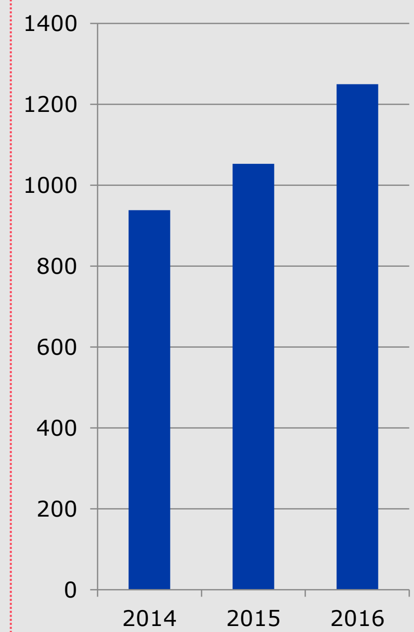
Our employees

9,133 employees in 2016



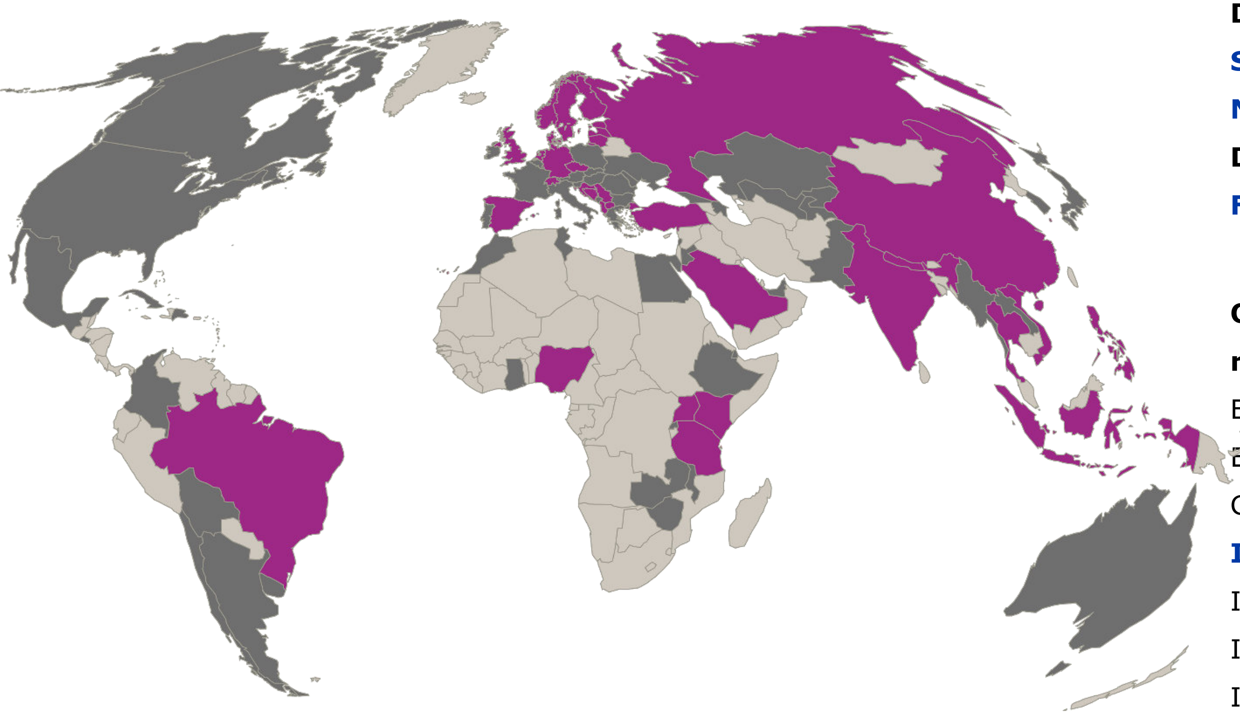
Turnover

1,25 US$ Bn. (1,16 € Bn.)



ÅF's presence worldwide

Global expertise backed by local knowledge



Domestic Markets:

Sweden
Norway
Denmark
Finland
Czech Republic
Switzerland
Spain

Other main offices with engineering resources:

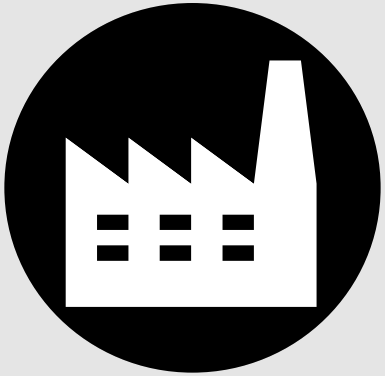
Brazil
Estonia
Germany
India
Indonesia
Iran
Italy
Kenya
Kingdom of Saudi Arabia
Lithuania
Macedonia
Myanmar
Nepal
Nigeria
Russia
Serbia
Tanzania
Thailand
The Netherlands
Turkey
United Kingdom
Vietnam

ÅF has offices and projects
ÅF has carried out projects

Our offer

One business – three business sectors

Energy



Industry

Infrastructure

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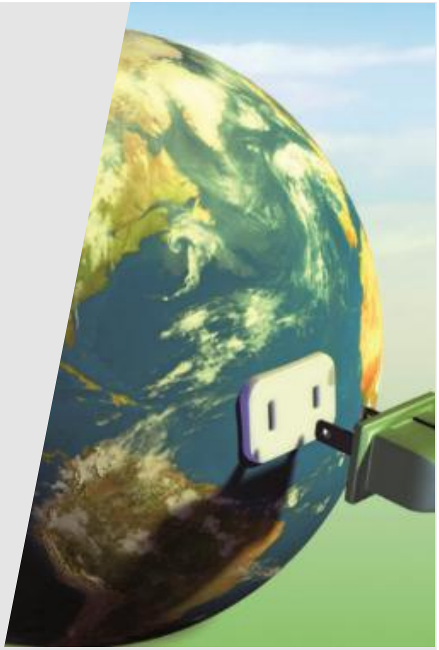
  - Competences and services
  - A selection of recent projects
- **ÅF in Pump Storage Power Plants**
  - Examples for Potential Studies – Concept/Feasibility Studies - Design and Construction



Energy

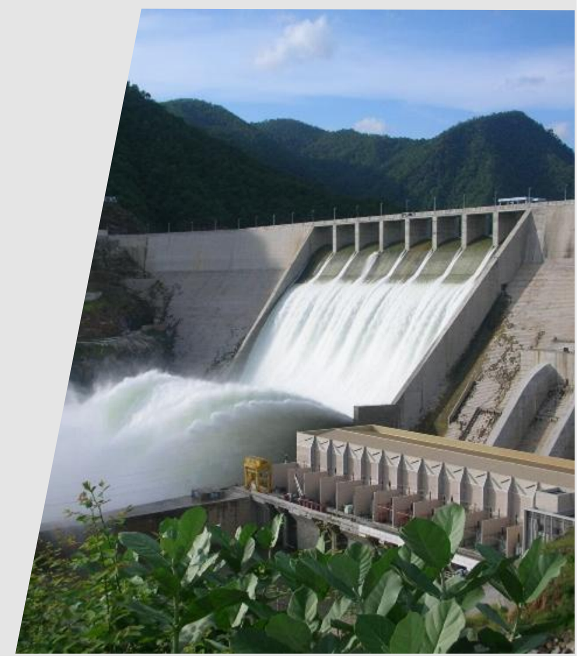
ÅF is one of the world's engineering and consulting companies within energy

OUR CLIENTS ARE FOUND IN:

- Hydropower
- Nuclear energy
- Renewable energy
- Thermal energy
- Transmission and distribution

WE ARE EXPERTS IN:

Consultancy and engineering services in energy markets, covering the full lifecycle of an investment project in the fields of power generation, transmission and distribution



Our offering

Offering

Full scale of technical and financial advisory services:

- Hydro Power
- Thermal Energy
- Nuclear Energy

Further fields of activities:

- Renewable Energy
- Power Distribution
- Market Modeling Studies
- Energy Policy Issues

Clients

- Power utilities
- Energy related industry
- Government/municipalities
- Local authorities
- Transmission/Distribution companies
- International funding institutions
- Construction companies
- Industrial companies

Competences

Feasibility Studies → **Project Development** → **Implementation** → **Operation & Maintenance**

Consulting studies

Project management, Contractor supervision

Expert services

Basic design, Design review

Engineering management, Supervision and Design review

Detail engineering

ÅF in the market

We rank #1 pure engineering company in the world

- 10th largest international design firm in power
- The largest international independent power engineering company

Some top clients around the world

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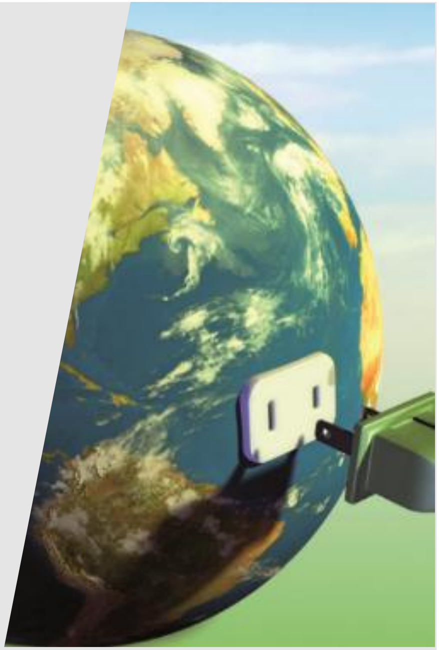
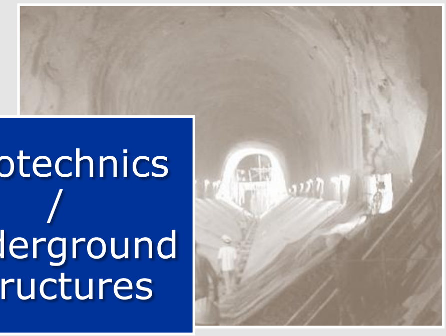


Hydro Power

Competences and services

Hydropower Plants

Dams / Reservoirs



Geotechnics / Underground Structures

Mechanical & Electrical Equipment

Hydraulic Steel Structures

Environment /Social Impact Assessment

Hydro Power

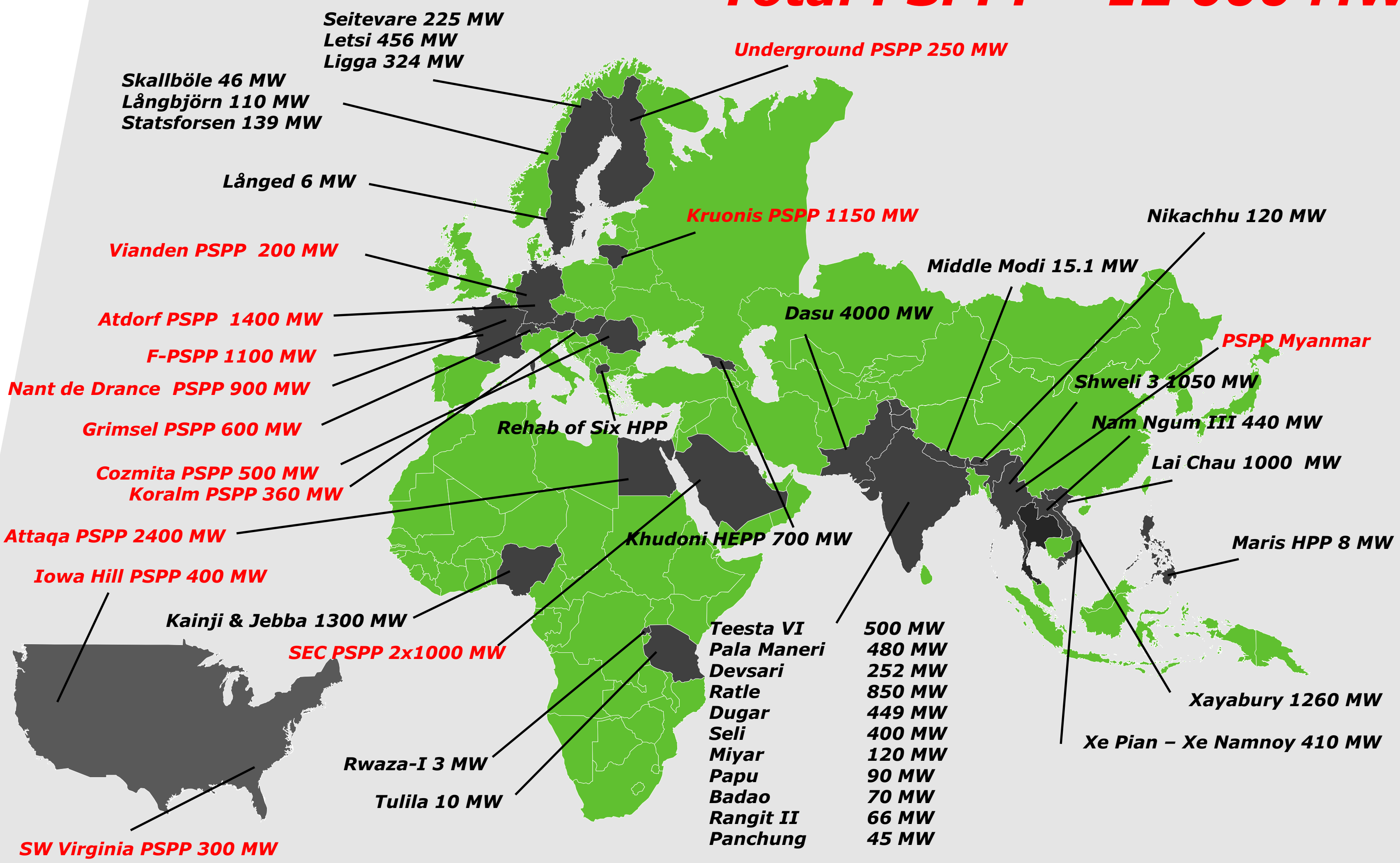
Our service portfolio

- *Expertise and experience, gained **over more than 100 years***
- *Planning, design and construction management of hydro-electric power and multipurpose projects, including studies to enhance optimum compatibility with the environment and the fulfilment of increasing safety requirements.*

Hydro Power

A selection of recent projects – Feasibility / Tender Stage

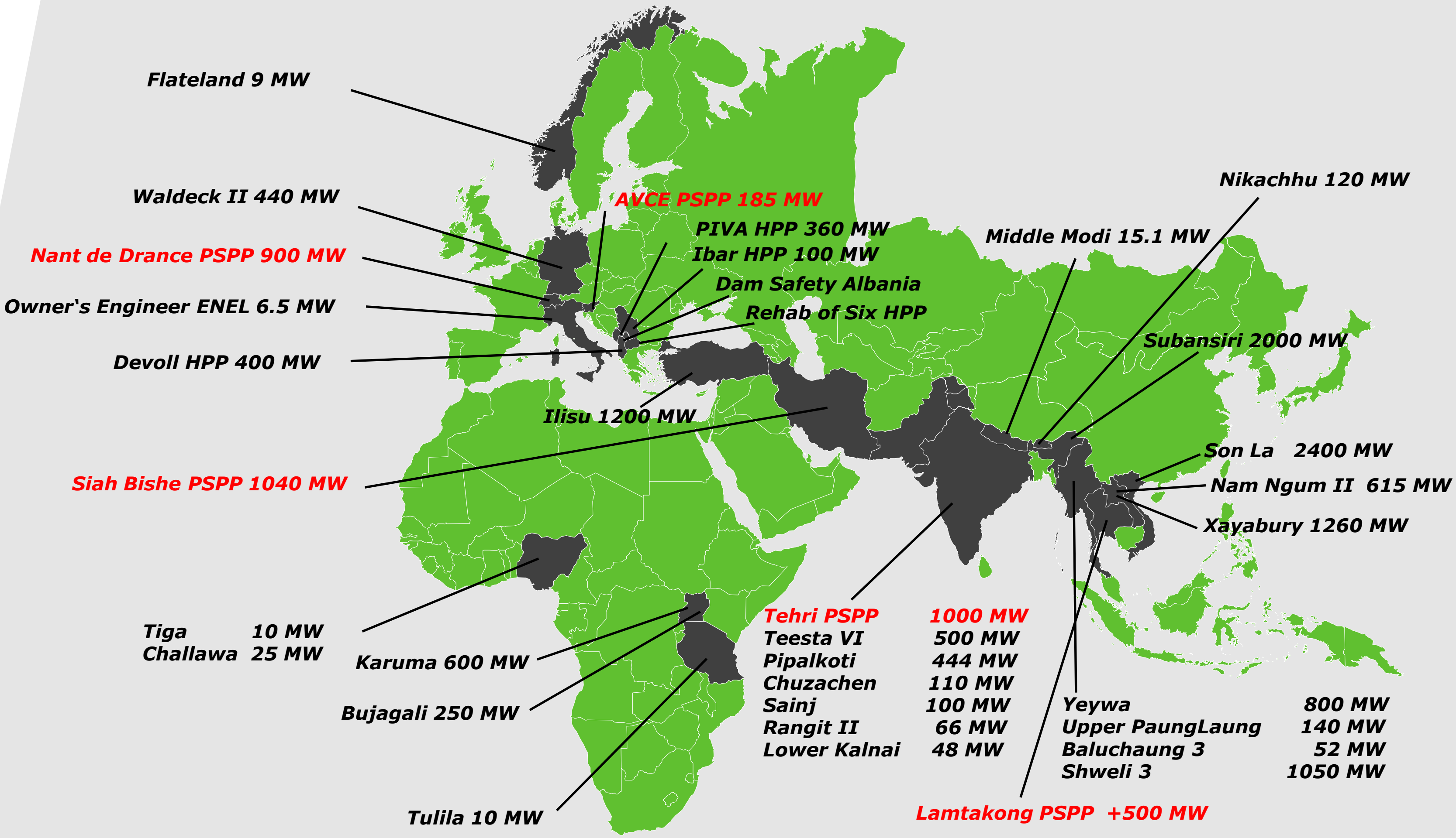
Total PSPP: ~ 12‘000 MW



Hydro Power

A selection of recent projects – Construction / Supervision Stage

Total PSPP: ~ 3'600 MW



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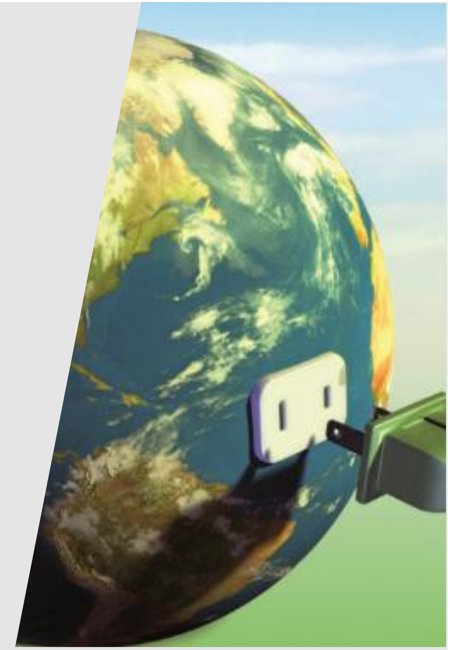
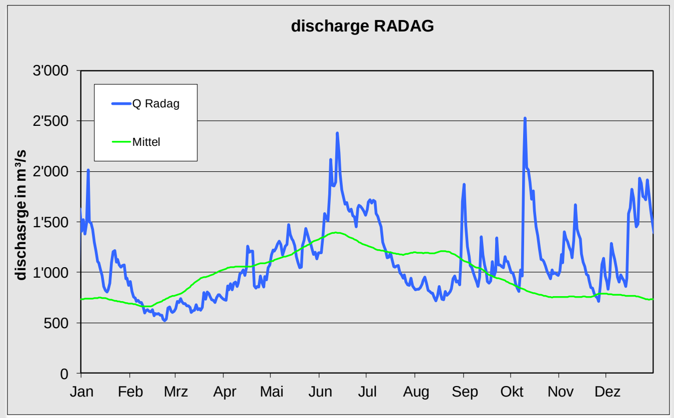


Hydro Power

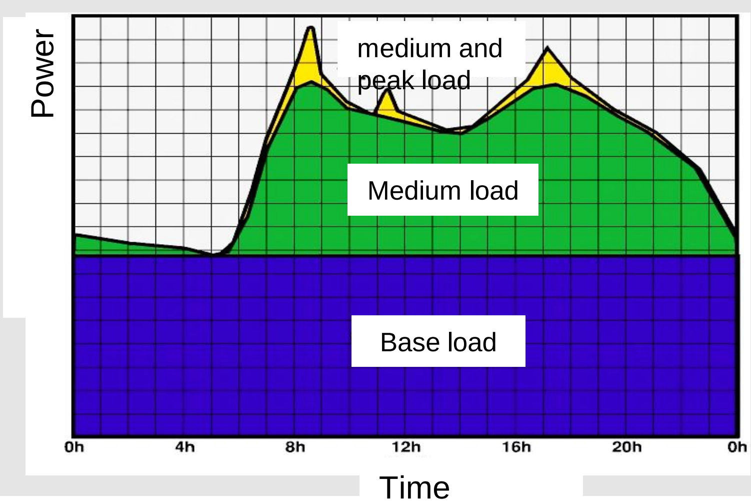
Pumped Storage Power Plants (PSPP)

History of pump storage operation

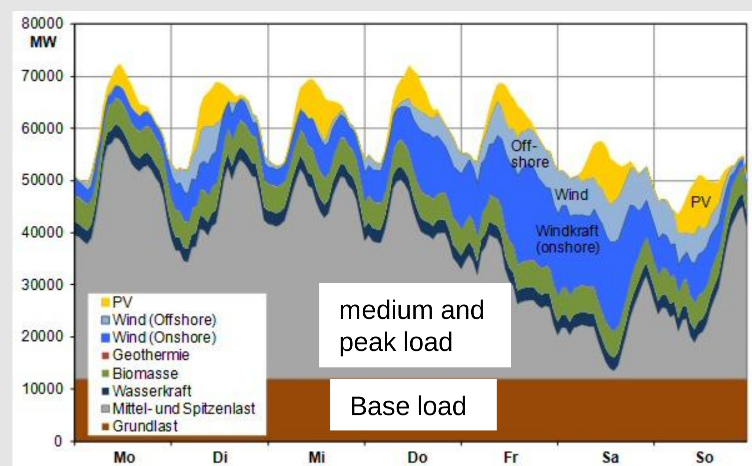


Annual energy storage at a local level

Economic optimization of nuclear power



Storage of renewable energy, security of supply



Hydro Power

Pumped Storage Power Plants (PSPP)

Key Reasons/Benefits for Pumped Storage Power Plants

- Flexibility to storage electricity of renewable/nuclear energy
- Compensation of volatility of renewable energy and improvement of operation of thermal power production (optimization of conventional must-run capacities); Reduction of part of fossil dependence.
- The volatility of prices and the average price of electricity will be stabilized.
- The electricity system is stabilized overall.
- Security of supply and quality of supply for industrial and private customers are ensured even with a high expansion of renewable energies
- Grid services: load balancing, Black start and isolated grid operation, Regulation energy, Ancillary services
- PSPP: mature technology, very flexible, fast acting, high performance, limited impact on environment, long operation life

Hydro Power

Our services and experience in Pumped Storage Power Plants (PSPP)

- **Potential Studies**
  - Example of Myanmar PSPP
- **Concept/Feasibility Studies**
  - Recent projects
  - Magna and Baysh PSPP, Saudi-Arabia
- **Design and Construction**
  - Recent Projects
  - Specific solutions for civil and EM

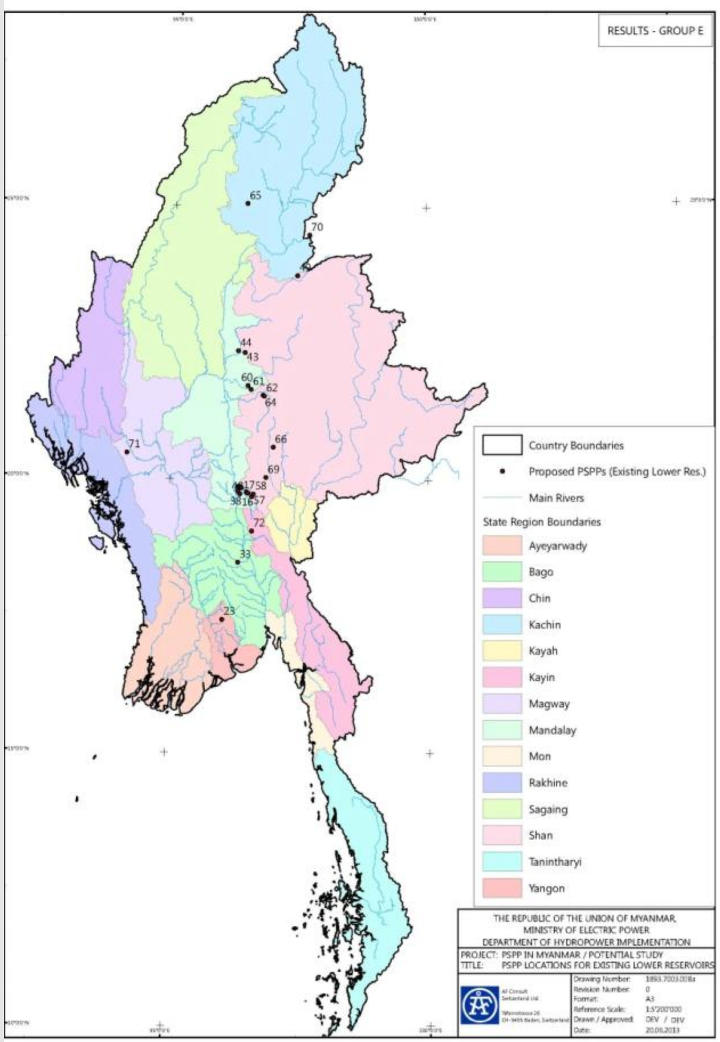
PSPP, Myanmar

- 2013

ÅF`s role

Evaluate a list of potential locations for PSPP in Myanmar in order to:

- regulate power demand
- flatten out load variations on the power grid
- Allow an energy management by helping:
  - the electricity network stability,
  - providing reserve energy and
  - responding to sudden changes



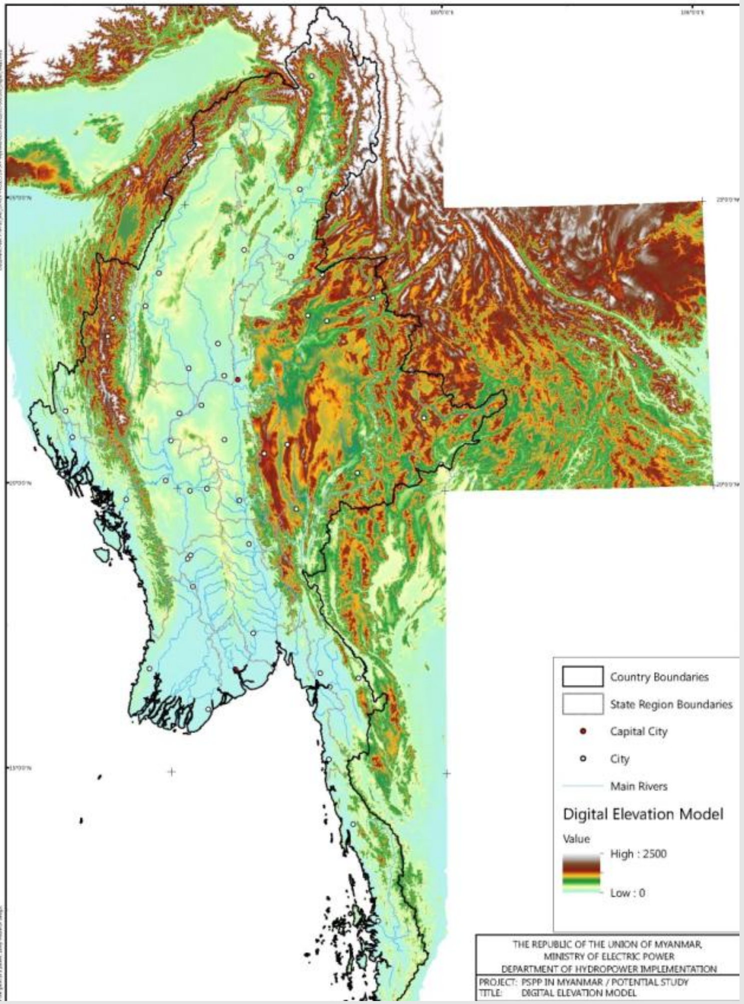
PSPP, Myanmar

Methodology and Basic Data

- Based on the application of Geographic Information Systems (GIS), guided by pre-defined criteria according to the needs of the Study.
- Undertaken a ranking analysis, based on investment cost, installed capacity and distance to power demand centres within Myanmar.

Myanmar Base Map ←

1. DEM
2. Rivers
3. Contour Lines
4. Regions



PSPP, Myanmar

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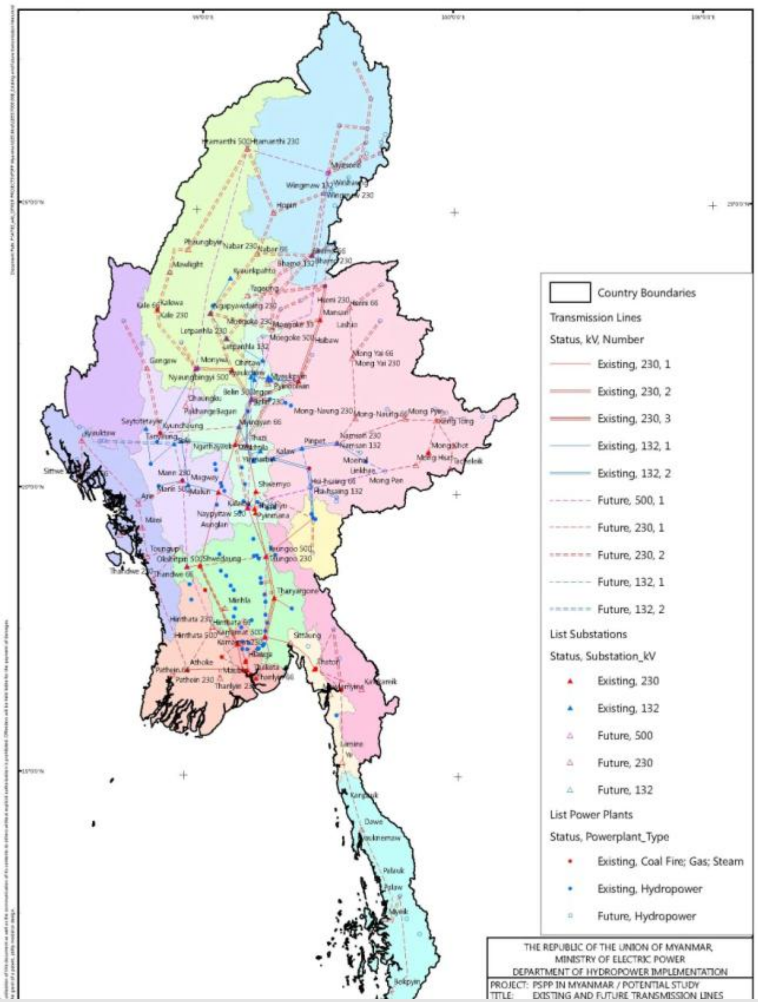
Myanmar Base Map ← 1. DEM 2. Rivers 3. Contour Lines 4. Regions

↓

Power Infrastructure ← 1. Existing and Future HPP 2. Existing and Future transmision lines. 3. Existing and Future substations



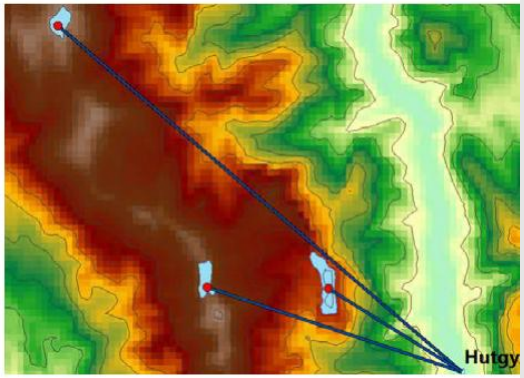
PSPP, Myanmar

Methodology and Basic Data

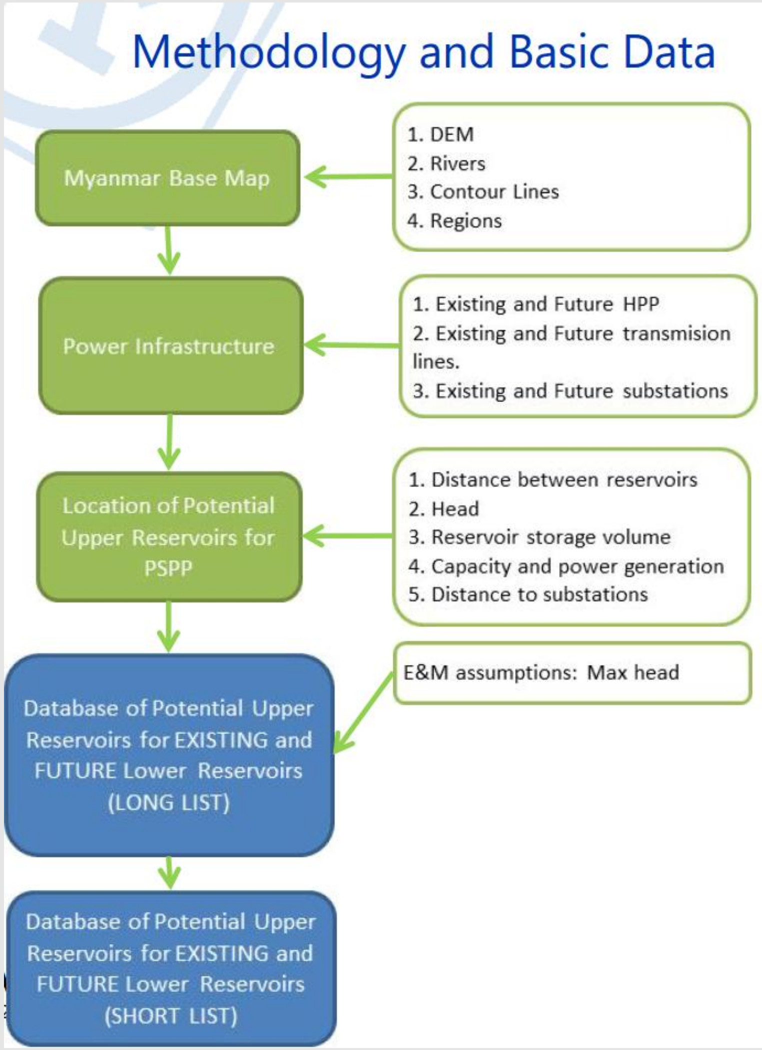
1. DEM 2. Rivers 3. Contour Lines 4. Regions	Myanmar Base Map
1. Existing and Future HPP 2. Existing and Future transmision lines. 3. Existing and Future substations	Power Infrastructure
1. Distance between reservoirs 2. Head 3. Reservoir storage volume 4. Capacity and power generation 5. Distance to substations	Location of Potential Upper Reservoirs for PSPP

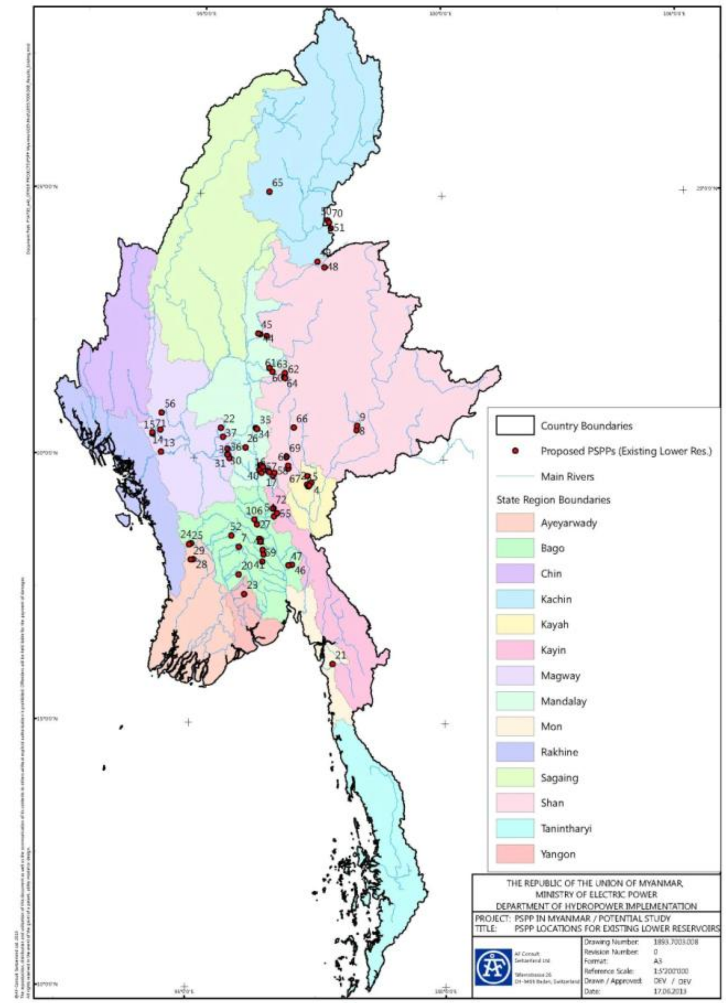
- L < 10km
- H >200m
- V >1.5hm³ daily operation – 7h turbinning / 9h pumping
- Height of the upper res.= 25m.
- Limiting reservoir: Upper one

:-Colenco

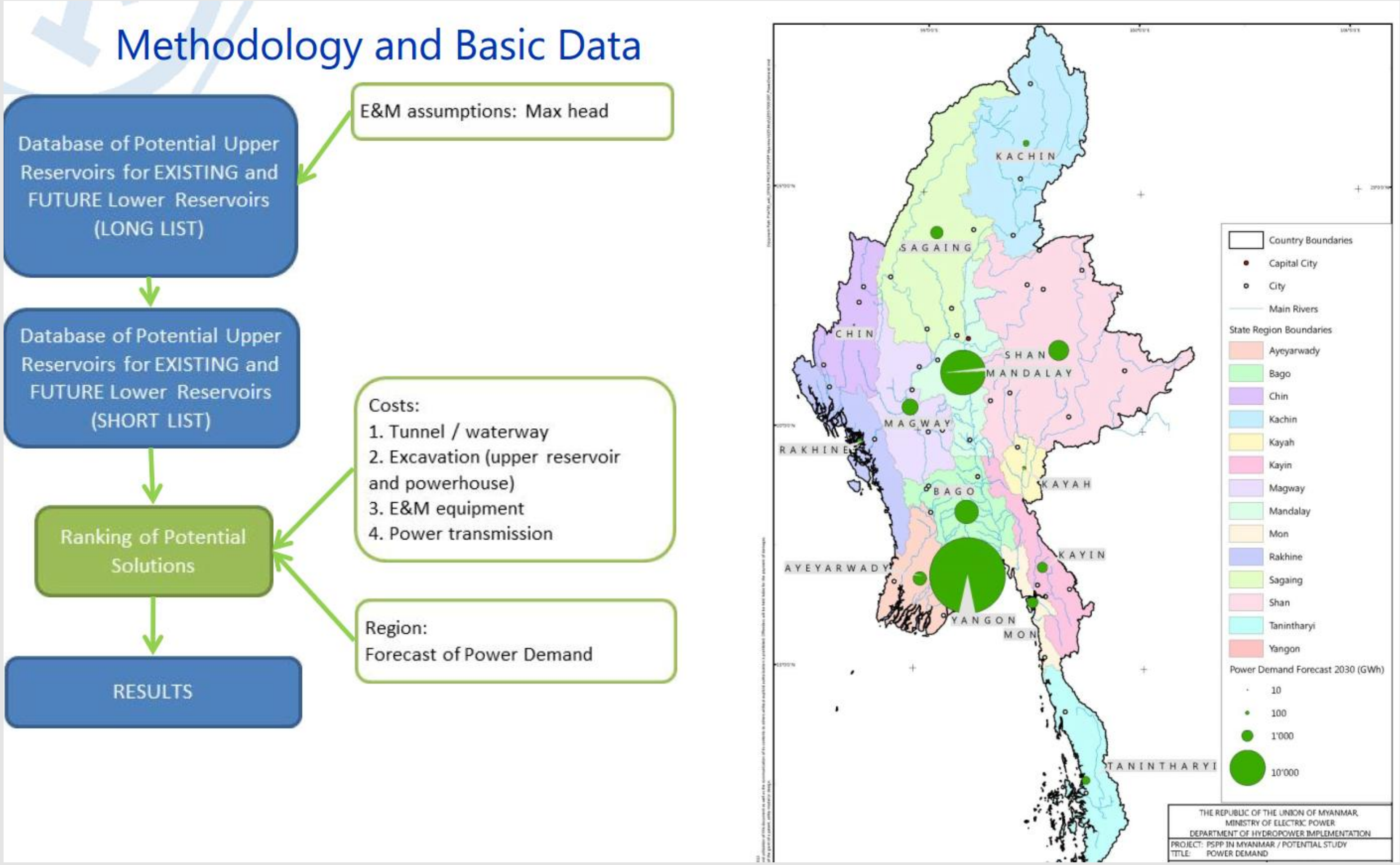


PSPP, Myanmar





PSPP, Myanmar



PSPP, Myanmar

Summary and Conclusions

- List of potential PSPP sites were identified based on current available knowledge (topography, river network, existing and future power infrastructure , regional forecasted power demand, and economic viability).
- Results of the Study present the best PSPP locations, ranked separately according to their economic viability (Euro/MW) and according to regional power demand (location of the project).
- Geographic Information System (GIS) technology was used to develop spatial and interactive electronic maps for Myanmar.

Hydro Power

Our services and experience in Pumped Storage Power Plants (PSPP)

- **Potential Studies**
  - Example of Myanmar PSPP
- **Concept/Feasibility Studies**
  - Key services
  - Example: Magna and Baysh PSPP, Saudi-Arabia
- **Design and Construction**
  - References
  - Specific solutions for Civil and EM

Hydro Power

A selection of recent projects – Feasibility / Tender Stage

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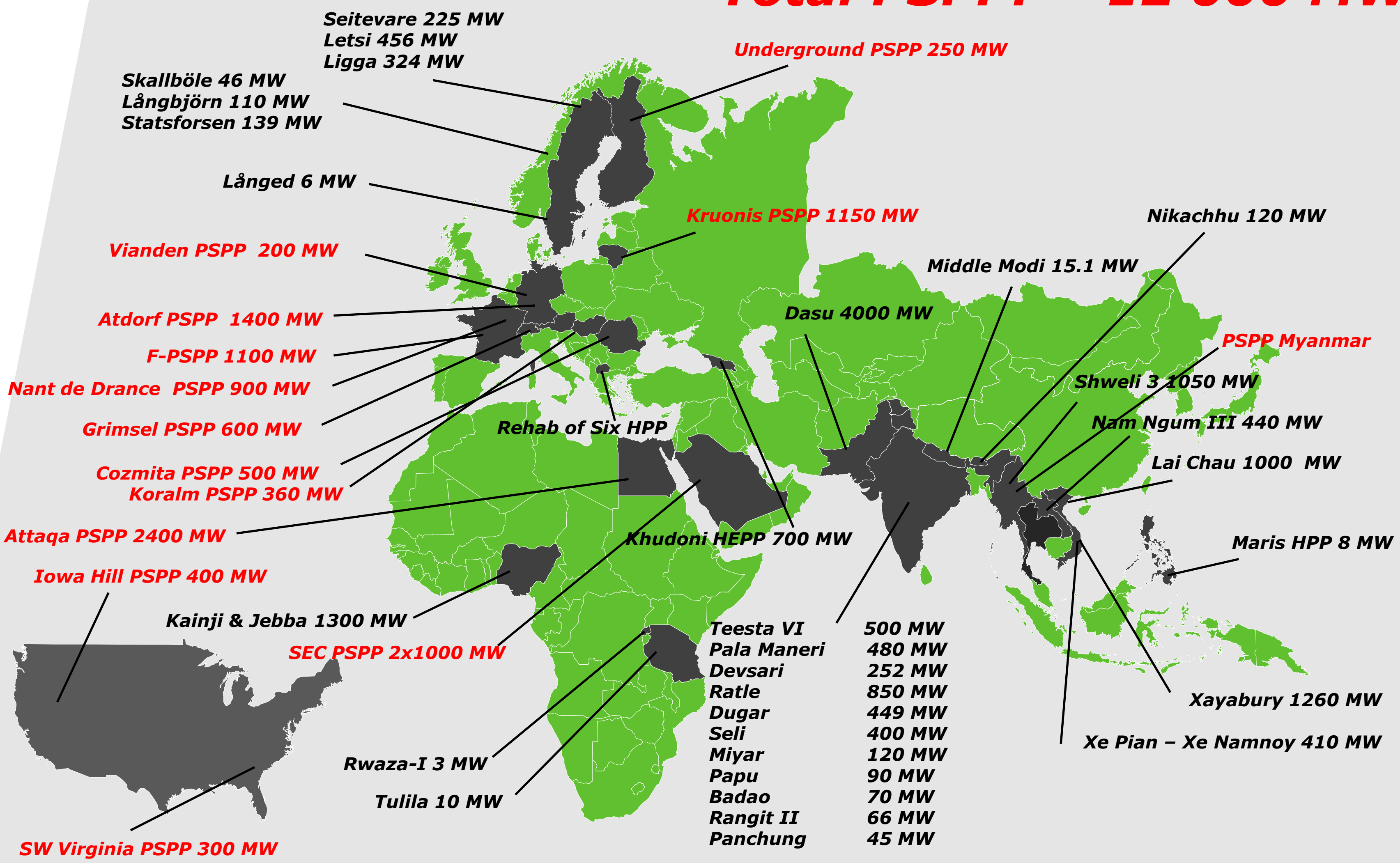
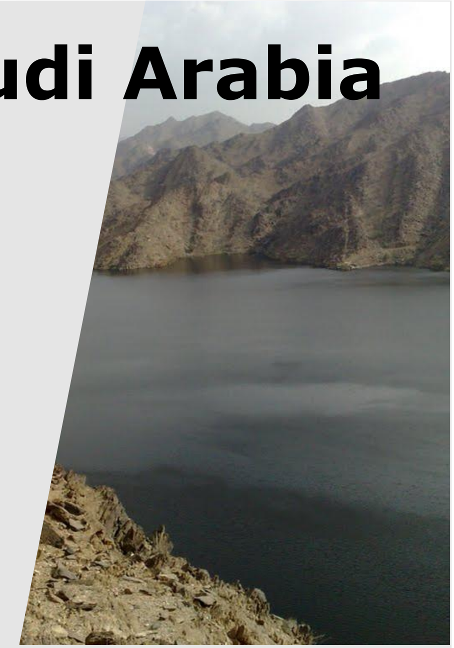


Magna and Baysh PSPP, Saudi Arabia

- 2016 – 2018
- 2 x 1000 MW

ÅF`s role

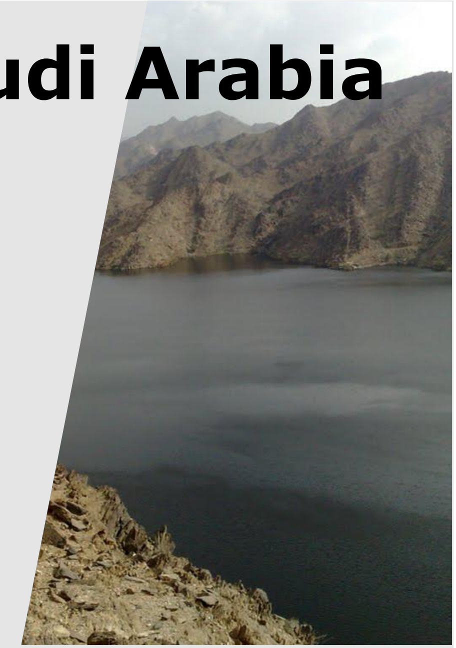
- Concept Design/Feasibility Study, Tender Documents and Financial Feasibility for two PSPP’s
- Alternative Studies
- Environmental & Social Impact Assessment
- TOR for Site Investigation Works
- Support during EPC Bidding



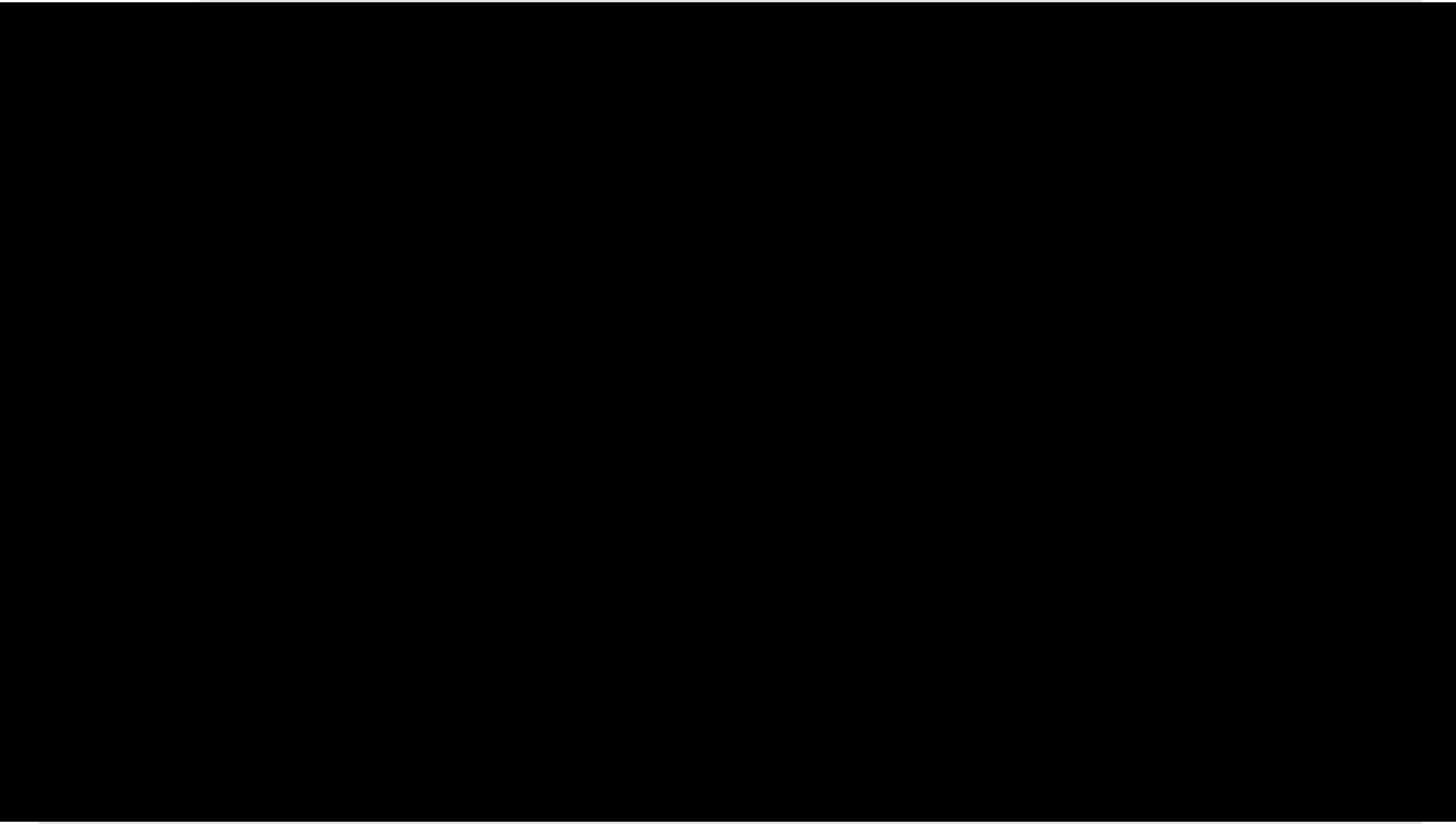
Magna and Baysh PSPP, Saudi Arabia

Key Characteristics:

- Two 1000 MW schemes, located in the South close to Yemen (Baysh PSPP) and in the North at the Red Sea (Gulf of Aqaba, Magna PSPP)
- Magna PSPP in combination with a Desalination Plant to be fed via Red Sea
- Baysh PSPP in combination with an existing flood-regulation reservoir (Baysh Reservoir)
- Design Heads: 520 - 720 m
- Rated Unit Capacity 250 MW
- Number of Unit: 4 with total Capacity of 1000 MW
- Type of Machine: Reversible Pump Turbines, multi-stage Pump



Magna and Baysh PSPP, Saudi Arabia



Hydro Power

Our services and experience in pump storage power plants (PSPP) for FS Phase

(1) Civil design aspects

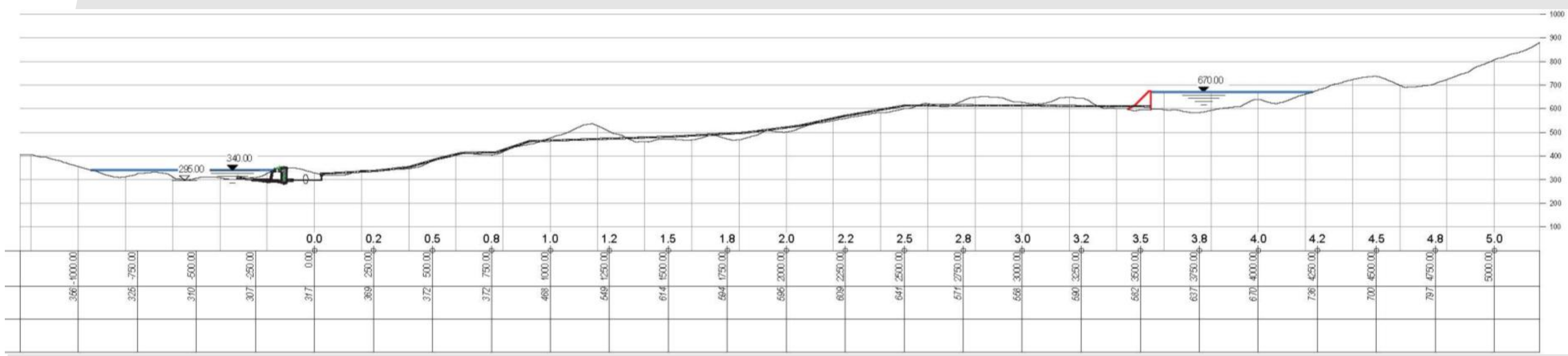
- Underground versus surface layout
- Project Optimization

(2) Electromechancial design aspects

- Grid Requirements
- Black Start Ability/Auxilliary Power Supply
- Electromechanical Equipment
- Transient Study

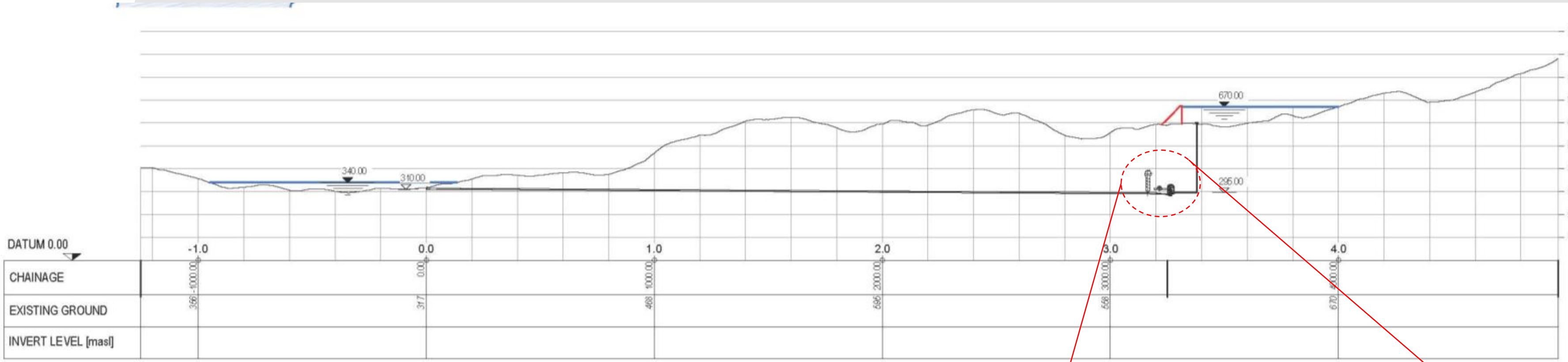
Magna and Baysh PSPP, Saudi Arabia

Civil Design – Underground vs. Surface Layout

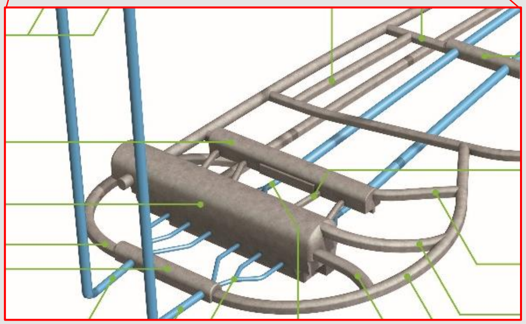


Magna and Baysh PSPP, Saudi Arabia

Civil Design – Underground vs. Surface Layout

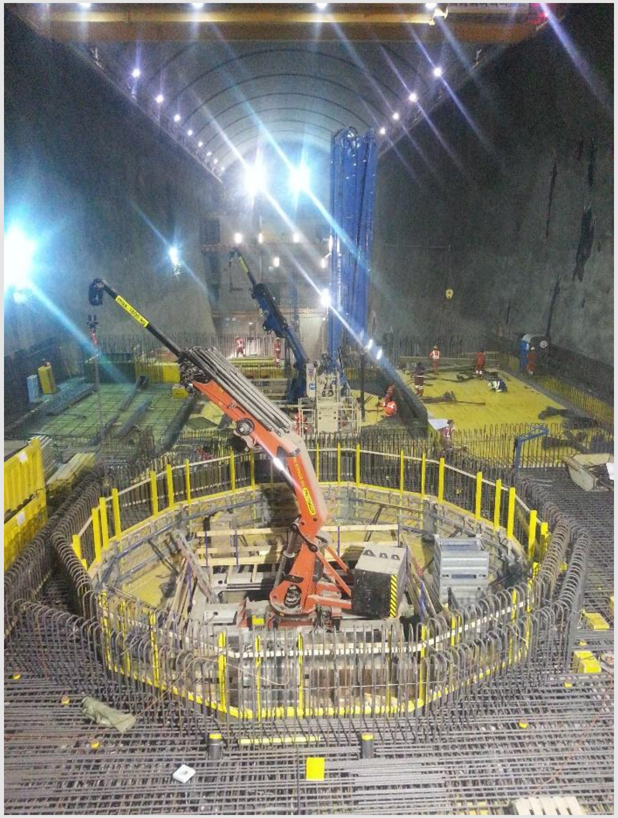


- PH Cavern Length for 4 x 250 MW: ~120 m
- Transformer Cavern required (to be < 100 m [Losses, Costs])
- Access Gallery around 3 km length required



Magna and Baysh PSPP, Saudi Arabia

Civil Design – Underground vs. Surface Layout



Magna and Baysh PSPP, Saudi Arabia

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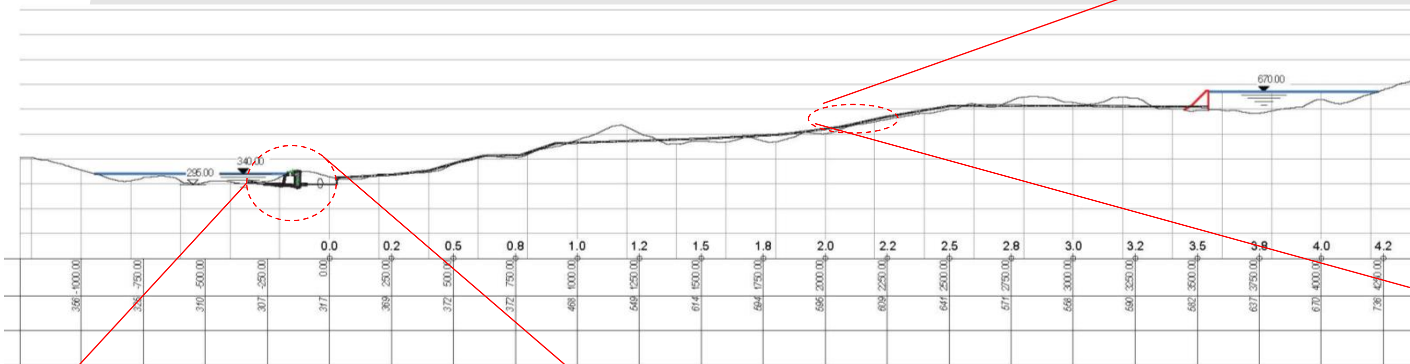
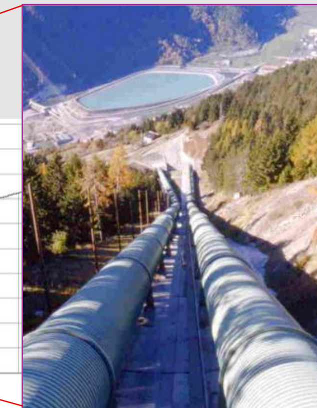
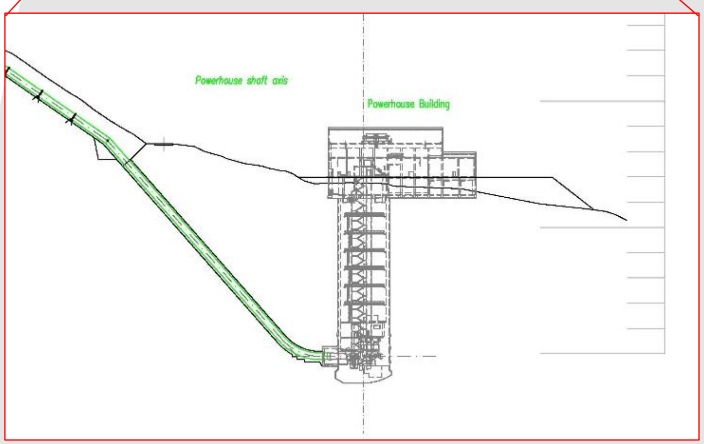






- Two Powerhouse Shafts housing each 2 x 250 MW
- PH Shaft Depth: ~70 m
- 1 PH Superstructure operating for the 2 Shafts
- Transformer located on the surface adjacent to superstructure
- Two surface, steel lined penstocks, dia ~ 6m

Avce PSPP, Slovenia

- 2003 – 2011
- 180 MW

ÅF`s role

- Review of the basic design
- Scheme optimization
- Final design, technical specifications
- Detailed design of the civil works
- Technical support during the civil construction
- Assistance during commissioning

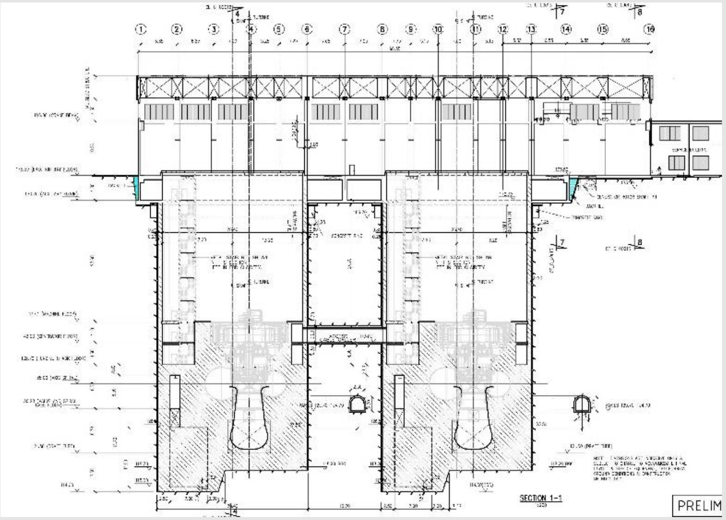
Avce PSPP, Slovenia

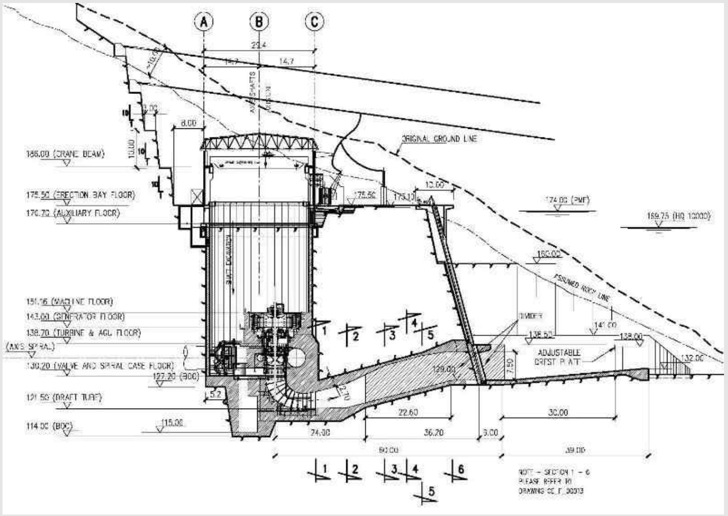
Key Characteristics:

- In operation in 2010
- Upper reservoir: 634 masl
- Upstream reservoir capacity: 2.2 Mio. m3
- Net Head: 630
- Number of Unit: 1 with Capacity of 180 MW
- Type of Machine: Asynchronous
- Rated flow per unit: ~ 35 m3/s

Magna and Baysh PSPP, Saudi Arabia

Civil Design – Underground vs. Surface Layout





Magna and Baysh PSPP, Saudi Arabia

Civil Design – Underground vs. Surface Layout

Underground Layout	Surface Layout
+ Shorter High Pressure Tunnel	+ Access
+ Less Steel lining required	+ Constructability
+ Less critical to earthquakes	+ Power Evacuation
+ Conventional, downstream surge tank required	- Upstream, pressurized surge tank required
- Complexity (and Risk/Costs) of Underground Construction	- Safety against earthquakes
- Access to Underground Works	- Length of High Pressure Waterways, Steel Lining
- Power Evacuation	- Maintenance, Operation Costs (Surgetank, Penstock)

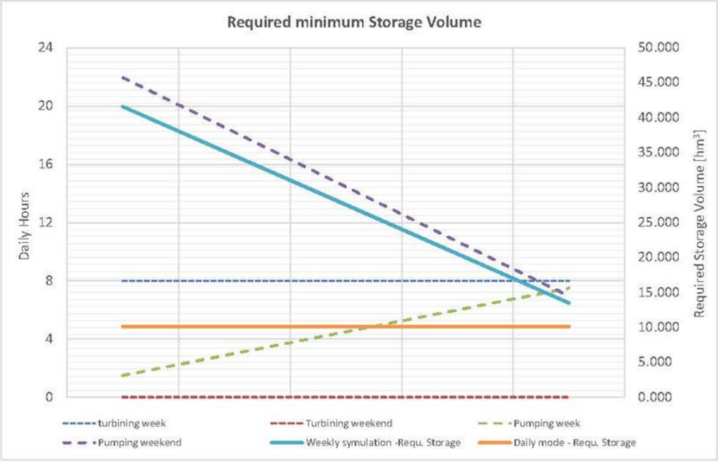
Magna and Baysh PSPP, Saudi Arabia

Civil Design – Considerations on Project Optimizations

Key Characteristics

- Design charge
- Required life storage

	Time				Required Life Storage		Required Life Storage	
	Week		Weekend					
	Turbining	Pumping	Turbining	Pumping	Weekly	Daily	Weekly	Daily
I	8.0	1.5	0.0	22.0	41.086	9.621	41.575	10.110
II	8.0	3.0	0.0	18.2	34.067	9.621	34.556	10.110
III	8.0	4.5	0.0	14.5	27.048	9.621	27.537	10.110
IV	8.0	6.0	0.0	10.7	20.029	9.621	20.518	10.110
V	8.0	7.5	0.0	7.0	13.010	9.621	13.499	10.110



Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Grid requirements

- Grid frequency xx Hz ?
- Power capacity factor (cos phi)?
- Black start and isolated grid operation?
- Regulation energy?
- Active and reactive power requirements?
- Ancillary services?

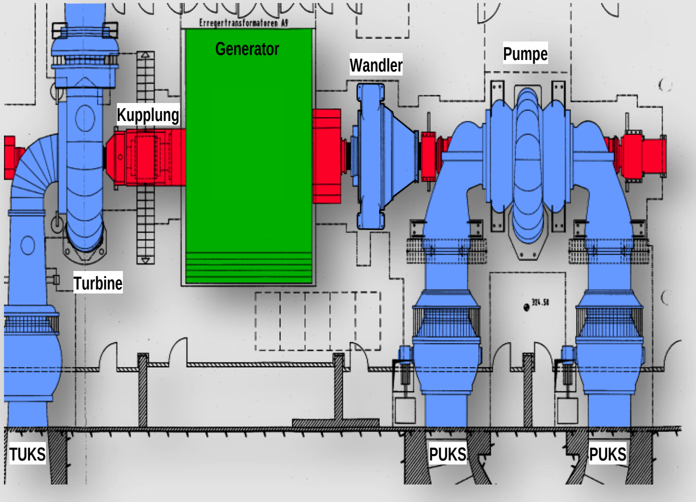
➢ **Unit type (ternary machine, single stage pump turbine, etc.)**

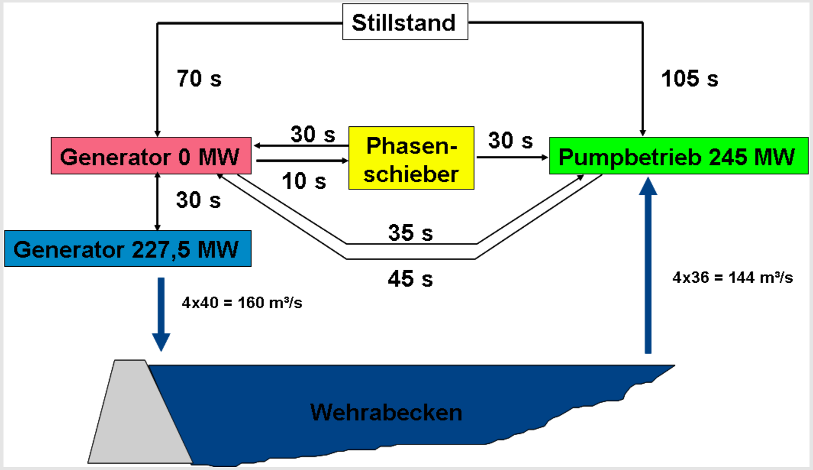
Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Electromechanical Equipment

Horizontal Ternary Layout





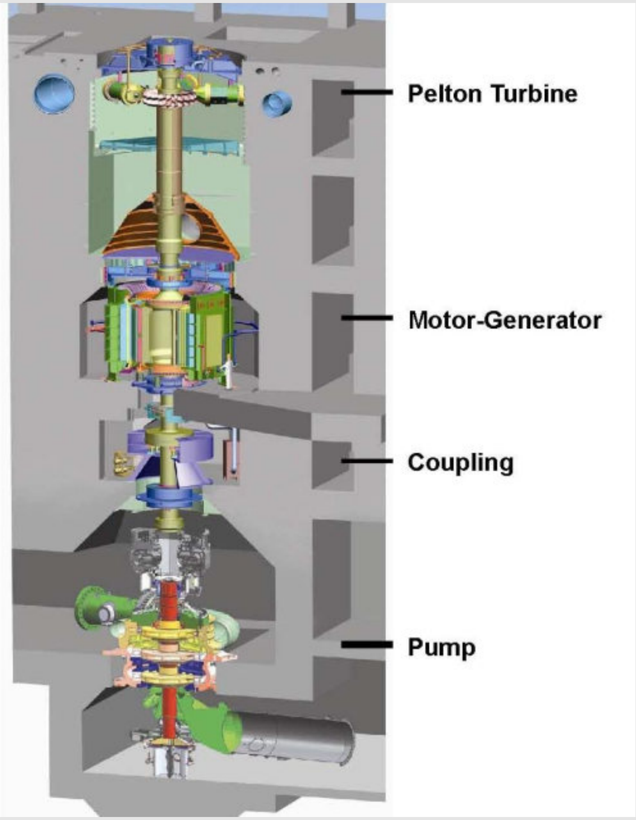
Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Ternary Machine Set: Basics

- **Advantage:**
  - Fast mode change
    Turbine ←→ Pump
  - Start to pump mode in water
  - Optimized Turbine- and Pump efficiency
  - Possibility of direct hydraulic short circuit
    (Regulating energy)

- **Disadvantage:**
  - Increased Investment
  - Additional space requirement
  - Additional valves



Source: Andritz Workshop Vienna, 2012

Magna and Baysh PSPP, Saudi Arabia

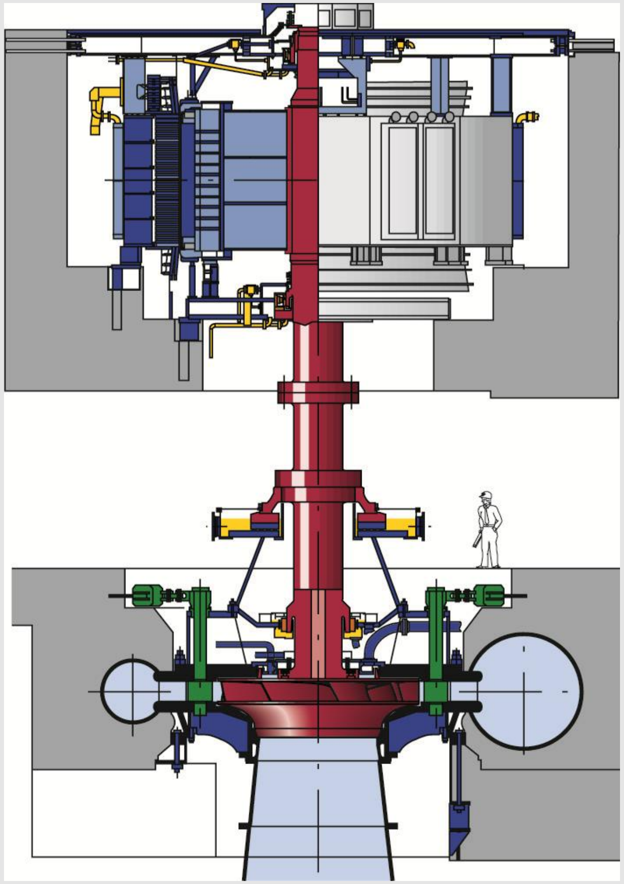
Electromechanical Aspects

Goldisthal/Germany: reversible pump turbine

		(synchron)	(asynchron)
Number of units	[-]	2	2
runner diameter	[m]	4.59	4.59
nominal speed	[rpm]	333	300-346
max. turbine output	[MW]	325	300
max. pump power	[MW]	262	291
max pump head	[m]	338	339

variation of pump power > 100MW

Source: Vattenfall, Voith Hydro

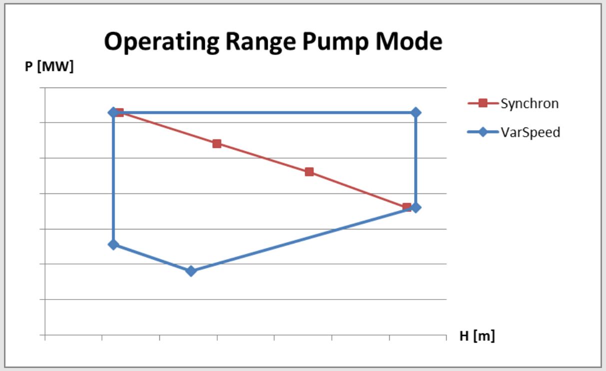


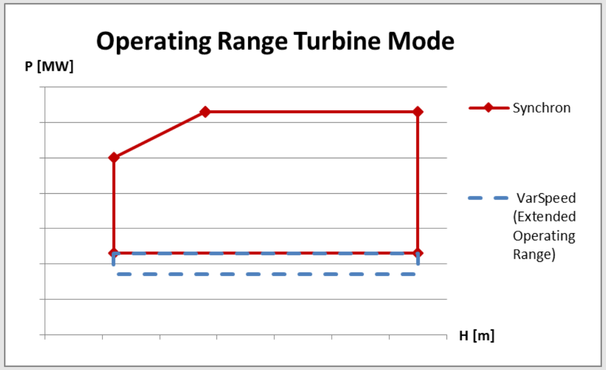
Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Advantages of Vario Speed machines

- Performance regulation in pump mode
- Improved turbine efficiency at part load operation
- Bigger operating ranges in pump and turbine mode
- Ancillary services (better active and reactive power regulation)





Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Comparison of Vario Speed machines

Synchronous machine with full size converter

- Relatively new converter technology
- Two suppliers for converters
- Smaller machine dimensions / bigger converter dimensions
- Smaller operating costs
- More cooling needed
- Approx. > 1% losses (based on converter power i.e. generator power)
- No phase reversal switches needed

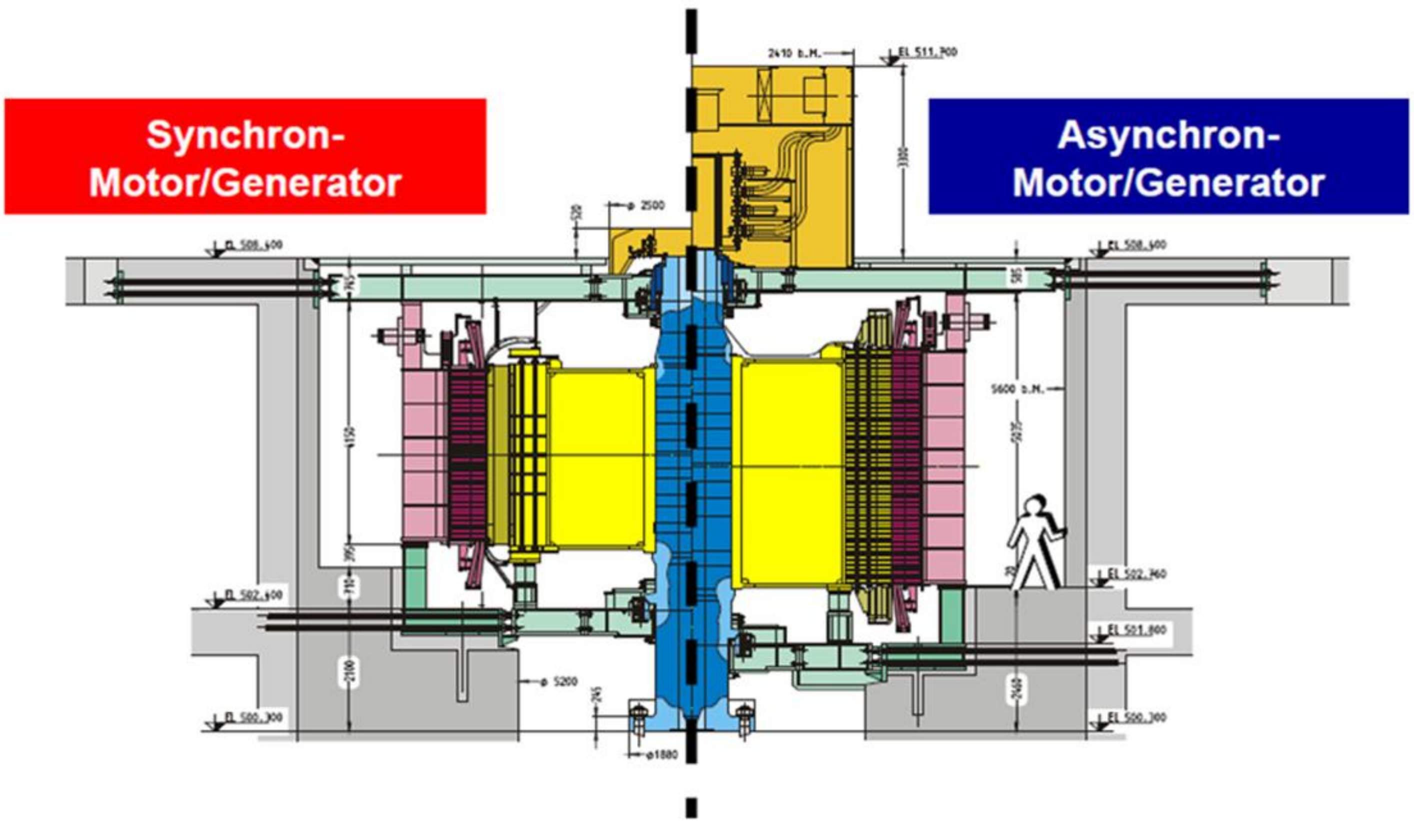
Double-fed asynchronous machine

- Known technology
- Few suppliers
- Bigger machine dimensions / smaller converter dimensions
- Higher maintenance costs (Slip rings)
- Need less cooling
- 3% losses (based on converter power i.e. converter power approx. 24 MVA)

Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

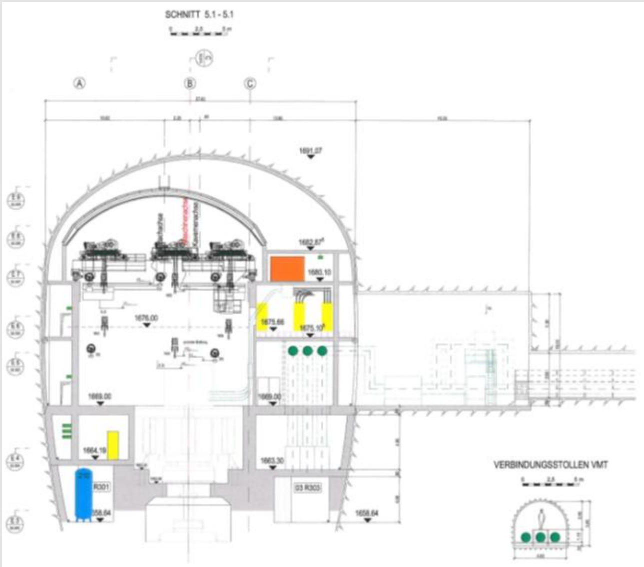
Comparison of machine dimensions

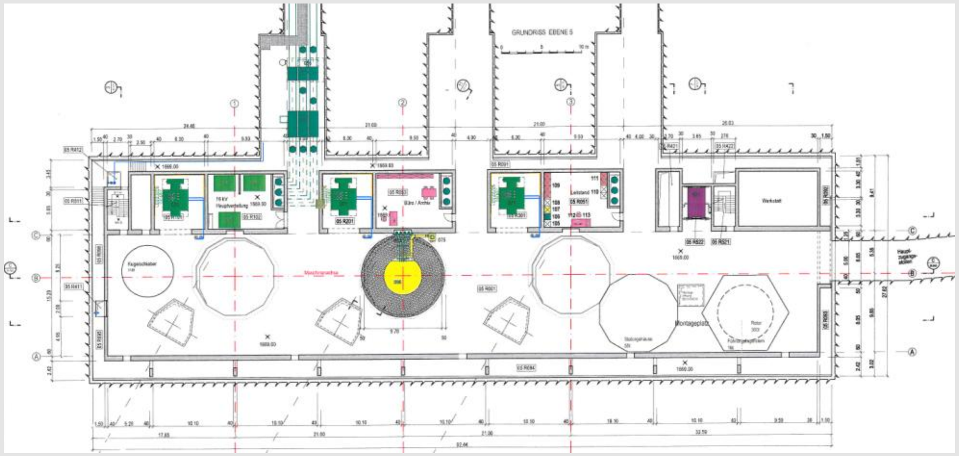


Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Arrangement for Vario Speed with 24 MVA Converter (Asynchron Machine)

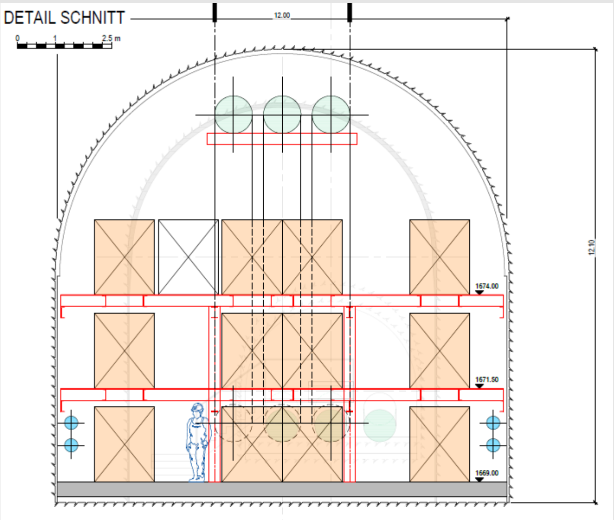


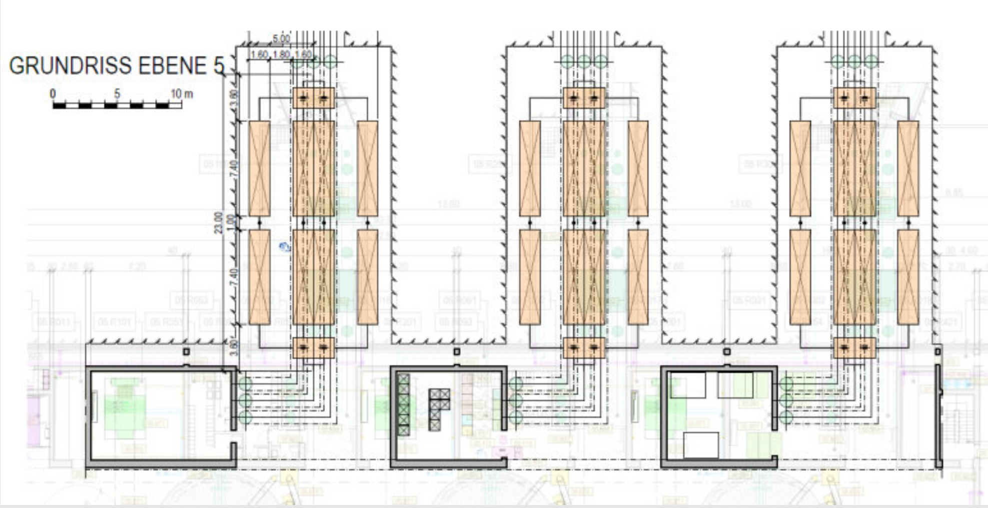


Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Arrangement with Full Size Converter (Synchron Machine) for 230 MVA Units



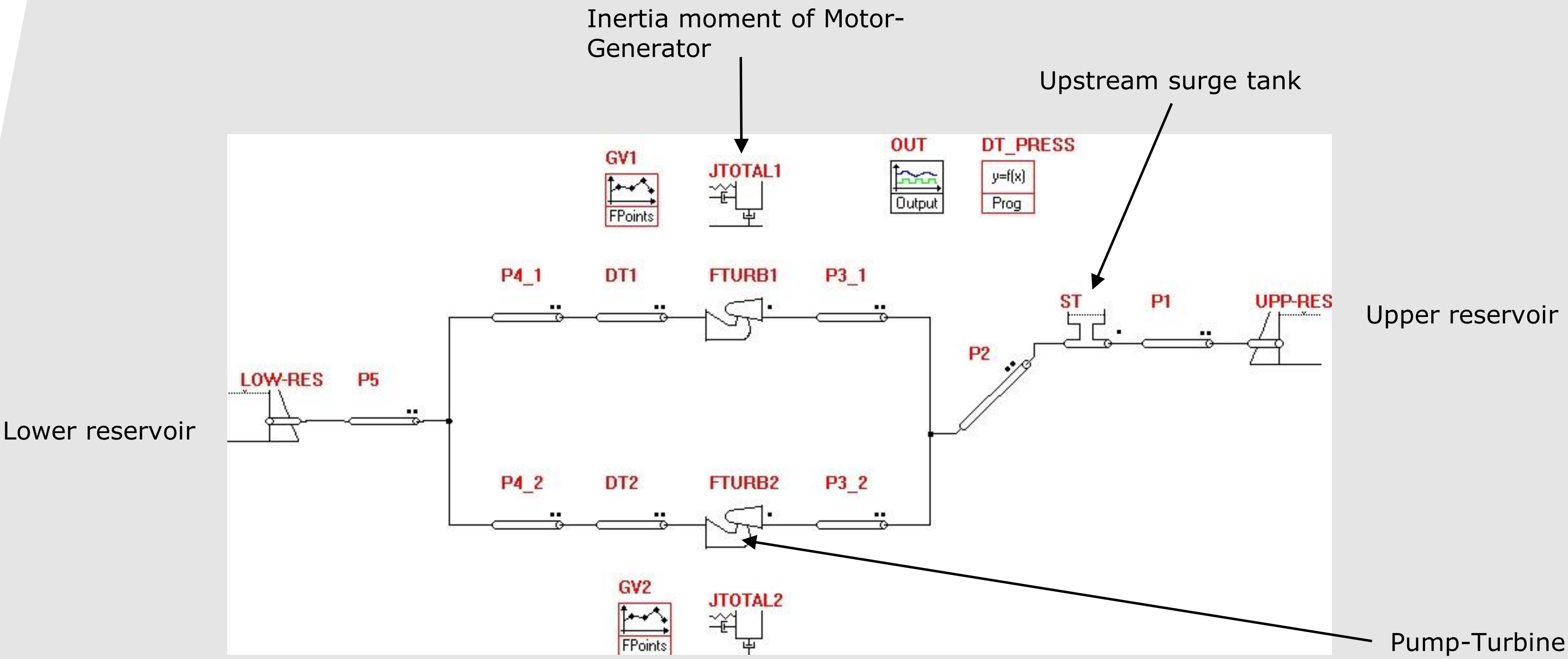


Magna and Baysh PSPP, Saudi Arabia

Electromechanical Aspects

Modeling of Layout (Transient Study with Simsen-Hydro-Software)**:**

- Spiral case pressure
- Need/Dimension of Surge tank/Surge tank water oscillation
- Draft tube cone pressure/level of units (submergence)



Hydro Power

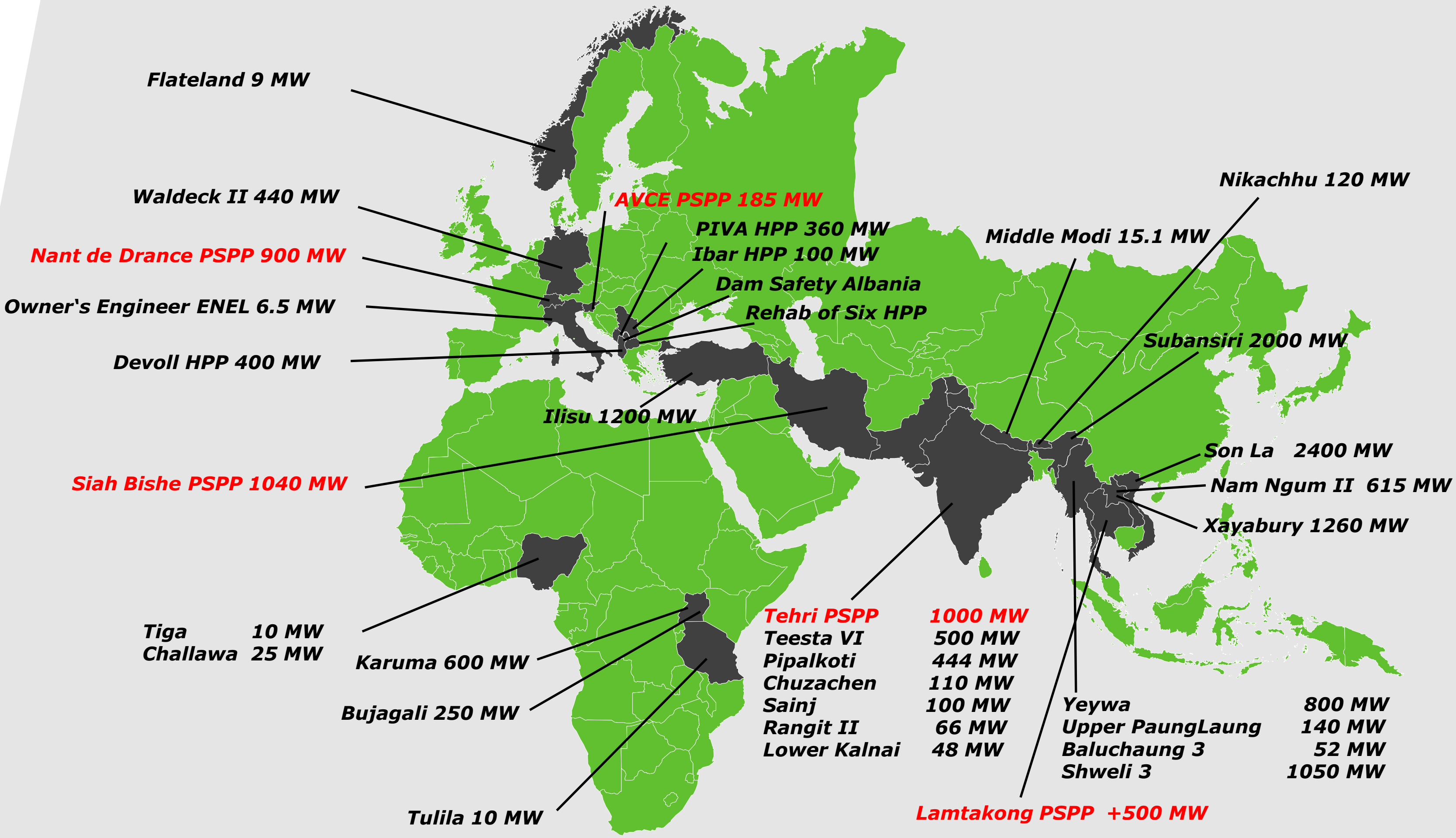
Our services and experience in Pumped Storage Power Plants (PSPP)

- **Potential Studies**
  - Example of Myanmar PSPP
- **Concept/Feasibility Studies**
  - Recent Projects
  - Example: Magna and Baysh PSPP, Saudi-Arabia
- **Design and Construction**
  - Recent Projects
  - Specific solutions for PH (BIM), intakes

Hydro Power

A selection of recent projects – Construction / Supervision Stage

Total PSPP: ~ 3‘600 MW



Siah-Bishe PSPP, Iran

- 2003 – 2009
- 1’040 MW

ÅF`s role

- Tendering and Contracting Services
- Project Management/Design Review
- Management Control
- Design Review/Approval
- Transfer of Technology
- Construction Management Support

Siah-Bishe PSPP, Iran

Key Characteristics:

- Upper Dam
  - CFRD
  - Height 85 m
  - Crest El. 2’410 m a s l
  - Dam volume 1.4 Mio. m3
  - Reservoir volume 3.5 Mio. m3
- Lower Dam
  - CFRD
  - Height 106.5 m
  - Crest El. 1’911.5 m a s l
  - Dam volume 4.93 Mio. m3
  - Reservoir volume 3.6 Mio. m3

Siah-Bishe PSPP, Iran

Key Characteristics:

- Headrace tunnel: 2 x Ø 5.7 m; 2’015 m and 1’973 m
- Pressure shaft: 2 x Ø 5.0 m; 760 m
- Max. Gross Head: 520 m
- Number of Unit: 4 with total Capacity of 1’040 MW in underground powerhouse
- Type of Machine: 4 vertical Francis pump-turbine
- Rated flow turbine operation: 260 m3/s
- Rated flow pump operation: 200 m3/s

Tehri PSPP, India

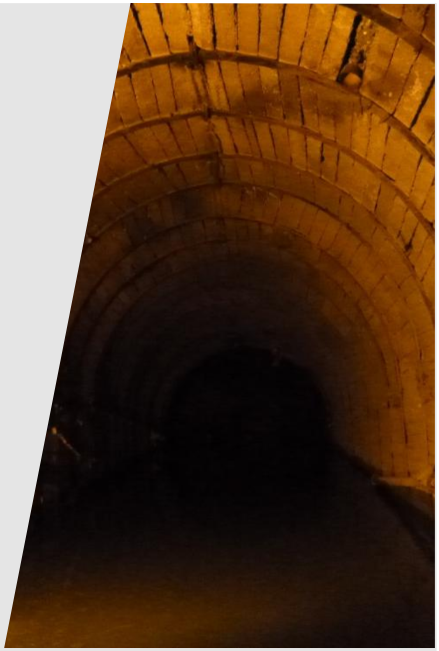
- 2016 – ongoing
- 1000 MW

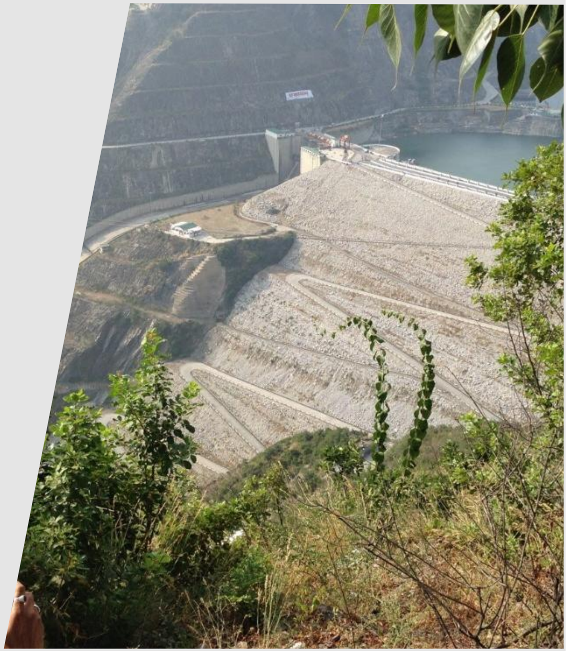
ÅF`s role

- Detailed Design Review and Design Updates for the EPC Contractor

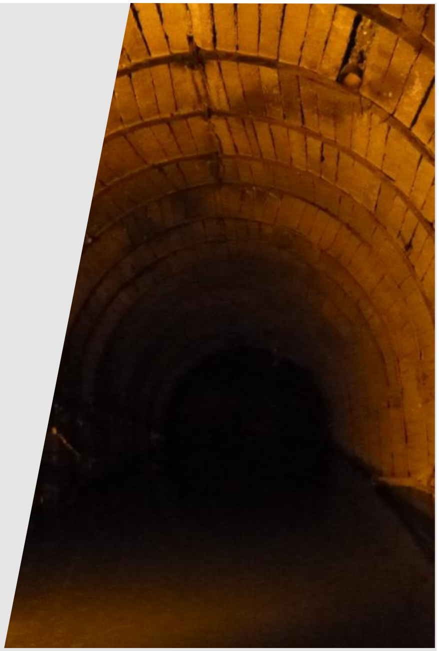
- Preparation Design Updates for
  - Powerhouse & busduct Tunnels
  - BVC and PAC Caverns
  - U/S & D/S Surge Shaft Chambers
  - U/S & D/S Surge Shafts
  - Bus bar Cavern
  - TRT Outfall Structures
  - Lower PAC
  - Ventilation Tunnels
  - Upper and Lower Penstock Tunnel/Shaft

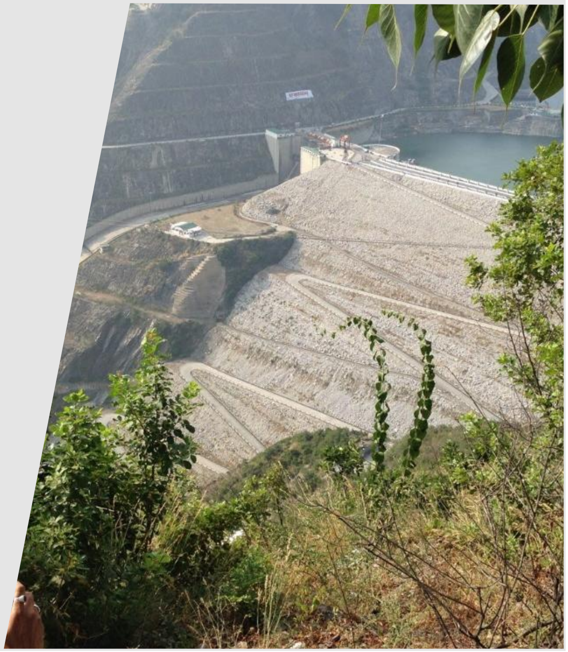
- Preparation of TOR Model Studies
- Update of Geological & Geotechnical Reports & Mappings





Tehri PSPP, India



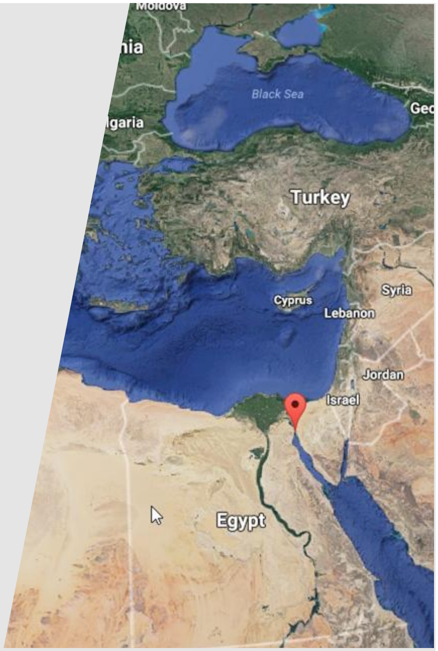


Key Characteristics:

- Entire Scheme Underground, connecting two existing reservoirs
- Transformer Cavern shared with the associated 1000 MW conventional Hydropower Scheme
- Design Head: 188 m
- Rated Unit Capacity 250 MW
- Number of Unit: 4 with total Capacity of 1000 MW
- Type of Machine: Variable Speed, vertical
- Size of Power Cavern (LxWxH): 201 m x 25.4 m x 57.3 m

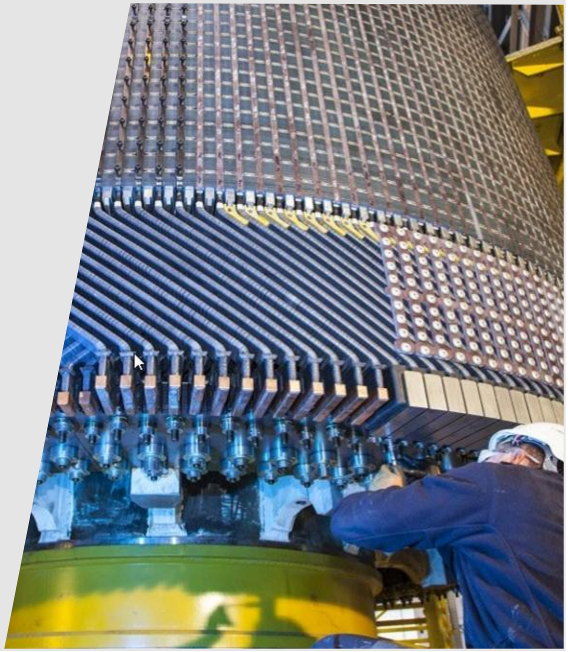
Attaqa PSPP, Egypt

- 2017 – ongoing
- 2’400 MW



ÅF`s role

- Owners Engineer
- Project management including project control of legal and finance of related technical aspects;
- Engineering review of EPC concept and detail design deliverables;
- Quality control, assurance services and supplier surveillance;
- Construction monitoring, supervision and management;
- Commissioning and start-up supervision.



Attaqa PSPP, Egypt

Key Characteristics:

- 6 x 400 MW reversible pump/turbine units for a total capacity of 2,400 MW;

- 600 m of gross head;

- Upper and Lower freshwater reservoirs with dams), each with a live storage volume of 7.3 Mio m³;

- 6 large diameter high pressure penstocks;

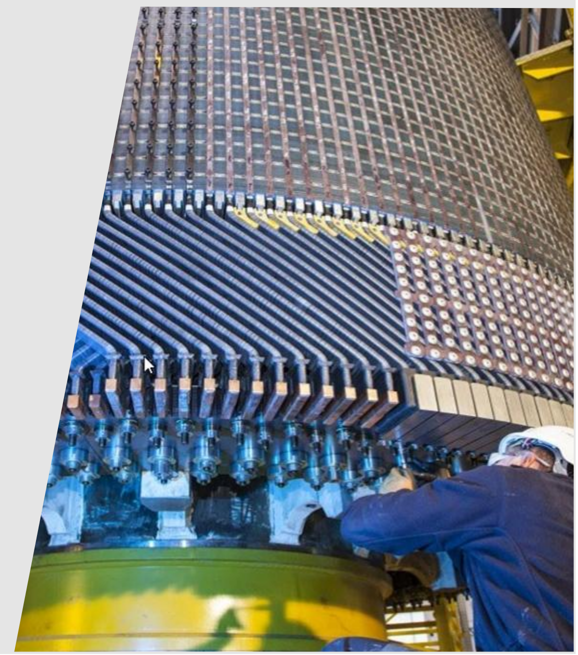
- Underground powerhouse;

- Underground surge chamber(s);

- A high voltage transmission line and substation;

- Upper and Lower intakes/outlet structures

- All associated mechanical equipment including gates, trash racks and valves.

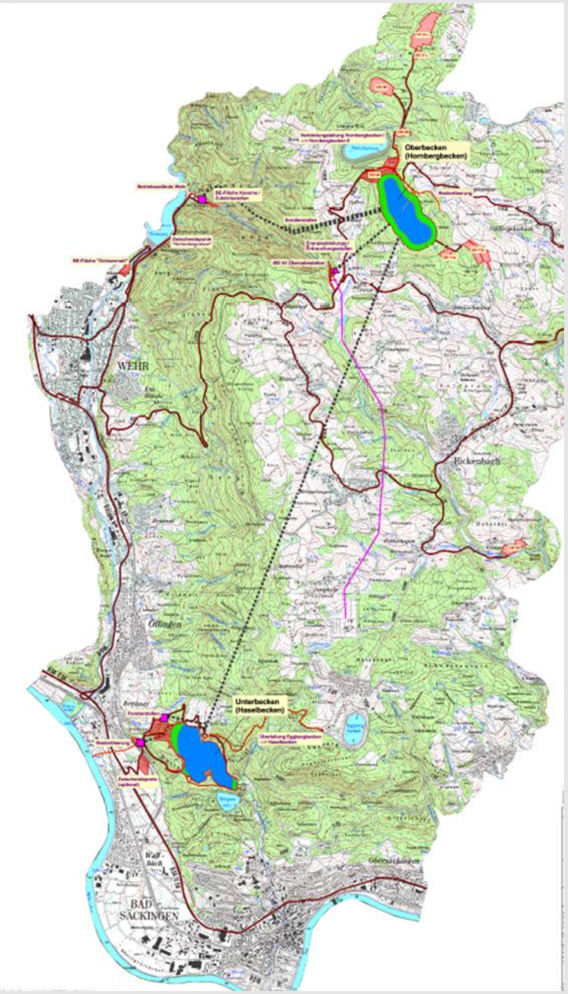


Atdorf PSPP, Germany

- 2011 – 2018
- 1’400 MW

ÅF`s role

- Review of Feasibility and Basic Design
- Basic-, tender- and construction design
- Design review for main equipment
- Site engineering and management
- Site inspection and monitoring
- Shop inspection
- Tests & commissioning



Atdorf PSPP, Germany

Key Characteristics:

- Dams: RCC Main Dam / 2 Retention Dams
- New Cavern
- New artificial Upper Reservoir with 9 Mio m3 Volume
- New artificial Lower Reservoir with 9 Mio m3 Volume
- Net Head: 620 m
- Number of Units: 6 with total Capacity of 1’400 MW
- Type of Machine: Variable Speed Asynchronous

Koralm PSPP, Austria

- 2015 – 2022
- 940 MW (4 x 235 MW)

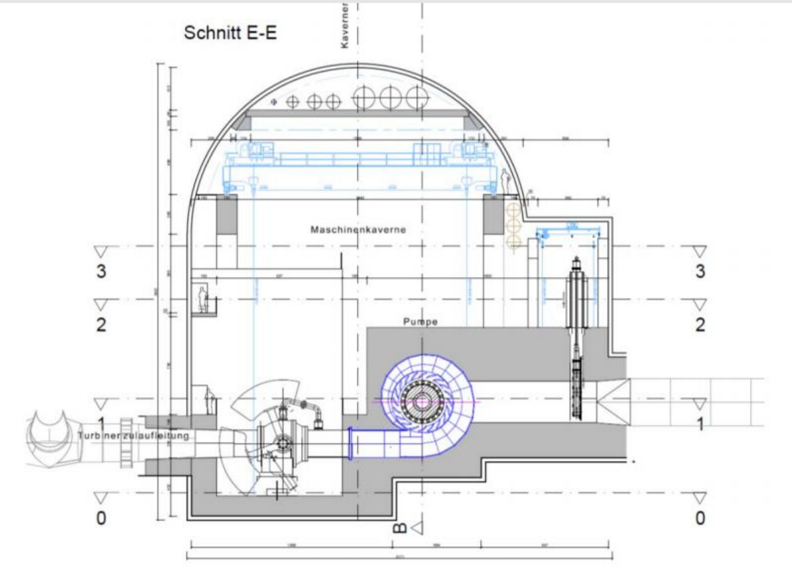
ÅF`s role

- Concept review
- Feasibility study
- Overall project management
- Basic, tender and construction design
- Design review for main equipment
- Site engineering and management
- Site inspection and monitoring
- Tests & commissioning

Koralm PSPP, Austria

Key Characteristics:

- Upper reservoir
  - Capacity: 4.6 Mio. m³
  - Earth fill dam 87 m
  - Crest length 640 m
- Upper tunnel
  - Length 1’100 m, diameter 8.8 m
- Vertical shaft
  - Length 650 m, diameter 5.4 m
- Cavern powerhouse
- Type of Machine: 4 Ternary machine sets à 235 MW
- Lower tunnel
  - Length 3’900 m, diameter 7.0 m
- Lower reservoir
  - Capacity: 4.6 Mio. m³
- Max. Head: 653 m
- Rated flow per unit: 38.7 m^3/s



Nant de Drance PSPP, Switzerland

- 2005 – ongoing
- 900 MW

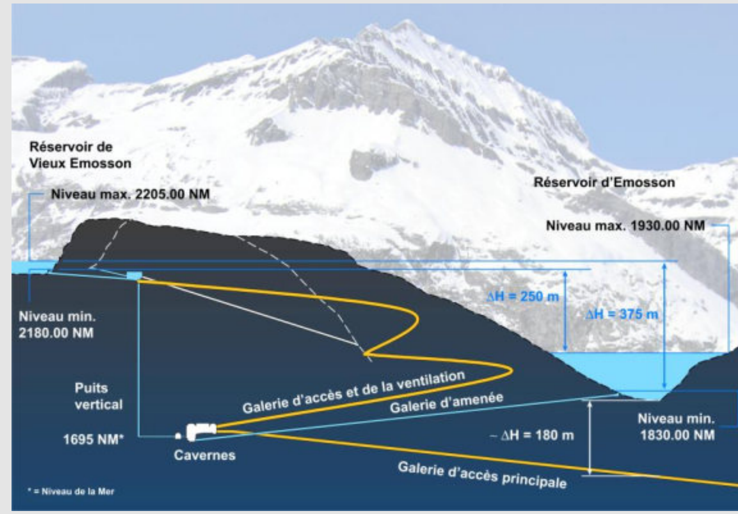
ÅF`s role

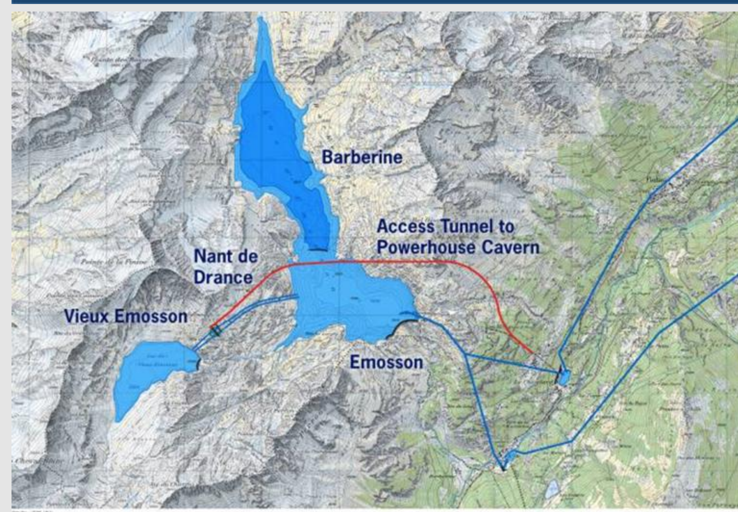
- Feasibility study
- Overall project management
- Basic, tender and construction design
- Design review for main equipment
- Site engineering and management
- Site inspection and monitoring
- Shop inspection
- Tests & commissioning

Nant de Drance PSPP, Switzerland

Key Characteristics:

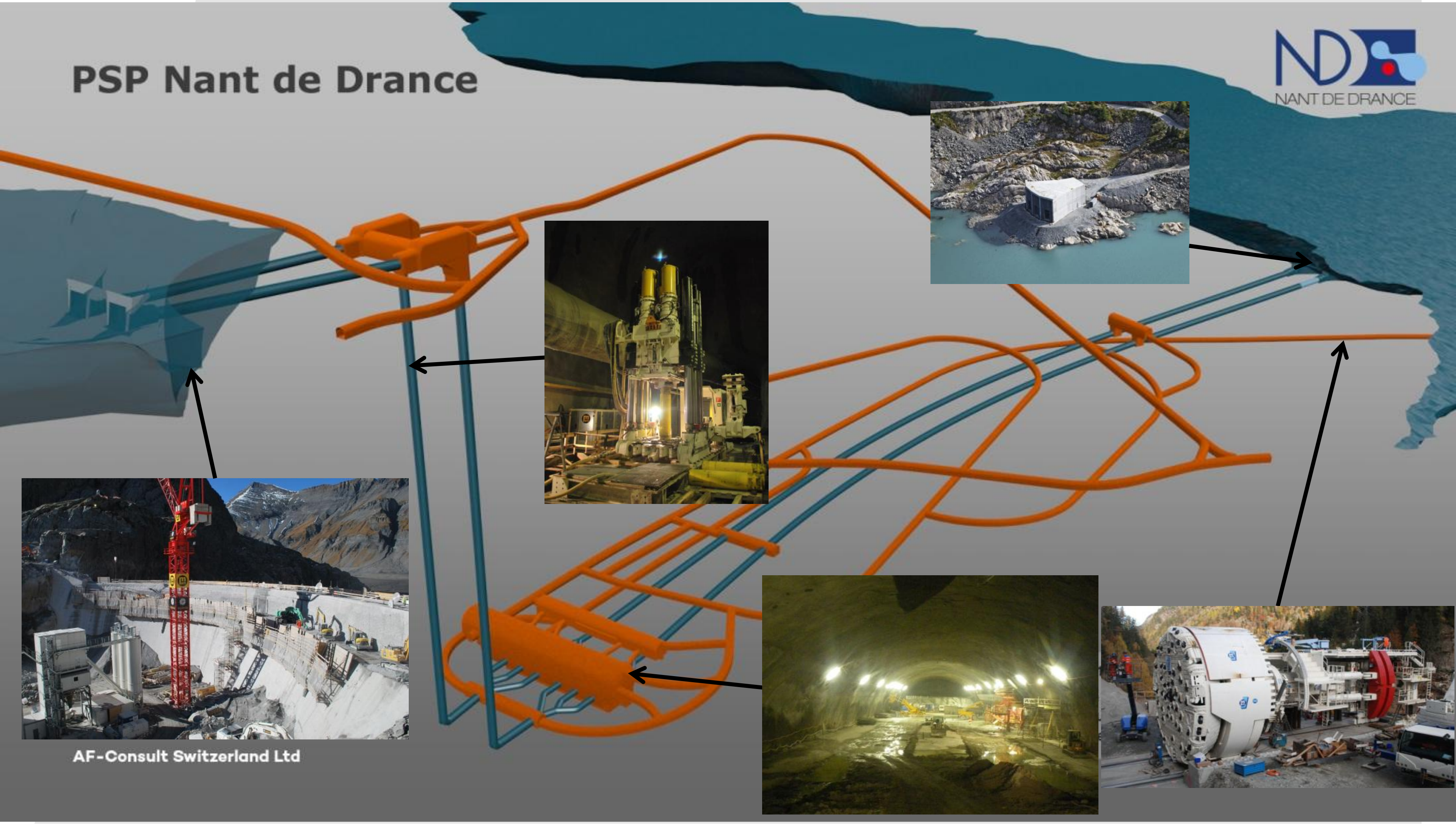
- Construction stage
- Dam: Arch Dams (existing)
- Dam height
  - Upstream: 20 m to be increased (64 m)
  - Downstream: 185 m (existing)
- Upstream reservoir capacity: 22 Mio. m3
- Max. Head: 390 m
- Number of Unit: 6 with total Capacity of 900 MW
- Type of Machine: Variable Speed Asynchronous
- Rated flow per unit: 60 m3/s





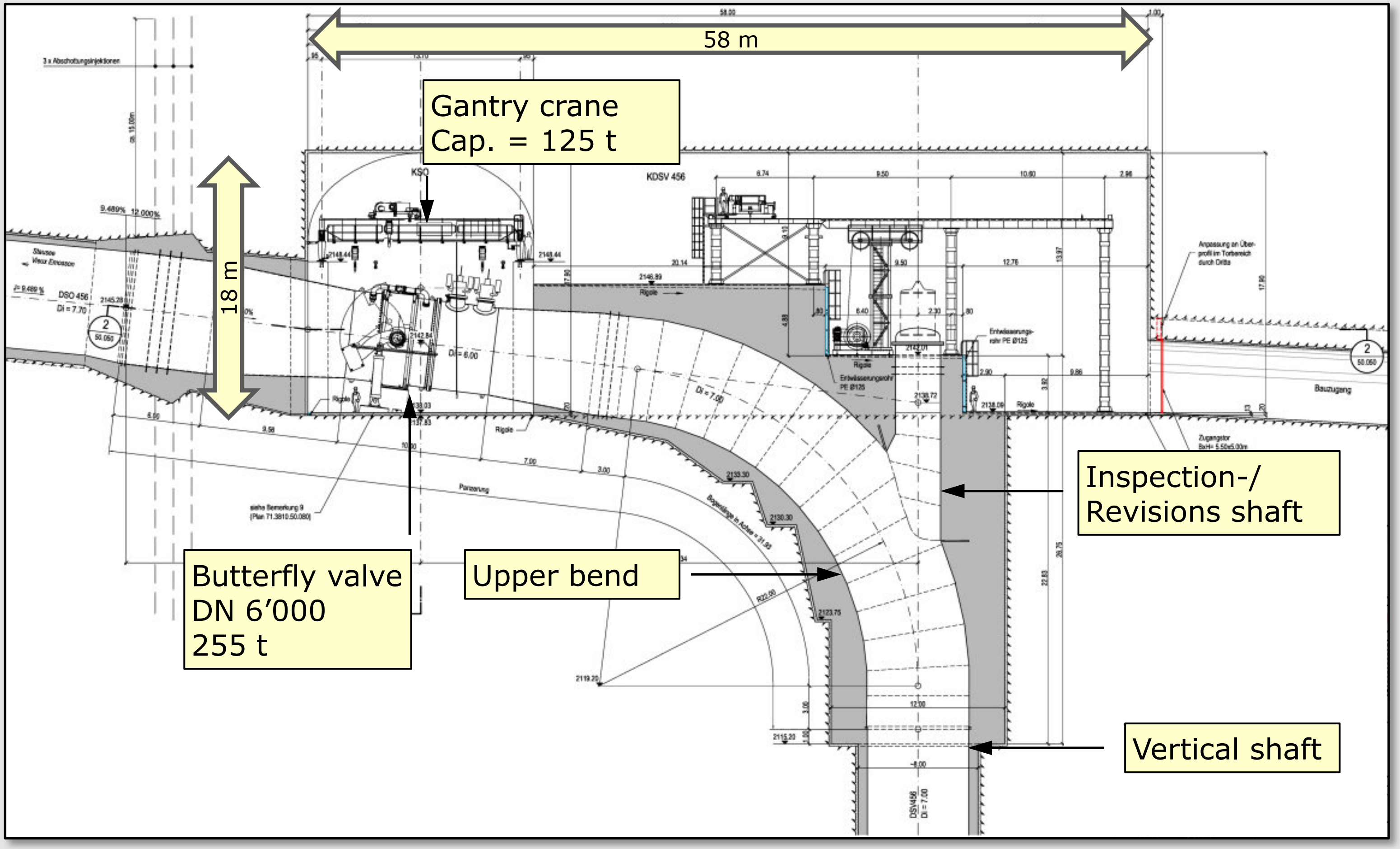
Nant de Drance PSPP, Switzerland

Nant de Drance PSPP, Switzerland



Nant de Drance PSPP, Switzerland

Main Structures – Upper Valve Chamber



Longitudinal section upper valve chamber

Nant de Drance PSPP, Switzerland

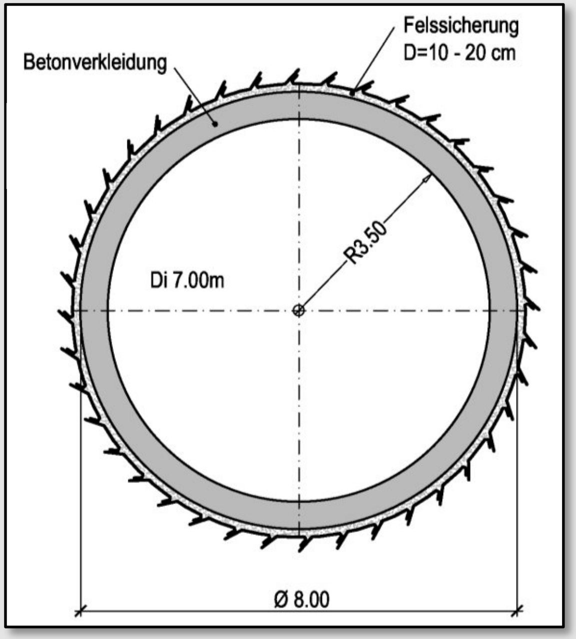
Upper Valve Chamber

Upper valve chamber:
L x B x H: 70 m x 16 x 18 m, V: ~ 20’000 m^3
Hosts butterfly valves
Design factor: Size of steel components

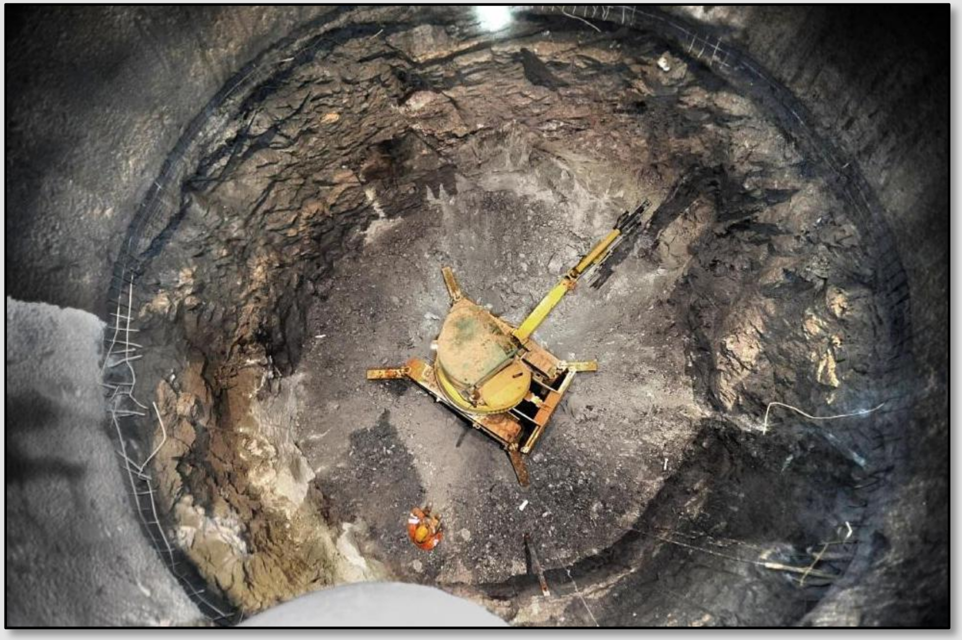
Nant de Drance PSPP, Switzerland

Vertical Shaft

- Height [m]: 444
- Inner diameter [m]: 7.0
- Average flow velocity [m/s]: 4.7



Section

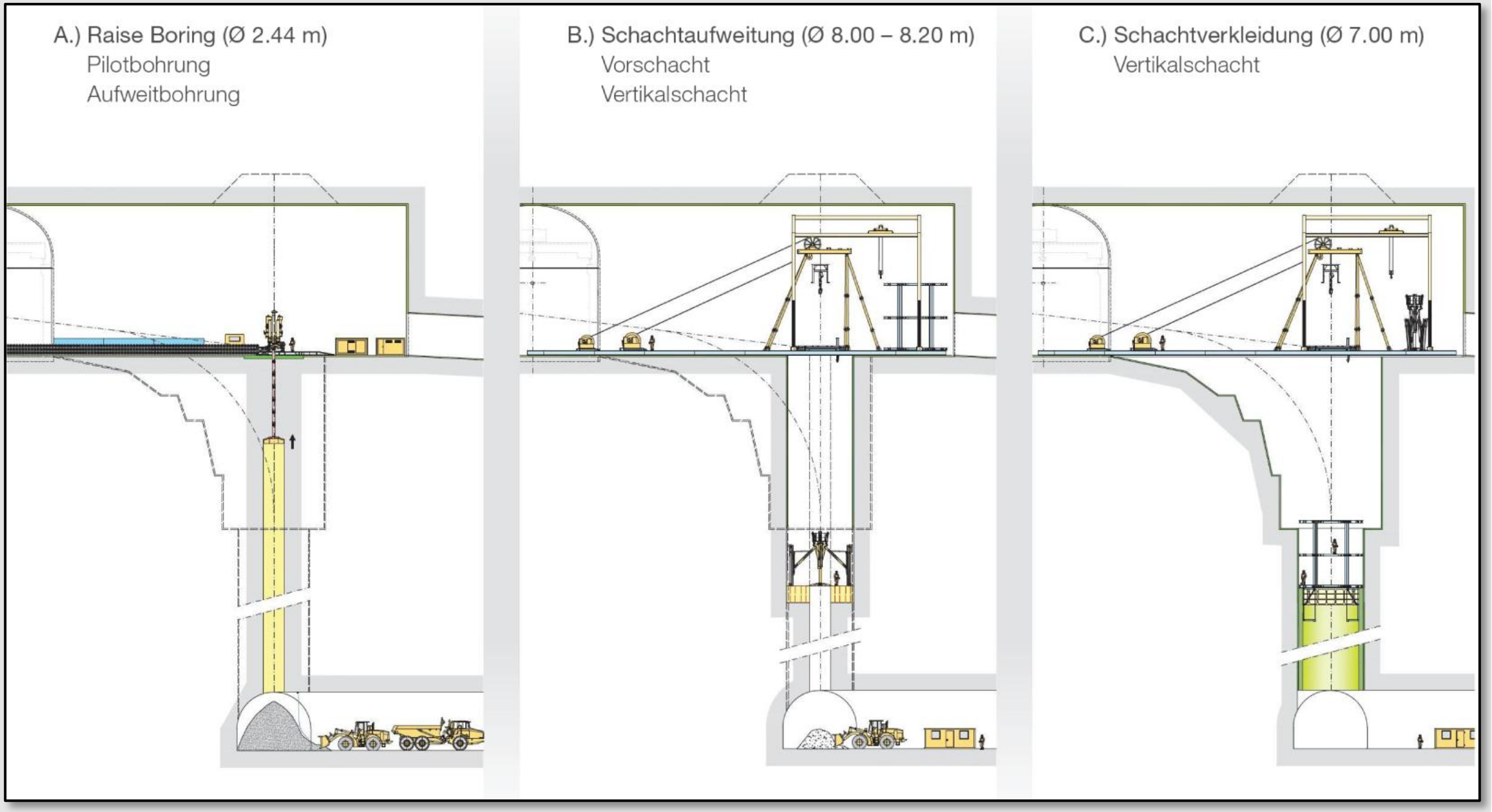


Widening of shaft

Nant de Drance PSPP, Switzerland

Vertical Shaft – Excavation method

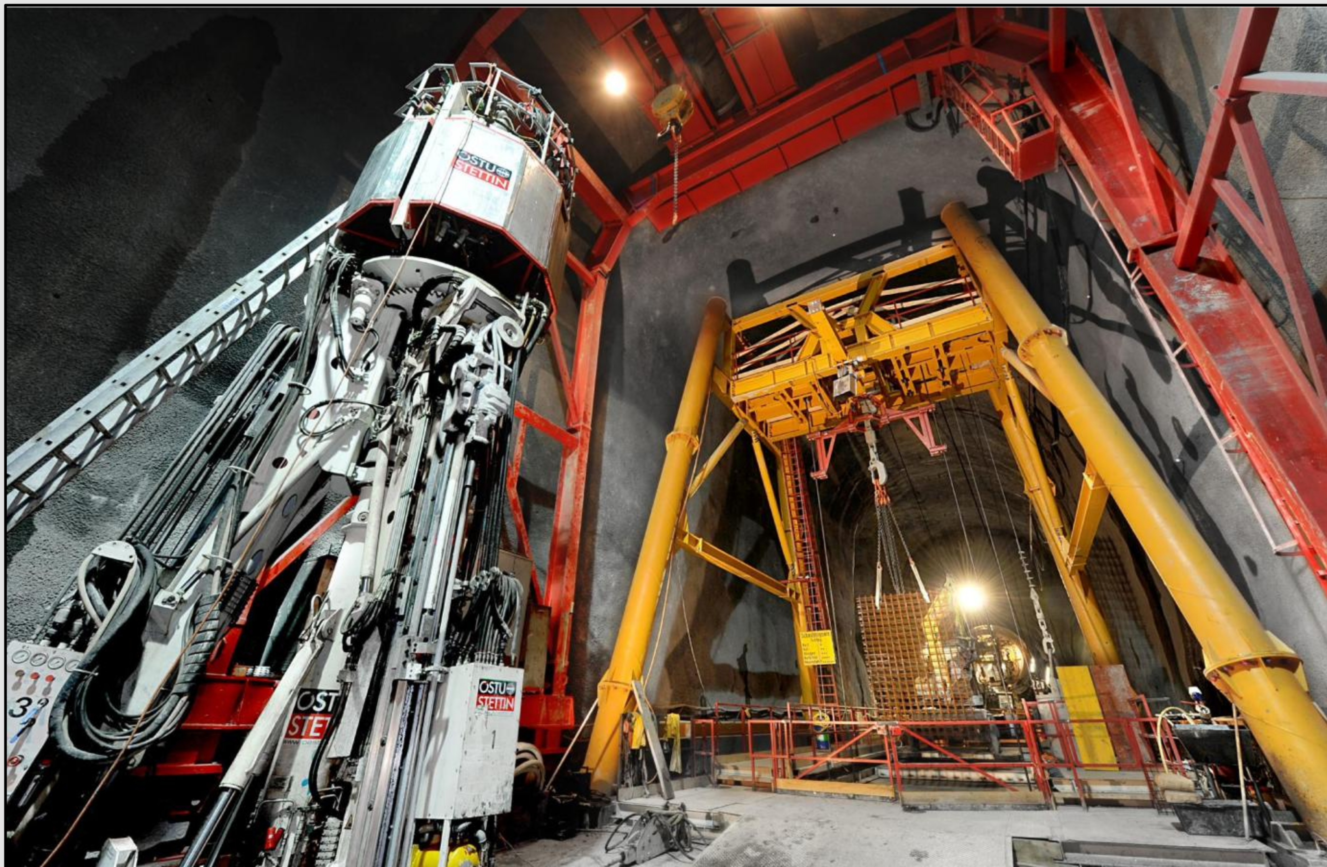
1. Pilot drilling
2. Raise-drill 2.4 m
3. Drill & blast to 8 m



Process description
(Zmölnig, M. (2014): Vertical Shafts of Nant de Drance)

Nant de Drance PSPP, Switzerland

Vertical Shaft



Raise-boring-equipment
(Stakne, P. et al. (2014): Alpine Experience of Shaft Construction and Shaft Grouting)

Nant de Drance PSPP, Switzerland

Vertical Shaft – Pilot drilling

Excavation method:
1. Pilot drilling
2. Raise-drill 2.4 m
3. Drill & blast to 8 m

Nant de Drance PSPP, Switzerland

Vertical Shaft – Raise-drill 2.4 m

Excavation method:

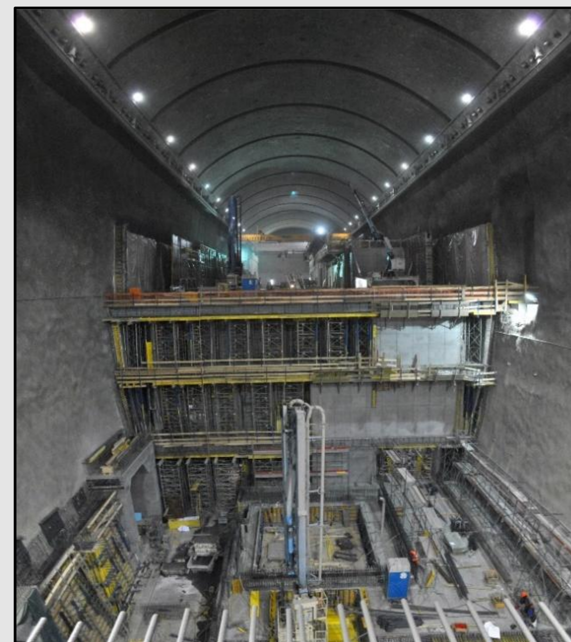
1. Pilot drilling
2. Raise-drill 2.4 m
3. Drill & blast to 8 m

Nant de Drance PSPP, Switzerland

Powerhouse Cavern Design with BIM (Building Information Modelling)

- Length [m]: 194
- Width [m]: 30.5
- Height [m]: 53
- Excavation volume [m^3]: 272’000

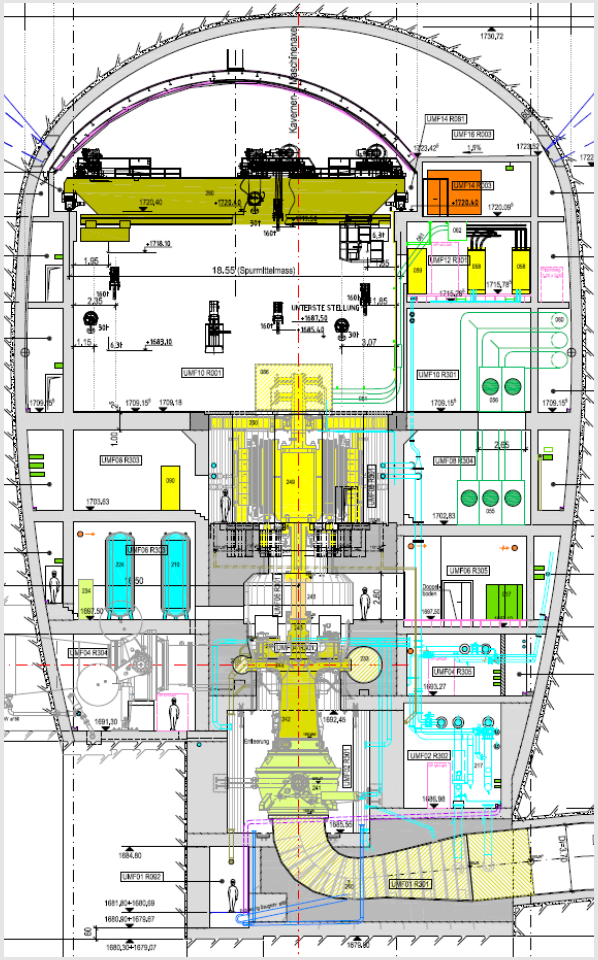
Powerhouse main floor (2016)

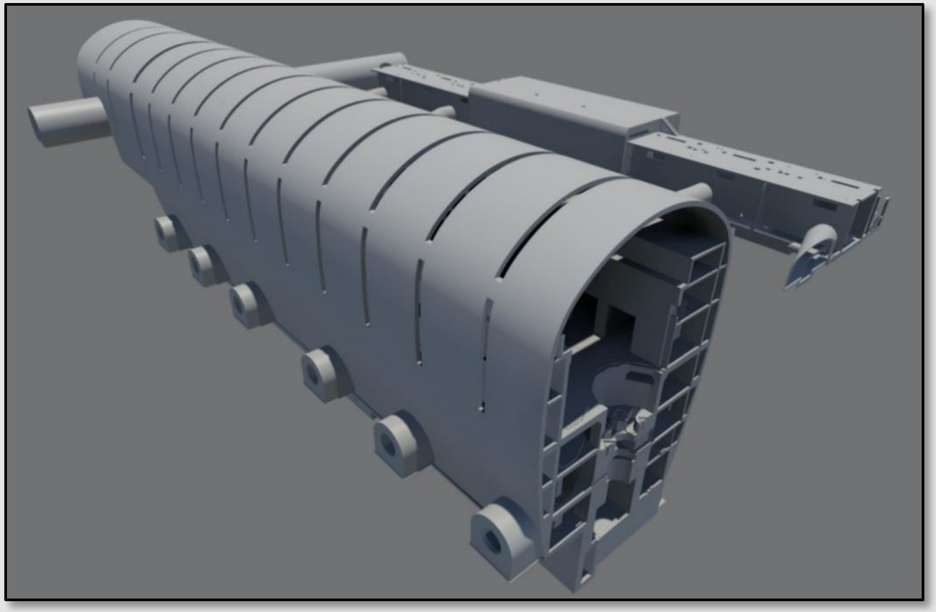


Concreting phase (2015)

Nant de Drance PSPP, Switzerland

Powerhouse Cavern

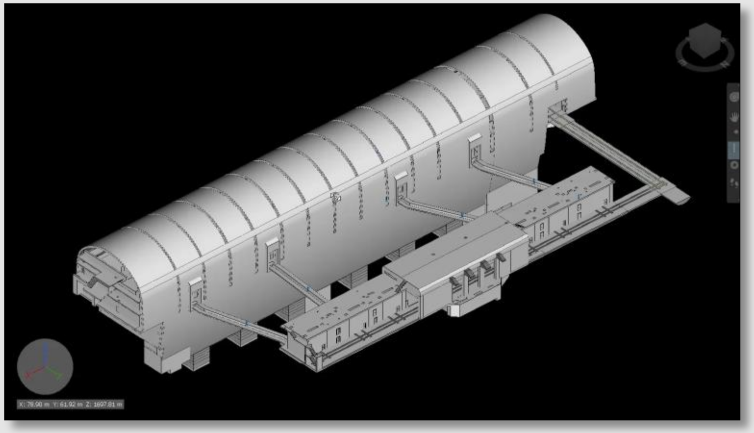




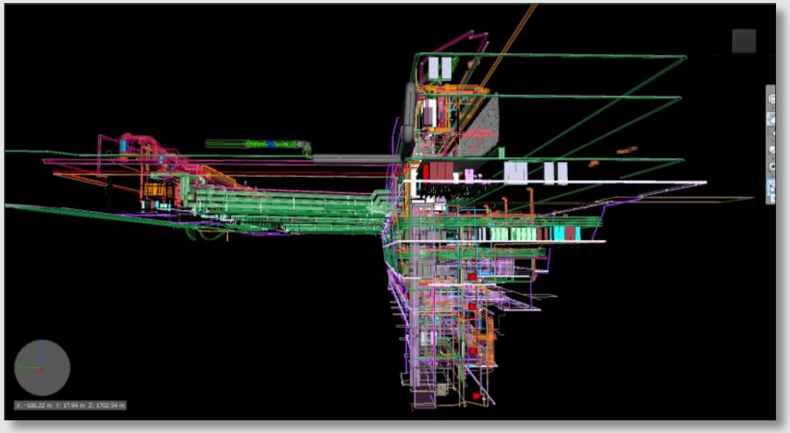
Powerhouse cavern: 6 vario-speed pump turbines 150 MW each
L x B x H: 194 x 30.5 x 53 m

Nant de Drance PSPP, Switzerland

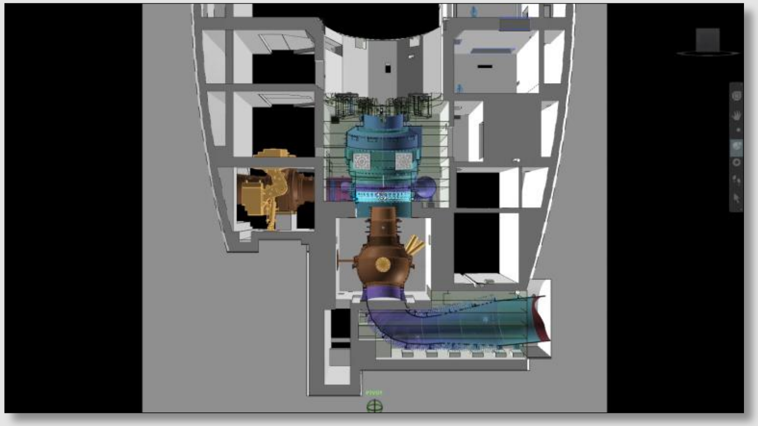
Powerhouse Cavern – 3D Modelling & Clash Detection (BIM)



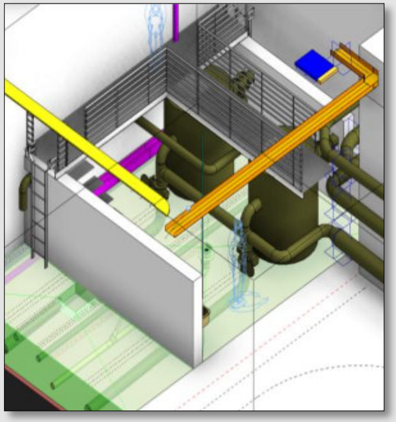
Powerhouse & transformer caverns



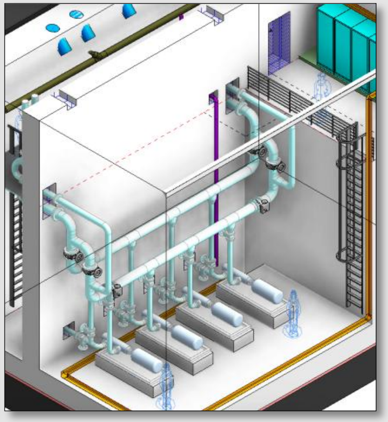
Piping and ducting systems



Turbine pit



Oil separator



Pump sump

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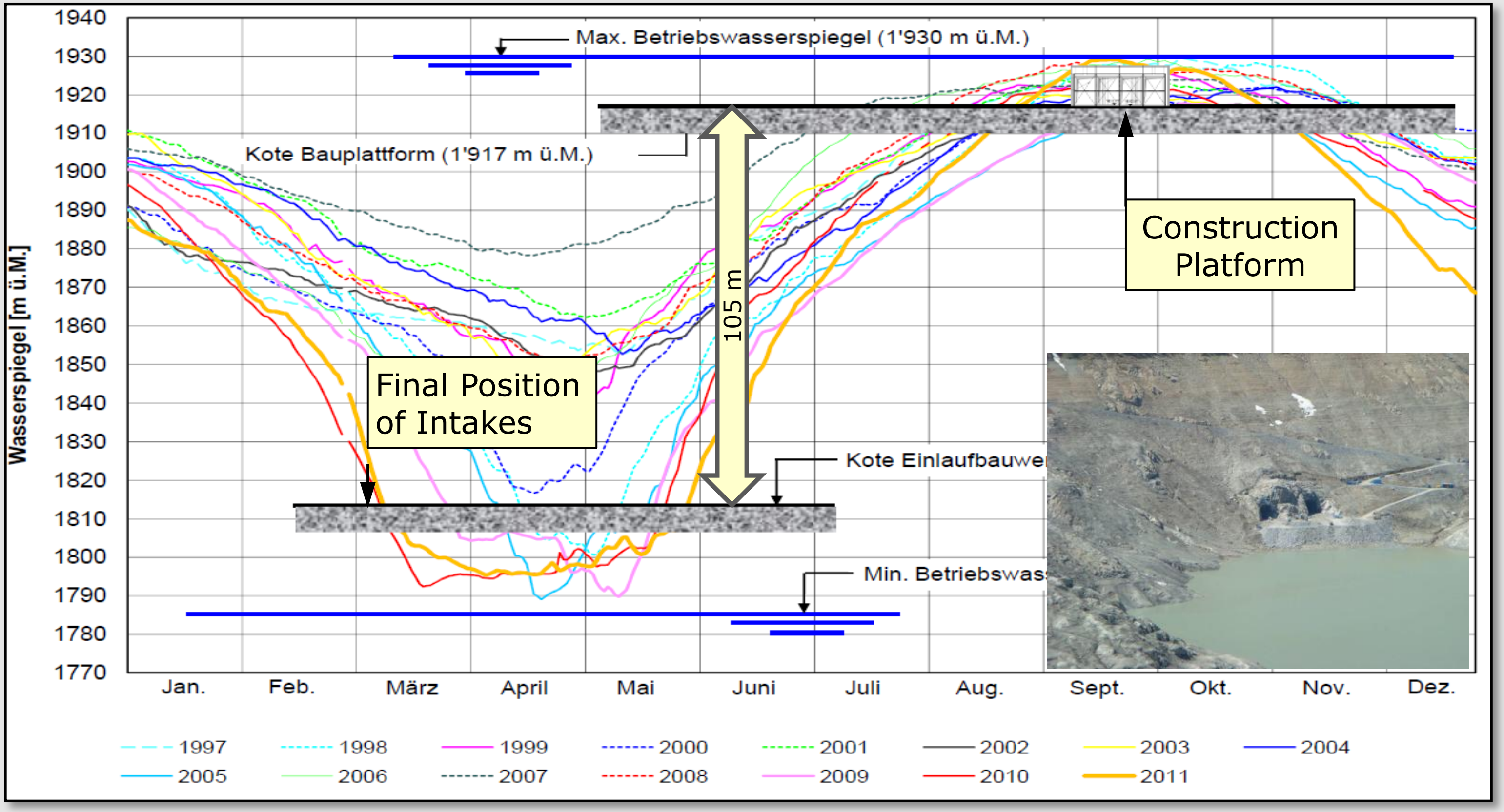
Construction of the Lower Intakes



Reservoir operation at Emosson (1997 - 2011)

Nant de Drance PSPP, Switzerland

Construction of the Lower Intakes

Several Construction Methods were studied:

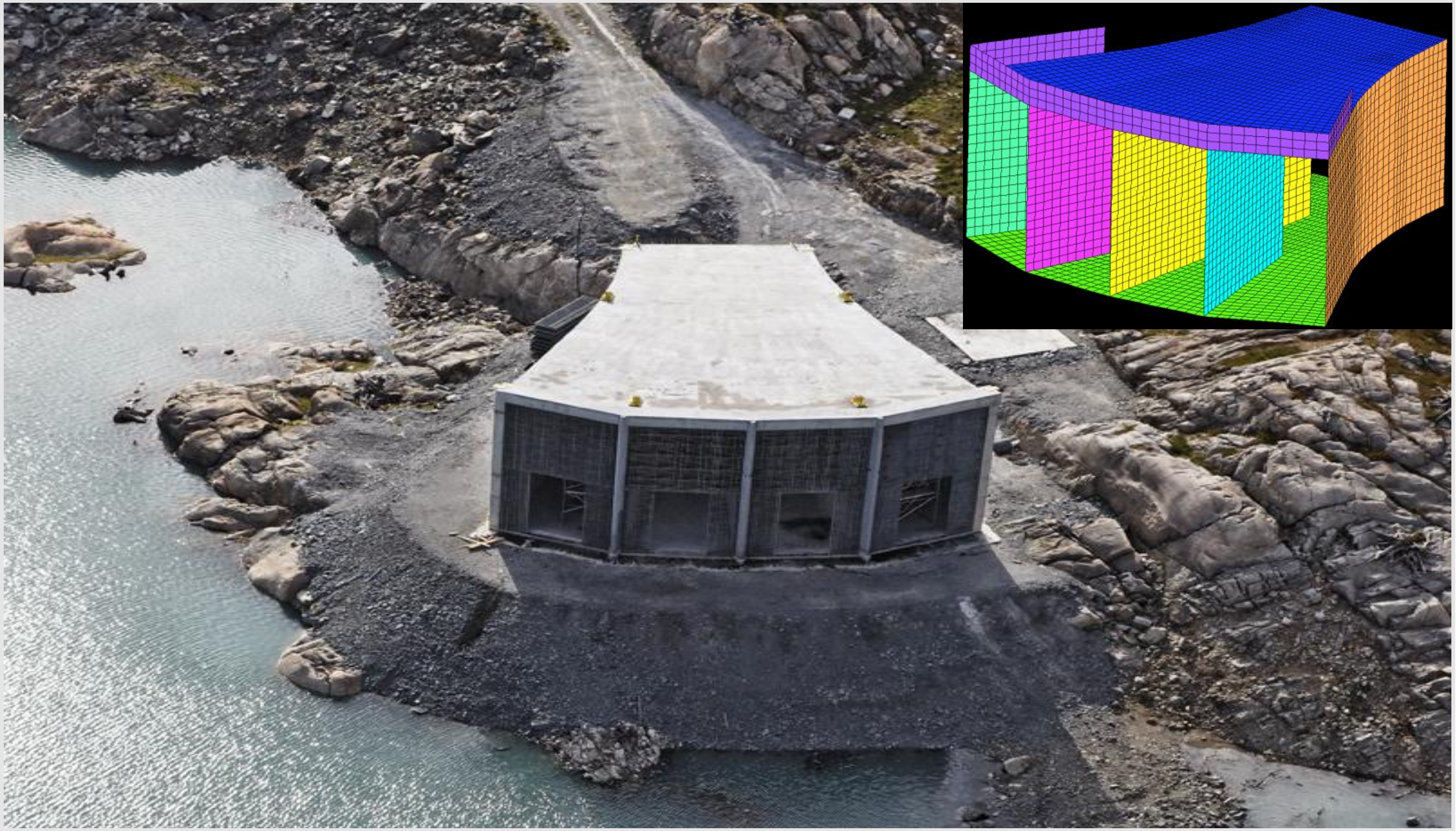
- In situ with fresh concrete or prefabricated concrete elements
- Construction on a **platform and transport of the final intakes to their final position**

Lower intake floated into its final position

Lower intakes – construction phase

Nant de Drance PSPP, Switzerland

Construction of the Lower Intakes



Nant de Drance PSPP, Switzerland

Placing the Lower Intakes

Hydro Power

Thank you and welcome to ÅF

ÅF, Hydro Power

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Switzerland
www.afconsult.com

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www.afconsult.com

Self-Scheduling of Pumped-Storage Hydro Power Generation in Electric Power Markets

P. Kanakasabapathy
Associate Professor

Department of Electrical Engineering
AMRITA
VISHWA VIDYAPEETHAM
UNIVERSITY
Established u/s 3 of the UGC Act 1956
A multi campus university accredited by NAAC with 'A' grade

February 9, 2018

Outline of Presentation

Pumped Storage Power Plant

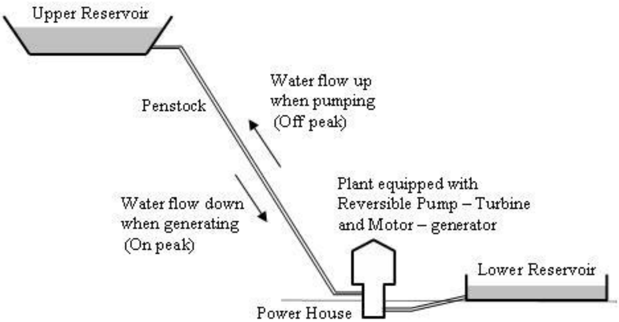

Figure: 1. Schematic Diagram of Pumped Storage Plant

Pumped Storage Power Plant

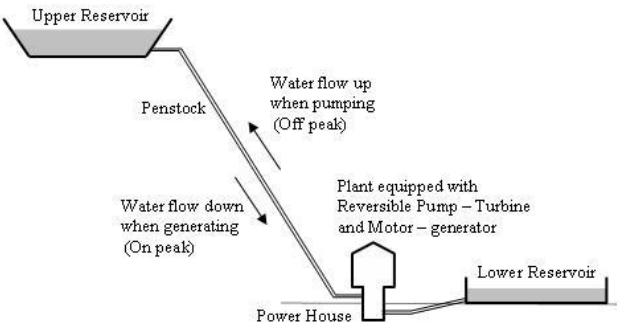

Figure: 1. Schematic Diagram of Pumped Storage Plant

- Large-scale energy storage technology
- Still in active operation because of its operational flexibility
- Provide rapid response to changes in system loading or spot price
- Take part in energy markets and ancillary services markets

Introduction

Reforms in Energy Sector

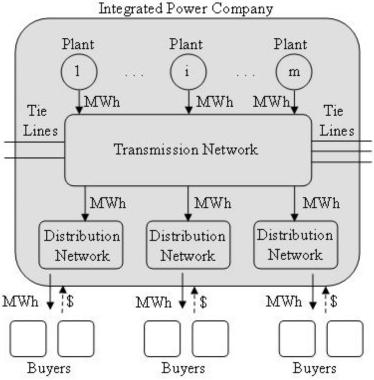

Figure: 2. Classical Power Systems

Reforms in Energy Sector

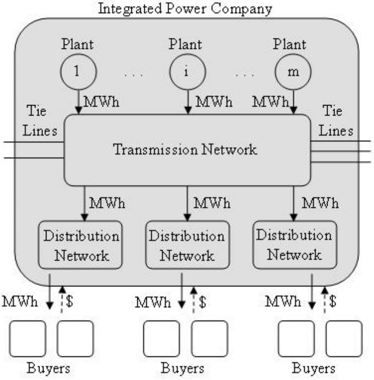

Figure: 2. Classical Power Systems

- Market based environment
- Competitive energy trading

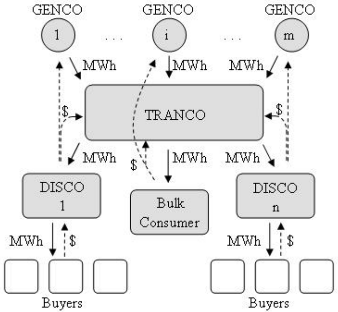

Figure: 3. Restructured Power Systems

Introduction

Reforms in Energy Sector

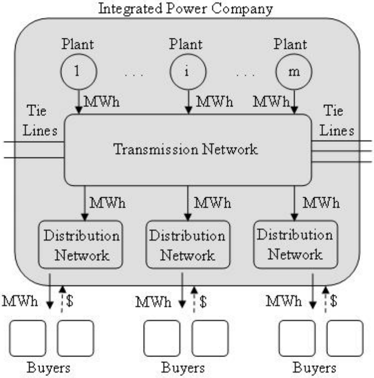

Figure: 2. Classical Power Systems

- Market based environment
- Competitive energy trading

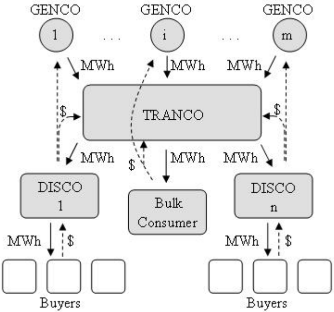

Figure: 3. Restructured Power Systems

- Open access of infrastructure and improved reliability of service
- Distinct energy and ancillary service products - Additional sources of revenue - Choice of market that returns the highest profit

Electricity Market Models

Bilateral Contracts Model

- Specific contracts between supplier and consumer
- Appropriate access and transmission pricing standards
- Transfer the traded power over transmission utility

Electricity Market Models

Bilateral Contracts Model

- Specific contracts between supplier and consumer
- Appropriate access and transmission pricing standards
- Transfer the traded power over transmission utility

PoolCo Model

- Pool of producers and customers served by transmission system
- Competition among utilities to trade power
- Centralized market place (Px) clears the market and define the Market Clearing Price (MCP)

Introduction

Electricity Market Models

Bilateral Contracts Model

- Specific contracts between supplier and consumer
- Appropriate access and transmission pricing standards
- Transfer the traded power over transmission utility

Hybrid Model

- Combines the features of previous two market models
- Choice of bilateral contracts and power pool
- Power pool serve all buyers and sellers who choose to compete

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Types of Markets

- Day-ahead, Hour-ahead and Real Time Energy Markets
- Capacity based Ancillary Services Markets (TMSR, TMNSR, TMOR)
- Voltage regulation and reactive power support services

Introduction

Pumped-Storage in Competitive Market

- Highly variable, cyclical grid demand as well as the energy price in electricity markets
- Growing reliance on intermittent renewable energy sources like wind and photo-voltaic generation
- Frequent situations of surplus power generation to cater the available load [Ontario - Sep. 2006]

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- Market opportunities for energy storage systems - better energy management in the fields of micro grids and distributed generation
- Ability to purchase low cost power whenever it is available and sell whenever there is high demand
- Pumped-storage can provide efficiently the ancillary grid services, such as reserve generation and network frequency control

Regulatory Price Regime Vs Electricity Market Regime

Literature Review

Regulatory Price Regime

- All the units including pumped-storage are owned by single entity
- Pumped storage is scheduled to replace high cost (thermal/gas/diesel) energy during peak loads - Hydro-thermal coordination
- Cost of the energy replaced - Performance measure
- Marginal cost method & peak-shaving algorithm

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Electricity Market Regime

- Optimal strategy towards maximizing the personal benefit for operating in a competitive environment
- Determination of the optimal bids for generation (MW) and corresponding price ($\$/MW$)
- Suitable time slot for storage plant to operate as generator and pump
- Profit maximization from energy and ancillary services markets

Regulatory Price Regime Vs Electricity Market Regime

Literature Review

Strategic Bidding

- Based on forecasted MCP in the subsequent trading periods
- Based on estimations of bidding behaviour of rival participants
- Based on the game theory

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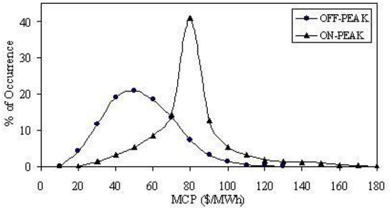

Figure: 4. Distributions of Day-ahead Hourly Market Clearing Price (MCP)

Motivation

- Distribution of MCP - Exploitation of cyclic patterns of market price dynamics
- In a typical market, real time energy trading $< 5\%$, and the remaining is traded in the bilateral contracts and the day-ahead energy market
- Strong incentives for pumped-storage to develop bidding strategy and optimize self-schedule for energy and ancillary services trades

Pumped Storage Self-Scheduling

Objectives

1. Development of optimal bidding strategy - day-ahead pool based and hybrid electricity markets
2. Formulation of mathematical model and suitable algorithm to implement the strategy and maximize the profit
3. Management of uncertainties and investigation of the impact of operating pumped-storage plants in the market social welfare

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Scope

- Limited to independent pumped storage power plant, which is a price taker and do not possess any market power
- Study relies on forecasted MCP
- Only the reserve markets which are attractive for pumped-storage are considered (TMSR, TMNSR and RFRR)
- Data representing specific plants & specific market - Concepts and techniques developed could have general application

Concept of Marginal Cost

It is economical to make an offer of η_p MWh generation during t_g hours, if there exists a time duration of t_p hours to bid for buying 1 MWh, such that the ratio of the MCPs during pumping and generating is less than the plant cycle efficiency η_p

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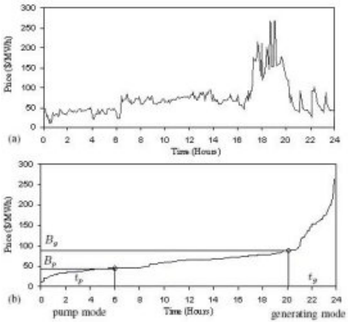

Figure: 5. Market Clearing Price curve.
(a) Daily MCP, (b) Composite MCP

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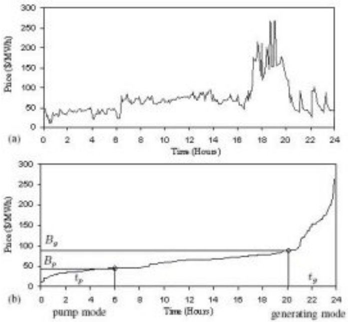

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Economic Constraint

$$B_g \geq \frac{B_p}{\eta_p} \qquad \cong \qquad B_g \geq 1.5\ B_p \qquad (1)$$

Self-Scheduling in Pool-Based Electricity Market

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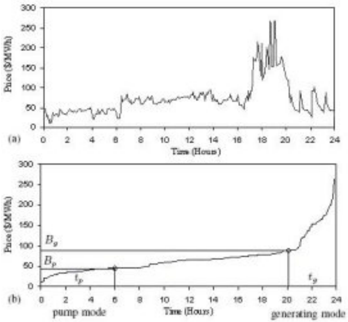

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Economic Constraint

$$B_g \geq \frac{B_p}{\eta_p} \quad \cong \quad B_g \geq 1.5\ B_p \qquad (1)$$

Operating Time Constraint

$$t_{pmax} = \frac{T - (E_{in}/P_g)}{1 + \eta_p\,(P_p/P_g)} \qquad (2)$$

Making energy balance, t_g for any given t_p can be estimated

Mathematical Model

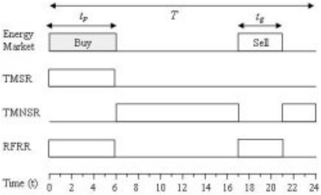
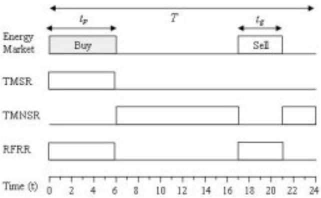


Figure: 8. Bidding space diagram for energy and ancillary services

Mathematical Model



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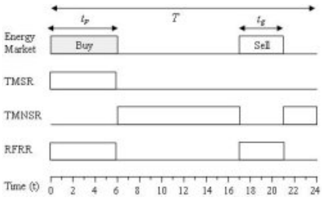
Energy Market

Revenue from energy trading during the generating mode

$$\mathbf{P} = \sum_{i=1}^{t_g} P_g(i) B_g(i) \tag{3}$$

Mathematical Model



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$$\mathbf{P} = \sum_{i=1}^{t_g} P_g(i)B_g(i) + \sum_{j=1}^{t_p} P_{rs}(j)B_{rs}(j) \quad (3)$$

Energy Market

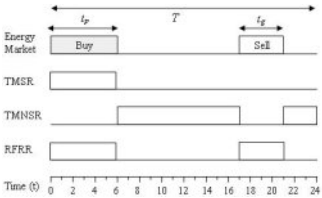
Revenue from energy trading during the generating mode

Syn-Reserve Market

Revenue by reducing pumping power during the pumping mode

Self-Scheduling in Pool-Based Electricity Market

Mathematical Model



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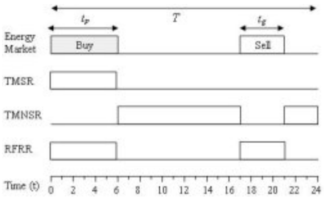
Non-syn Res. Market

Revenue from non-syn reserve bids when the unit is off-line

Self-Scheduling in Pool-Based Electricity Market

Mathematical Model



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Revenue from energy trading during the generating mode

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Revenue by reducing pumping power during the pumping mode

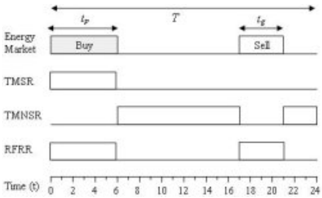
Non-syn Res. Market

Revenue from non-syn reserve bids when the unit is off-line

Energy Market

Payment for energy procurement during the pumping mode

Mathematical Model



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Energy Market

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Operating Cost

Running expenditure during pumping and generating $(t_p + t_g)$

Self-Scheduling in Pool-Based Electricity Market

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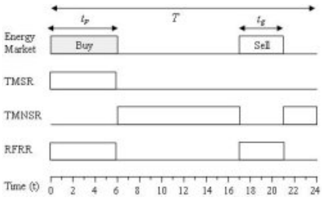

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Revenue from non-syn reserve bids when the unit is off-line

Energy Market
Payment for energy procurement during the pumping mode

Operating Cost
Running expenditure during pumping and generating $(t_p + t_g)$

Fixed Cost
Fixed expenditures including maintenance for the total period T

Case Study: Optimization using Sequential Scheduling

Lewiston-Niagara
Pumped Storage Plant
New York Power Authority

Plant Data

Capacity $= 200 - 300\ MW$,
$P_p = 250\ MW$, $\eta_p = 0.6667$

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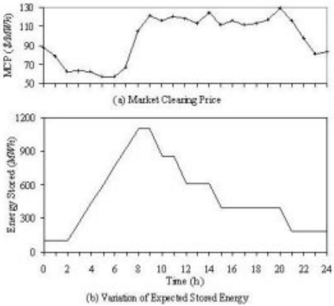

Figure: 9. Expected energy storage

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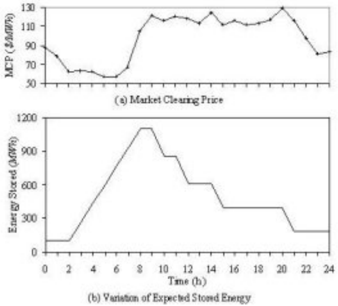

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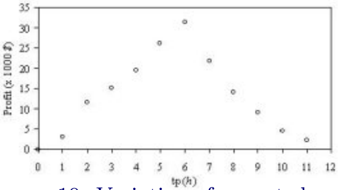

Figure: 10. Variation of expected profit

Daily Operating Strategy

Table: I. Optimal bidding strategy and bids in MW (4-10 May 2008)

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-1	0	0	0	0	0	0
2	-1	0	0	-1	0	0	-1
3	-1	-1	0	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	-1	-1	-1	0	-1	-1	0
7	0	-1	-1	0	0	0	0
8	0	-1	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0
11	0	0	0	0	0	0	0
12	1	1	0	0	0	0	0
13	1	0	0	1	1	0	0
14	1	0	0	0	1	0	1
15	0	1	0	0	0	0	0
16	0	0	0	1	0	1	1
17	0	0	0	0	0	1	1
18	0	0	1	0	0	1	0
19	0	0	0	0	0	0	0
20	0	0	1	0	0	0	0
21	1	1	1	1	1	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-250	0	0	0	0	0	0
2	-250	0	0	-250	0	0	-250
3	-250	-250	0	-250	-250	-250	-250
4	-250	-250	-250	-250	-250	-250	-250
5	-250	-250	-250	-250	-250	-250	-250
6	-250	-250	-250	0	-250	-250	0
7	0	-250	-250	0	0	0	0
8	0	-250	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	250	0	0	0	0	0
11	0	0	0	0	0	0	0
12	250	240	0	0	0	0	0
13	240	0	0	230	230	0	0
14	220	0	0	0	220	0	230
15	0	220	0	0	0	0	0
16	0	0	0	220	0	230	220
17	0	0	0	0	0	220	210
18	0	0	230	0	0	210	0
19	0	0	0	0	0	0	0
20	0	0	220	0	0	0	0
21	210	210	210	210	210	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

- '-' sign indicates pumping
- '+' sign indicates generating

Daily Operating Strategy

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Hr	Days of the week						
	S	M	T	W	T	F	S
1	-1	0	0	0	0	0	0
2	-1	0	0	-1	0	0	-1
3	-1	-1	0	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	-1	-1	-1	0	-1	-1	0
7	0	-1	-1	0	0	0	0
8	0	-1	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0
11	0	0	0	0	0	0	0
12	1	1	0	0	0	0	0
13	1	0	0	1	1	0	0
14	1	0	0	0	1	0	1
15	0	1	0	0	0	0	0
16	0	0	0	1	0	1	1
17	0	0	0	0	0	1	1
18	0	0	1	0	0	1	0
19	0	0	0	0	0	0	0
20	0	0	1	0	0	0	0
21	1	1	1	1	1	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-250	0	0	0	0	0	0
2	-250	0	0	-250	0	0	-250
3	-250	-250	0	-250	-250	-250	-250
4	-250	-250	-250	-250	-250	-250	-250
5	-250	-250	-250	-250	-250	-250	-250
6	-250	-250	-250	0	-250	-250	0
7	0	-250	-250	0	0	0	0
8	0	-250	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	250	0	0	0	0	0
11	0	0	0	0	0	0	0
12	250	240	0	0	0	0	0
13	240	0	0	230	230	0	0
14	220	0	0	0	220	0	230
15	0	220	0	0	0	0	0
16	0	0	0	220	0	230	220
17	0	0	0	0	0	220	210
18	0	0	230	0	0	210	0
19	0	0	0	0	0	0	0
20	0	0	220	0	0	0	0
21	210	210	210	210	210	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

- '-' sign indicates pumping
- '+' sign indicates generating

Table: II. Result summary: 4-10 May 2008

Day	t_p (h)	t_g (h)	Profit ($)	E_s^{max} (MWh)
Sun	6	4	45615	1100
Mon	6	4	31261	1100
Tues	4	3	20299	770
Wed	4	3	30063	770
Thu	4	3	19607	770
Fri	4	3	21109	770
Sat	4	3	28159	770
Total	32	23	196113	-

- Plant generates more during peak MCP period and pumps more when MCP is low
- Energy balance is maintained at the end of each day
- Energy storage capacity limit is not violated

Case Study: Optimization using Sequential Scheduling

Weekly Operating Strategy

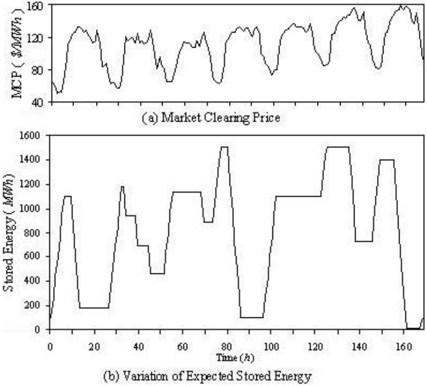
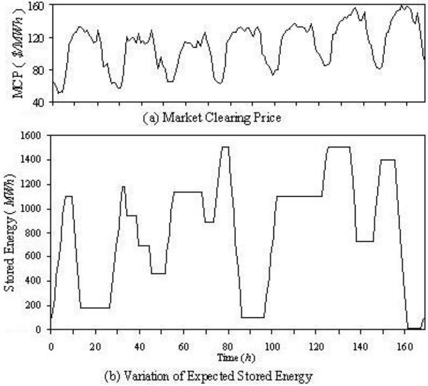


Figure: 11. Expected energy storage

Case Study: Optimization using Sequential Scheduling

Weekly Operating Strategy



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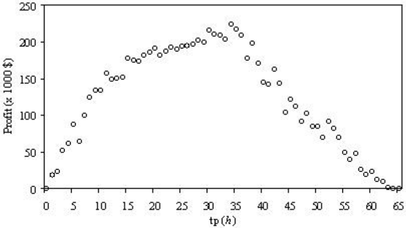

Figure: 12. Variation of expected profit

- Plant generates more on the later part of week and pumps more on early part of the week
- Energy balance is maintained only at the end of the week

Case Study: Optimization using Sequential Scheduling

Weekly Operating Strategy

Table: III. Optimal bidding strategy and bids in MW (4-10 May 2008)

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-1	0	0	0	-1	0	0
2	-1	0	0	-1	-1	0	-1
3	-1	-1	0	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	-1	-1	-1	0	-1	0	0
7	0	-1	-1	0	0	0	0
8	0	-1	0	0	0	0	0
9	0	0	0	1	0	0	0
10	1	1	0	1	0	0	0
11	1	0	0	1	0	0	0
12	1	0	0	1	0	0	1
13	1	0	0	1	0	0	1
14	0	0	0	1	0	0	1
15	0	1	0	0	0	0	1
16	0	0	0	0	0	1	1
17	0	0	0	0	0	1	1
18	0	0	0	0	0	1	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	1	1	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-1

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-250	0	0	0	-250	0	0
2	-250	0	0	-250	-250	0	-250
3	-250	-250	0	-250	-250	-250	-250
4	-250	-250	-250	-250	-250	-250	-250
5	-250	-250	-250	-250	-250	-250	-250
6	-250	-250	-250	0	-250	0	0
7	0	-250	-250	0	0	0	0
8	0	-250	0	0	0	0	0
9	0	0	0	270	0	0	0
10	250	250	0	260	0	0	0
11	240	0	0	240	0	0	0
12	220	0	0	230	0	0	260
13	210	0	0	220	0	0	250
14	0	0	0	200	0	0	240
15	0	240	0	0	0	0	230
16	0	0	0	0	0	270	210
17	0	0	0	0	0	260	200
18	0	0	0	0	0	240	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	230	250	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-140

- '-' sign indicates pumping
- '+' sign indicates generating

Case Study: Optimization using Sequential Scheduling

Weekly Operating Strategy

Table: III. Optimal bidding strategy and bids in MW (4-10 May 2008)

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-1	0	0	0	-1	0	0
2	-1	0	0	-1	-1	0	-1
3	-1	-1	0	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	-1	-1	-1	0	-1	0	0
7	0	-1	-1	0	0	0	0
8	0	-1	0	0	0	0	0
9	0	0	0	1	0	0	0
10	1	1	0	1	0	0	0
11	1	0	0	1	0	0	0
12	1	0	0	1	0	0	1
13	1	0	0	1	0	0	1
14	0	0	0	1	0	0	1
15	0	1	0	0	0	0	1
16	0	0	0	0	0	1	1
17	0	0	0	0	0	1	1
18	0	0	0	0	0	1	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	1	1	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-1

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-250	0	0	0	-250	0	0
2	-250	0	0	-250	-250	0	-250
3	-250	-250	0	-250	-250	-250	-250
4	-250	-250	-250	-250	-250	-250	-250
5	-250	-250	-250	-250	-250	-250	-250
6	-250	-250	-250	0	-250	0	0
7	0	-250	-250	0	0	0	0
8	0	-250	0	0	0	0	0
9	0	0	0	270	0	0	0
10	250	250	0	260	0	0	0
11	240	0	0	240	0	0	0
12	220	0	0	230	0	0	260
13	210	0	0	220	0	0	250
14	0	0	0	200	0	0	240
15	0	240	0	0	0	0	230
16	0	0	0	0	0	270	210
17	0	0	0	0	0	260	200
18	0	0	0	0	0	240	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	230	250	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-140

- '-' sign indicates pumping
- '+' sign indicates generating

Table: IV. Summary of results: Daily and Weekly operating strategies (4-10 May 2008)

Pumping power P_p kept constant at 250 MW

Strgy.	t_p (h)	t_g (h)	P_g^{av} (MW)	Profit (\$)
Daily	32	23	223.48	196113
Weekly	34	23	237.83	224036

E_s^{max}	: –	Daily:1100	Weekly:1500 MWh
P_g^{max}	: –	Daily: 250	Weekly: 270 MW

Weekly Operating Strategy

Table: III. Optimal bidding strategy and bids in MW (4-10 May 2008)

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-1	0	0	0	-1	0	0
2	-1	0	0	-1	-1	0	-1
3	-1	-1	0	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	-1	-1	-1	0	-1	0	0
7	0	-1	-1	0	0	0	0
8	0	-1	0	0	0	0	0
9	0	0	0	1	0	0	0
10	1	1	0	1	0	0	0
11	1	0	0	1	0	0	0
12	1	0	0	1	0	0	1
13	1	0	0	1	0	0	1
14	0	0	0	1	0	0	1
15	0	1	0	0	0	0	1
16	0	0	0	0	0	1	1
17	0	0	0	0	0	1	1
18	0	0	0	0	0	1	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	1	1	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-1

Hr	Days of the week						
	S	M	T	W	T	F	S
1	-250	0	0	0	-250	0	0
2	-250	0	0	-250	-250	0	-250
3	-250	-250	0	-250	-250	-250	-250
4	-250	-250	-250	-250	-250	-250	-250
5	-250	-250	-250	-250	-250	-250	-250
6	-250	-250	-250	0	-250	0	0
7	0	-250	-250	0	0	0	0
8	0	-250	0	0	0	0	0
9	0	0	0	270	0	0	0
10	250	250	0	260	0	0	0
11	240	0	0	240	0	0	0
12	220	0	0	230	0	0	260
13	210	0	0	220	0	0	250
14	0	0	0	200	0	0	240
15	0	240	0	0	0	0	230
16	0	0	0	0	0	270	210
17	0	0	0	0	0	260	200
18	0	0	0	0	0	240	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	230	250	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	-140

- '-' sign indicates pumping
- '+' sign indicates generating

Table: IV. Summary of results: Daily and Weekly operating strategies (4-10 May 2008)

Pumping power P_p kept constant at 250 MW

Strgy.	t_p (h)	t_g (h)	P_g^{av} (MW)	Profit (\$)
Daily	32	23	223.48	196113
Weekly	34	23	237.83	224036

E_s^{max} : –	Daily:1100	Weekly:1500 MWh
P_g^{max} : –	Daily: 250	Weekly: 270 MW

Table: V. Comparison of bidding strategies

Strategy	t_p (h)	t_g (h)	Profit (\$)
Trad. operation	42	28	177805
Fixed schedule	42	28	211143
Const. power bid	34	23	215140
Proposed strgy.	34	23	224036

Comparison and Observations

Power bids in weekly operating mode are greater than daily operating mode

- Maintains high water head over the week days
- Efficiently utilizes the reservoir capacity since energy balance is satisfied only at the end of the week

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Maximum energy stored in upper reservoir in respect of daily operating mode is comparatively less

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- Whatever energy stored is evacuated in the same day

Case Study: Optimization using Sequential Scheduling

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The pumping and generating time of daily operating mode are less

- Margin between the MCP of energy bids during pumping and generating modes should be economically maintained
- In weekly operating mode the MCP variations and the price margin are high when compared to the daily operating mode

Case Study: Optimization using Sequential Scheduling

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The pumping and generating time of daily operating mode are less

- Margin between the MCP of energy bids during pumping and generating modes should be economically maintained
- In weekly operating mode the MCP variations and the price margin are high when compared to the daily operating mode

More profit in weekly operating mode

- Energy prices in the beginning of the week are lower than the later part
- Water stored during the beginning of the week is retained and used later

Case Study: Optimization using ETPSO

Blenheim-Gilboa
Pumped Storage Project
New York Power Authority

Plant Data

Capacity $= 4 * 260\ MW$,
$P_p = 250\ MW$, $\eta_p = 0.6667$

Case Study: Optimization using ETPSO

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Pumped Storage Project
New York Power Authority

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Capacity $= 4 * 260\ MW$,
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Reservoir Data

Head $= 300 - 330\ m$,
$E_{min} = 1000\ MWh$,
$E_{max} = 8000\ MWh$, $E_0 = 1000\ MWh$

Case Study: Optimization using ETPSO

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Market Data

Price Forecasts: NYISO
MCP of New York Central region,
Reserve Market Prices:
$B_{rs} = 6\ \$/MWh$ $B_{rn} = 0.5\ \$/MWh$

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ETPSO-Convergence characteristics

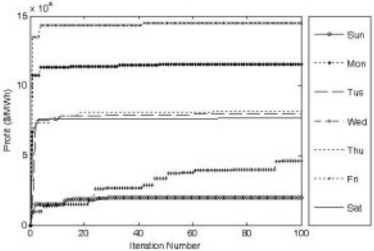

Figure: 16. Daily operating Mode

Case Study: Optimization using ETPSO

Blenheim-Gilboa
Pumped Storage Project
New York Power Authority

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Reservoir Data

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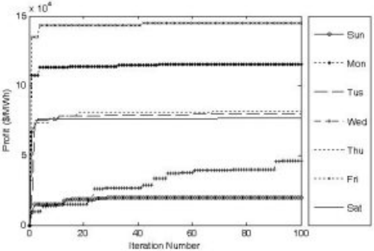

Figure: 16. Daily operating Mode

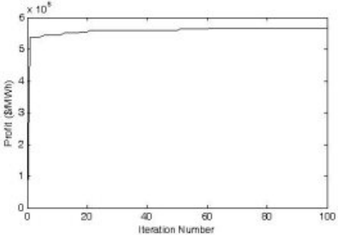

Figure: 17. Weekly operating mode

Results and Discussion

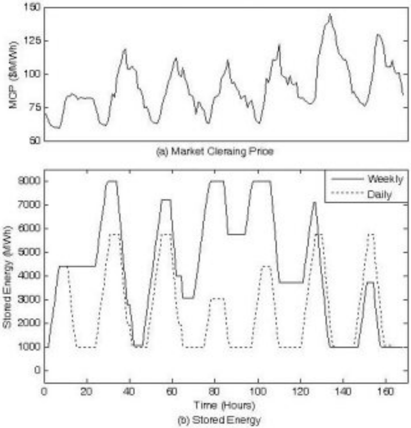

Figure: 18. Energy storage with respect to time

Results and Discussion

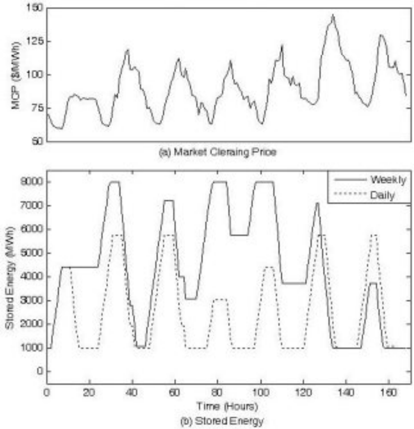

Figure: 18. Energy storage with respect to time

Table: VI. Optimal bidding schedule (22-28 June 2008)

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day	(A) Daily Operating Mode																							
Sun	0	0	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Mon	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	1	0	1	1	0	0	0	0	0	0
Tue	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	1	0	1	1	0	0	0	0	0	0
Wed	0	0	0	-1	-1	-1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
Thu	0	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Fri	-1	-1	-1	-1	-1	-1	-1	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Sat	0	-1	-1	-1	-1	-1	-1	-1	0	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0
	(B) Weekly Operating Mode																							
Sun	0	0	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mon	-1	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	1	1	0	1	1	0	0	0	0	-1	-1
Tue	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	1	1	1	0	0	1	0	0	0	0	0	-1	-1
Wed	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	-1	-1
Thu	-1	-1	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Fri	0	-1	-1	-1	-1	-1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Sat	0	0	0	-1	-1	-1	-1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0

- '-' sign indicates pumping
- '+' sign indicates generating

Results and Discussion

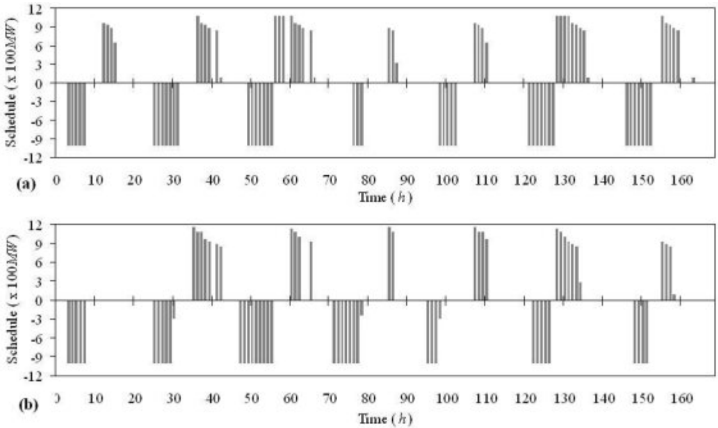

Figure: 19. Optimal power bids (22-28 June 2008) (a) Daily operating strategy, (b) Weekly operating strategy

Case Study: Optimization using ETPSO

Comparison of Results

- Two operating schedules: Daily and weekly
- Effective reservoir utilization in weekly scheduling
- ETPSO: Stochastic method - statistical evaluation
- Performance of ETPSO is compared with other evolutionary techniques
- Explores optimal time slots for self-scheduling
- With increased problem dimensionality, ETPSO gives comparatively faster solution

Case Study: Optimization using ETPSO

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- Two operating schedules: Daily and weekly
- Effective reservoir utilization in weekly scheduling
- ETPSO: Stochastic method - statistical evaluation
- Performance of ETPSO is compared with other evolutionary techniques
- Explores optimal time slots for self-scheduling
- With increased problem dimensionality, ETPSO gives comparatively faster solution

Table: VII. Performance of sequential and ETPSO methodologies

S - Schedule; D - Daily; W - Weekly

Pumping power P_p kept constant at 250 MW

S	t_p (h)	t_g (h)	P_g^{av} (MW)	Expec. Profit($)	Exe. time(s)
PSO					
D	42	35	202.46	565254	9.78
W	44	29	237.92	575299	709.45
Genetic Algorithm (GA)					
D	42	35	200.38	565260	7.12
W	43	29	236.37	575311	517.34
Sequential Methodology (SM)					
D	42	35	203.93	565246	1.08
W	45	30	239.67	575276	533.94
Proposed ETPSO					
D	41	35	199.14	565268	4.44
W	42	28	235.71	575376	350.86

Self-Scheduling in Combined Pool-Bilateral Market

Hybrid Market Model

- Combines the features of pool-based market and the bilateral contracts
- End-users have flexibility to purchase from either the pool or directly from the suppliers by exercising bilateral contracts

Self-Scheduling in Combined Pool-Bilateral Market

Hybrid Market Model

- Combines the features of pool-based market and the bilateral contracts
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Energy Market Sub-problem

Includes trading of power, both in bilateral contract and competitive market

$$\sum_{t \in T} B(t)\ P(t) =$$

$$\sum_{i=1}^{t_g^b} P_g^b(i)\ B_g^b(i) - \sum_{j=1}^{t_p^b} P_p^b(j)\ B_p^b(j) + \sum_{m=1}^{t_g^p} P_g(m)\ B_g(m) - \sum_{n=1}^{t_p^p} P_p(n) B_p(n) \quad (4)$$

Where,

Contract power during generating mode = $P_g^b(t)\ \forall\ t \in T$

Contract power during pumping mode = $P_p^b(t)\ \forall\ t \in T$

Case Study

- Two cases, varying bilateral contract period are considered
- Case-I : $t_p^b = t_g^b$ and $P_g^b = \frac{2}{3}P_p^b$
- Case-II: $t_g^b = \frac{2}{3}t_p^b$ and $P_g^b = P_p^b$

Case Study

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- Case-I : $t_p^b = t_g^b$ and $P_g^b = \frac{2}{3} P_p^b$
- Case-II: $t_g^b = \frac{2}{3} t_p^b$ and $P_g^b = P_p^b$

Table: VIII. Details of Agreed Bilateral Contract

Mode	hrs	Slot number	Power (MW)	Rate (\$)
Case-I				
Pump	3	3, 4, 5	250	47
Gen	3	18, 19, 20	160	89
Case-II				
Pump	3	3, 4, 5	250	47
Gen	2	18, 19	230	93

Case Study

- Two cases, varying bilateral contract period are considered
- Case-I : $t_p^b = t_g^b$ and $P_g^b = \frac{2}{3}P_p^b$
- Case-II: $t_g^b = \frac{2}{3}t_p^b$ and $P_g^b = P_p^b$

Table: VIII. Details of Agreed Bilateral Contract

Mode	hrs	Slot number	Power (MW)	Rate ($)
Case-I				
Pump Gen	3 3	3, 4, 5 18, 19, 20	250 160	47 89
Case-II				
Pump Gen	3 2	3, 4, 5 18, 19	250 230	47 93

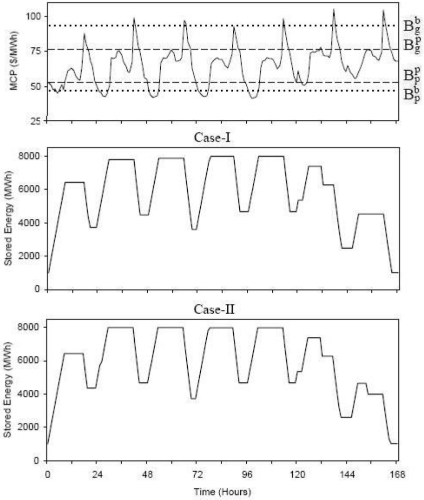

Figure: 21. Variation of Stored Energy with Respect to MCP over the Time

Case Study

Table: IX. Optimal Bidding Strategy: Combined Pool-Bilateral Market, Case-I and Case-II

Case I

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day 1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 2	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 3	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	-1
Day 4	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 5	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 6	0	0	-1	-1	-1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0
Day 7	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0

Case II

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day 1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	-1
Day 2	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 3	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	-1
Day 4	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 5	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 6	0	0	-1	-1	-1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0
Day 7	0	0	-1	-1	-1	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0

Self-Scheduling in Combined Pool-Bilateral Market

Case Study

Table: IX. Optimal Bidding Strategy: Combined Pool-Bilateral Market, Case-I and Case-II

Case I

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day 1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 2	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 3	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	-1
Day 4	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 5	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 6	0	0	-1	-1	-1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0
Day 7	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0

Case II

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day 1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	-1
Day 2	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 3	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	-1
Day 4	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Day 5	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	-1
Day 6	0	0	-1	-1	-1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0
Day 7	0	0	-1	-1	-1	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0

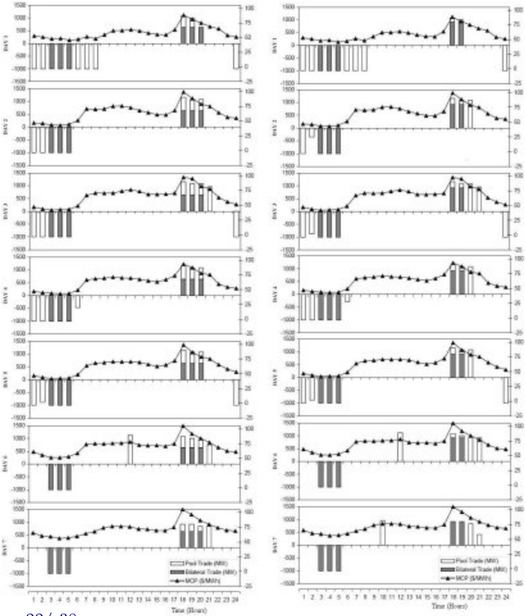

Figure: 22. Optimal Power Bids and Offers for Case-I and Case-II

Comparison and Observations

Table: X. Result Summary: Plant Operating Time

Pumping Time (hrs)				Gen Time (hrs)			
t_p^b	t_p^p	t_p^{p*}	t_p	t_g^b	t_g^p	t_g^{p*}	t_g
Pool Market Trading [Ning Lu]							
-	35	-	35	-	22	-	22
Combined Pool-Bilateral Market: Case-I							
21	17	0	38	21	24	4	25
Combined Pool-Bilateral Market: Case-II							
21	17	0	38	14	23	11	25

t_p^{p*} and t_g^{p*} indicate respective time periods excluding the time period overlapped with bilateral contracts

Case-II provides more flexibility for the operator to trade in the pool market

Comparison and Observations

Table: X. Result Summary: Plant Operating Time

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t_p^{p*} and t_g^{p*} indicate respective time periods excluding the time period overlapped with bilateral contracts

Case-II provides more flexibility for the operator to trade in the pool market

Table: XI. Economic Comparison of Combined Pool-bilateral Market

Revenues in $

Category	Pool Market	Hybrid Market	
		Case-I	Case-II
Bilateral	-	209160	210840
Pool	443473	243611	285024
Syn Res	210000	224100	218400
Non-syn	59940	55965	56790
Total	713413	732836	771054

Profits from various energy and ancillary service market sources

Case-II has proven profitable due to high degree of liberty

Market Uncertainty and Risk

Major uncertainties affecting pumped-storage self-scheduling

1. Uncertainty of energy market price forecast
2. Uncertainty of power delivery request from ancillary services markets

Market Uncertainty and Risk

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Uncertainty of MCP forecast

- Characterized by the variances of MCP of Energy and reserve markets.
- Self-scheduling problem is formulated by recognizing a measure of risk by introducing a rick tolerance factor β
- Impact of risk penalty factors on expected profit is investigated

Market Uncertainty and Risk

Major uncertainties affecting pumped-storage self-scheduling

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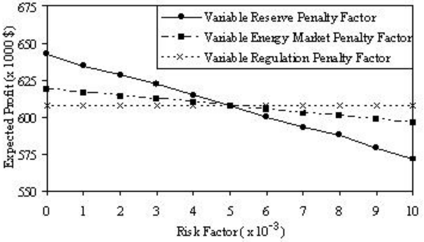

Figure: 23. Expected profit on variable risk factors

Market Uncertainty and Risk

Uncertainty of ancillary services power delivery request

- Successive self-scheduling using the sliding window technique to adjust the operation schedule of pumped-storage plant
- Dynamic updation of self-scheduling problem
- Considering the modified upper reservoir storage due to the delivered ancillary services in the previous day and the forecast of the day-ahead markets
- Updated before the beginning of a new day for next consecutive days of the scheduling period, i.e. for next 168 h

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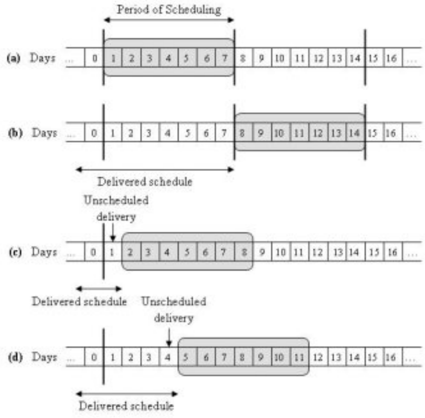


Figure: 24. Self-scheduling with uncertain power delivery request

Impact of Pumped-Storage on Market Social Welfare

Concept of social welfare

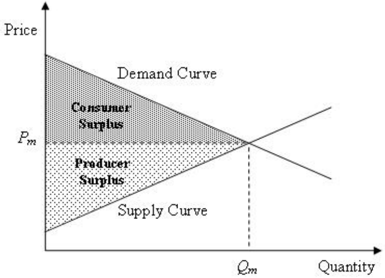
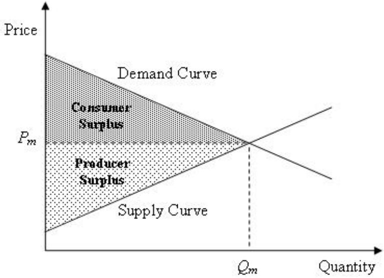


Figure: 25. Consumer and producer surplus

- Producers able to supply at lower cost than the MCP P_m
- Consumers willing to pay more than the actual MCP
- Amount of trade above the marginal cost

Impact of Pumped-Storage on Market Social Welfare

Concept of social welfare



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Residual Demand / Supply

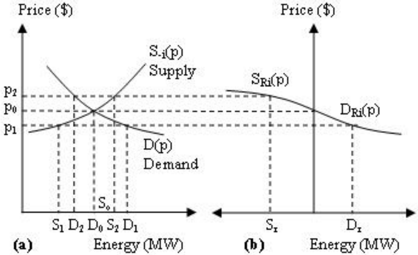
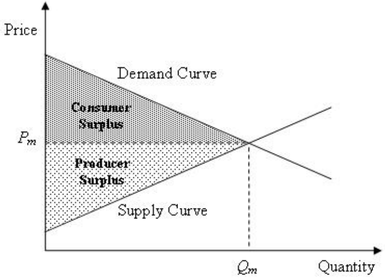


Figure: 26. Residual Demand / Supply Curve

Impact of Pumped-Storage on Market Social Welfare

Concept of social welfare



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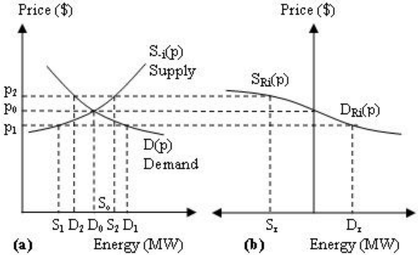


Figure: 26. Residual Demand / Supply Curve

Residual demand facing the generator

$$D_{Ri}(p_i) = \sum_{j=1, j\neq i}^{n} (D_j(p_j) - S_j(p_j)) \tag{5}$$

Residual supply facing the pump load

$$S_{Ri}(p_i) = \sum_{j=1, j\neq i}^{n} (S_j(p_j) - D_j(p_j)) \tag{6}$$

Impact of Pumped-Storage on Market Social Welfare

Plant Operating as Pump Load

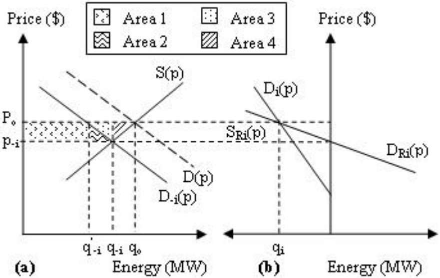


Figure: 27. Social Welfare Analysis: Plant Operating as Pump Load

Plant Operating as Pump Load

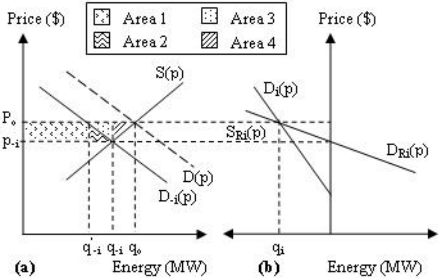


Figure: 27. Social Welfare Analysis: Plant Operating as Pump Load

Loss of consumer surplus $= \frac{\delta_p^P}{2}(q_{-i} + q'_{-i})$

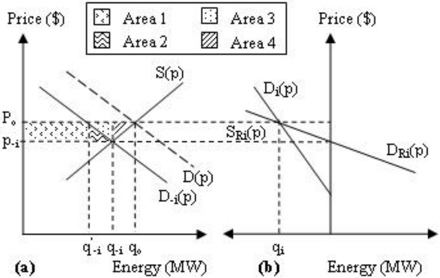
Gain of producer surplus $= \frac{\delta_p^P}{2}(q_0 + q_{-i})$

Increase in social welfare $= \frac{\delta_p^P}{2}(q_0 - q'_{-i})$

where $\delta_p^P = (p_0 - p_{-i})$ \$.

Impact of Pumped-Storage on Market Social Welfare

Plant Operating as Pump Load



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Plant Operating as Generator

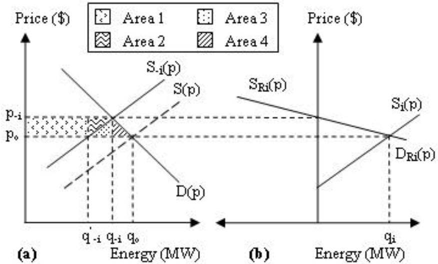

Figure: 28. Social Welfare Analysis: Plant Operating as Generator

Impact of Pumped-Storage on Market Social Welfare

Plant Operating as Pump Load

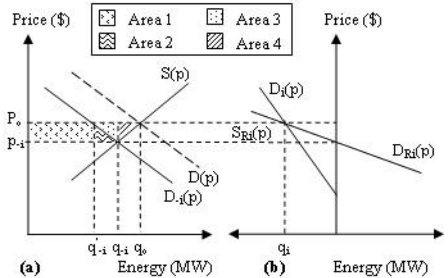

Figure: 27. Social Welfare Analysis: Plant Operating as Pump Load

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Plant Operating as Generator

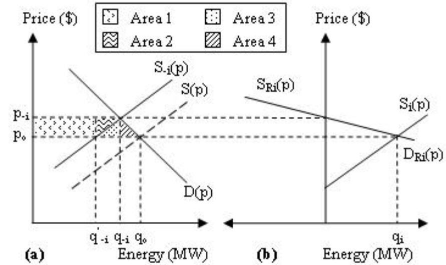


Figure: 28. Social Welfare Analysis: Plant Operating as Generator

Loss of producer surplus $= \frac{\delta_p^G}{2}(q_{-i} + q'_{-i})$

Gain of consumer surplus $= \frac{\delta_p^G}{2}(q_0 + q_{-i})$

Increase in social welfare $= \frac{\delta_p^G}{2}(q_0 - q'_{-i})$

where $\delta_p^G = (p_{-i} - p_0)$ \$.

Impact of Pumped-Storage on Market Social Welfare

Impact on Social Welfare of Market

- Pumping mode: Increase in producer surplus, decrease in consumer surplus, i.e. Benefits producers at the expense of consumers
- Generating mode: Increase in consumer surplus, decrease in producer surplus, i.e. benefits consumers at the expense of producers

Impact of Pumped-Storage on Market Social Welfare

Impact on Social Welfare of Market

- Pumping mode: Increase in producer surplus, decrease in consumer surplus, i.e. Benefits producers at the expense of consumers
- Generating mode: Increase in consumer surplus, decrease in producer surplus, i.e. benefits consumers at the expense of producers
- Pumping and generating mode: Increase net industry welfare
- Introduces more competition in the market, increase market social welfare by redistributing the resources across time
- Stabilize the energy prices and reduce the MCP swing over the time

Impact of Pumped-Storage on Market Social Welfare

Case Study

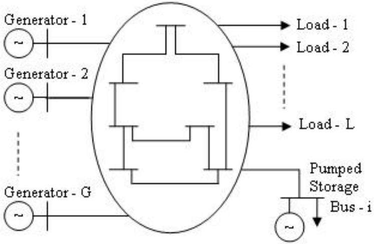


Figure: 29. Electricity Market with Pumped Storage Hydro-Power Plant

Impact of Pumped-Storage on Market Social Welfare

Case Study

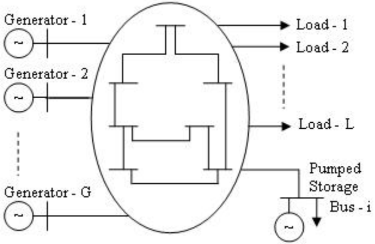


Figure: 29. Electricity Market with Pumped Storage Hydro-Power Plant

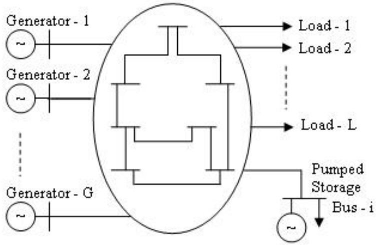
System Data

IEEE 118 Bus Test System

No. of dispatchable generators	: 53
No. of dispatchable loads	: 32
No. of non-dispatchable loads	: 66
No. of pumped storage plants	: 01
On-line generation capacity	: 9470 MW
Fixed Load (Non-dispatchable)	: 3051 MW
Pumped storage plant capacity	: 1000 MW

Impact of Pumped-Storage on Market Social Welfare

Case Study



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Fixed Load (Non-dispatchable)	: 3051 MW
Pumped storage plant capacity	: 1000 MW

- Market auction clearing mechanism take set of offers and bids in blocks
- These blocks converted into corresponding generator capacities and costs
- OPF solution - for clearing the market and find generator allocations, loads to be dispatched along with nodal prices
- Uniform pricing equal to LAO is followed for computation of nodal prices

Impact of Pumped-Storage on Market Social Welfare

Pumped Storage Plant Operating as Pump Load

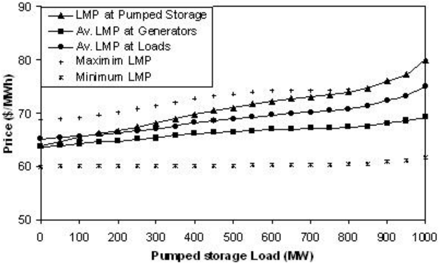

Figure: 30. Variation in LMP

- LMP increases as the pumped storage load increases
- Bus-66 LMP move towards maximum and reaches maximum when the pump load = 850 MW

Impact of Pumped-Storage on Market Social Welfare

Pumped Storage Plant Operating as Pump Load

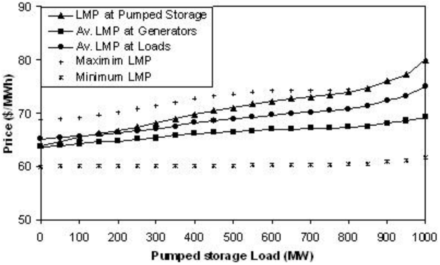

Figure: 30. Variation in LMP

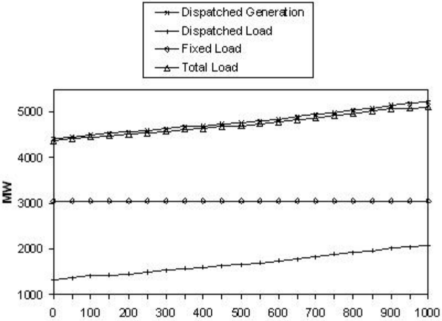

Figure: 31. Variation in Market Dispatch

- LMP increases as the pumped storage load increases
- Bus-66 LMP move towards maximum and reaches maximum when the pump load = 850 MW

- Rate of increase in market dispatch is less than that of pump load
- Consumers have negative impact that a fraction of thier dispatch is taken by pumped storage now

Impact of Pumped-Storage on Market Social Welfare

Pumped Storage Plant Operating as Generator

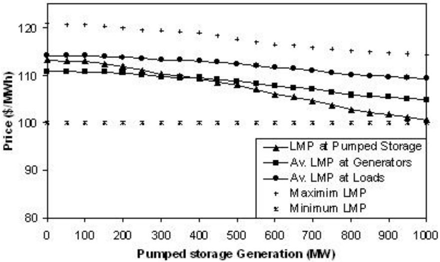

Figure: 32. Variation in LMP

- LMP decreases as the pumped storage plant generation increases
- Bus-66 LMP move towards minimum and at one stage, reaches minimum among all the system buses

Pumped Storage Plant Operating as Generator

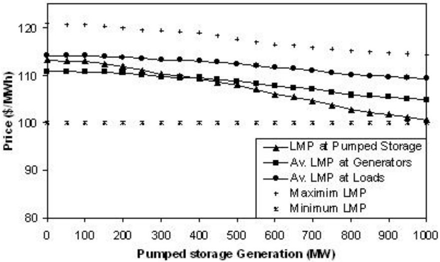

Figure: 32. Variation in LMP

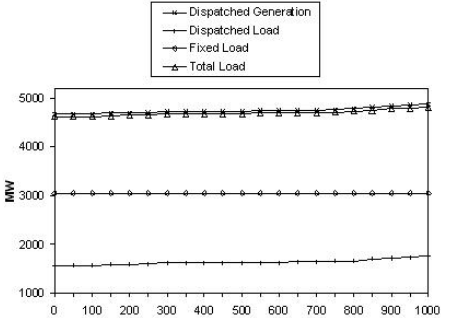

Figure: 33. Variation in Market Dispatch

- LMP decreases as the pumped storage plant generation increases
- Bus-66 LMP move towards minimum and at one stage, reaches minimum among all the system buses

- Rate of increase in market dispatch is less than pumped storage supply
- Consumers have positive impact due to the transfer of surplus from producers to consumers

Impact of Pumped-Storage on Market Social Welfare

Net Increase in Social Welfare

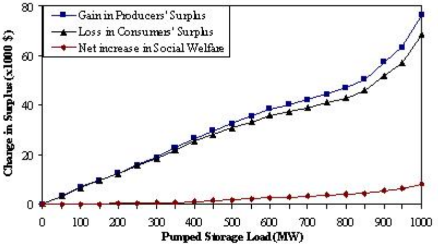

Figure: 34. Variation in producers and consumers surplus along with net increase in social welfare during pumping mode

- Transfer of surplus from consumers to producers
- Producers will have a positive impact
- Other consumers will have negative impact

Impact of Pumped-Storage on Market Social Welfare

Net Increase in Social Welfare

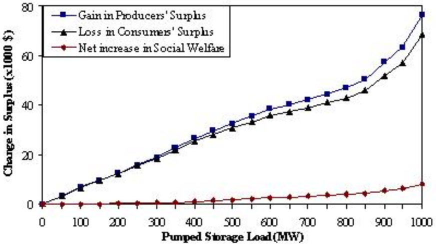

Figure: 34. Variation in producers and consumers surplus along with net increase in social welfare during pumping mode

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- Other consumers will have negative impact

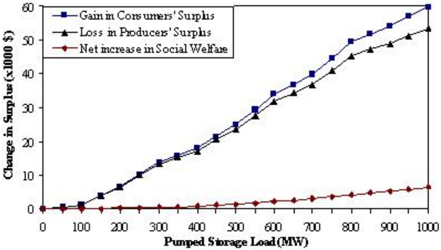


Figure: 35. Variation in producers and consumers surplus along with net increase in social welfare during generating mode

- Transfer of surplus from producers to consumers
- Consumers will have a positive impact
- Other suppliers will have negative impact

Impact of Pumped-Storage on Market Social Welfare

Profit of Pumped Storage Plant

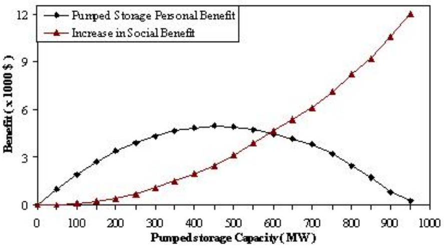
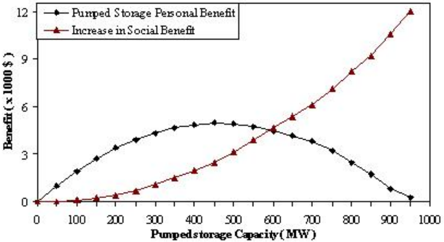


Figure: 36. Variation in pumped-storage personal benifit and market social benifit

- When plant is operated as pump and as generator for an hour each
- Net increase in social benefits corresponding to the personal benefit of pumped-storage plant

Impact of Pumped-Storage on Market Social Welfare

Profit of Pumped Storage Plant



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Market Price Stabilization

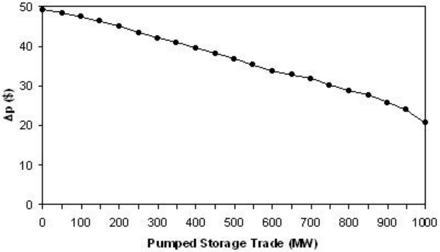

Figure: 37. Variation of difference in MCP between pumping and generating mode

- MCP swing $\Delta_p = \delta_p^P + \delta_f + \delta_p^G$
- Pumped storage energy trade stabilizes the price swing in the market over the time

Conclusions

1. Bidding strategy for pumped-storage plant to determine it's optimal self-schedule and trade in an electricity market is developed
2. ETPSO based optimization algorithm which is adaptive for the variation in water head on generation level is developed
3. Validation of the proposed strategy on realistic pumped-storage power plants has proven attractive

Conclusions

1. Bidding strategy for pumped-storage plant to determine it's optimal self-schedule and trade in an electricity market is developed
2. ETPSO based optimization algorithm which is adaptive for the variation in water head on generation level is developed
3. Validation of the proposed strategy on realistic pumped-storage power plants has proven attractive
4. Uncertainty management - The probabilistic MCP forecast is handled with trade-off between expected profit and risk, and uncertain ancillary services delivery request is addressed using the dynamic self-scheduling approach
5. Inference on energy market shows that pumped-storage energy trade increases the net social welfare and stabilizes the market price dynamics

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Thank You

PRESENTATION- OUTLINE

- About WAPCOS

WAPCOS Experience in

- Hydroelectric Projects
- Pumped Storage Projects

- Power Scenario- An Overview
- Pumped Storage Technology- Description
- What it Offers
- Case Studies
- Preparation of DPR- Latest Guidelines
- Conclusion and Wayforward

WAPCOS Profile

Established under the aegis of Ministry of Water Resources in June 1969 under Companies Act, 1956

- ✓ To share India's experience and expertise
- ✓ Facilitate Diplomatic Initiatives
- ✓ To augment endeavors of State and Central agencies

Major Fields of Specialization

Water Resources

- Irrigation, Drainage and Water Management
- Ground Water Exploration and Minor Irrigation
- Flood Control and River Morphology
- Dam and Reservoir Engineering
- Water Bodies and Lakes Conservation
- Agriculture Including Dry Lands Farming
- Rainfed and Irrigated Agriculture
- Watershed Management
- Natural Resources Management

Power

- Hydro Power
- Thermal Power
- Pumped Storage Projects
- Transmission & Distribution
- Rural Electrification
- Non-conventional Sources of Energy

Infrastructure

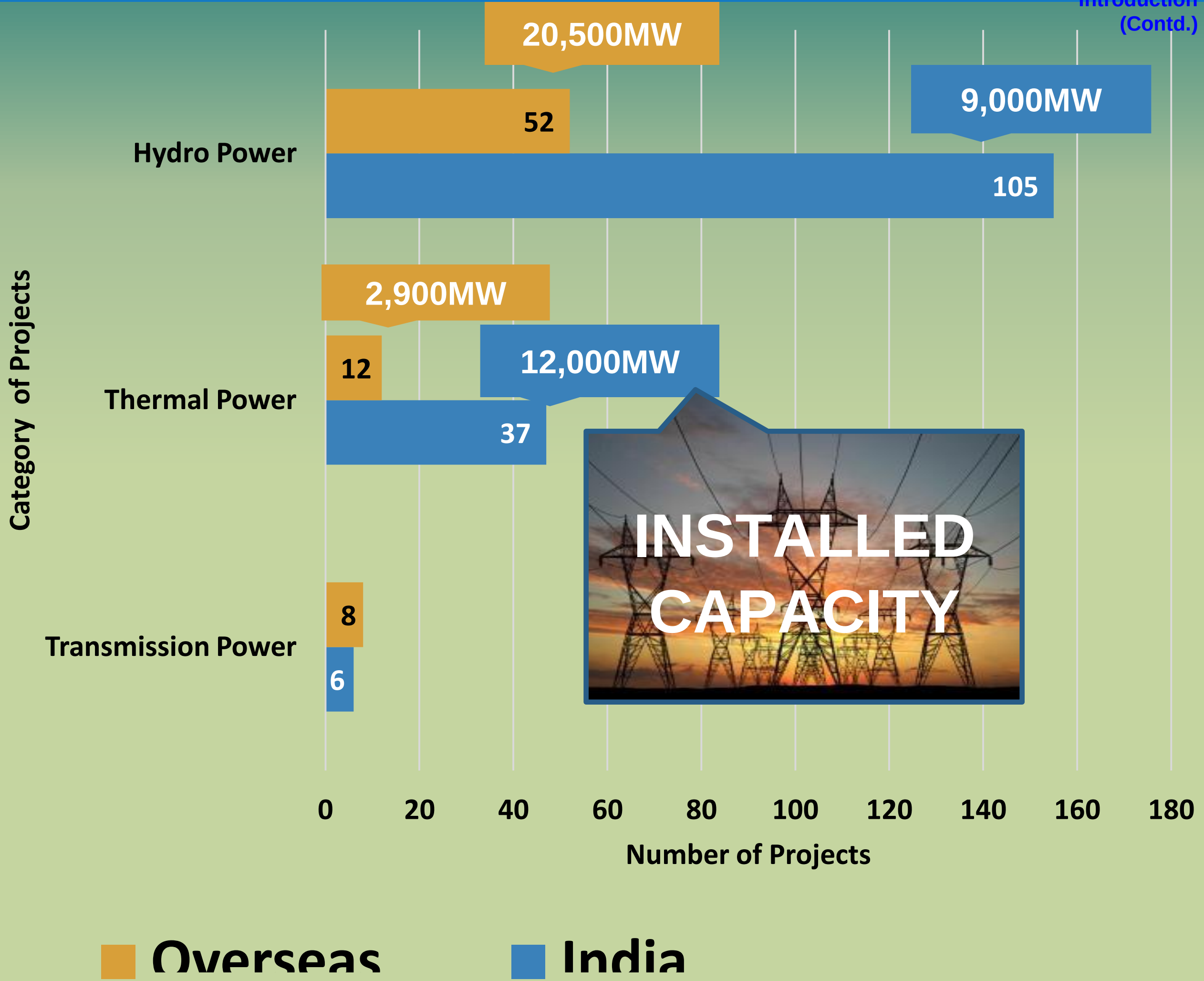
- Water Supply, Sanitation and Drainage
- Environment
- Ports & Harbours and Inland Waterways
- Urban and Rural Areas Development
- Roads and Highway Engineering

Range of Consultancy Services

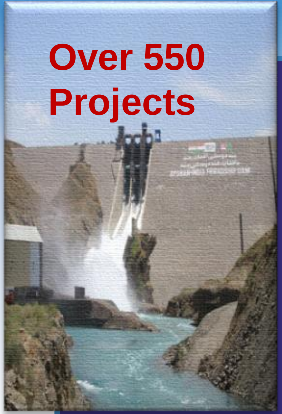
- Preliminary Investigations/ Reconnaissance
- Feasibility Studies/Planning/Project Formulation
- Baseline and Socio-Economic Surveys
- Field Surveys & Investigations and Testing
- Institutional/Human Resource Development
- Ghat Development
- Engineering Designs, Drawings and Tendering Process
- Project Management and Construction Supervision
- Operations and Maintenance

USP
POWER

Concept to
Commissioning



USP
WATER RESOURCES



In Irrigation, Water Resources, Flood Control, Ground Water, Agricultural etc.

Contributed in Development of Irrigation Potential of Over 15 Million Ha.

In India & Abroad in the fields of Irrigation, Hydro Power, Thermal Power, Ports & Harbor

Environmental Impact Assessment Studies

USP
INFRASTRUCTURE

In Water Supply & Sanitation, IEC, Rural & Urban Development, Roads and Highways Engineering, etc.

WILLINGNESS TO GO 'EXTRA MILE'

Ports and Inland Navigation Projects

Surveys & Investigations/Modeling/ Detailed Engineering

Registration with International Organizations

- World Bank
- Asian Development Bank
- African Development Bank
- Japan Bank for International Cooperation
- United Nations Office for Project Services

Supporting Organisations

WATER, POWER, INFRASTRUCTURE
MINI RATNA-1

WAPCOS

CENTRAL WATER COMMISSION

GEOLOGICAL SURVEY OF INDIA

अनुसंधान के माध्यम से सेवा
Service Through Research

CENTRAL WATER AND POWER RESEARCH STATION

SURVEY OF INDIA

CENTRAL ELECTRICITY AUTHORITY

CENTRAL GROUND WATER BOARD

केन्द्रीय मृदा एवं सामग्री अनुसंधानशाला
Central Soil And Materials Research Station

CENTRAL SOIL & MATERIALS RESEARCH STATION

Quality Management System

❖Consultancy Services

➢Quality Management System conform to ISO 9001:2008 for Consultancy Services in Water Resources, Power and Infrastructure Development Projects

✓Valid upto October, 2017


IRCLASS
SYSTEMS AND SOLUTIONS PRIVATE LIMITED

CERTIFICATE OF APPROVAL

Issued by Indian Register Quality Systems
(A Division of IRCLASS Systems and Solutions Private Limited)

This is to certify that the Quality Management System of

Organisation: Wapcos Limited
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has been assessed and found conforming to the following requirement

Standard Certified: ISO 9001:2008
Scope: Consultancy Services in Water Resources, Power and Infrastructure Development Projects

Certificate No.: IRQS/1410709 granted on: 22nd October 2014

Originally Certified: 24/10/2008 Current Issue Date: 24/10/2014 Valid Till Date: 23/10/2017

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Indian Register Quality Systems

Shashi Nath Mishra
Head IRQS

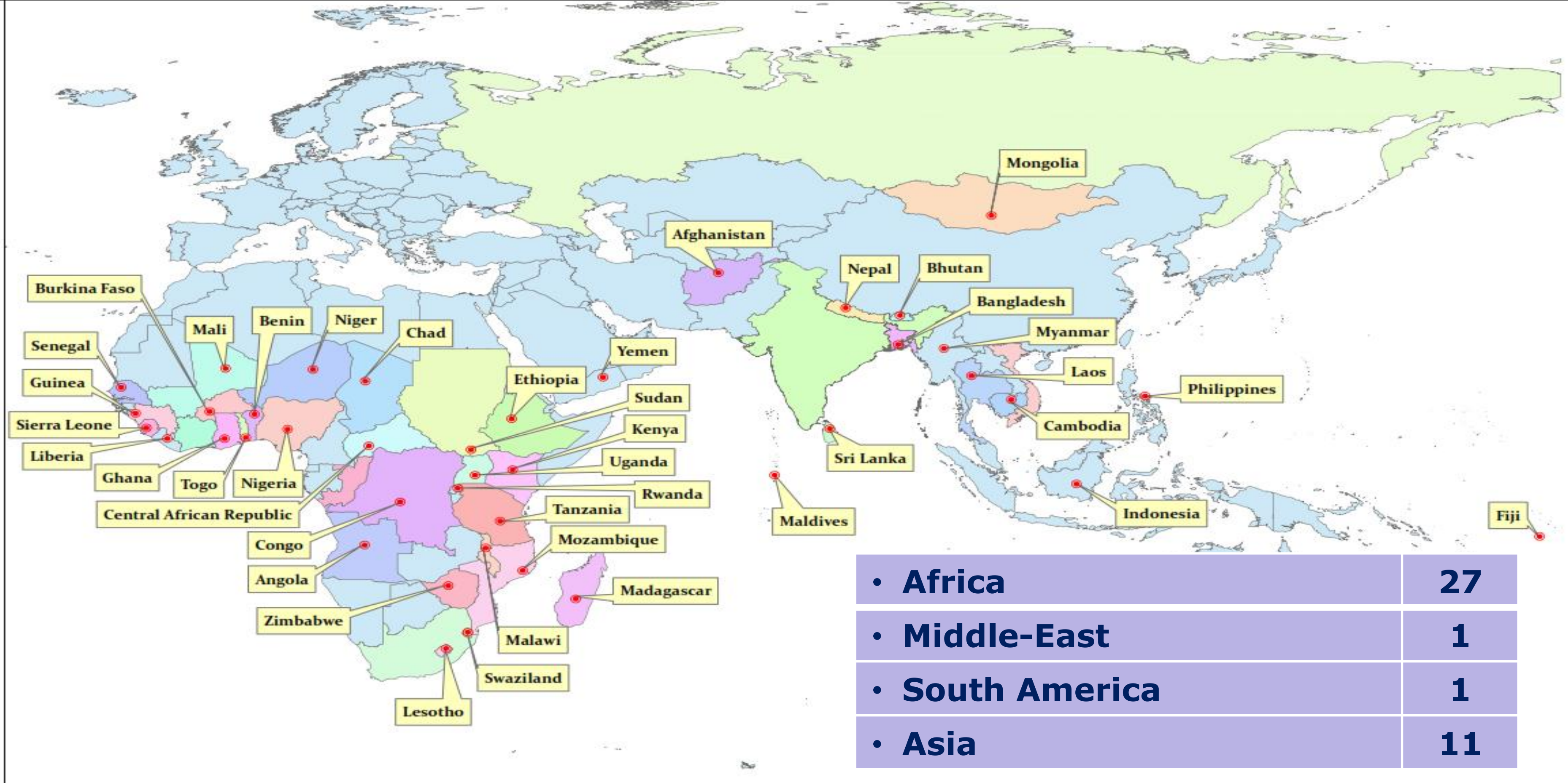
This approval is subject to continued satisfactory maintenance of the Quality Management Systems of the organization to the above standard,which will be monitored by IRQS. The use of the Accreditation Mark indicates accreditation with respect to activities covered by the certificate with accreditation no. C071

Condition Overleaf

Head Office: 52A, Adi Shankaracharya Marg.Opp.Powai Lake, Powai Mumbai - 400 072 India

- WAPCOS is accredited by NABET for conducting EIA Studies for Projects in the areas of River Valley, Thermal Power, Mines, Ports & Harbours and Building Construction

Operations Abroad



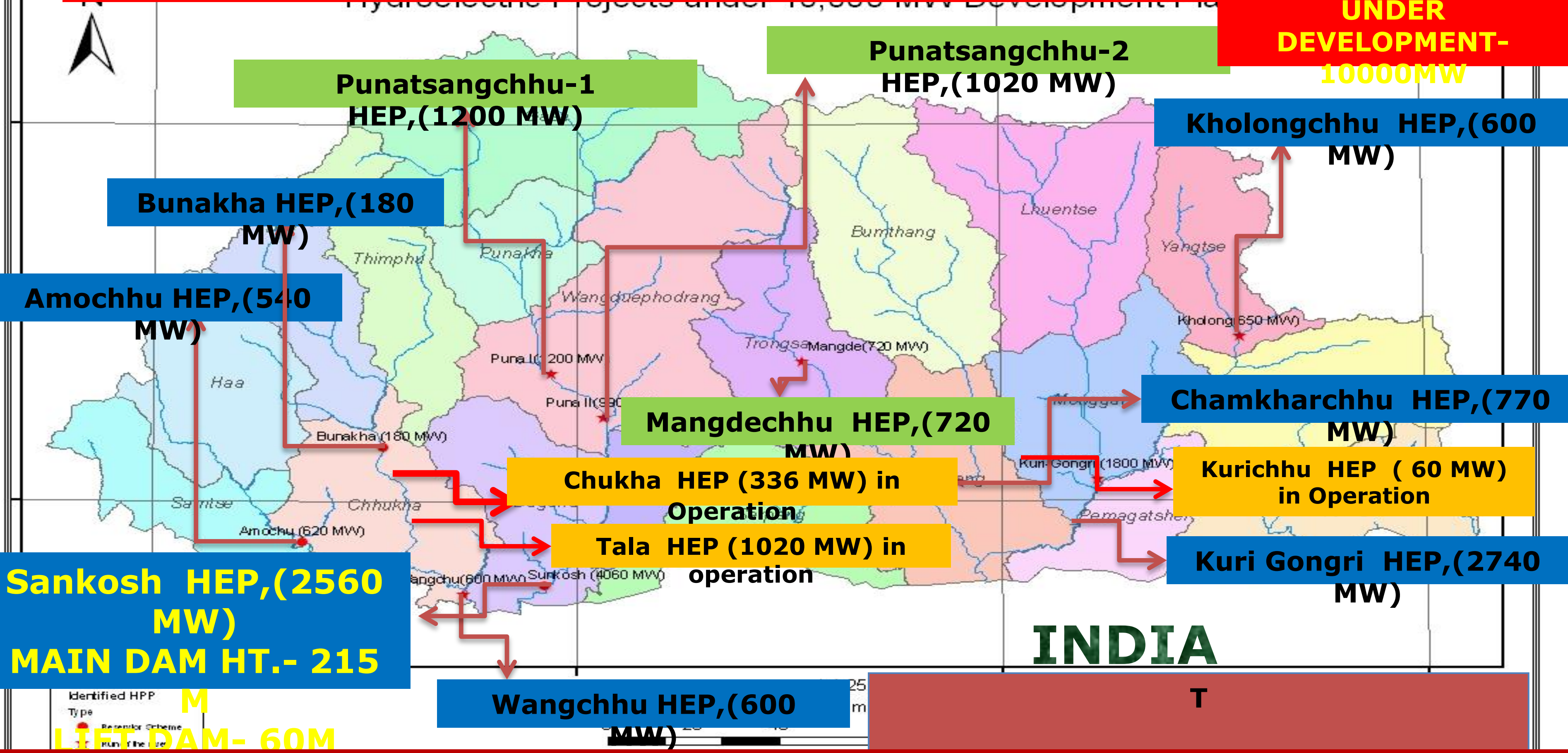
• Africa	27
• Middle-East	1
• South America	1
• Asia	11

Operations in India

REGIONAL/FIELD OFFICES

Hydropower Development in Bhutan

UNDER OPERATION- 1416 MW
UNDER DEVELOPMENT- 10000MW



Hydropower Potential of Bhutan is 30000 MW, Feasible is 23760 MW

Hydropower Development in India

- WAPCOS successfully completed 71 PFR's of H.E. Projects in India in year 2003-2005 under PM's 50000 MW Initiative for Hydro power Development

- WAPCOS has recently been appointed consultants by Central Electricity Authority (CEA) for Basin-wise review of balance Hydroelectric Potential including Pumped Storage Projects & Preparation of Basin Reports for following basins:

- Indus Basin
- Ganga Basin
- Brahmaputra Basin
- **West Flowing rivers of Southern India**
- East flowing rivers of Southern India

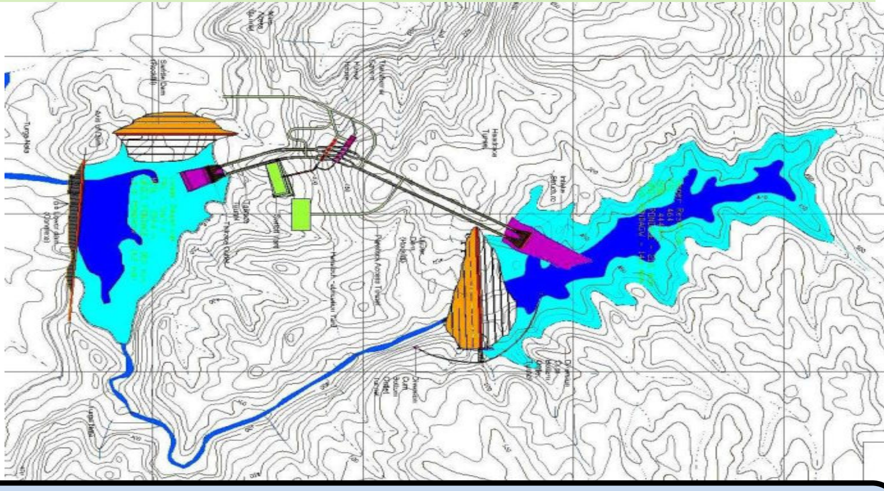
WAPCOS EXPERIENCE IN PUMPED STORAGE PROJECT

Type	**–** Pumped Storage Project
Installed capacity	– 4 x 225 MW
Power	– 5,400MWh
Location	– West Bengal
Peak duration	– 6 Hours

PURULIA PUMPED STORAGE PROJECT (4 x 225 MW), INDIA

(Under operation since 2007)

Type	**–** Pumped Storage Project
Installed capacity	– 4 x 250 MW
Power	– 5,000MWh
Location	– West Bengal
Peak duration	– 5 Hours



TURGA PUMPED STORAGE PROJECT (4 x 250 MW), INDIA

(TEC obtained in 2016)

WAPCOS EXPERIENCE IN PUMPED STORAGE PROJECT

Client: OHPC,
Government of **Odisha**

Scope of Services:

- Preparation of DPR
- Surveys and Investigations

UPPER INDRAVATI PUMPED STORAGE PROJECT [600 MW]

Client: TANGEDCO, **Tamilnadu**

Scope of Services:

- Review of DPR
- Tender Engineering & Detailed Design Engineering
- Construction Supervision

KUNDAH PUMPED STORAGE PROJECT [500 MW]

SHARAVATHY PSP, 1000 MW, KARNATAKA

- The Project is Pumped Storage Project, (1000 MW) for which the Detailed Project Report (DPR) is being prepared .
- WAPCOS has been recently appointed as the Engineering Consultant of the Project for Preparation of PFR,DPR including Surveys and Investigation by KPCL.

Bandu PSP, 900 MW, West Bengal

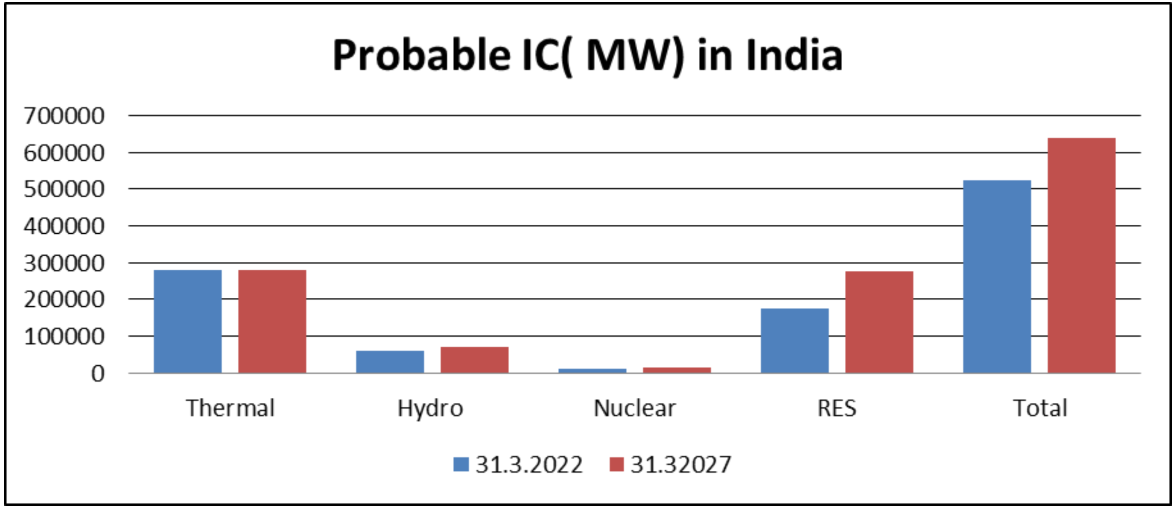
- The Project is Pumped Storage Project, (900 MW) for which the PFR is being prepared .
- WAPCOS has been recently appointed as the Engineering Consultant of the Project for Preparation of PFR by WBSEDCL.

Lugu Pahad PSP, 1500 MW, West Bengal

- Lugu Pahad PSP,3000 MW- Damodar Valley Corporation , Jharkhand
- Upper Kolab PSP, OHPC

POWER SCENARIO- An Overview

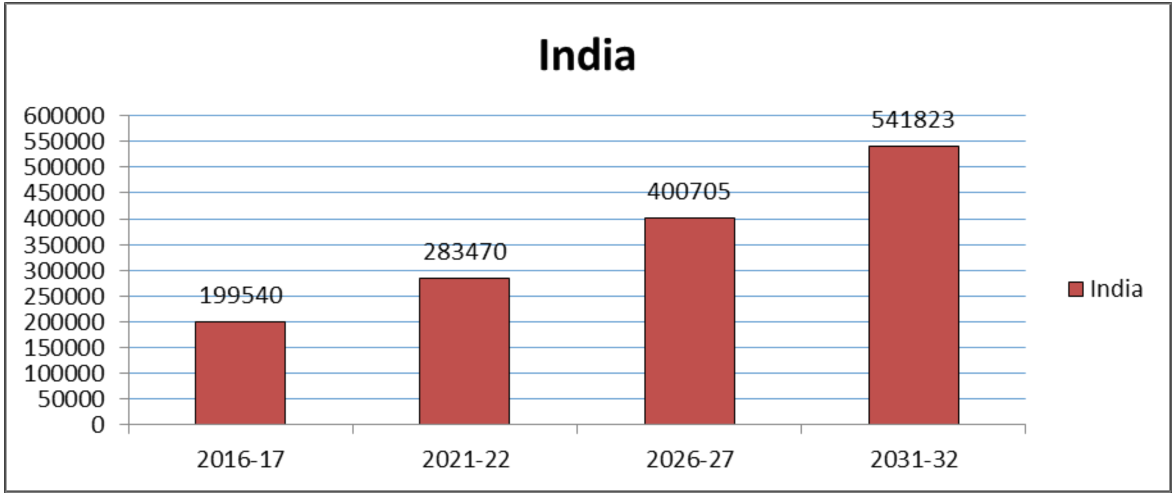
	As on 31.3.2022	As on 31.3.2027
Thermal	278481	278481
Hydro	59828	71828
Nuclear	10080	14880
RES	175000	275000
Total	523389	640189
Hydro share (%)	**11.4**	**11.2**



POWER SCENARIO- An Overview

Forecast of Annual Peak Load (MW) for terminal years of 12th to 15th plan

	2016-17	2021-22	2026-27	2031-32
All India	199540	283470	400705	541823

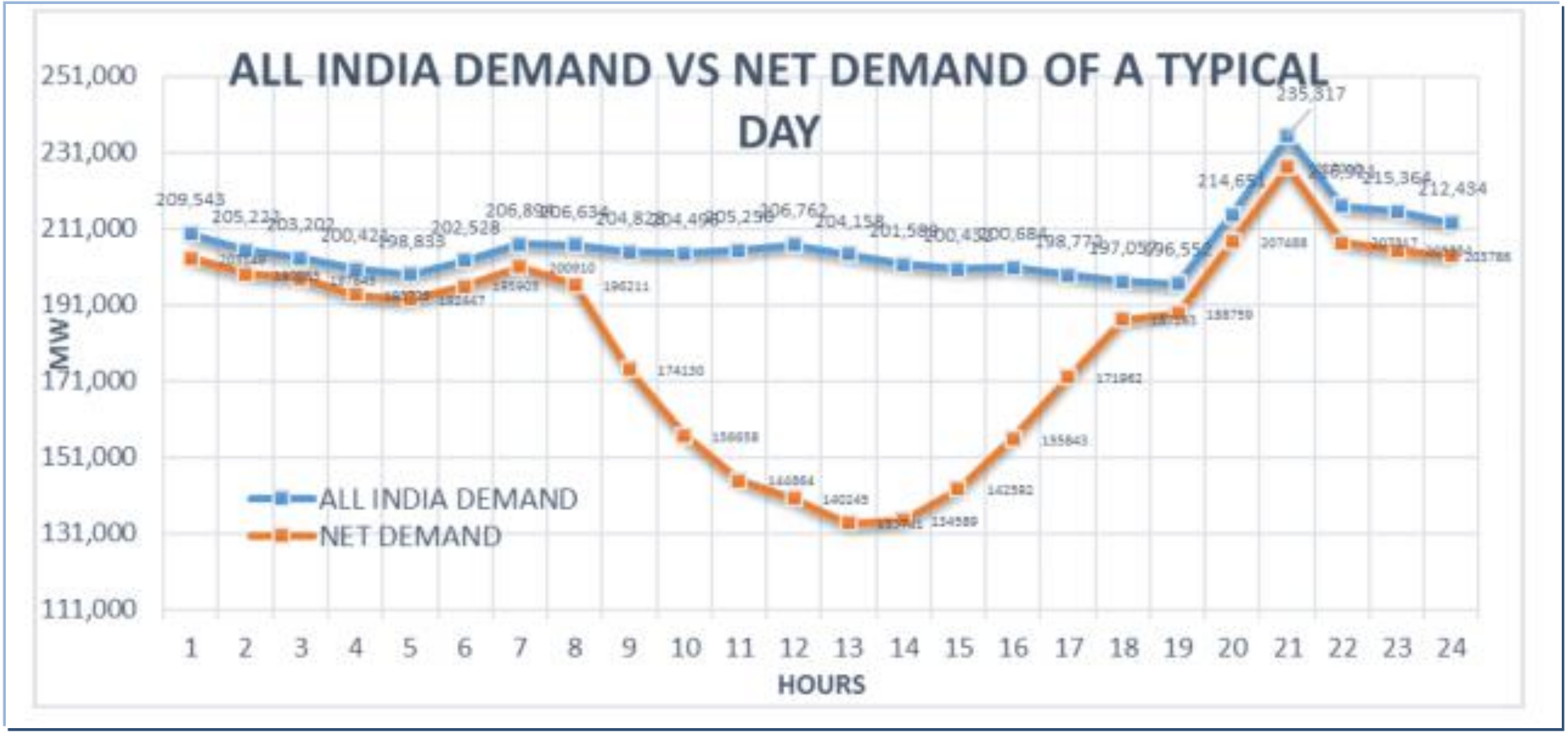


RENEWABLES- PROJECTIONS

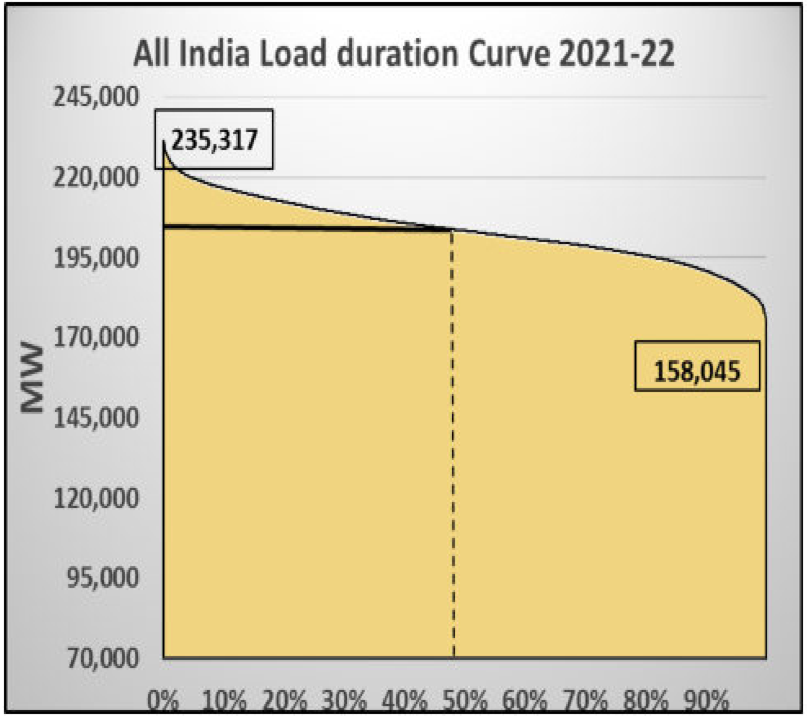
- As per Draft NEP 2016 -All – India Installed Capacity of RES to **175 GW** and **275 GW** by 2021-22 and 2026-27 respectively
- An average of **20% of Installed Capacity** is expected to be Solar as per Government's Policy.
- The projected installed capacity for 2021-22 and 2026-27 are given below:

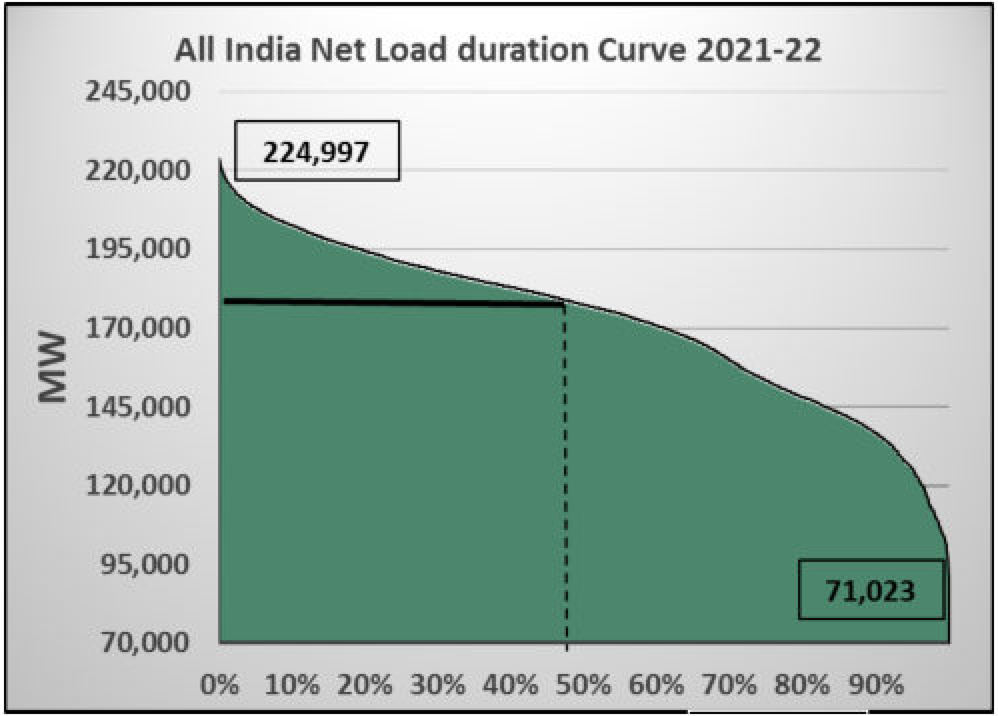
	2026-27		2021-22	
Fuel Type	Capacity (MW)	%	Capacity (MW)	%
Hydro	71,828		59,828	
Coal + Lignite	2,48,513*		2,48,513*	
Gas	29,968		29,968	
Nuclear	14,880		10,880	
Total Conventional Capacity *	**3,65,189**	**57%**	**348,389**	**67%**
Total Renewable Capacity	**2,75,000**	**43%**	**175,000**	**33%**
Total Capacity by 2026-27	**6,40,189**	**100%**	**523,389**	**100%**

CHALLENEGES- INTEGRATION OF RENEWABLES



CHALLENGES- INTEGRATION OF RENEWABLES

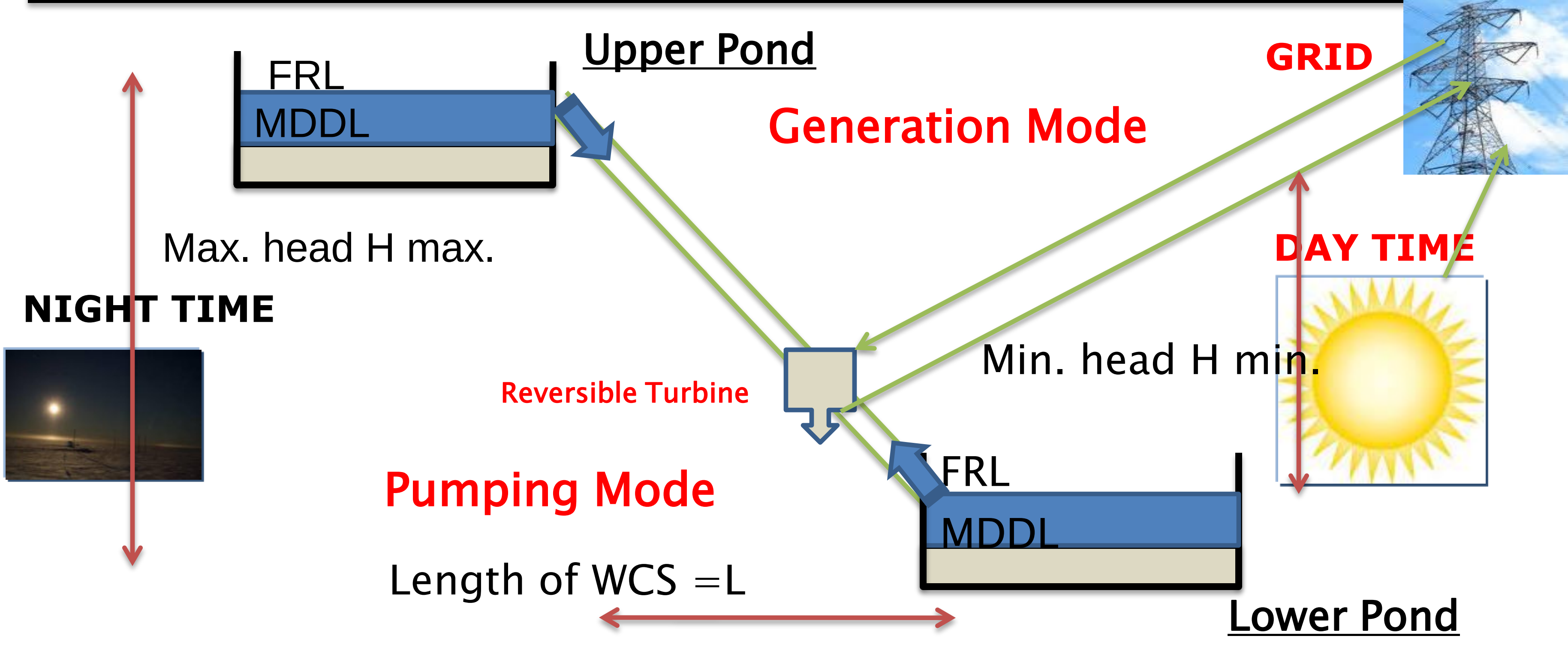




Pumped Storage Technology

- In order to address this problem the efforts were made to evolve various **ENERGY STORAGE** means.
- **Technology Description:**
- The basic arrangement - Involves two storage reservoirs upper and lower separated at vertical difference with reversible turbine /pump between the two reservoirs.
- The technology is a **Mechanical storage of the energy.**
- Water is lifted to the upper reservoir by pumping mechanism through extra electricity during off-peak time.
- The stored potential energy in the upper reservoir is used to generate electricity by turbines when they are needed.
- Pumping is similar to **Charging the Batteries** for future use.
- This is a **Natural** Battery with associated inherent advantages .

Pumped Storage Project



$L/H_{max.}$ Ideally around 5 to 7

$H_{max}/H_{min.} < 1.5$

Pumped Storage - What It Offers

- **GRID LEVEL**
- It utilizes grid power during off peak hour when frequency is high and supply power during peak hour and whenever required.
- Regulates frequency to meet sudden load changes in the network.
- Improve grid controllability, Grid stability and Security
- **THERMAL STATIONS**
- Increase capacity utilization of Thermal stations
- Reduce operational problem of thermal stations during Light load period
- **GENERAL**
- Provides Black Start facility
- It addresses intermittence of renewable energy to a large extent
- It improves the tradability of power in the electricity market
- It helps improve hydro thermal mix ratio
- Availability of spinning reserve at almost no cost to the system
- Pumped Storage Schemes improve over all economy of power system operation

Pumped Storage Projects- Technical Complexities Involved

- **General**
- **Essentially require two reservoirs - Results in**
- Submergence Issues
- Land Requirement Issues
- R& R Issues
- More requirement of Construction material
- **Site Specific Requirements**
- Two reservoir to be in close vicinity due to L/H ratio – Difficult to Find
- High Head Makes PSP attractive- Few sites in India
- Desired topography and river meandering to have short WCS
- Desired topography and Geology conducive to have straight WCS
- Steep River gradient to have maximum head in minimum distance
- Difficulties in siting two Intake structures for upper and Lower pond
- Large head variations between FRL and MDDL and associated slope stability issues
- Large head variation impacts Machine design

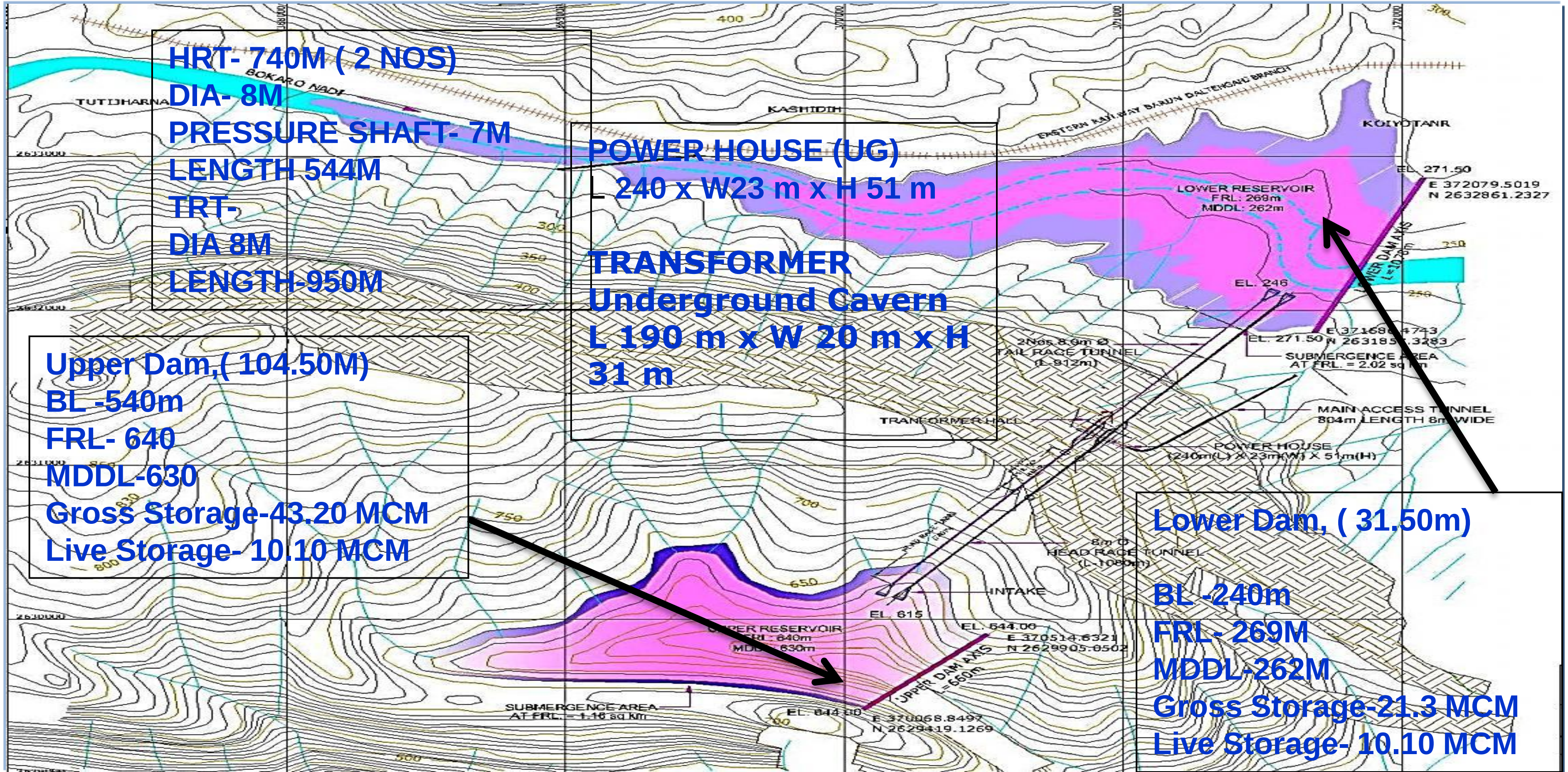
Need of Innovative & Cost Effective Engineering

- The viability of any Pumped Storage Project has always been an issue due to cycle efficiency
- Besides many other factors , above issues often result in increased cost thereby affecting the viability of the project.
- **Hence identification of suitable site, planning and design requires utmost care and judicious decision making to develop Pumped storage projects**.
- Given the paucity of new sites, it is difficult to find new sites for installation of Pumped Storage Projects various innovative combinations must be considered for installing Pumped Storage Project.
- Special efforts should be made to utilise existing H.E. projects with adequate reservoir storage.
- The planning and design of each of the above three types are distinctly different from each other and require meticulous planning at each stage of development

Options Available- Case Studies

- **New Pumped Storage Projects** (Both new reservoirs to be made)-
  - **Lugu Pahar Pumped Storage Project, 6X250MW, Jharkhand**
- **Within the Existing Projects** (One Reservoir exists and One new reservoir is to be made)
  - **Turga Pumped Storage Project, 4X250 MW), West Bengal**
- **Within the Existing projects** (Both reservoirs exists)
  - **Sharavathy Pumped Storage Project, 8X250 MW, Karnataka**

New Pumped Storage Projects (Both new reservoirs to be made)-
Lugu Pahar Pumped Storage Project, 6X250MW, Jharkhand



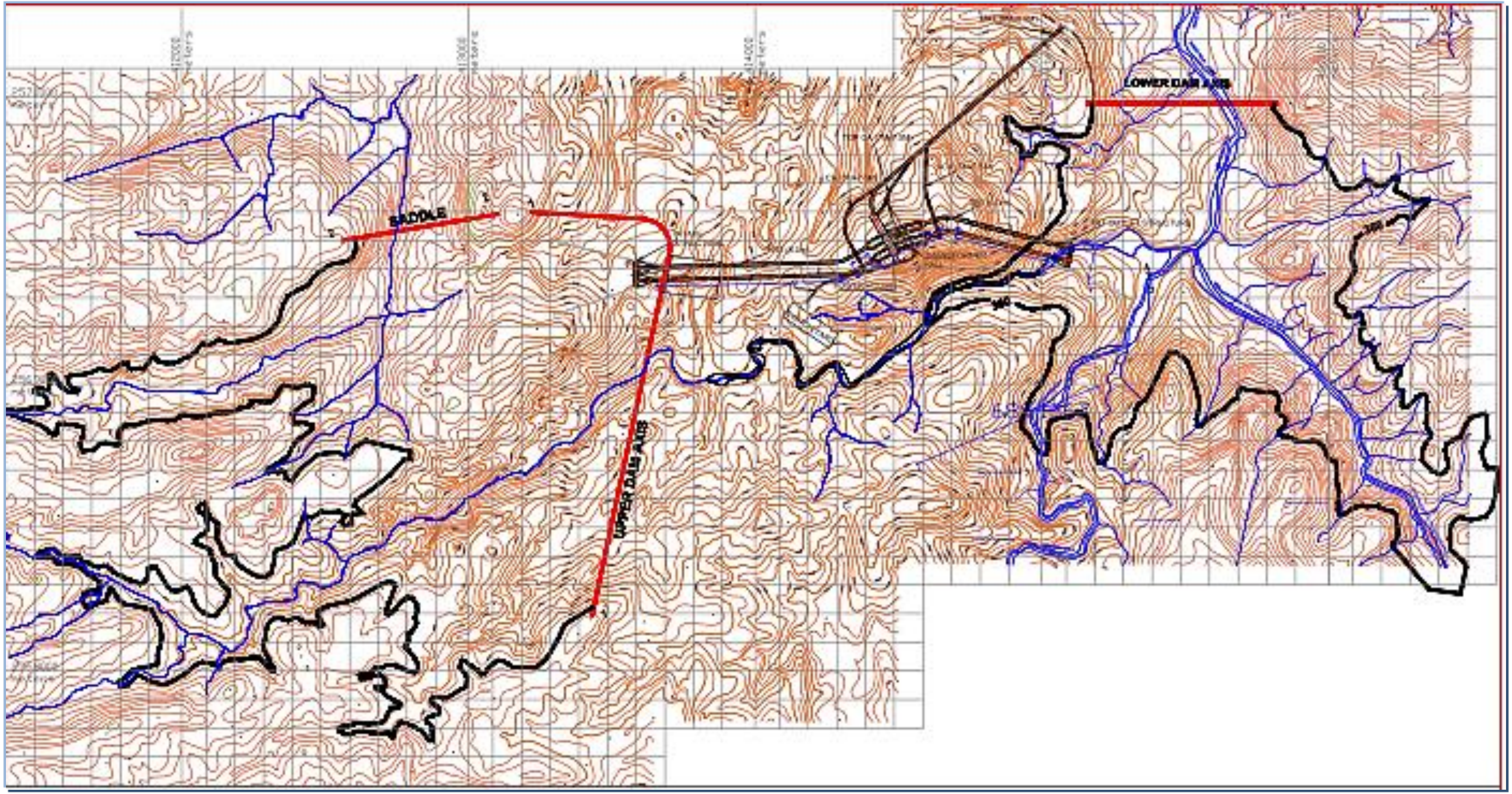
Project Features

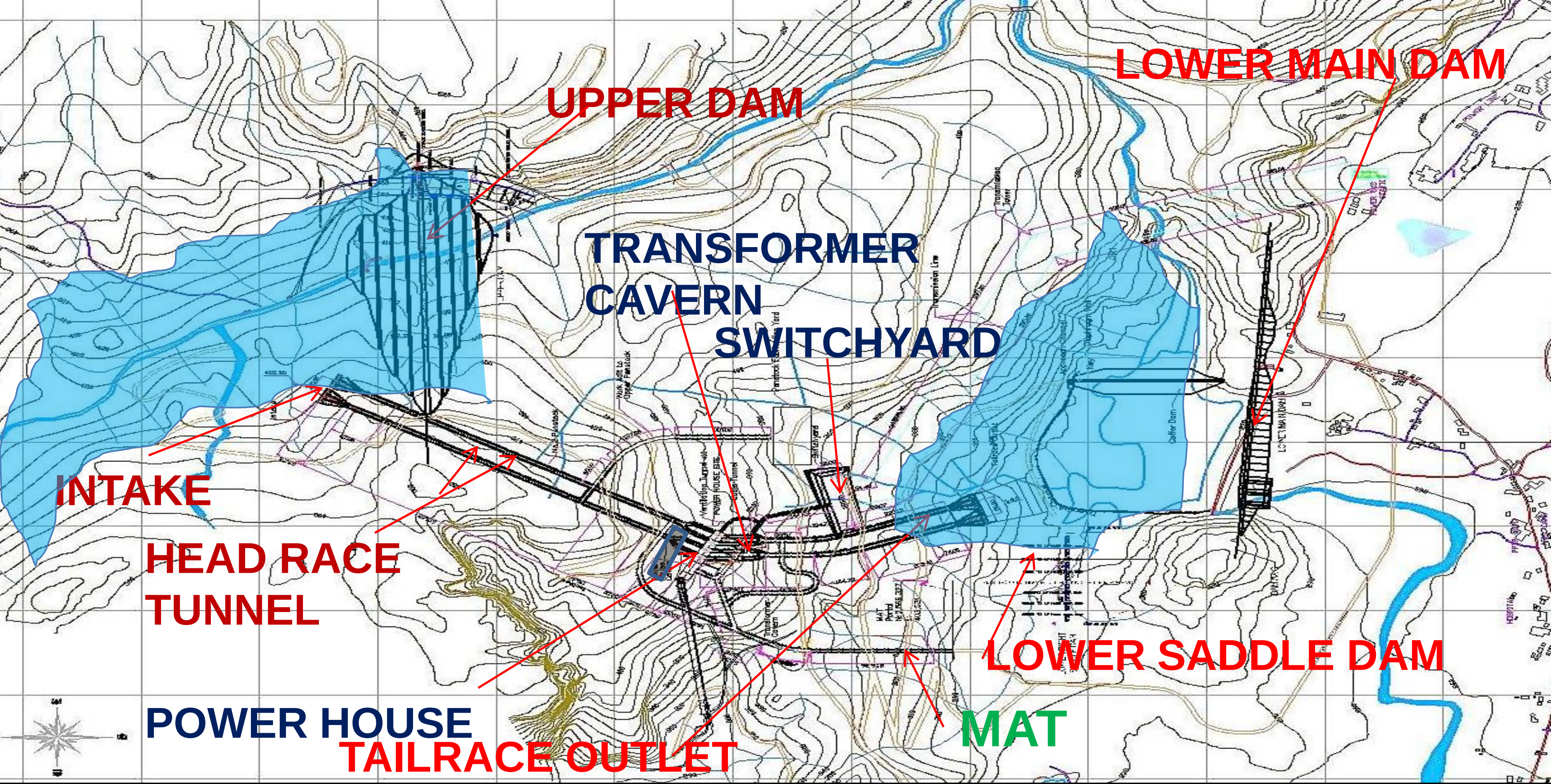
- The Lugu pahar Pumped Storage project envisages construction of:

- A 104.50 m high Rockfill New upper dam with central impervious clay core.
- Live storage of **10.10 M cum** with FRL at 640.0 m and MDDL at 630.00 m;
- A 31.50 m high Rockfill New lower dam with central impervious clay core.
- live storage of 10.10 M cum with FRL at 269.00 m and MDDL at 262.00 m;
- 2 (two) No. 740 m long, 8.0 m diameter headrace tunnel
- 2 (two) No. 544 m long, 7.0 m diameter pressure shaft
- 2 (two) No. 950 m long, 8.0 m diameter headrace tunnel
- An underground power house having an installation of 6 Francis type reversible pump-turbine driven generating units of 250MW capacity each

- An installed capacity of 1500 MW has been adopted based on the simulation studies carried out for different FRLs and installed capacities to provide peaking benefits for 6 hours.

New Pumped Storage Projects (Both new reservoirs to be made)-
Bandu Pumped Storage Project, 900 MW, West Bengal





Within the Existing Projects (One Reservoir exists and One new reservoir is to be made)-

Turga Pumped Storage Project, 4X250 MW), West Bengal

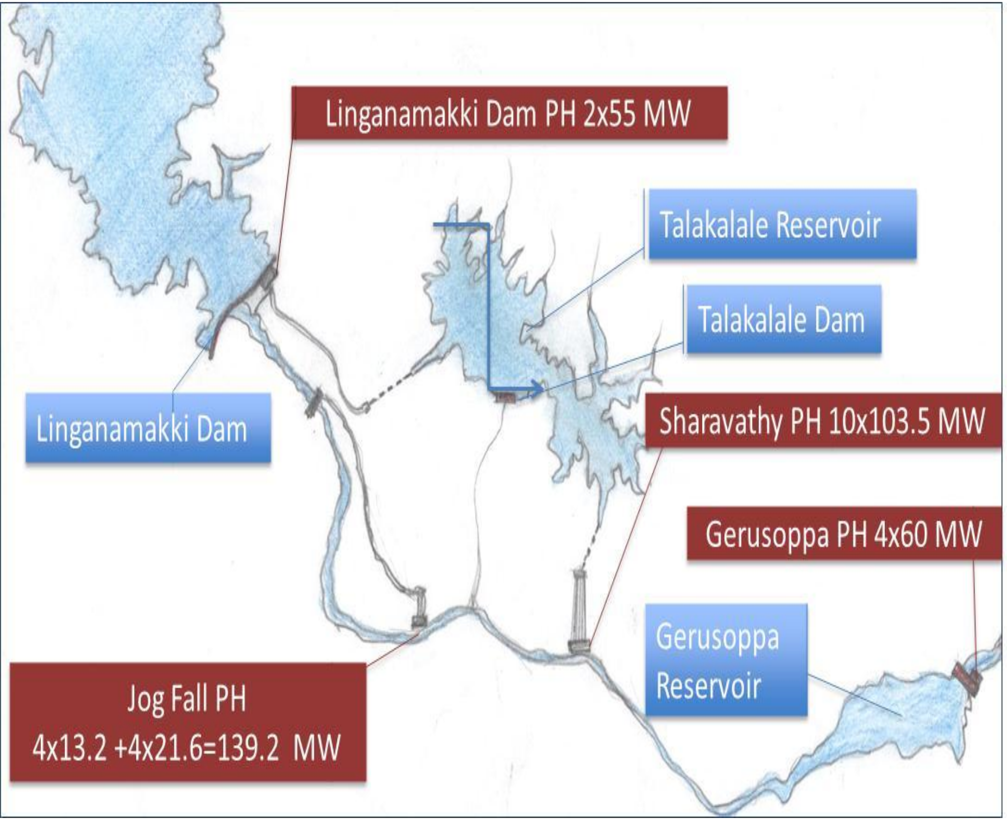
Project Features

The Turga Pumped Storage project envisages construction of:

- A 63.50 m high Rockfill New upper dam with central impervious clay core.
- Live storage of **14.20 M cum** with FRL at 464.0 m and MDDL at 444.40 m;
- A 64 m high concrete dam modified at existing lower dam location.
- live storage of 14.20 M cum with FRL at 316.50 m and MDDL at 280.40 m;
- 2 (two) No. 932 m long, 9.0 m diameter circular steel lined headrace tunnel
- An underground power house having an installation of 4 Francis type reversible pump-turbine driven generating units of 250MW capacity each
- 2 (two) No. 10m dia 605 m long tail race tunnels to carry the power house releases to lower reservoir.
- An installed capacity of 1000 MW has been adopted based on the simulation studies carried out for different FRLs and installed capacities to provide peaking benefits for 5 hours.

Within the Existing projects (Both reservoirs exists)

Sharavathy Pumped Storage Project, 8X250 MW, Karnataka



- Project with installed capacity of 2000 MW is planned between existing Talakalale and Gerusoppa reservoir The proposed pumped storage project is an additional installation utilising the existing Sharavathy system consisting of Liganamakhi, Talakalale Dam and Gerusoppa Dam.
- Five (5) reservoirs regulate monsoon surplus waters of the Sharavathy and adjacent streams.
- KPCL has three major hydroelectric stations in the basin with a total installed capacity of 1330 MW.

Plant Planning & Installed Capacity

Storage Available at Two Reservoirs for Pumped Storage Project

Sr. No.	Reservoir	FRL (m)	MDDL (m)	Live Storage (MCM)
1	Talakalale	522.12	520.59	13.6
2	Gerusoppa	55.00	43.50	58.21

Sharavathy PSS- Storage Requirement (MCM) for Different Installed Capacity for 6 hours peaking operation

Installed Capacity (MW)	Total Storage Requirement (MCM)	Storage Required for existing Sharavathy HEP (MCM)*	Storage Required for Sharavathy PSS (MCM)
1000	6.81	1.63	5.18
1250	8.11	1.63	6.48
1500	9.41	1.63	7.78
1750	10.7	1.63	9.07
2000	**12.0**	**1.63**	**10.37**

*During 6 hours of Peaking operation

It would be seen from above that sufficient storage is available at upper reservoir for Sharavathy Pumped Storage scheme for installation of 2000 MW. The lower reservoir at Gerusoppa with live storage of 58.21 MCM would not pose any constrain in the selection of installed capacity.

Project Layout Evolution

Objective

- Shortest Water Conductor System
- Straight WCS (Minimum Bends) for better Hydraulics

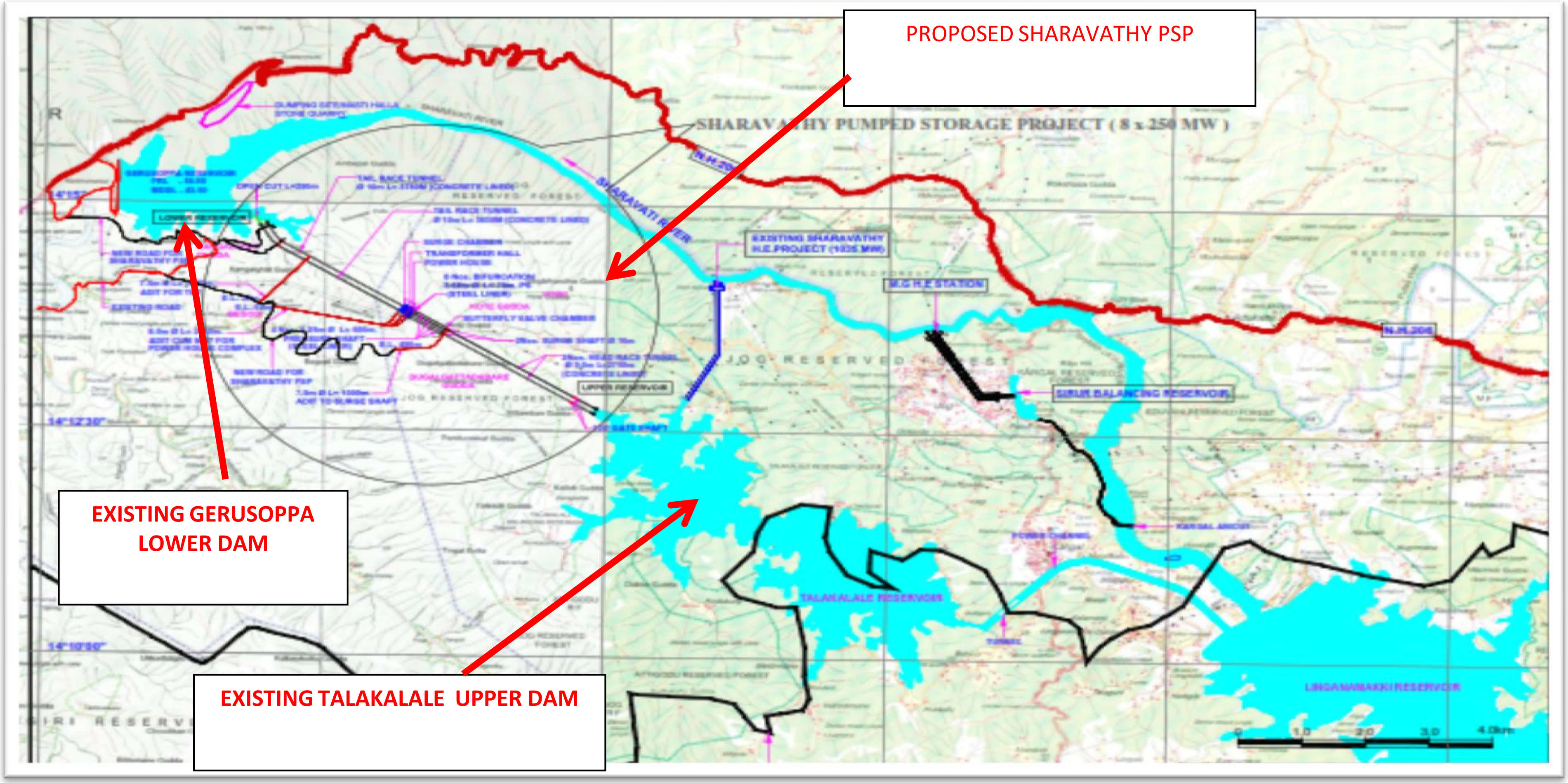
From Topographical & Geological Considerations

- Location of Intakes
- Location of Surge Shafts
- Location and Orientation of Power house
- No infringement with any Existing structure

Constraints

- Proximity to Sharavathy WLS
- To Minimize over ground Project Components such as Portals, roads etc.
- No Alterations in the existing Reservoir Levels

Within the Existing projects (Both reservoirs exists)-Sharavathy Pumped Storage Project, 8X250 MW, Karnataka



PROJECT FEATURES

The Sharavathy Pumped Storage project envisages construction of:

- 2 (two) No. intake with trash racks having mechanical raking arrangement.
- 2 (two) No. 2.726 Km long, 9 m diameter circular concrete lined headrace tunnels including cut & cover.
- 2 (two) No. 0.828 Km long, 5.25m diameter inclined circular steel lined (including horizontal) pressure shafts
- 2(two) no. 16m dia circular Surge Shafts 52m high.
- An underground power house having an installation of 8 Francis type reversible pump-turbine driven generating units of 250MW capacity each
- 2 (two) no. 3.780 Km & 3.830 Km long concrete lined tail race tunnels to carry the power house releases to lower reservoir.

Plant Planning & Installed Capacity

The factors influencing the Installed Capacity of Pumped Storage Scheme :

- The requirement of daily peaking hours of Operation
- Operating head
- Live Storage available in the reservoirs and their area capacity Characteristics
- Operating Parameters of existing Sharavathy HEP Project (1035 MW)

Computer Software for Daily Operation Simulation

- The operation in either mode viz. generation or pumping, results in **continuous change in the levels** of the two reservoirs as also consequently change in the operating head on the machines.
- The impact of such continuous variations in head is best captured by simulation of operation of the scheme considering shorter time intervals of 10 minutes.
- An efficient computer software developed helps in carrying out various alternative simulation by changing key parameters such as levels in both reservoir, component diameters, length of WCS, efficiency etc. in order to optimize the parameters.

Operation Simulation

Microsoft Excel
:ro-EnabledWorksl

APPROACH & ACTIVITY SCHEDULE

- Preparation of DPR – Involves various inter connected activities.
- Interface within WAPCOS and KSEB required.
- Interface with all the appraisal agencies like
- CEA/CWC/GSI/CSMRS to achieve the objective within the prescribed time limit.
- WAPCOS shall deploy Interdisciplinary teams comprising of well experienced experts, professional staff and other supporting staff.

TEAM COMPOSITION

- Advisory Group
  - To review entire project in line with KPCL requirement and the works of different Expert Groups

- Experts Sub-Groups
  - Project hydrology
  - Project geology
  - Geological and geotechnical explorations at various project sites
  - Construction materials investigation
  - Project optimization
  - Civil designs & Hydro-mechanical works
  - Hydropower planning
  - Electro-mechanical Designs
  - Construction methodology and equipment planning
  - Project cost estimates
  - EIA study
  - Economic And Financial Analysis

Technical Approach, Work plan & Activity Schedule

1	**Mobilization of Resources and setting up of site office**
2	Collection of additional data/ information
3	**Preparation of PFR-** Based on available information prepare PFR & submit it for ToR in MoEF
4	Preparation Detailed Project Report (DPR)- PRE- DPR Stage & EIA/EMP studies
5	Forest Area survey
6	**Survey and Investigations**
6.1	Construction materials Survey & testing for coarse and fine aggregates etc.
6.2	**Hydrographic Survey at Intake Locations to Plan Both Intake Structure in the reservoirs**
6.3	Geological mapping of Project area
6.4	Core Drilling
6.5	Exploratory Drifting
6.6	Laboartory Testing & Insitu testing
7.0	Hydrology- Review of Water Availability and Flood studies
8.0	Civil Design- Review of Designs for Talakalale dam and Gerusappa dam
9.0	Finalisation of project Layout and Obtaining of Pre DPR clearances
10.	**Acceptance of DPR for Examination by CEA**

Technical Approach, Work plan & Activity Schedule

	Preparation of Complete DPR after Prior Clearances
7.0	Civil Designs - Power Intakes ,HRT, Power House Complex and appurtenant works , TRT
8.0	EIA/EMP Studies
9.0	Transmission studies
10.0	Construction Programme & Equipment Planning
11.0	Preparation of detailed drawings for DPR stage
12.0	Preparation of BOQ, Rate analysis and cost estimate
13.0	Economic and financial analysis
14.0	Preparation of DPR
15.0	Submission of draft DPR in CEA
16.0	Compliance of Comments of different appraisal agencies on draft DPR
17.0	**Submission of Final DPR for TEC**

Key Surveys & Investigation

Sl. No.	Description of Item	Remarks
1	Sub Surface Core Drilling	At Power House complex, HRT,Surge Shafts, pressure Shafts, TRT. Miscellaneous Location as per requirement
2	Exploratory Drifting	Exploratory Drift to power House Cavity Including cross cuts
3	Geo-Physical Investigation	At Power House complex
i)	Seismic Profiling	At Power House complex
4	**Geotechnical Investigation**	
i)	Field In situ Tests	Deformation Modulus & Hydro-fracture Tests
ii)	Laboratory Tests	Rock Mechanics tests
iii)	Construction Material Tests	Coarse and fine aggregates etc
5	Conducting Field Permeability Test	
6	Site Specific Seismic design parameters	
7	Topographical Survey	As per requirement

ACTIVITY SCHEDULE FOR PALLIVASAL PUMPED STORAGE PROJECT, KERALA

Sl.No.	ACTIVITY	Months	DPR PREPARATION AND SUBMISSION																								ASSISTANCE TO KSEB IN APPRAISAL &TEC					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	DESCRIPTION																															
1	Data Collection from KSEB and other agencies by WAPCOS	0.5																														
2	Review of available data/records, peliminry site visit	0.5																														
3	Preapartion of PFR and ToR for MoEF	3																														
4	Topographical Survey	6																														
5	Geotechnical Investigation , and Geological Mapping	18																	DRIFT													
6	Hydrological Studies	6																														
7	Power Potential Study based upon Hydrological Study	6																														
8	Construction Material Survey & Investigation and all Testing	12																														
9	Preapartion & Submission of chapters for Pre DPR clearance	10																														
10	Design of main civil works like review of Dam Design, Intake structure, Power House complex based upon Topographical survey & Geological Inputs.	6																														
11	Design of H/M equipments	4																														
12	Design of E/M equipment i.e. Switchyard etc.	6																														
13	Preparation of DPR stage Drawings	4																														
14	Construction Scheduling and Euipment Planning.	3																														
15	Quantity Estimate, Analysis of Unit Rates, Preparation of BOQ.	5																														
16	Preparation of Draft DPR its submission	4																														
17	Assistaance to KSEB during Appraisal & TEC	6																														

NEW CEA GUIDELINES - PRE-DPR STAGE CLEARANCES

Sl. No.	Aspect	Sl. No.	Aspect
1	Hydrological	6	Cons. Material & Geotechnical
	Design Flood	7	Inter-State
2	Geological	8	International
3	Foundation Engg. and Seismic	9	ROR/Storage
4	Power Potential		
5	Project General Layout and Planning		

APPRAISAL STAGE CLEARANCES

Sl. No.	Aspect	Sl. No.	Aspect	Sl. No.	Aspect
10	Dam/Barrage Design	15	Power Evacuation	21	Civil Quantities
	Embankment	16	Cost of E&M and Misc Works	22	Civil Cost
11	Gates/HM Design	17	Phasing of E&M and Misc Works	23	Phasing of Civil Works
12	Instrumentation	18	Legal (CEA)	24	Financial and Commercial aspects (F&CA)
13	Hydel Civil Design	19	Construction Power aspects		
14	E&M Design	20	Plant Planning		

Hydro Power vs. PSP

- Does not change the River ***Hydrological Regime***- Major obstacle for Hydro Power
- No impact on ***u/s and d/s development*** - Major issue in HE development
- ***Uniform Generation*** round the year- large variability Seasonwise
- ***Peaking operation*** does not adversely affect d/s river reach- Major cause of concern in HEP
- Most 1000 MW PSP on small **Tertiary Streams** – Minimum Infrastructure requirement
- Installed capacity depends on ***Topography and operation hrs***. and not Hydrology- More Flexible

Conclusion & Way forward

- In view of large scale induction of Renewables in near future development of Pumped Storage projects needs focused attention and support.
- Pumped Storage project planning is distinctly different from conventional Hydro Planning.
- There are inherent complexities and site specific constraints in planning and design of Pumped Storage Projects.
- Hence, meticulous planning with judicious decision making is essential while making trade offs between priorities which are at times competing with each other.
- There are only few good Pumped Storage sites , which meet the requirement of a good pumped storage development in India.

Conclusion & Way forward

- Many identified sites have now become unavailable due to stringent Environmental , and Social stipulations together with difficulties in land acquisition.
- Many sites may be unavailable due to proximities to the national Parks etc.
- In view of above , it is of utmost importance that all the possible new sites are explored in totality.
- Efforts should be made to study all the existing projects having one reservoir or two reservoir in proximity and explore the possibility of installation of Pumped Storage projects within the existing system.
- This will minimize many adverse impacts and address developmental challenges.
- The PSP development within existing projects will greatly reduce the cost and help making Pumped storage project economically viable.

Conclusion & Wayforward

Policy Issues

- Considering the necessity of the PSP, enabling policy framework is in active consideration and need of the hour.
- The PSP is destined to be a GRID Element with associated financial support.
- **It will be a Must run Case and will be an important asset to the system soon.**
- **By the time Sharavathy project becomes operational , all these mechanism are likely to be in place.**
- **At present , Purulia PSP (900 MW) is being successfully operated by WBSEDCL.**

WAY FORWARD

WAPCOS IS FULLY EQUPPED TO CARRY OUT ABOVE WORK IN MOST PROFESSIONAL & TIME BOUND MANNER


Thank you

Investigation, Planning, Design new Hydro Pumped Storage Projects

Peter Matt



Topics

- General basic design
- Implementation of new pumped storage projects
- Upgrading existing plants

Basic questions?

- What is the business case? – Controll energy, balancing, generation, **flexibility, storage** ……
- Topography , geology, precipitation, environmental protection; environmental conservation, ecological mitigation measures, **existing schemes,** …..
- Accessibility to a high voltage transmission line
- Transport connection of the site
- Site procedure
- Financing
- ……………

Control Range of units

Ternary Units

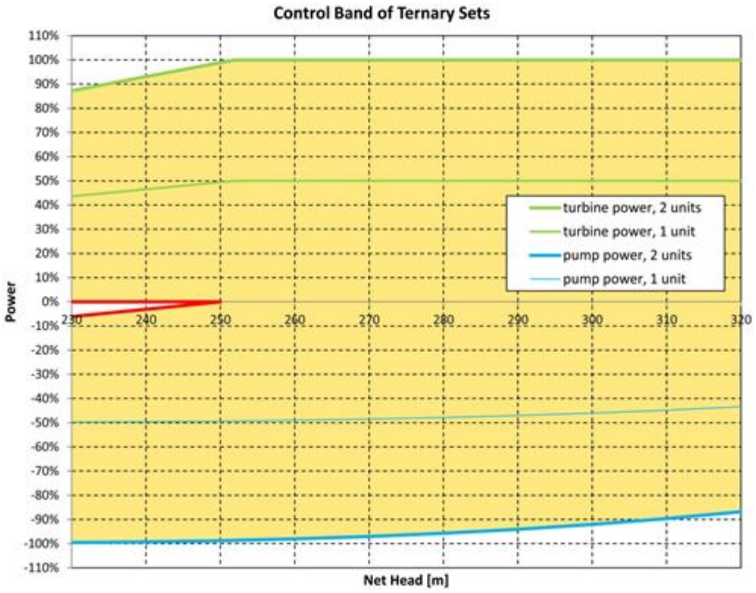


Fig. 1: Power control band of a ternary set

Pumpturbine

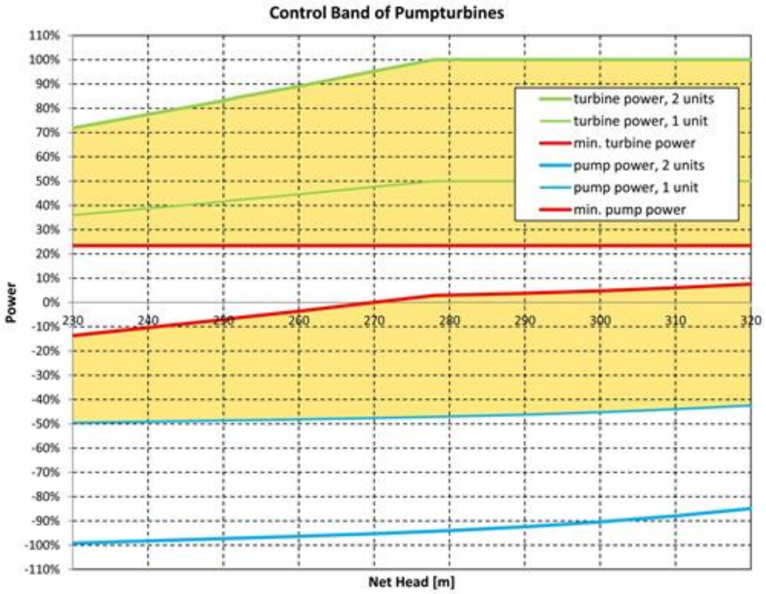


Fig. 2: Power control band of a pumpturbines without part-load stabilisation

Source: Vorarlberger Illwerke AG

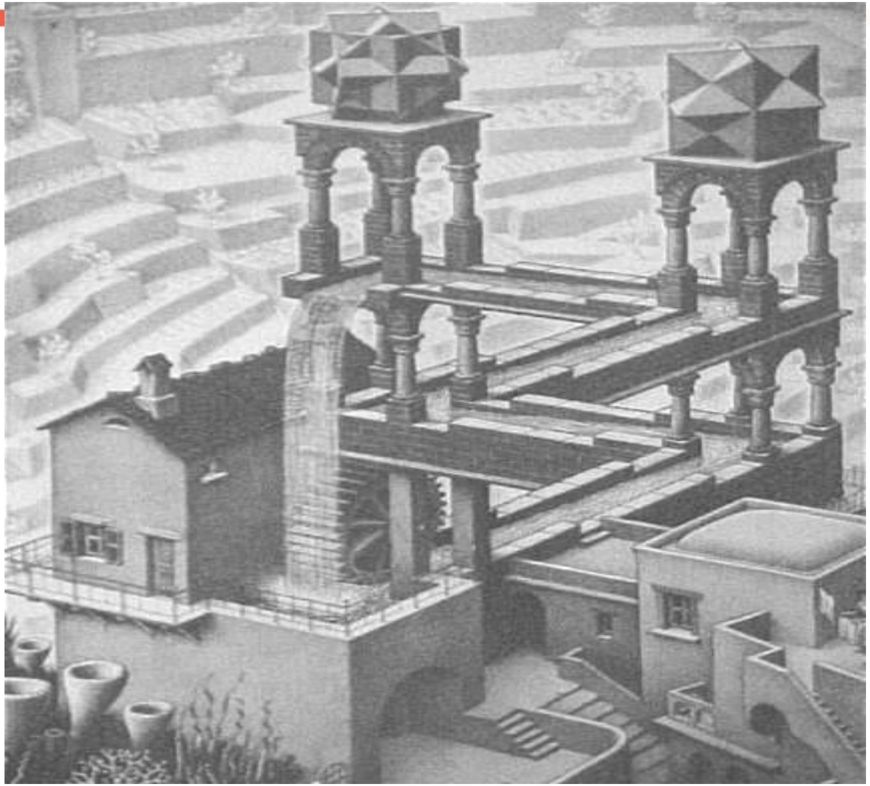
Hydraulic Short Circuit - SC

Vorarlberger Illwerke AG

Waterfall

M.C. Escher

1961

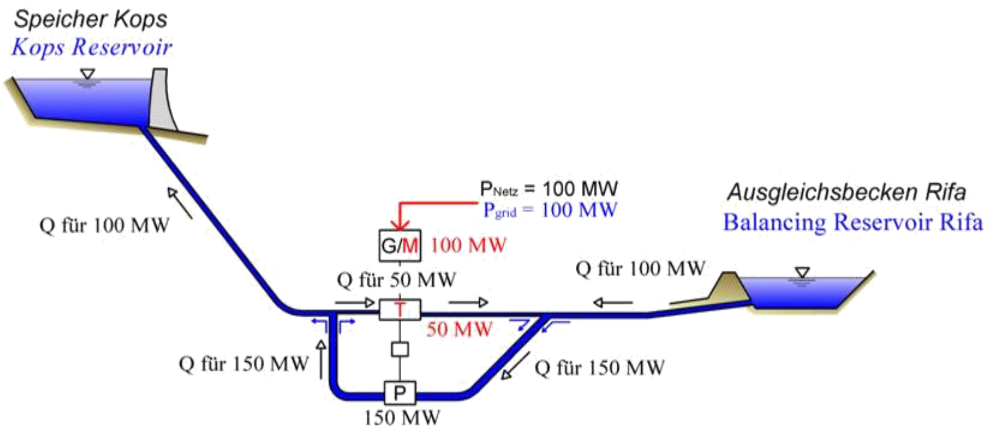


Flexibility & Dynamic
between Turbine and Pump Mode

"Hydraulischer Kurzschluss" "Hydraulic shortcut"

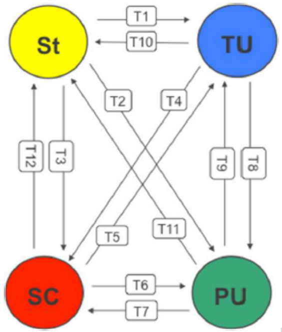
z.B.: Überschussleistung im Netz 100 MW e.g.: Power surplus in the grid 100 MW

Pumpleistung 150 MW Pump capacity 150 MW



G/M	Generator / Motor läuft mit 100 MW	Generator / Motor takes 100 MW from the grid
T	Turbine (bei Kops II Pelton) erzeugt 50 MW	Turbine generates 50 MW
P	Pumpe "bekommt" 150 MW	Pump "gets" 150 MW
Q	Durchfluss	discharge

Mode changes: Flexibility and Dynamic



T	Pump Turbine Mode change			time [seconds] A	B	C	D	E
1	Standstill	→	TU-Mode	90	75	90	90	65
2	Standstill	→	PU-Mode	340	160	230	85	80
5	SC-Mode	→	TU-Mode	70	20	60	40	20
6	SC-Mode	→	PU-Mode	70	50	70	30	25
8	TU-Mode	→	PU-Mode	420		470	45	25
9	PU-Mode	→	TU-Mode	190	90	280	60	25

Reversible PT
A – advanced conventional
B – extra fast response conventional
C – VarSpeed,

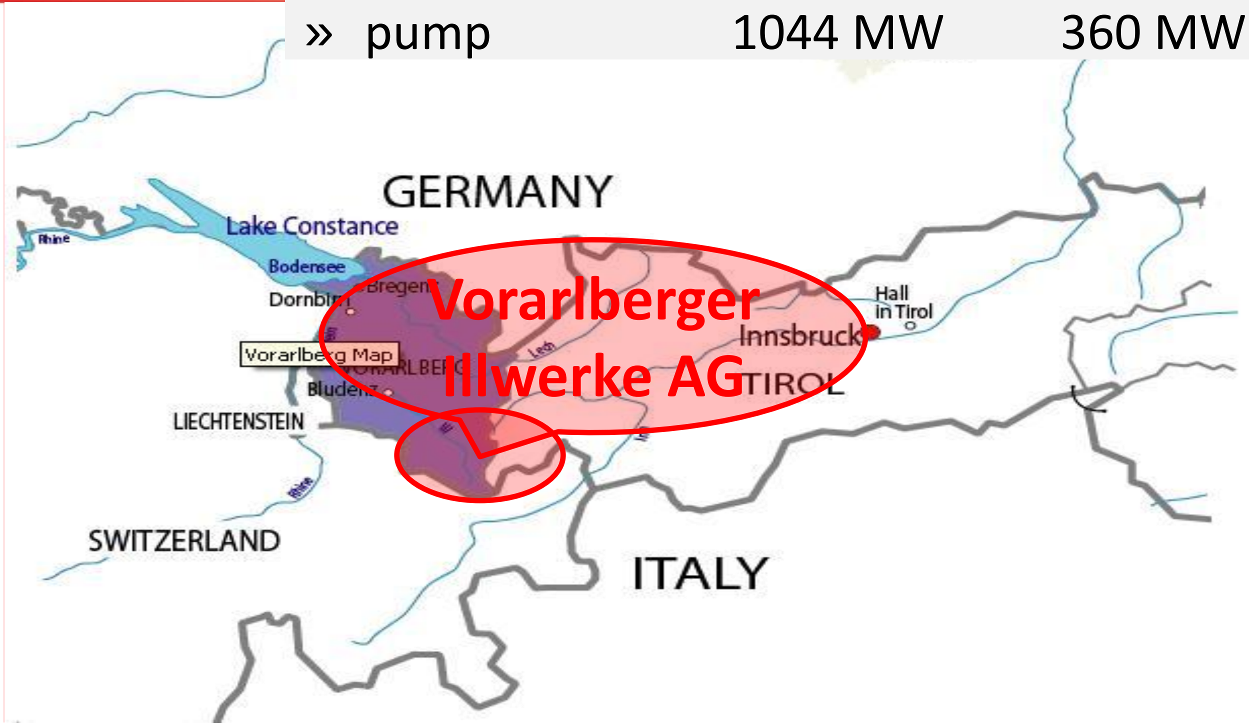
Ternary set
D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine
E – same as E but vertical with Pelton Turbine

Dr. Klaus Krüger
Leiter R&D Voith Hydro Holding
klaus.krueger@voith.com

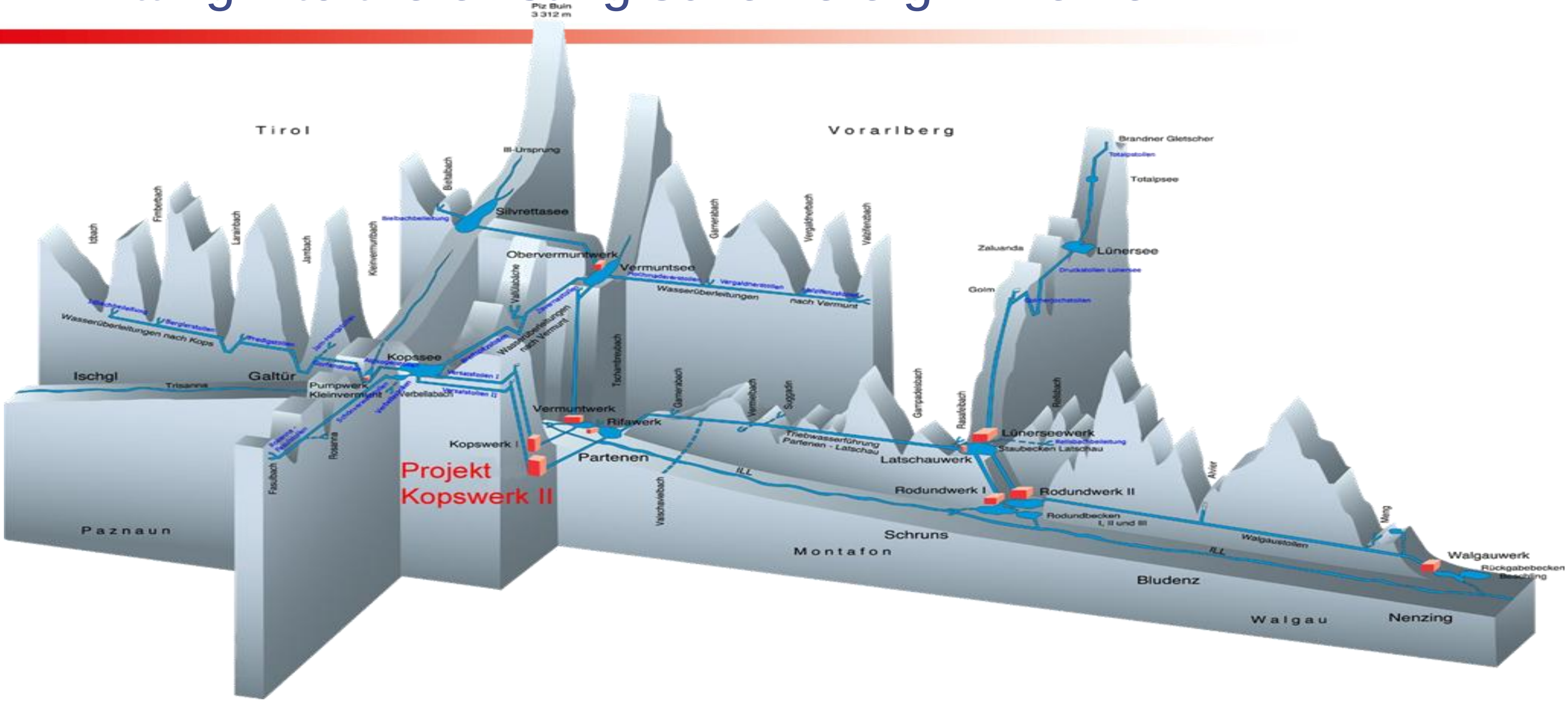
Situation

Installed capacity

	exisiting group	OVW II	group 2018
» turbine	1814 MW	360 MW	**2174 MW**
» pump	1044 MW	360 MW	**1404 MW**

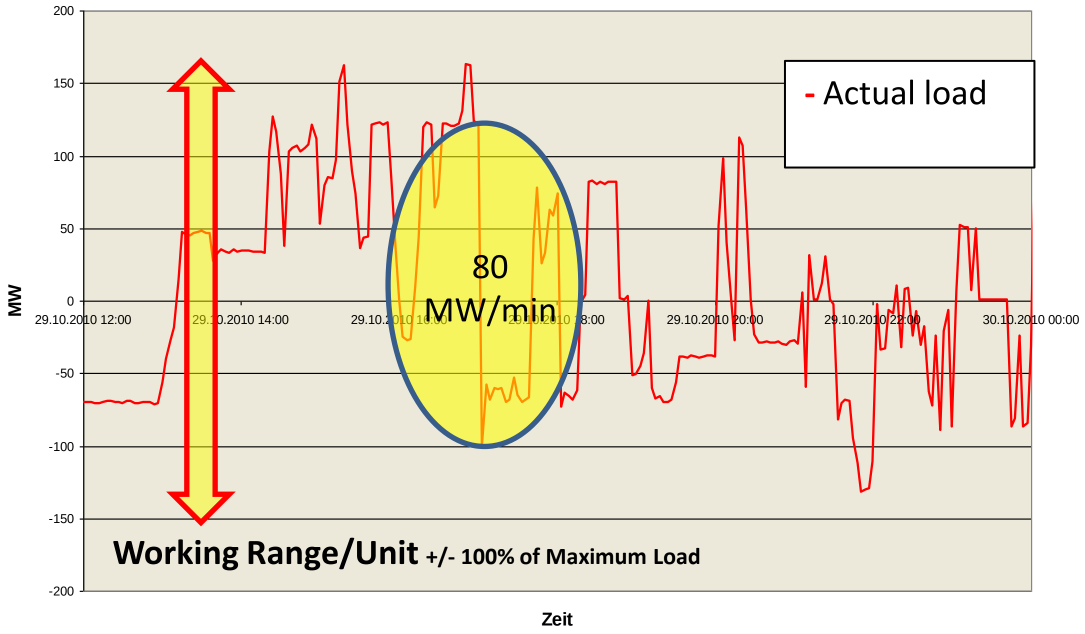


New Projects: **Kops II**
Fitting into the existing scheme e.g. Illwerke



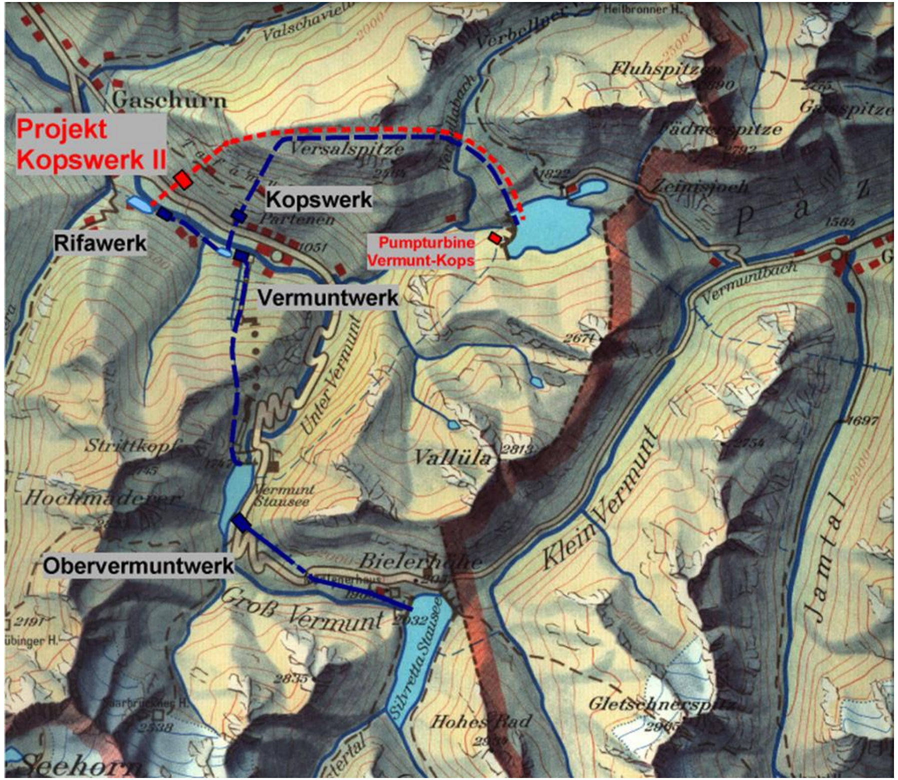
Vorarlberger Illwerke AG

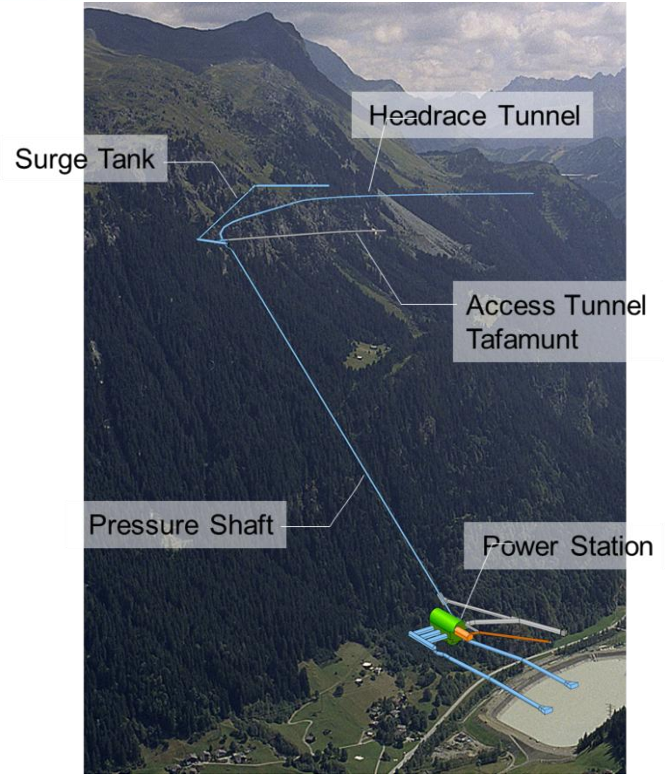
Typical Day Diagram
one unit Kops II



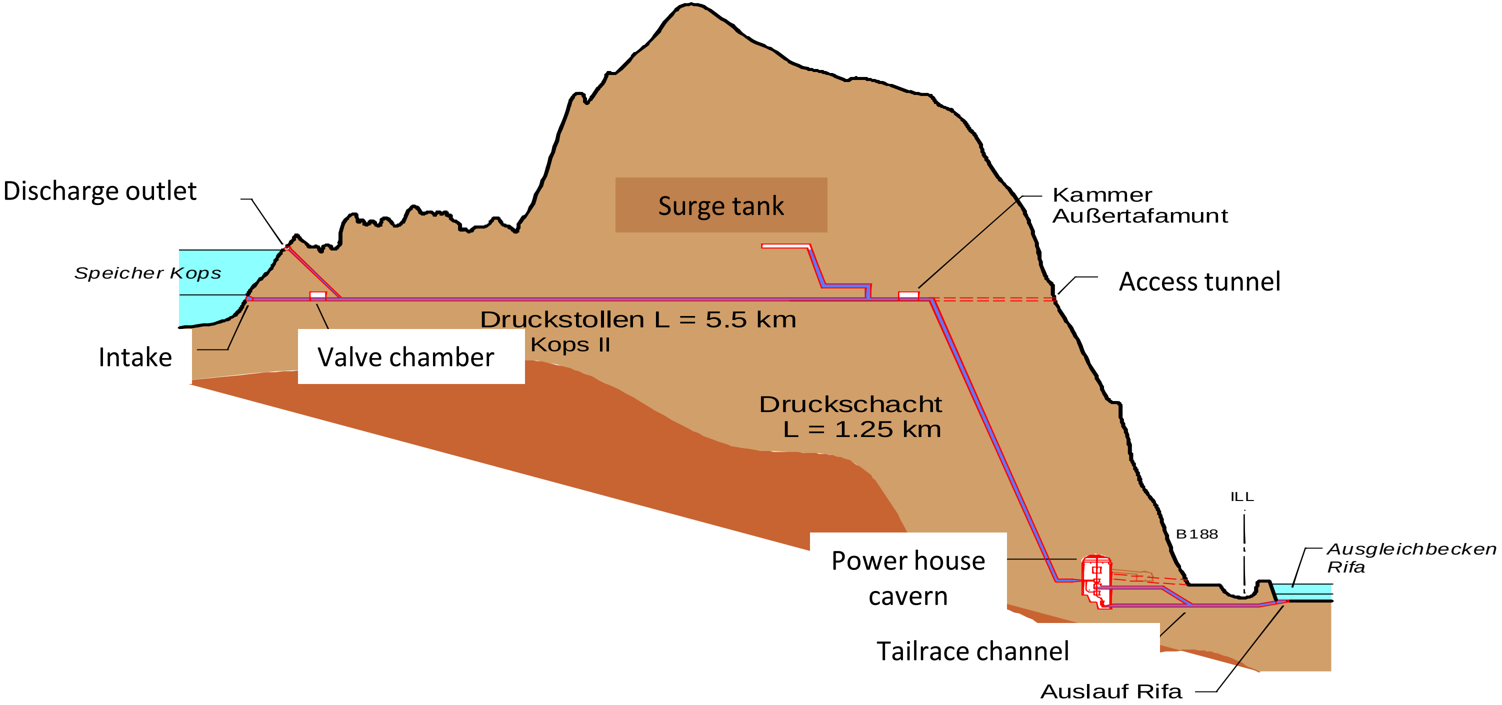
Scheme Kops II

Vorarlberger Illwerke AG



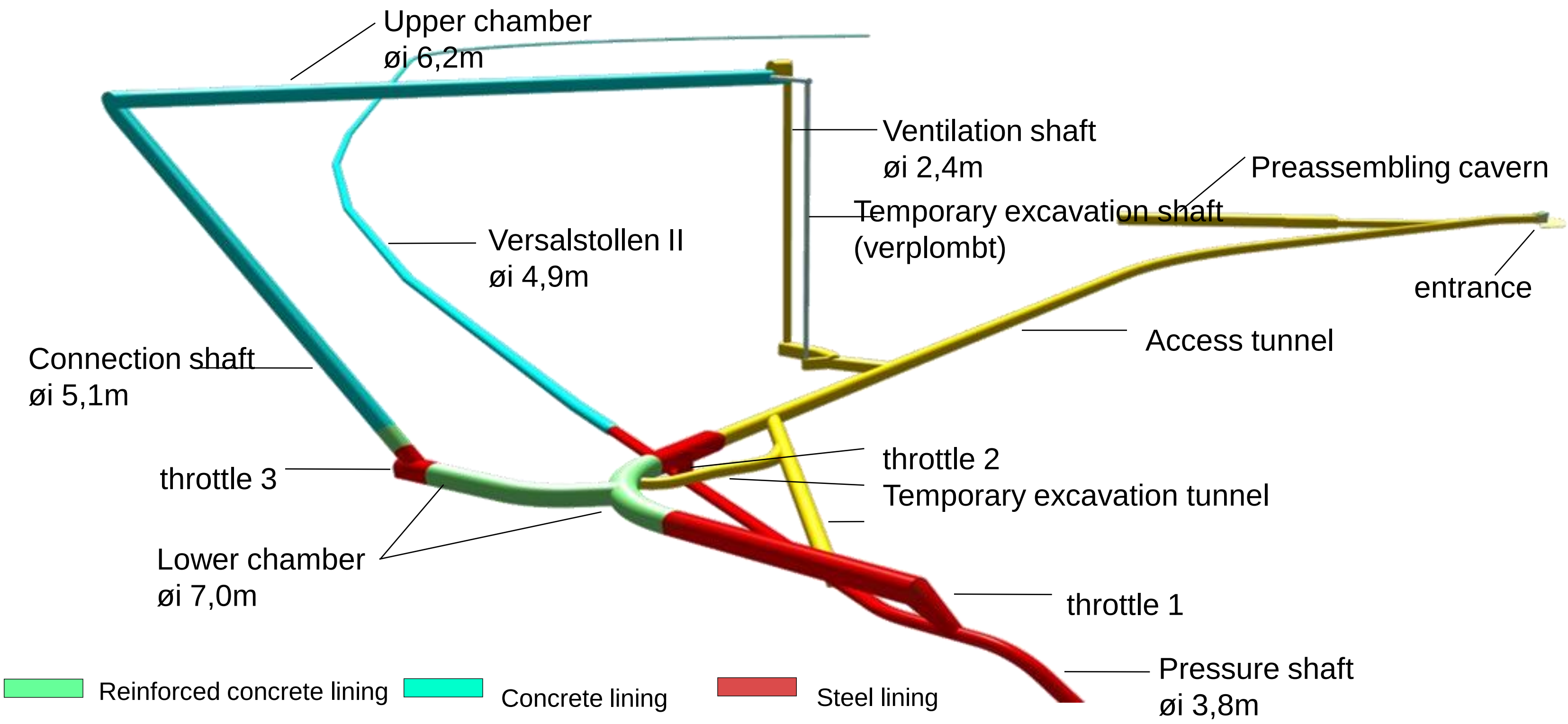


Longitudinal section KOW II

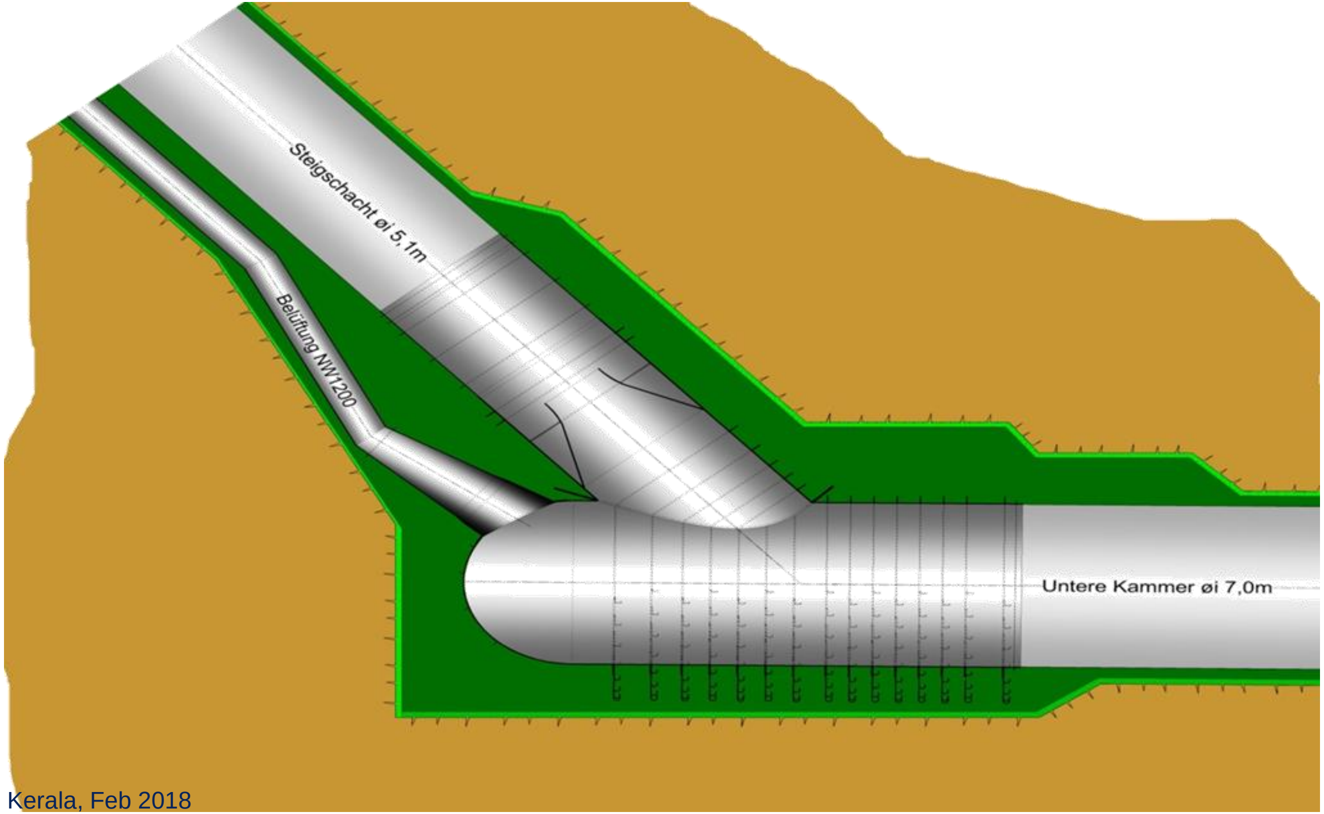


Surge tank KOW II

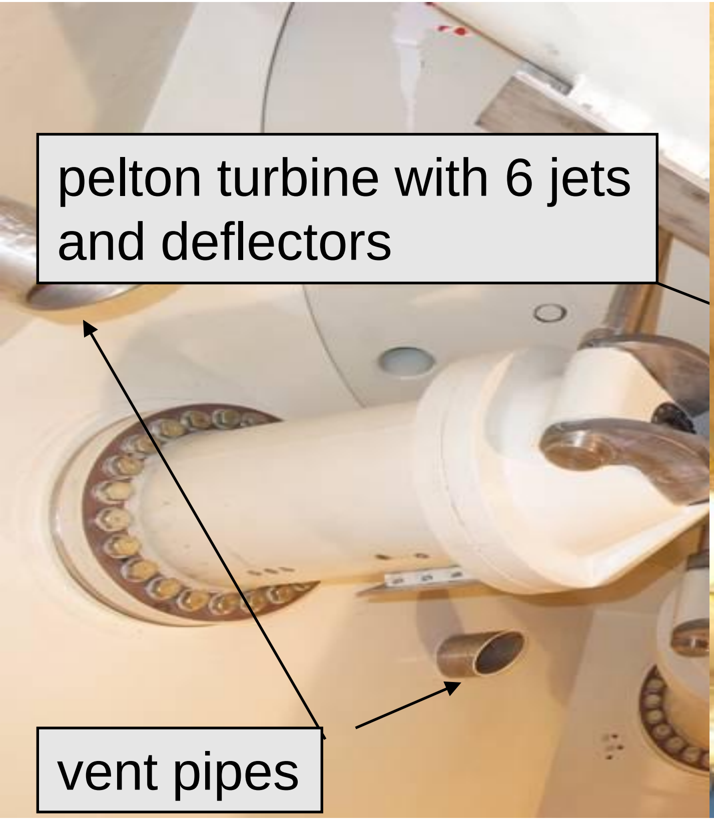
Vorarlberger Illwerke AG

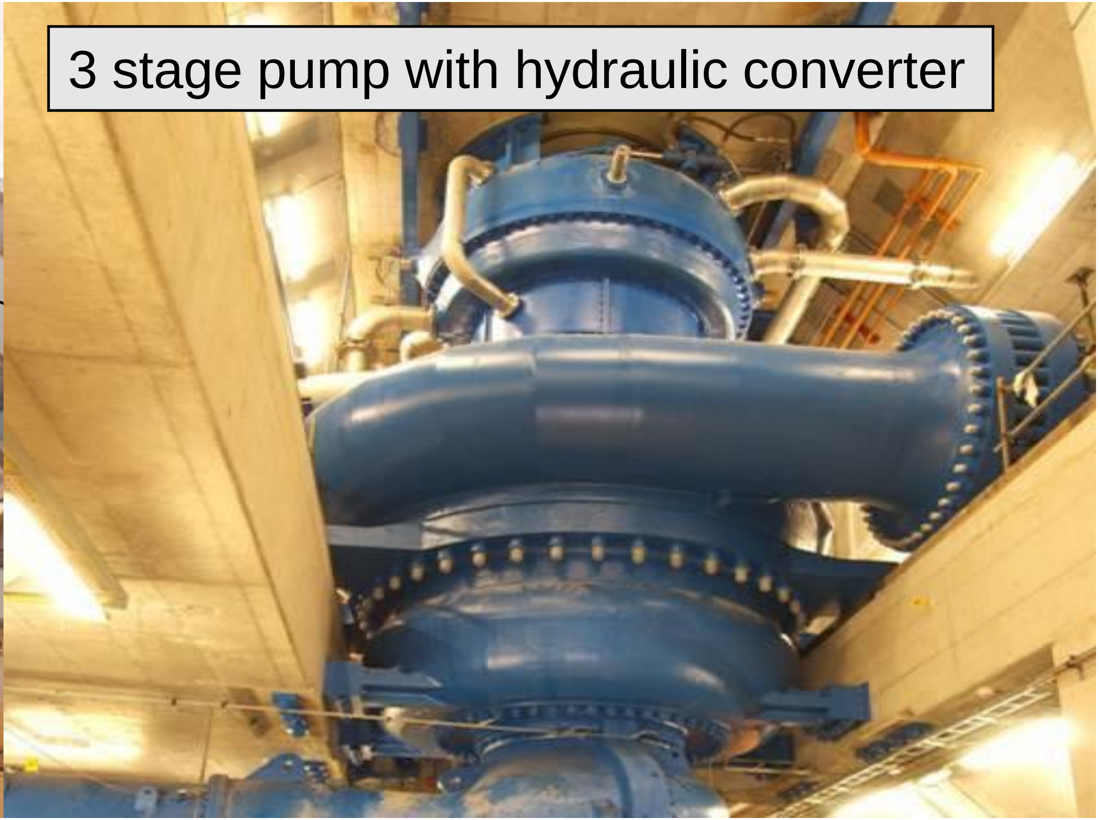


Surge tank KOW II, throttle lower chamber

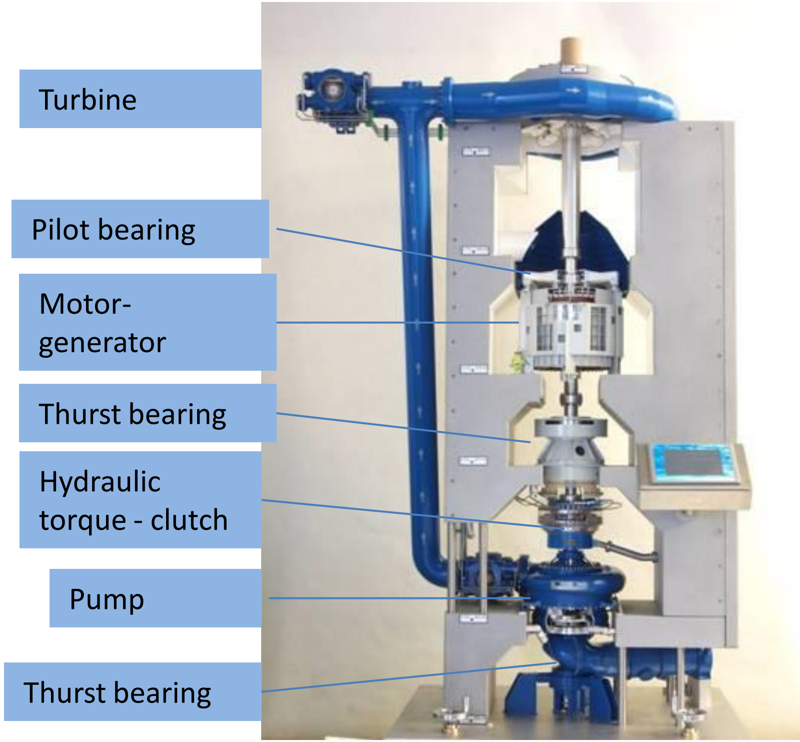


Kops II, Power Station with 3 units





Kops II

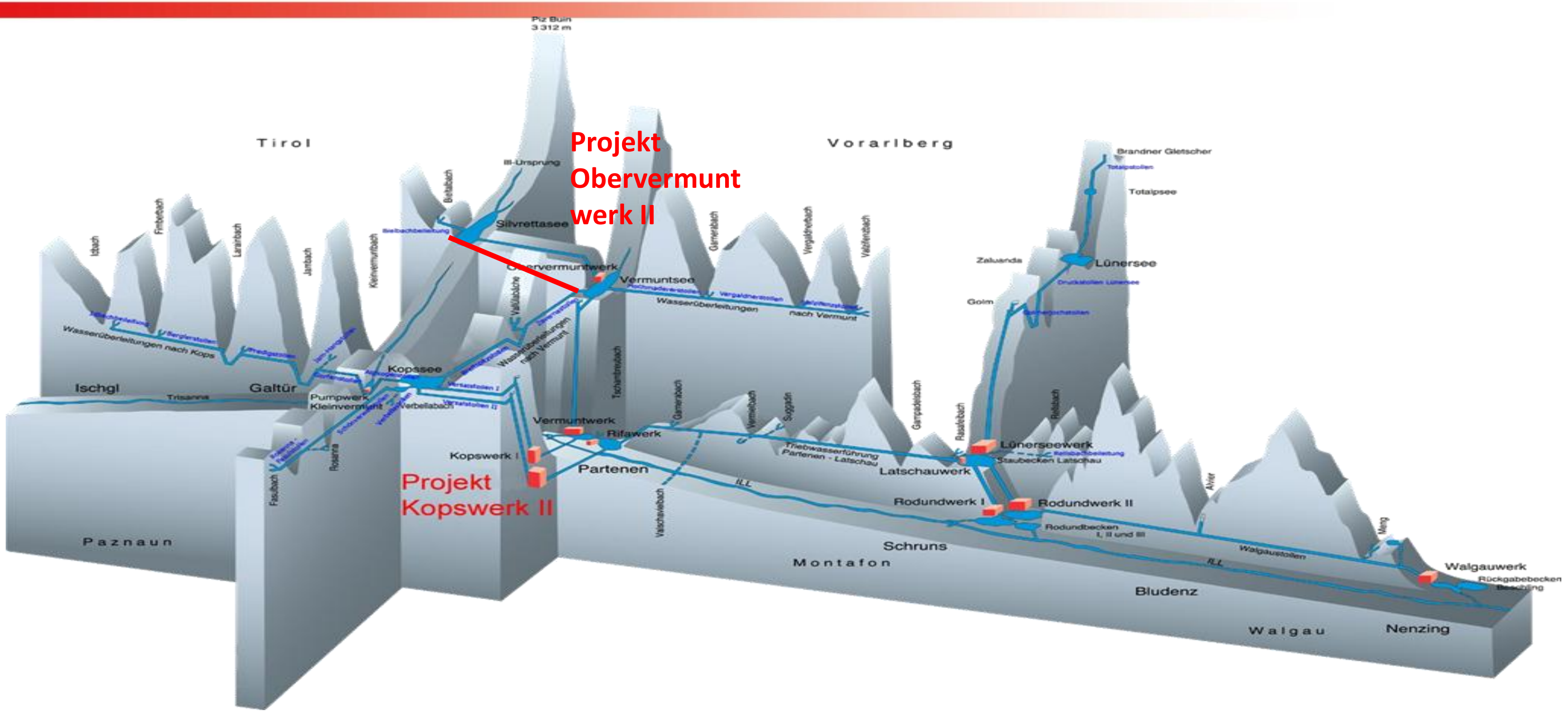


10 years of experiences

- 8000 hours/annual per unit
- 10 – 20 changes of operation mode P/T
- The flexible operation meets exactly the demand of the volatile energy market

New Projects: **Obervermuntwerk II**
Fitting into the existing scheme e.g. Illwerke

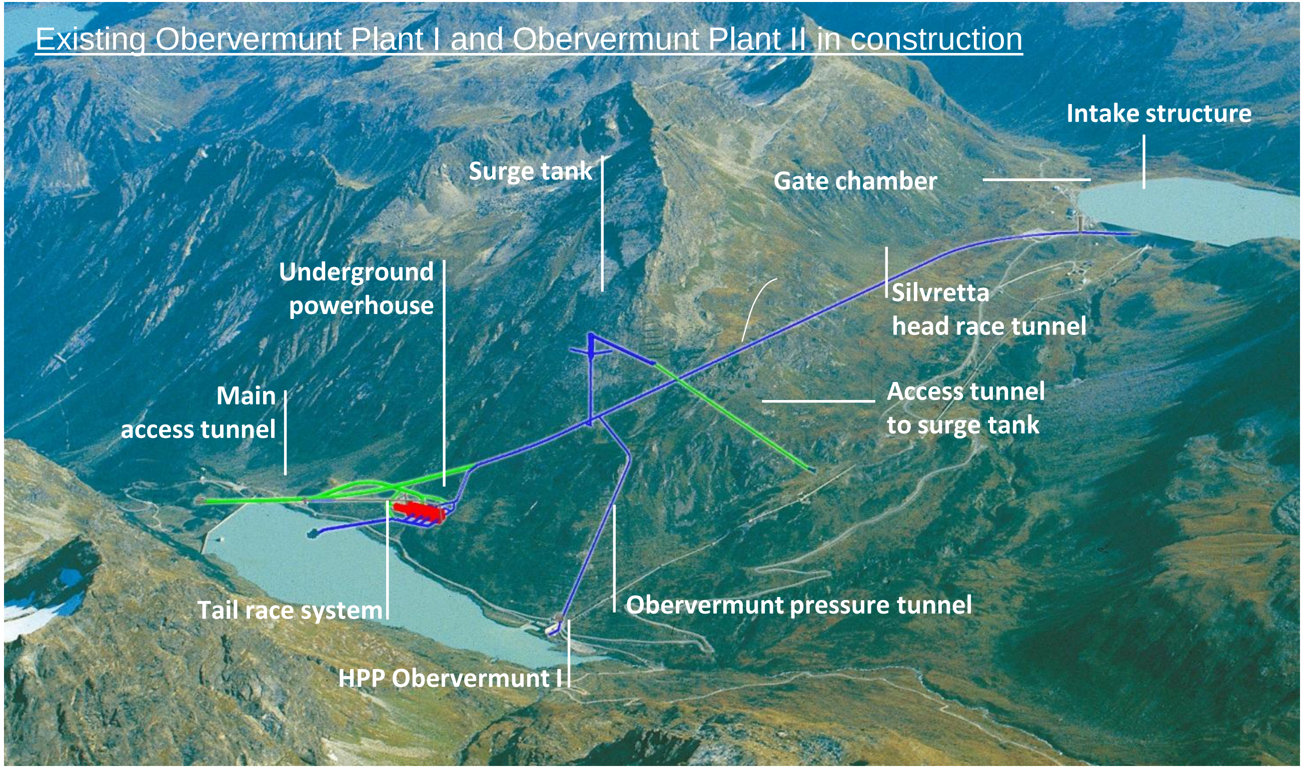
Vorarlberger Illwerke AG



illwerke vkw

Obervermuntwerk II (2014- 2018)

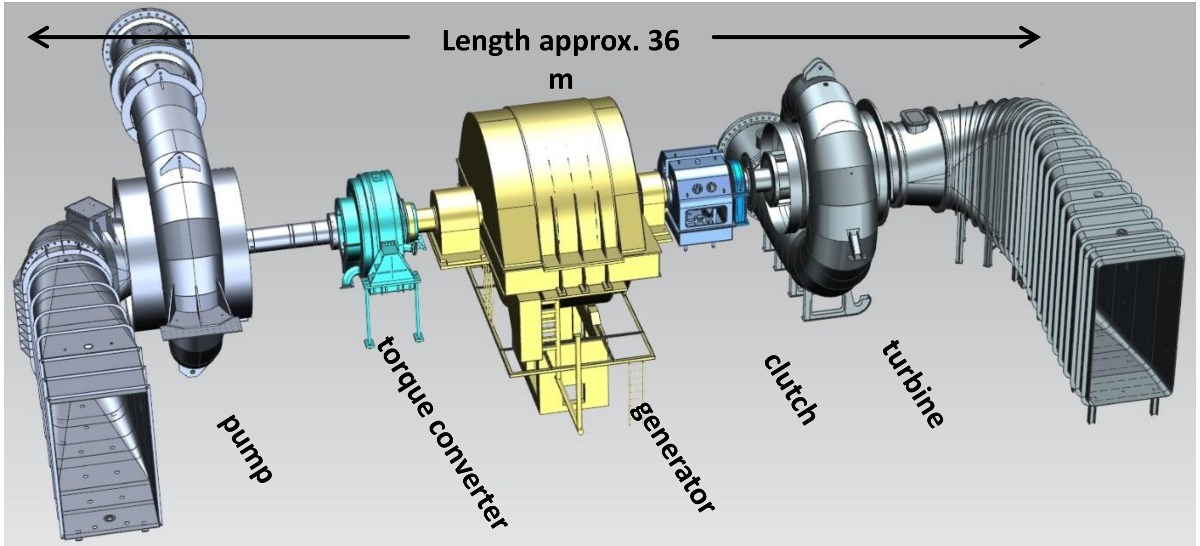
Vorarlberger Illwerke AG



Technical Concept

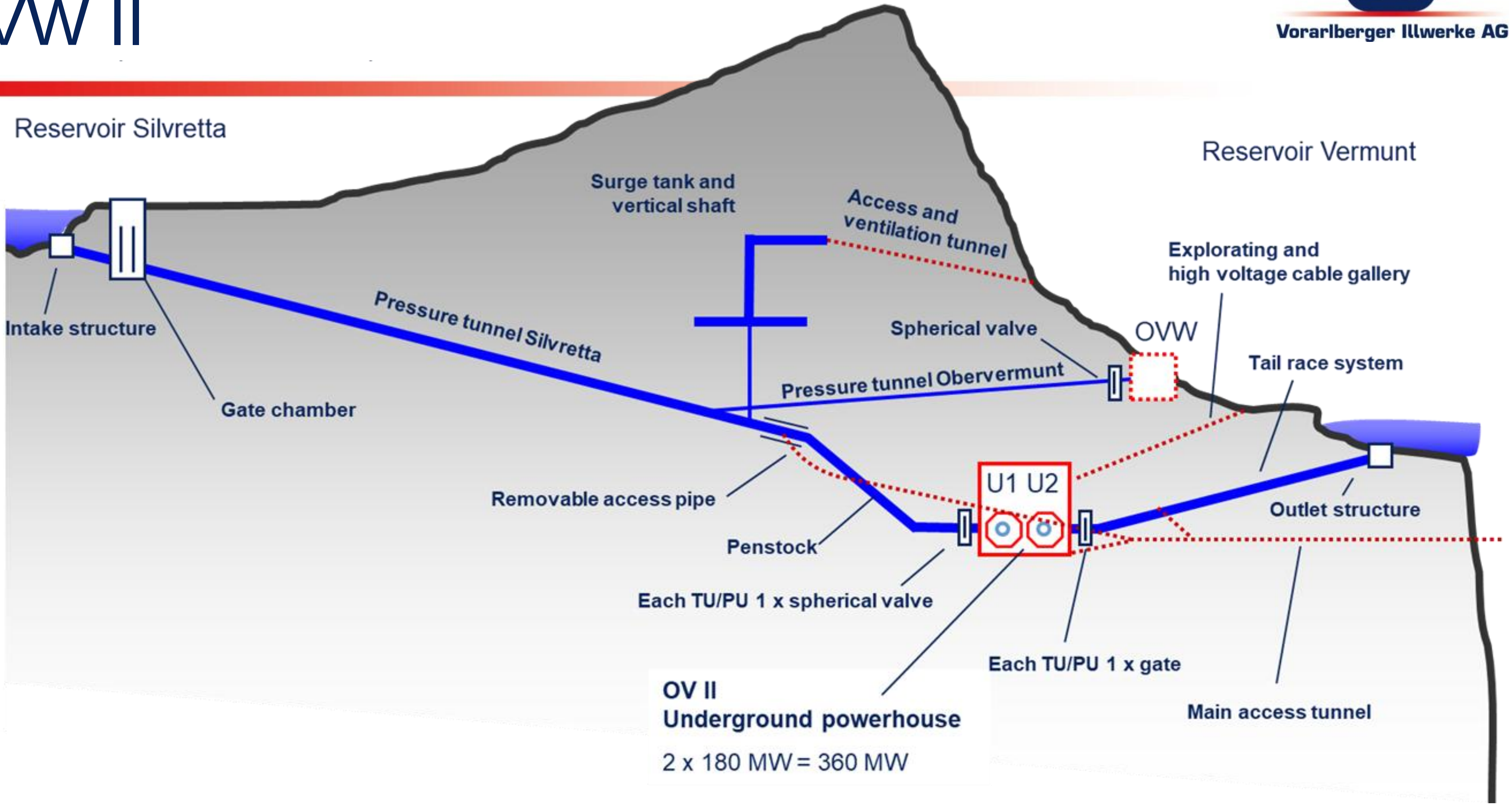
- Two horizontal units, each existing of Francis turbine, clutch, motor-generator, torque converter and pump
- The turbines are full adjustable from 100% to 0% without any part-load limit

Ternary Units:



Longitudinal Section OVW II

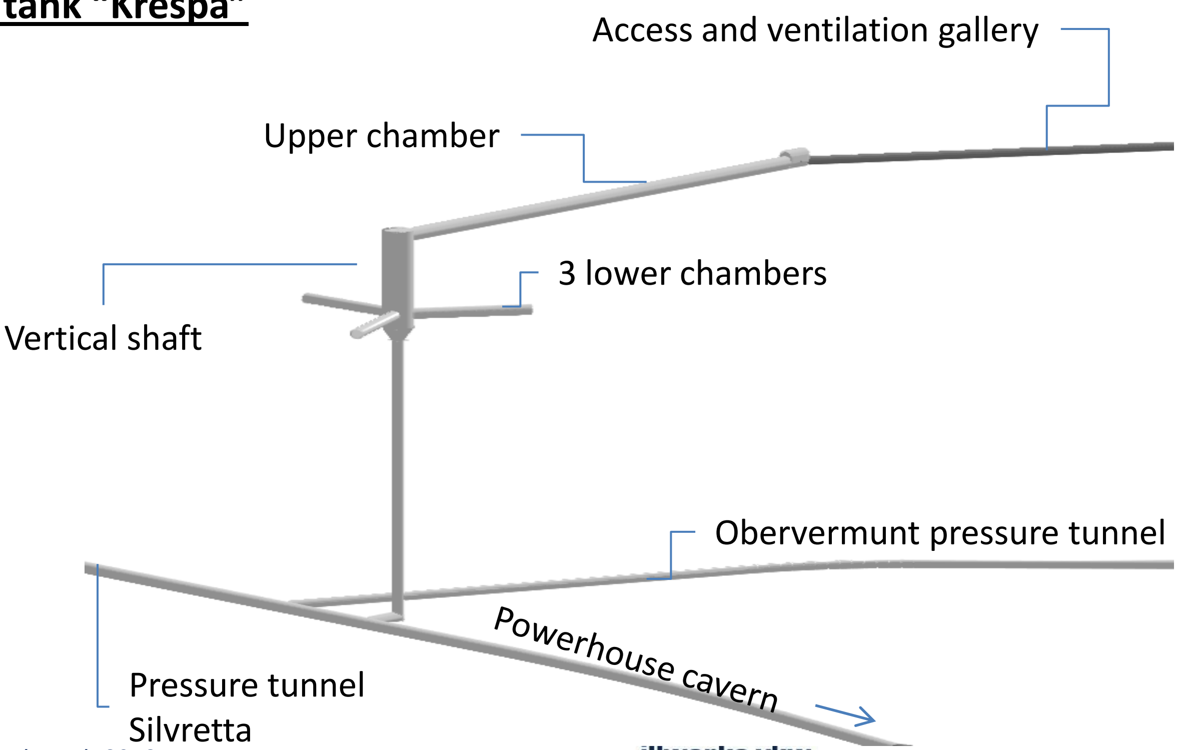
Vorarlberger Illwerke AG



Surge Tank OVW II

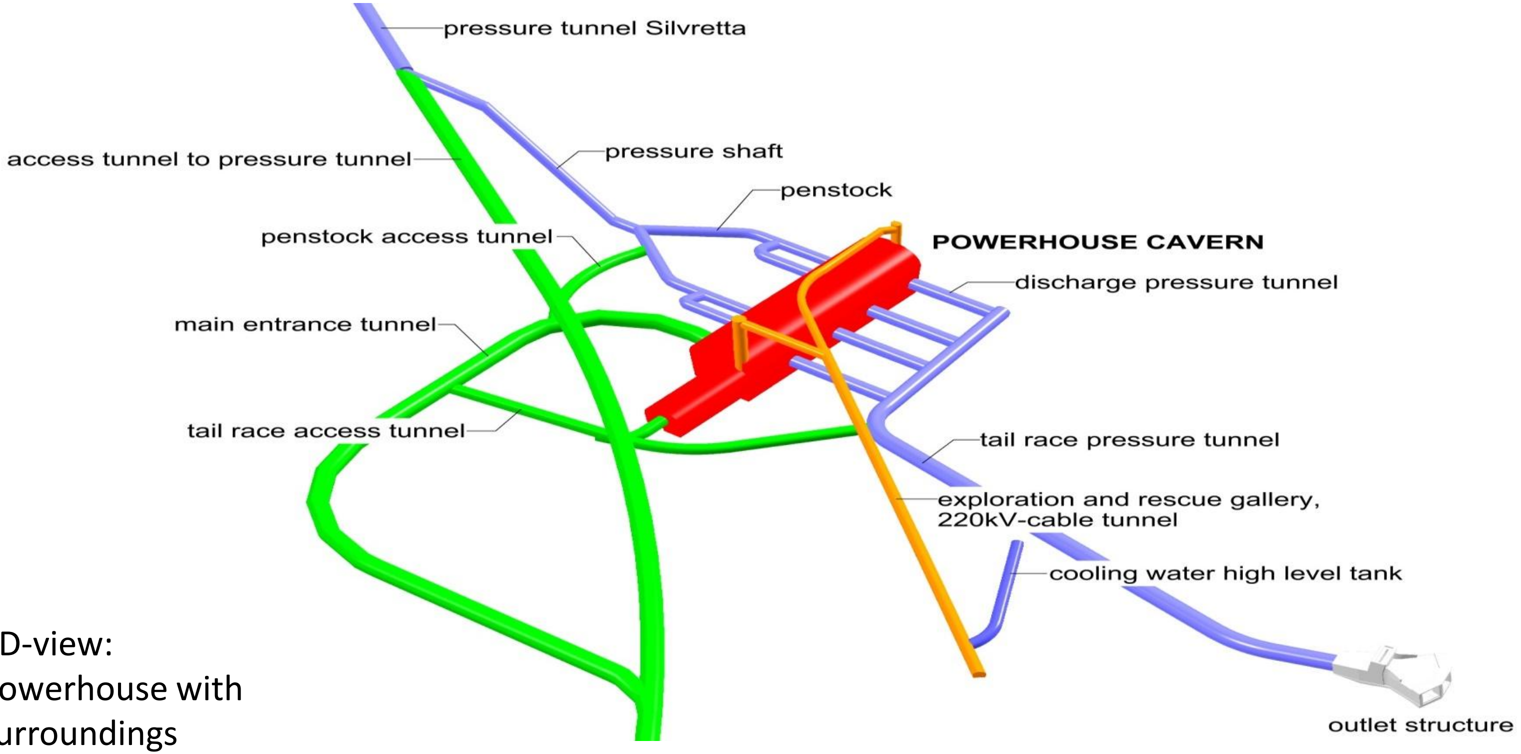
film

Surge tank "Krespa"



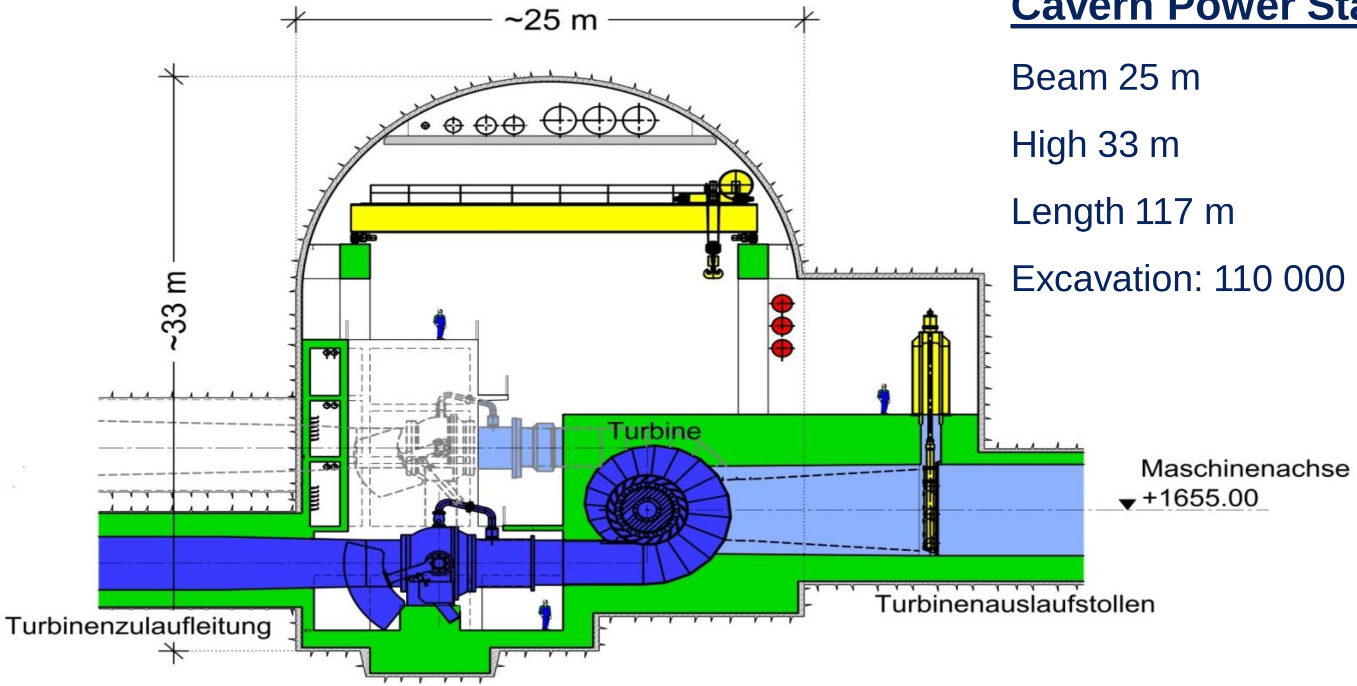
Technical Concept Power House

Vorarlberger Illwerke AG



3D-view:
Powerhouse with
surroundings

Cross Section Power Station



Cavern Power Station

Beam 25 m

High 33 m

Length 117 m

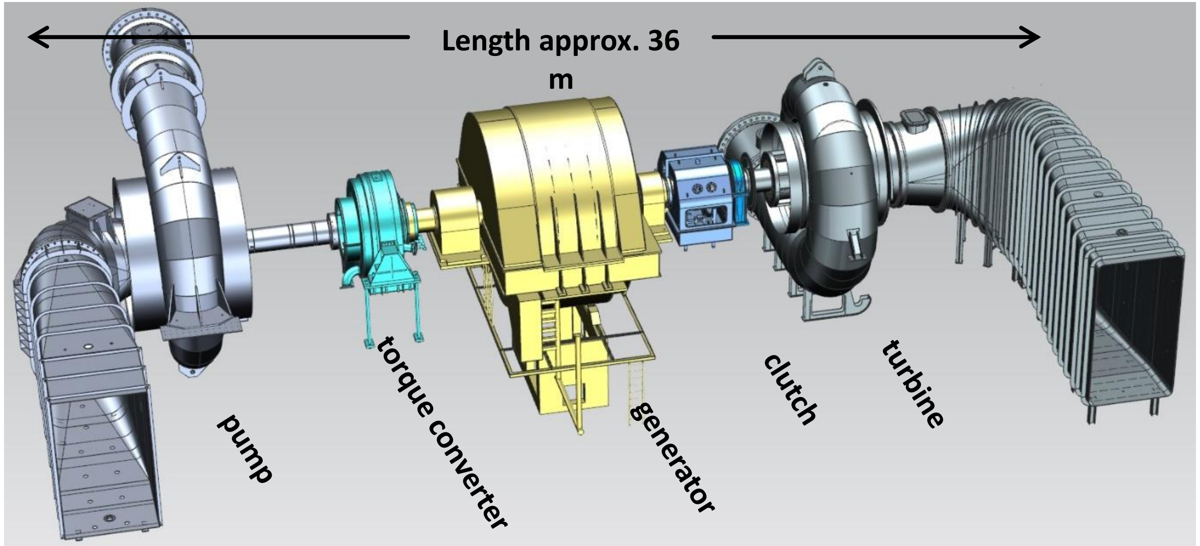
Excavation: 110 000 m³

Technical Concept

Vorarlberger Illwerke AG

- Two horizontal units, each existing of Francis turbine, clutch, motor-generator, torque converter and pump
- The turbines are full adjustable from 100% to 0% without any part-load limit

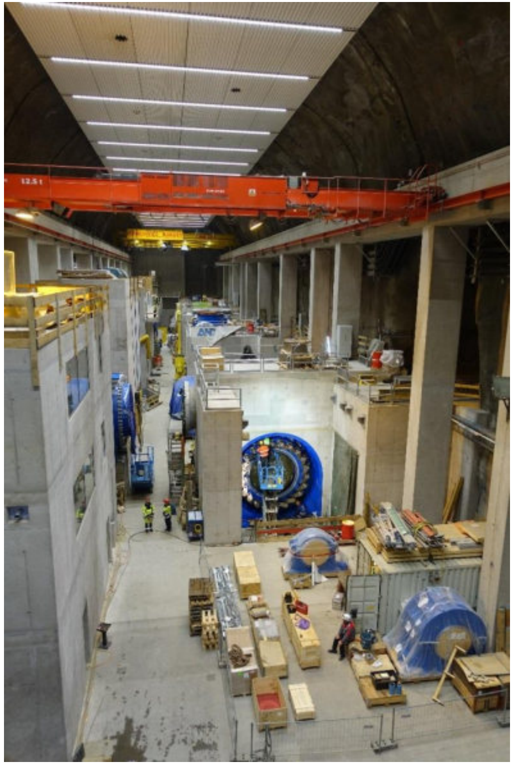
Ternary Units:



Obervermuntwerk II: machine cavern under construction

Vorarlberger Illwerke AG

Obervermuntwerk II



Vorarlberger Illwerke AG

Obervermuntwerk II

film

Vorarlberger Illwerke AG

Turbine mit adjustable Distributor

Runner Pump

Data Confrontation
Kops II and Obervermuntwerk II

Vorarlberger Illwerke AG

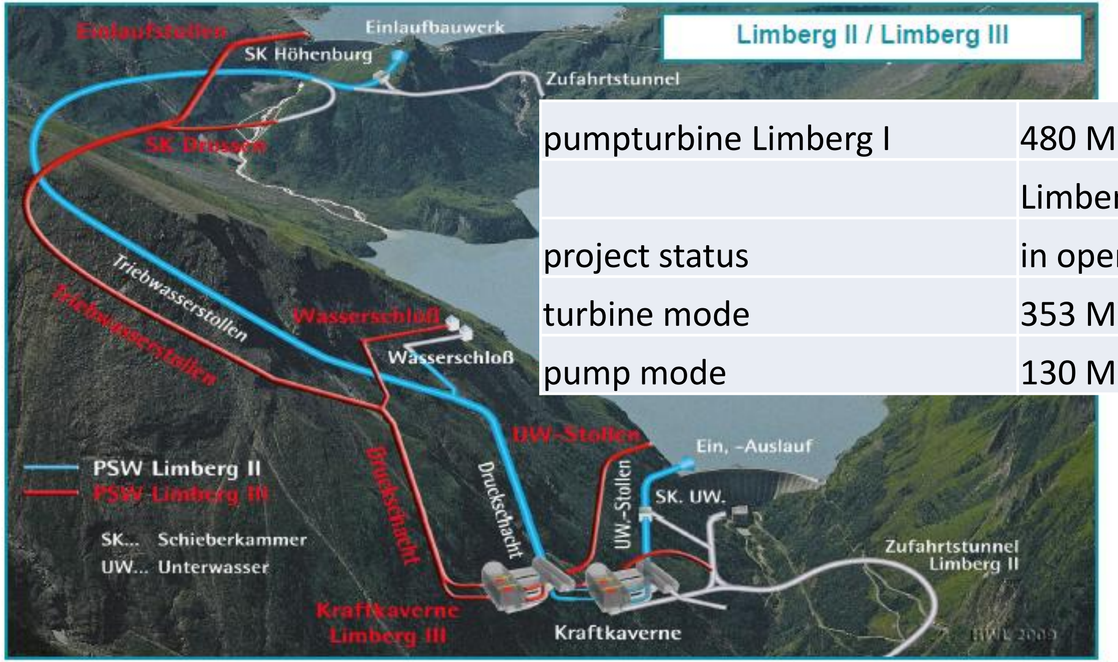
Technical Data	KOPS II	OBERVERMUNT II
Long term Storage	75 GWh	30 GWh
Short term Storage	3 GWh	4 GWh
Capacity Turbine Mode	520 MW 3 Units à 173 MW	360 MW 2 Units à 180 MW
Capacity Pump Mode	450 MW 3 Units à 150 MW	360 MW 2 Units à 180 MW
Full load hours pump mode	6 hours	11 hours
Working Range	-450 MW until + 520 MW	-360 MW until +360 MW
round trip efficiency	0,8	0,8
life time	80 years	80 years
cycles	10^5-10^6	10^5-10^6
power costs	850 EUR/kW	1100 EUR/kW

Limberg II / Limberg III

Vorarlberger Illwerke AG

Verbund

Wasserkraft in Österreich



pumpturbine Limberg I	480 MW (2x240 MW)
	Limberg II / Limberg III
project status	in operation / EIA approved
turbine mode	353 MW / 833 MW
pump mode	130 MW / 610 MW

Benefits of HPP

Vorarlberger Illwerke AG

- Pumped storage is currently the most efficient and economical method for the integration of RES
- Hydropower contributes to a safe and affordable supply
- Storage power plants supports the energy transition in a renewable way
- Austria has an excellent reputation internationally with hydropower and corresponding know-how
- Austria offers not only current but especially energy services

Benefits of the Usual Pumped Storage

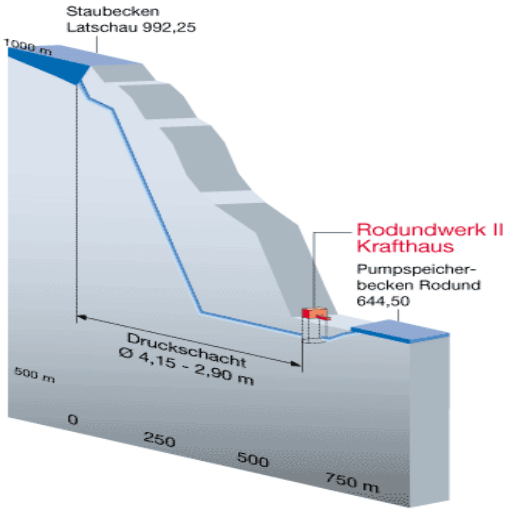
- Supplying power during peak demand
- Improving the power factory of the system
- Providing black start facility, voltage control, reactive power, inertia load
- „Smoothing“ the load demand curve
- Task of a „fire brigade“ for quick hydroelectric generation

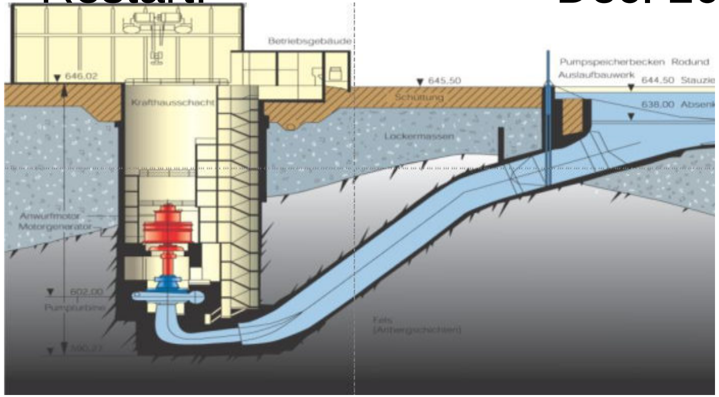
Rodund II

Efficency Hydropower, Refurbihsment

Technical Data:

- Load Capacity: 295 MW
- Discharge: 98 m³/s
- Gross head: 348 m
- First time operation: 1976
- Restart: Dec. 2011

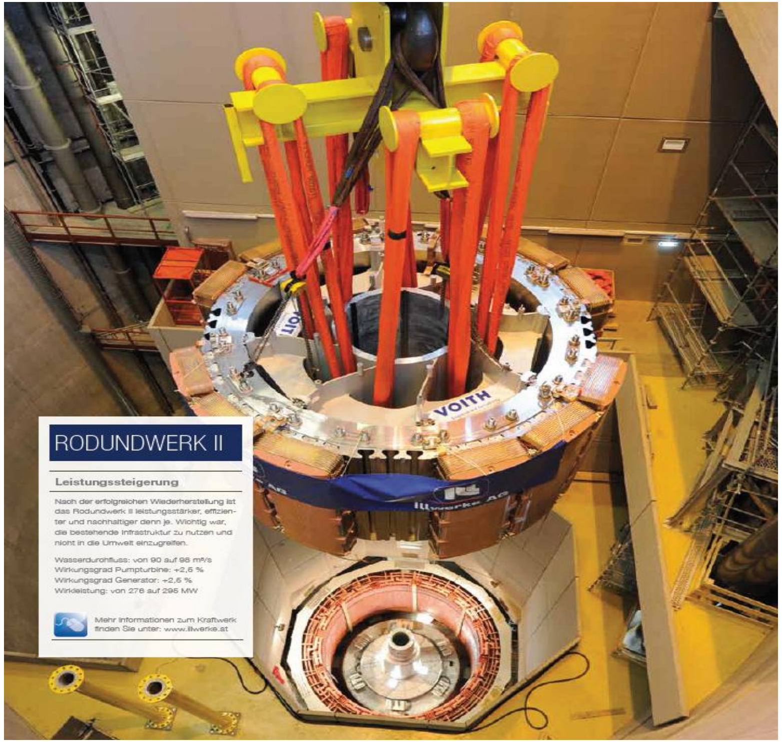




Rodund II

Efficency Hydropower

Vorarlberger Illwerke AG



Restart: December 2011
R&D: Part load stabilization between 0 and 110 MW

Power Plant LÜNERSEEWERK

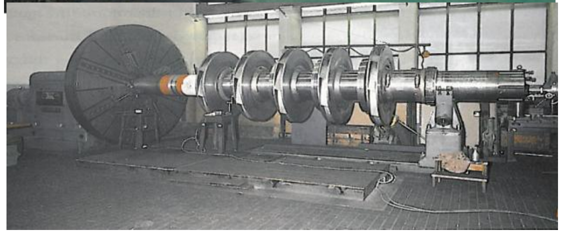
Efficency Hydropower, Refurbishment

Vorarlberger Illwerke AG

Technical data:

- constructed 1954 -1958
- first time of operation 1958

- 5 ternary units 280 MW
- gross head 974 m
- turbine mode 232 MW
- pump mode 224 MW
- energy / a 371 GWh
- pump storage 201 GWh



Refurbishing

Vorarlberger Illwerke AG

Uprating - PHS Lünersee

Vorarlberger Illwerke AG

Reservoir „Lünersee“:

- **Sea Level 1970 m**
- **Storage Capacity 78 Mio m³**
- **Energy Storage 260 GWh**
- **Max Daily Storage 5,4 GWh**

Uprating – HPP Kops I (new runners, jets, housings)

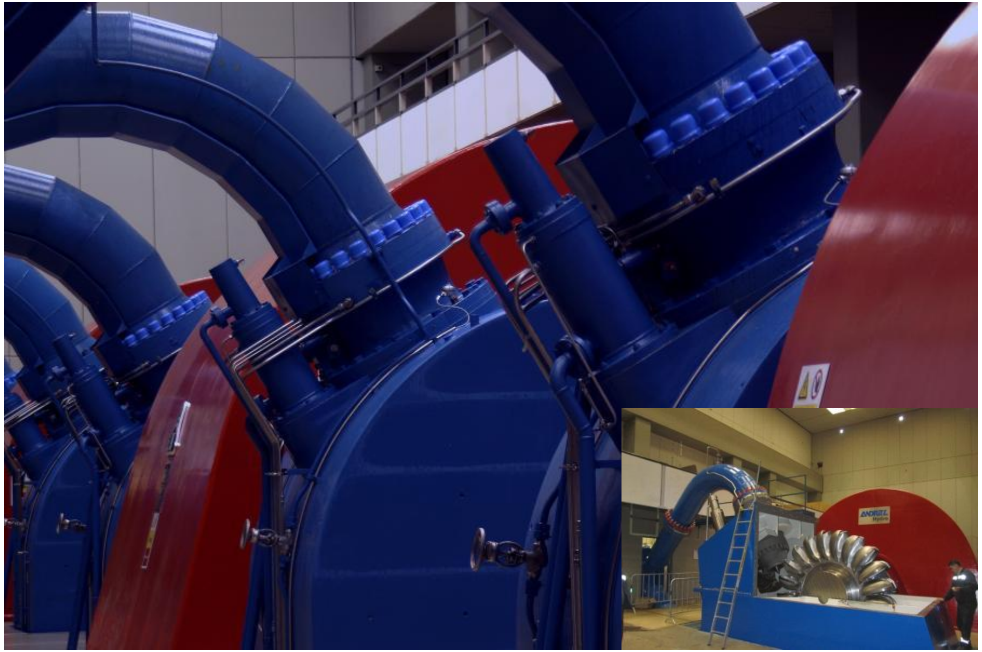
Vorarlberger Illwerke AG

technical data:

- Construction 1962 - 1969
- Commissioning 1968

- 3 units (turbine, generator)

- Gross head 780 m
- Turbine mode 247 MW => **276**
- Energy/a 392 GWh



Thank you

Questions ?
Don`t hesitate to contact me
peter.matt@illwerke.at
www.illwerke.at

Execution of Construction Work

Site Section D
(main section, status quo)

Section D – concrete mixing plant

Section D – concrete mixing and aggregat processing plant

Section D – ropeway for material transport - MS 1

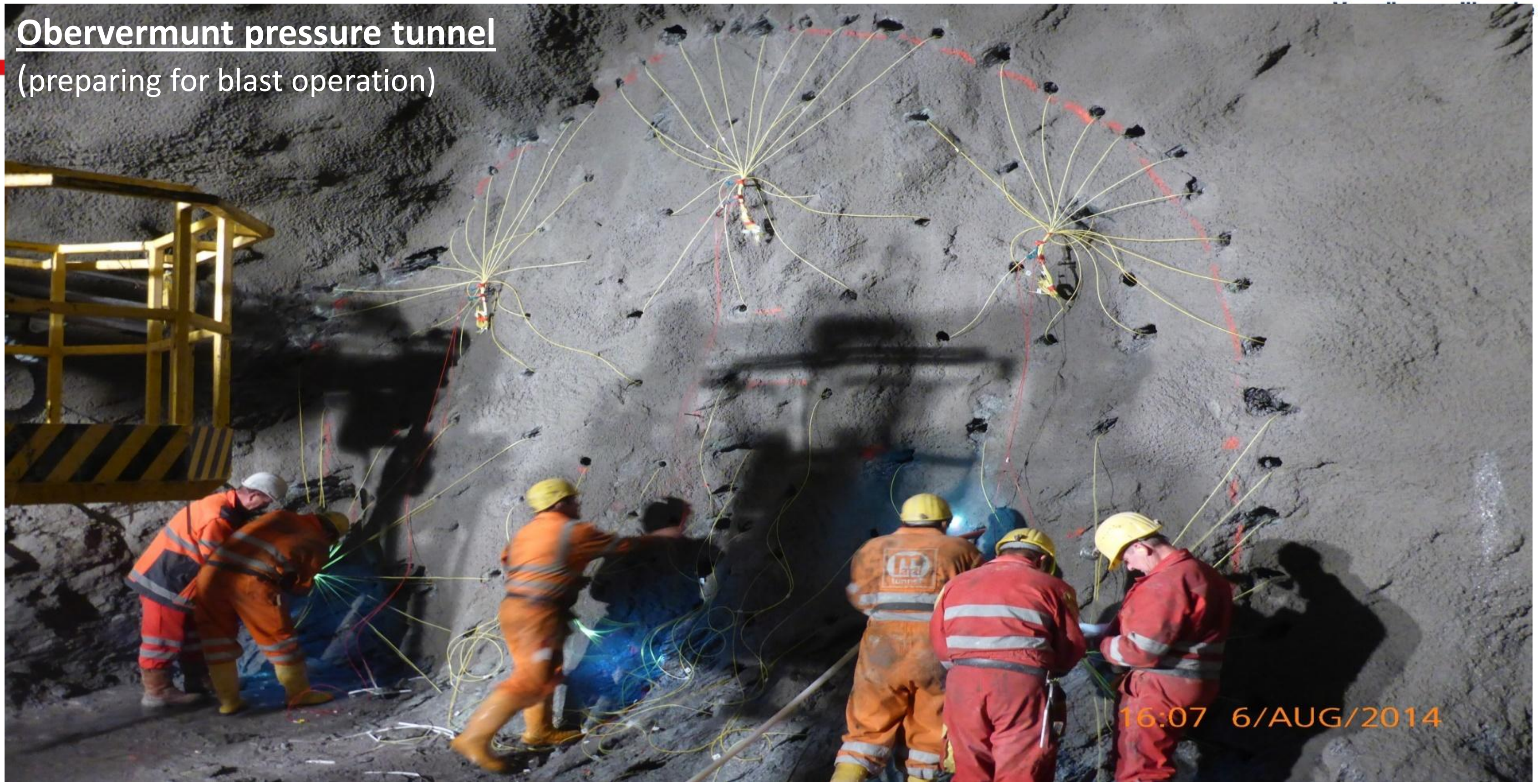
Execution of Construction Work

Vorarlberger Illwerke AG

Main access tunnel to powerhouse cavern

(excavation and support method: pipe roof support)

Execution of Construction Work



Execution of Construction Work

Site Section D

(status quo)

Section D – ropeway for material transport

Section D – ropeway for material transport - MS 1

Section D – ropeway for mate l transport

Pumped Storage Schemes & Role of Regulators

P. V. SIVAPRASAD
Director,
Kerala State Electricity Regulatory Commission

Regulatory Commissions

- **CERC at the center**
  - **Powers to regulate centrally owned generating companies and companies having composite scheme for generation and sale of electricity in more than one State**
  - **To regulate inter-State transmission/Trading**
- **SERCs in the State**
  - **Powers to regulate intra-State generation, transmission and distribution**
- **CERC vis a vis SERCs**
  - **No hierarchical relationship, however, SERCs are to be guided by the principles of tariff determination specified by CERC**
- **Forum of Regulators-consisting of Chairpersons of CERC &SERCs for harmonization of regulation**

Role of Regulators in Indian Power Sector

- **Regulations**
  - **Tariff Regulations**
  - **Licensing Regulations -Transmission, Distribution, Trading**
  - **GRID Code**
  - **Standards of service regulations etc.**
- **Procedural regulations**
  - **Conduct of business regulations**
  - **Payment of fees etc.**
- **Regulatory Orders**
  - **Determination of tariff**
    - **Generation,**
    - **Transmission and**
- **Real-time Operation related orders-UI, Grid security etc.**
- **Adjudication of disputes**
- **Open Access procedures**
- **Advisory role to the Governments**
- **Promoting RE**

Provisions in the Tariff Policy 2016 regarding pumped storage schemes..

- **One of the objective is to ‘ Promote Hydroelectric Power generation including Pumped Storage Projects (PSP) to provide adequate peaking reserves, reliable grid operation and integration of variable renewable energy sources.**
- **Tariff for electricity sold to DISCOMs through long term PPAs shall be determined by the CERCs / SERCs as the case may be.**

Role of the SERCs as the Regulator in promoting pumped storage schmes

- Determination of Tariff for the electricity generated from PSP and supplied to DISCOMs
- Approval of power purchchase agreement to be entered into between the generator and DISCOMs.
- Ensuring safety and security of the grid.., especially in the present context of large scale integration of RE, with adequate electricity storage schemes.

Tariff Determination

- Based on the technical and financial parameters specified by the Commission through Regulations, based on cost plus principles. (Section 61 & 62 of the EA-2003).
- Components of Tariff
  - Interest on Debt
  - Return on Equity
  - Operation and Maintenance expenses
  - Depreciation
  - Interest on working capital
- Annual FC shall be born by the beneficiaries, and ultimately pass on to the end electricity consumers.
- The PSP can operate the plant as a merchant power plant.

Power purchase agreement with Distribution licensee

- Prior approval of the Commission is mandatory as per the provisions of the Electricity Act, 2003.(Section 86(1)(b) of the EA-2003.
- The Commission is duty bound to ensure that, quality electricity is supplied to the consumers at reasonable cost.

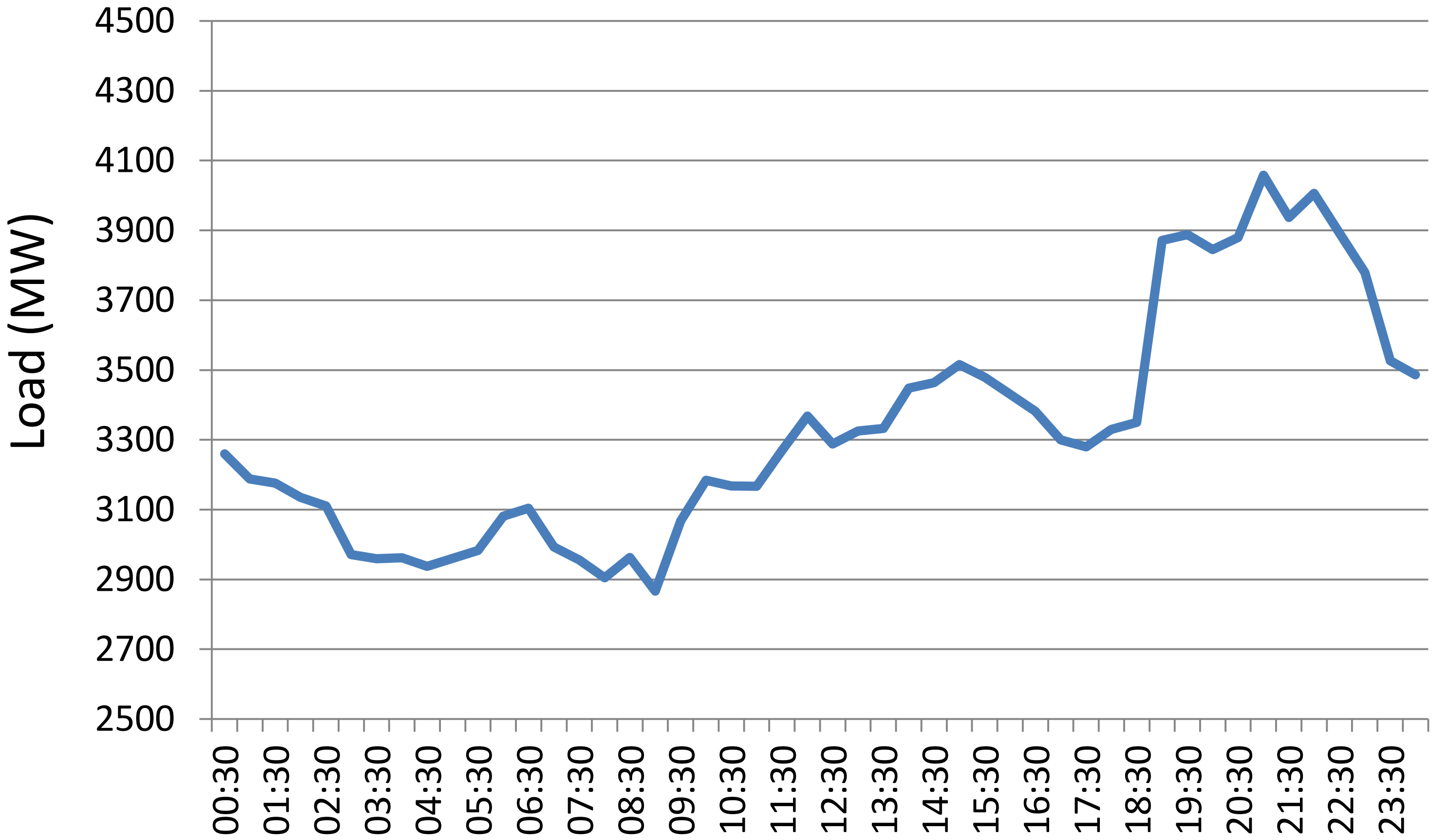
The Commission may consider the following while granting investment approval/ approval for PPA by the KSEB Ltd for PSS..

- Present features of the Kerala power system, its constraints, the consumer mix etc.
- What is the future growth of the electricity demand?
- Supply options available to meet the future demand and its impact on retail tariff.
- Whether the system requires a PSS or not, if so what capacity.
  - Quantify the benefit to the Kerala power system and also its impact on consumers.
  - How it can be utilized.

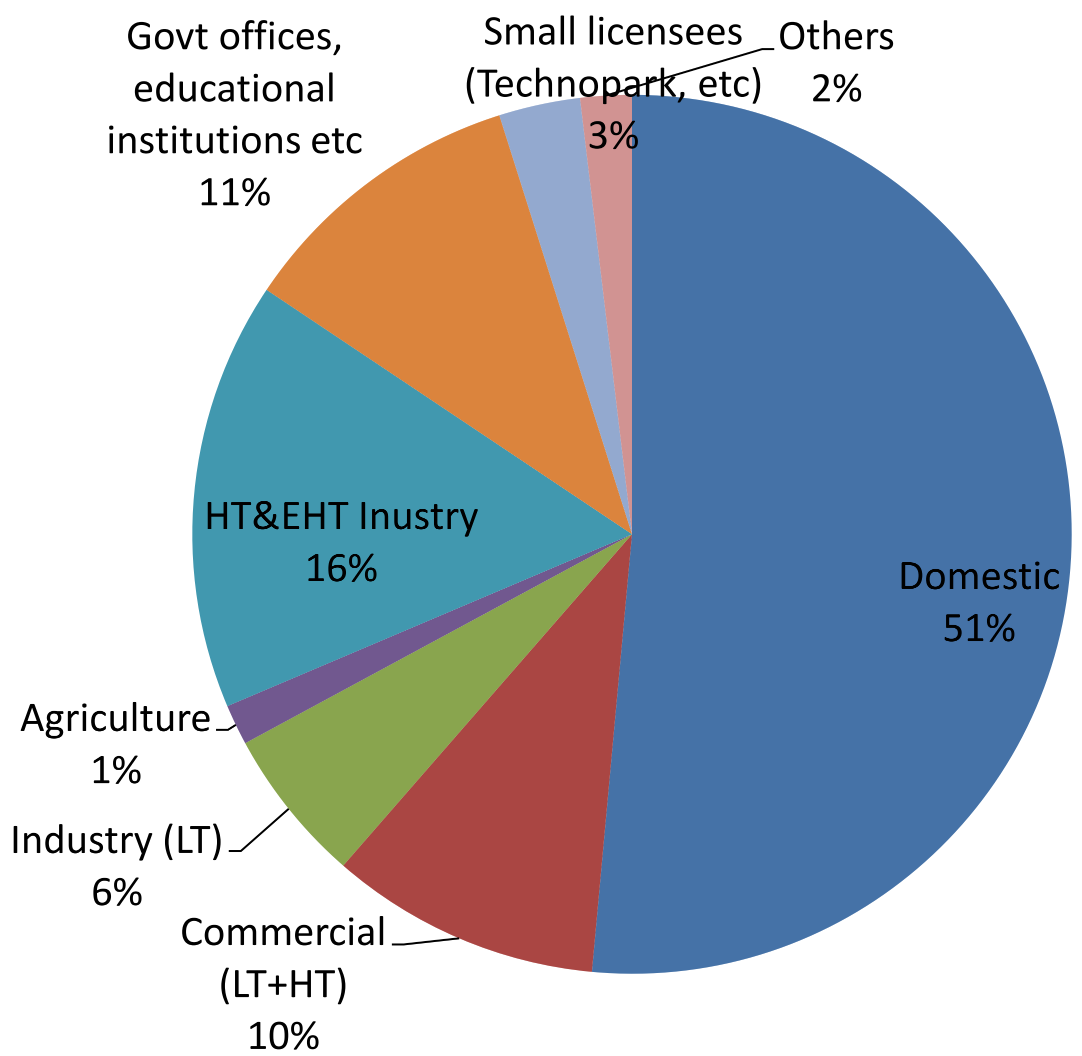
Kerala Power System

- Consumer strength- about 120 lakhs
- Daily consumption- Average -70 Million Units (Annual about 25500 MU)
  - Annual increase – about 6%
    - about 1200 MU
- Peak demand – about 4000 MW
  - Annual increase – about 250 MW

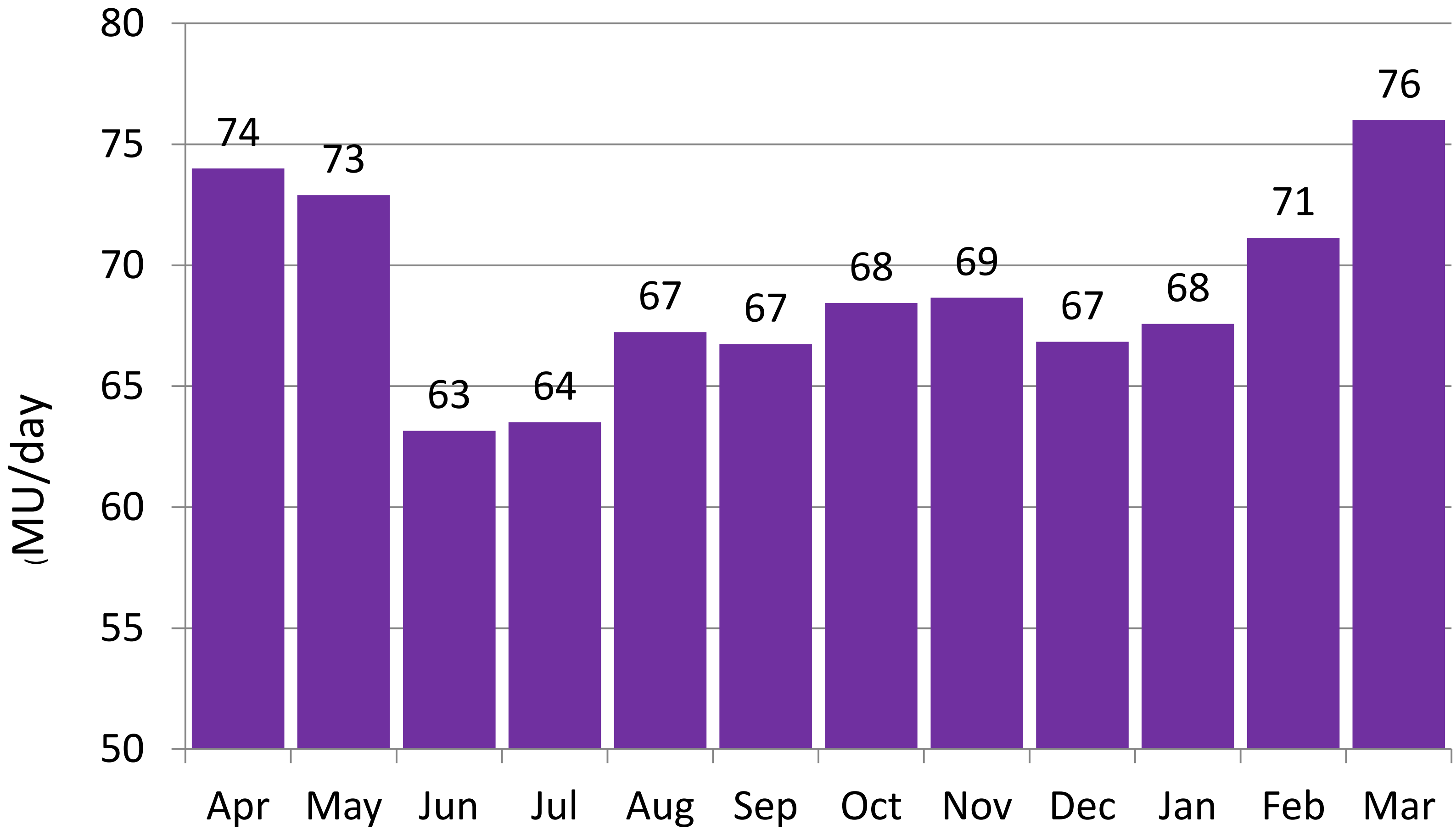
Daily Load Curve (Typical)



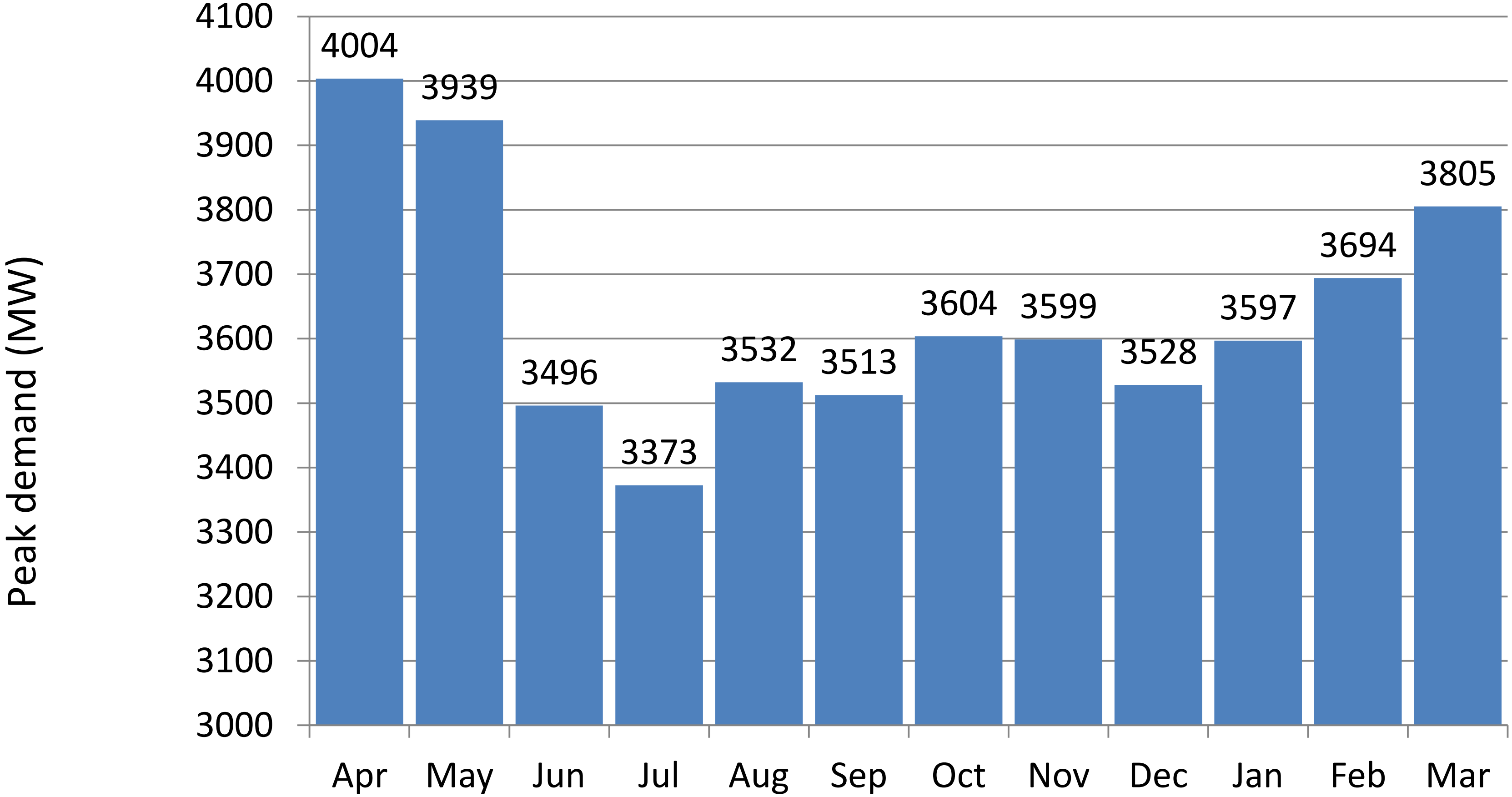
Consumption pattern



Monthly variation of Electricity Demand (MU/day)



Monthly variation of peak demand (MW)



How the electricity demand of the State is being met?

- Historically, till the early 80's, the entire demand is being met by internal hydro.
- In 90's, about 80% of the demand is being met by hydro and balance from thermal (Central Generating Stations).
- Now, about 75 % of the electricity requirement of the State is being met by procuring power from outside the State

Source	1990-91	2016-17	2017-18 (est) (normal monsoon)
Hydro (internal)	80.4%	18.0%	25.6%
IPP & Wind (internal)	0.0%	0.6%	0.6%
CGS (Outside the State)	19.6%	45.7%	43.5%
Traders & short terrm (Out side the State	0.0%	35.7%	30.3%

Own generation and Power purchase by KSEB Ltd

Sl No	Particulars	Installed Capacity	Capacity available	Annual energy availability
		(MW)	(MW)	(MU)
1	Hydro	2100	1650 to 1750	6500 to 7000
2	CGS (outside the State)	1700	1350	11000.00
3	IPPs (outside the State)	1415	1203	9905.98
4	Wind-IPPs	57		109.85
5	Solar KSEB own including 50 MW plat at Kasargod	57.25		95.29
		5329.25	4203	27611.12

Renewable Addition Plan by the Central Government

Source	Capacity as on 31.07.2017		Capacity target for March-2022	
	(MW)	(%) of total	(MW)	(%) of total
Solar	13652	23%	100000	57%
Wind	32562	55%	60000	34%
Small Hydro	4390	7%	5000	3%
Biomass & MSW	8296	14%	10000	6%
Total	58900	100%	175000	100%

Renewable Purchase Obligation

Year	RPO PROPOSED as percentage of total consumption excluding hydro		
	Non-solar RPO (%)	Solar RPO (%)	Total (%)
2017-18	6.00	1.50	7.50
2018-19	7.00	2.75	9.75
2019-20	8.00	4.00	12.00
2020-21	9.00	5.25	14.25
2021-22	10.25	6.75	17.00

Addl solar capacity required- about 1000 MW to meet the Solar RPO, will results in generation by 5.0MU/day during sunny days

RE sources in the State.. Issues and challenges

- Potential RE sources of the State
  - Small Hydro (capacity upto 25 MW)
  - Wind
  - Solar
- Infirm nature,
  - SHP and Wind – Seasonal and generation limited to monsoon months.
  - Solar- generation limited to day time- maximum upto 6 hrs per day

- Low Plant Load Factor
  - Small Hydro- 30%
  - Wind – 22%
  - Solar-19
  - KERLA SYSTEM LOAD FACTOR about 72%??
- Forecasting and scheduling threats, grid security & safety issues
- Very limited storage facility to absorb the variability of RE.

PSS is an effective energy storage solution..

- To cater the peak demand..
- To address the variability and infirm nature of RE..
  - Enhance the reliability of power generated from RE
- Optimum utilisation of the available sources and the electricity market..
  - Enhance the market value of electricity..
- Address the hydrology risk..

Commercial justification..

- Capital cost may be slightly higher..
- Additional electrical energy for pumping, which may increase the effective cost of the energy delivered..
- Overall per unit cost of electricity from PSS may be higher than conventional power..
- ToD pricing (energy charge during peak hours - 6pm to 10pm is 50% higher). ToD mandatory for
  - All HT&EHT consumers
  - LT- Industrial consumers having connected load above 20 kW

Recommendations of the Standing Committee on Energy (2015-16) Sixteenth Loksabha

Pumped Storage System

2.6 The Committee note that 96,524 MW capacity of pumped storage scheme has been identified in the country. Out of this, capacity of 4,785.6 MW is under operation and 1,080 MW is under construction, whereas 1,000 MW projects DPR are prepared and submitted to CEA. The Committee find that development of pumped storage scheme in the country is at a rudimentary stage and its present utilization against the total potential is meager. Considering the vast network of electricity grid in the country and the quantum of electricity demand, it is not difficult to gauge the range of fluctuation in power demands. Pumped storage schemes are meant for storing energy and using at times when demands for electricity soars. Hence, pumped storage scheme will be quite beneficial for developing ancillary power market and in meeting sudden high demands of electricity. The Committee, therefore, recommend that due attention should also be given to develop identified pumped storage schemes in the country.

THANKS

IMPACT OF PUMPED STORAGE PLANT
on
STRESSED POWER SYSTEMS

-A case study on Kerala Power System

Outline

- Introduction
- Stressed Power System
- Major Challenges in the Operation of Stressed Power Systems
- Energy Storage is beneficial
- Why Pumped storage ?
- Kerala power system at a glance
- Features of Kerala Power System
- Main problems faced by Kerala power System
- Cost of power purchase
- Importance of PSP in Kerala System
- Study of Commercial Impact of PS
- Optimal Generation scheduling problem
- Demand & supply of the system
- Mathematical Formulation Problem
- Simulation results
- Scope of mixed pumped storage operation
- Additional Capacity determination
- Conclusion

Introduction

- Economic operation of power system
- Optimal utilization of natural resources
- System wise study is necessary

Stressed Power System

- **Insufficient own resources**
- **Large variation in peak and off peak power demand**
- **Substantial short term power purchase**
- **High impact of fluctuations in power market on system operation**
- **Increasing addition of renewables**

Major Challenges in the Operation of Stressed Power Systems

Economic operation of Power system is affected by

- Change in market structure in the deregulated environment of power system operation
- Evolution towards more renewable energy sources like solar, wind etc.
- Uncertainty in amount of power availability
- Uncertainty in time and duration of availability
- Fluctuations in market price

Energy storage will have a strong impact on the operation of such systems

Energy Storage is beneficial

- Load factor of the system can be improved ensuring better utilization of own resources
- Market price variations can be effectively utilized
- Integrated operation of renewables like wind and solar is possible
- Overall economy of system operation can be improved
- Reliability of the system can be enhanced

Why Pumped Storage ?

- Most economical large scale storage
- High cycle efficiency (0.75-0.85)
- Quick start and stop
- Operational simplicity
- Less maintenance
- Long life
- Better utilization of hydro potential

Impact of pumped storage on Kerala power system

– A case study

Kerala power system at a glance

- Installed Capacity:
  - Hydel :70%
  - Thermal :30%
- Peak Deficit :12%
- Average energy availability from hydel :40%

The dominance of hydro is not reflected in the consumption

Features of Kerala Power System

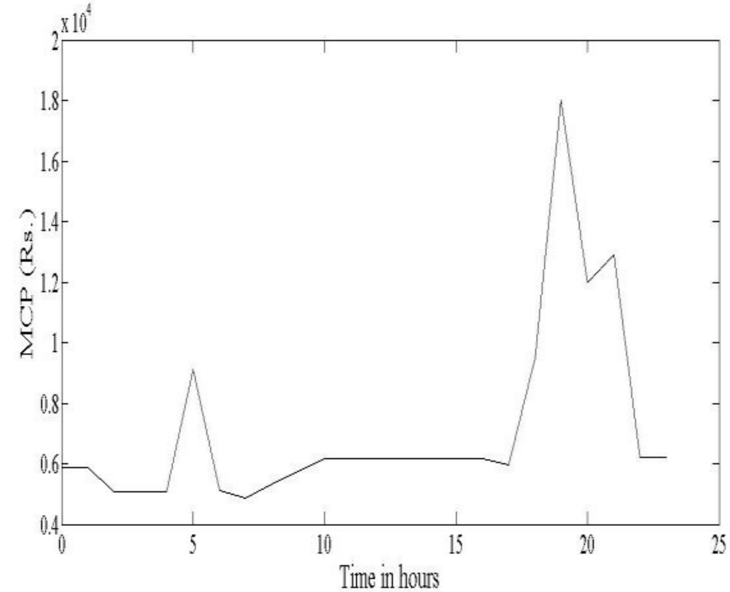
- Relatively poor energy resources (absolutely no fossil fuel reserves)
- Dependency on Monsoon (more than 70% hydro)
- Adverse consumer mix(nearly 80% are domestic consumers to whom energy is sold at subsidized price Rs 1.9 as against Rs 4.6)
- Low load factor (evening peak is almost double that of base load, lowest in Southern grid)
- High cost of thermal power (the increase in demand is met by costly power purchase liquid fuel stations)
- Adverse LT-HT ratio (6:1 against 1:1as per norm which has adverse effect on distribution installation & distribution loss)

Main problems faced by Kerala power System

- Peak Power deficit
- The hydel source is monsoon dependant and hence availability is limited for two thirds of an year
- Geographical and environmental restrictions prevent construction of new stations
- Substantial power purchase mainly due to peak power deficit

Market price

- Highly variable in nature, beyond the control of the utility
- Cost is high when demand is high and is less during off peak
- A deciding role in economic operation of the system



Storage is the solution

Purchase and **store** when energy is **cheaper** (off-peak load) and **release** the same when **peak demand** appears

Importance of PSP in Kerala System

- Abundance of hydro potential. Effective utilization of hydro resources
- Load factor of the system can be improved ensuring better utilization of other resources
- Increasing Renewable penetration cause significant fluctuation in market price. Need a quick responding storage option
- Economy can be improved by energy arbitrage
- Reliability of the system can be increased

Study of Commercial Impact of PS

Problem Formulation

- The commercial impact of PSP is evaluated from the optimal generation schedule with and without a fictitious PSP
- Annual saving is obtained by comparing both the schedules assuming an installation cost of 4 corers/MW for the PS plant
- Optimal capacity of the PSP corresponding to maximum savings is found by assuming different capacities for the plant

Optimal Generation scheduling problem

- **Objective**: Minimize the total operating cost for the day
- **Constraints**:
  - Demand-Supply balance
  - Power& Energy availability from Hydro plants for the day
  - Power & Energy availability from CGS
  - Operational constraints on the LF plants eg. Combined cycle operation
  - Power purchase limit during peak hours
  - Energy availability from purchase for the day.

Demand & power supply

- System demand is met by
  - hydel stations
  - allocation from central generating stations,
  - liquid fuel stations
  - power purchase from Traders/power exchanges

Scheduling is done by load dispatch centre on merit order basis. Merit order is prepared on the basis of energy cost/MWhr.

Mathematical formulation of the Problem

- The optimal scheduling problem is formulated as an integer programming problem
- Solved using a MILP/LP solver GLPK
- Optimal schedule is prepared for the existing system and with PSP

Optimal scheduling

- Objctiv Funtion
- Min $C = \Sigma\ (C_C.P_C(i) + C_T P_{BT}(i) + C_{PUR}(i)\ P_{BPUR}(i)) +$
  $\Sigma(C_H P_H(j) + C_{PUR}(j)(P_p(j) +$
  $\Sigma(C_T P_{PT}(k) + C_H P_H(k) + C_{PS}.P_{PS}(k))$

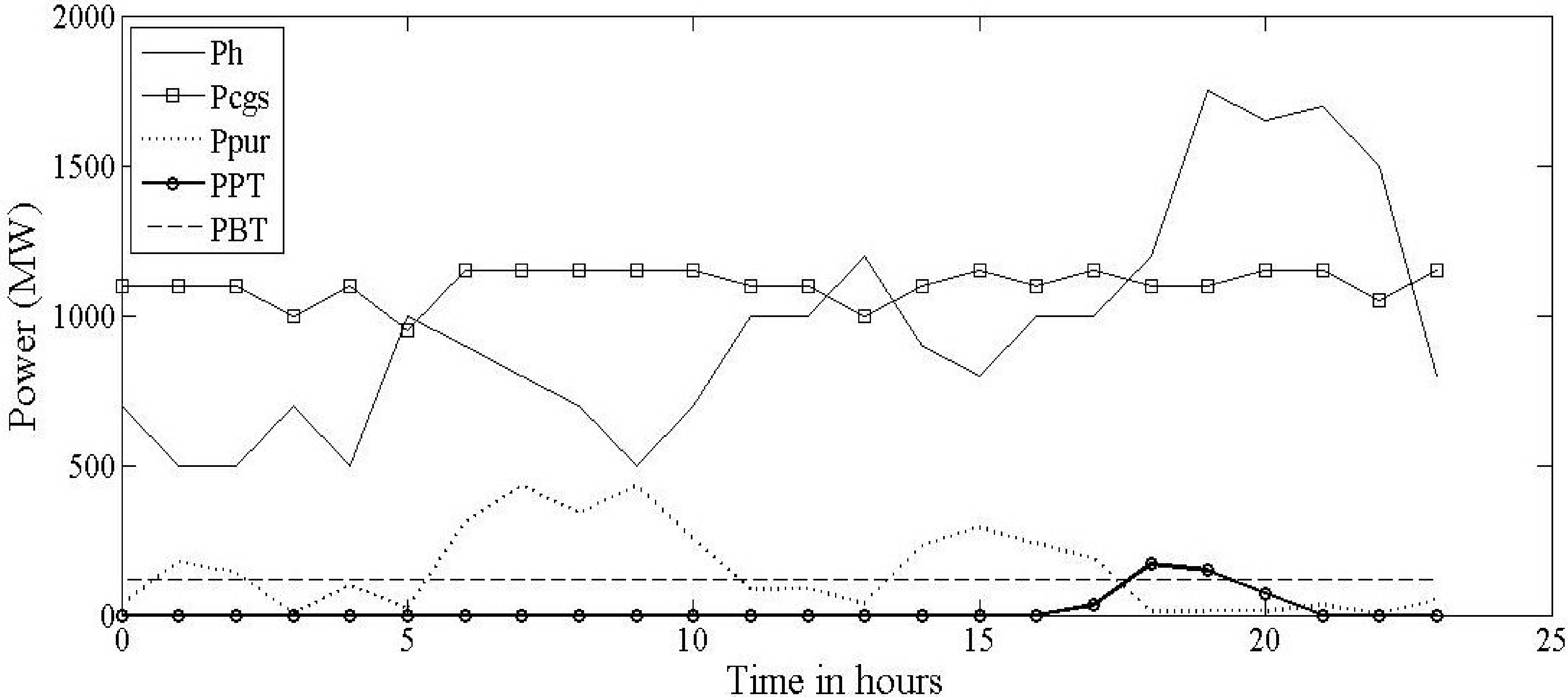
- Sub to:

$\Sigma P_c(t) <= P_{ct}max$
$\Sigma P_H(k) = P_{Ht}$
$\Sigma P_H(j) <= P_H max$
$P_P\ (j) = P_{max}$
$P_{PSmax} = P_{max}$
$P_{PT}(k) <= P_{PT}max$
$\Sigma P_{BT}(i) = P_{BTt}$
$P_{PUR}(j) >= P_{PURmin}$
$P_{PT}(k) + P_C(k) + P_H(k) + P_{PS}(k) + P_{PUR}(k) = P_L(k)$
$P_{BT}(j) + P_C(j) + P_H(j) + P_{PUR}(j) - P_P(j) = P_L(k)$
$\Sigma P_{PS}(i) <= \Sigma Pp(i)*\eta$
$E_U(k) = E_u(k-1) - P_{PH}(k) - P_{PS}(k)$
$E_U(j) = E_u(j-1) - P_{BH}(j) + \eta.P_p(j)$
$E_L(j) = E_L(j-1) - \eta.P_P(j)$
$E_U(i) >= E_{Umin}$
$E_U(i) <= E_{Umax}$

$E_L(i) >= E_{lmin}$
$E_L(i) <= E_{Lmax}$
$E_U(0) = E_{Ui}$
$E_{Li}(0) = E_{Li}$

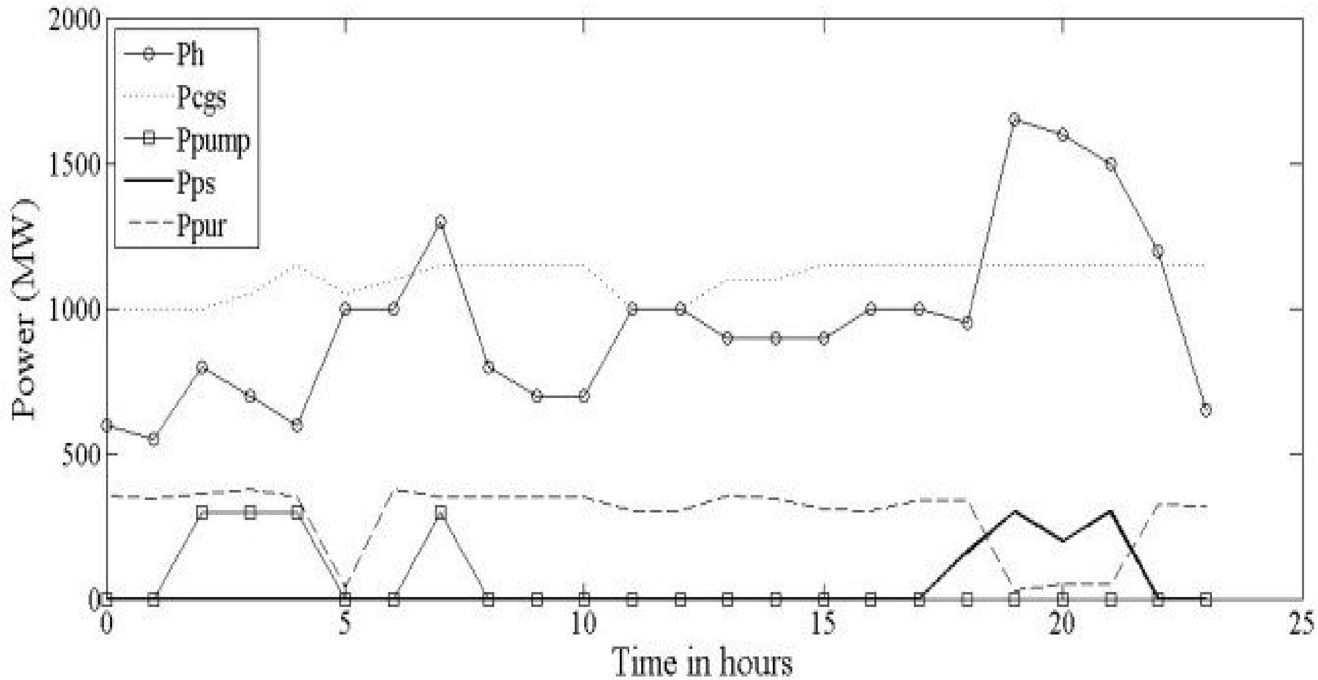
- The above problem is solved first for the existing system and then with a PS plant.
- The integer programming problem is solved using free software package GLPK which contains an MIP/LP solver.

Simulation & Results without PSP



- A costly liquid fuel station running as base load plant just because of non availability of sufficient power to meet the critical peak demand
- **Pushes the operating cost of the system to a high value**

DA generation scheduling results with a grid energy storage



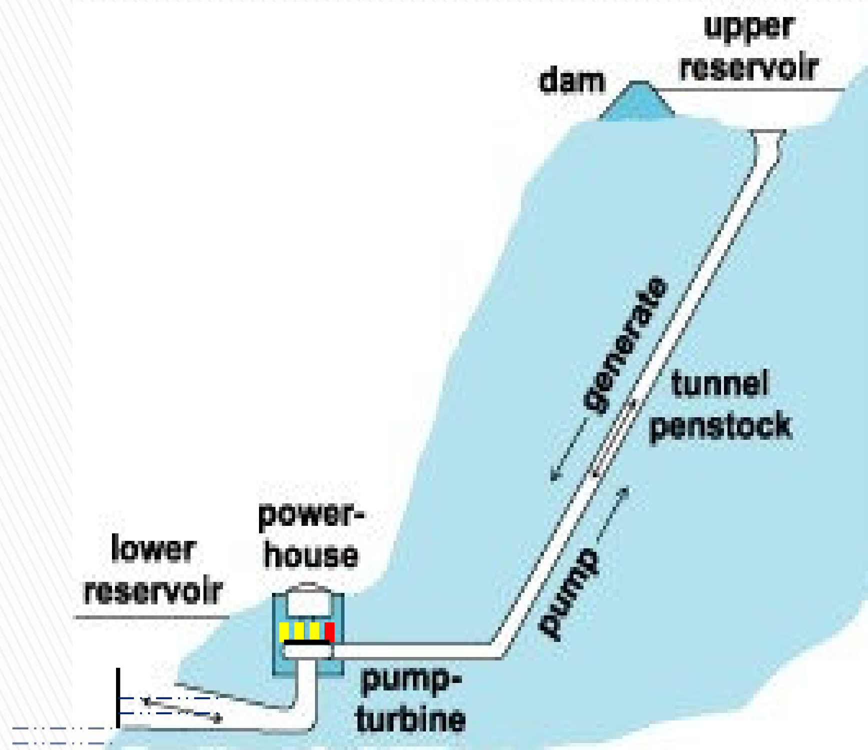
- Revised schedule with a fixed capacity pumped storage plant
- Costly LF plants are replaced by the PS plant
- A substantial saving of 1.14 Cr. in operating cost per day

Scope of mixed pumped storage operation

-An empirical study

Concept of Mixed Pumped Scheme (MPSS)

- Conventional Hydro plants retrofitted with a PS unit in the power house and a suitable sump in the tail race



Advantages of MPSS over PSS

- Less capital investment
- Minimum environmental impact

Development of MPSS

- Feasible in existing hydro plants with significant spillage during monsoon season and extra storage capacity during summer season

- Proposal is to bring an additional capacity which is ensured year round

Additional Capacity determination

- Step1: Classification of reservoir data* based on storage level

Category	Storage (% of FRL)	Reservoir status
1	80-100	Chance of spillage
2	50-80	Safe level
3	<50	Limited storage

* Plant capacity is 48MW (4x8+16) and data analyzed for the period 2006-10

Contd..

- Step2: Additional capacity determination

Category	Capacity
1	Capacity (P_1) determined from average spill/day during the season
2	Control the off peak generation so that extra peak capacity (P_2) can be introduced based on the inflow rate of the season
3	Pumped storage operation whose capacity (P_3) is not calculated in this study

Calculations

- P_1 in MW= $\frac{S.1000}{24}$ **,S is the av.spillage in million units**
- P_2 in MW= $\frac{I.1000}{p}$ **,I is the total inflow for p number of hrs and p the no.of peak hrs**
- Determination of P_3 requires a detailed study which is beyond the scope of this work

Results

Category	Additional capacity	Mode of operation during the season	% Duration of operation in an year
1	16	Round the clock generation	30
2	12	Peak hour generation	15
3	–	PS operation	55

Unit size & Sump Capacity

- Unit size is selected as **8 MW** considering
  - the possibility of FL operation in all the 3 seasons
  - the availability of the unit in case of a breakdown

Sump capacity is estimated as **0.185MCM** which is necessary for 4 hrs of peak load (for the test system) generation

Conclusion

- Preliminary study shows the viability of PS plant in Kerala Power System operation
- Extra hydro potential is available in existing plants which can be easily tapped out for Energy Management
- MPSS is very effective in improving demand response
- The proposed method is extremely simple for the system managers to adopt and implement

Thank You

DVC: Flood Control, Irrigation, Water Supply, Drainage and Power Generation

- **Original Plan of DVC:** ***For a Century-long effort of taming the highly destructive turbulent Damodar river during floods & utilizing its huge water resources, the Planners proposed a scheme of construction of 7 multipurpose Storage dams at Konar, Aiyar, Panchet, Bokaro, Tilaiya, Deolbari & Maithon with a Barrage & canal network system.***

DAMODAR VALLEY CORPORATION

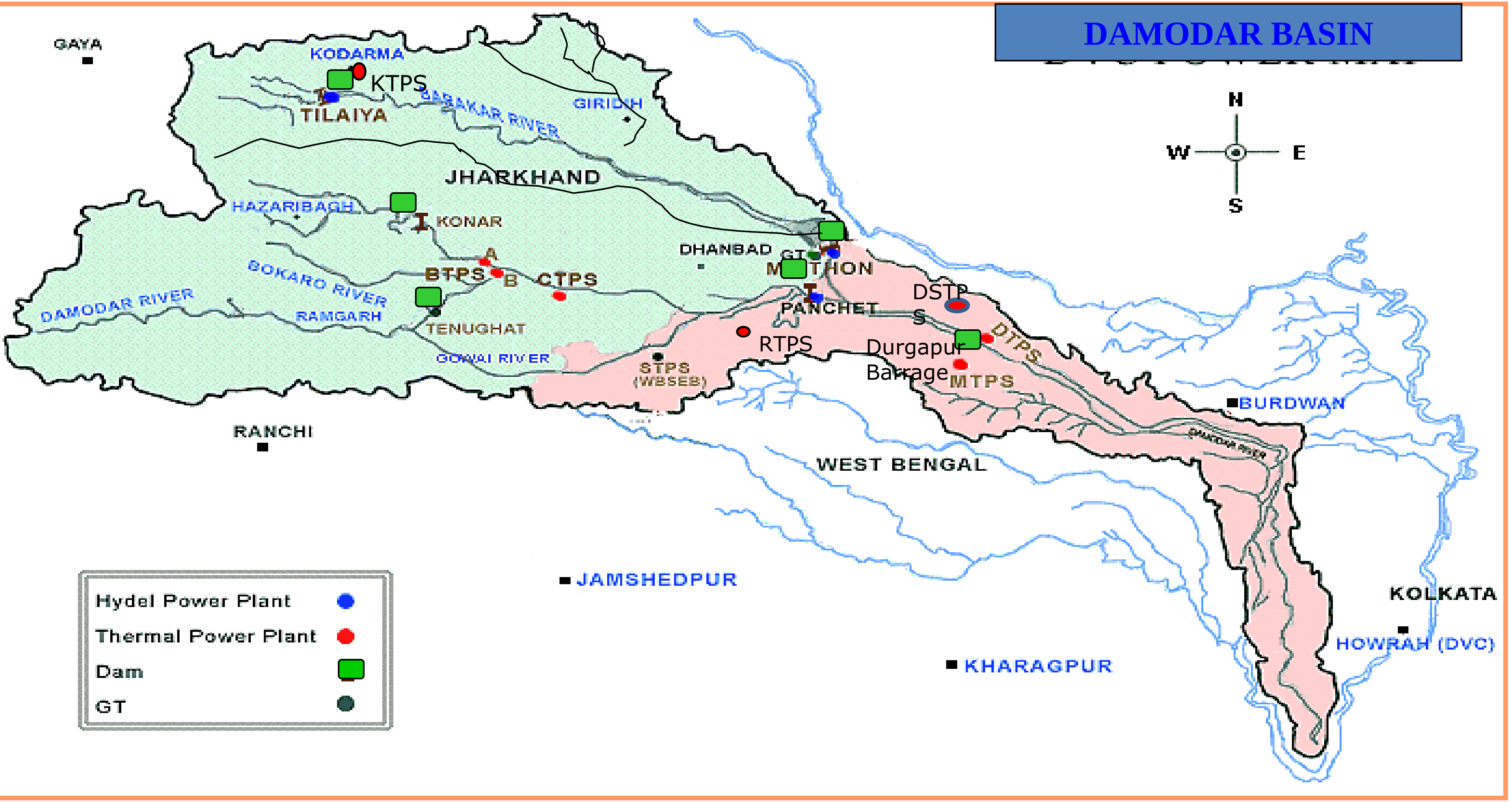
- ***CAME INTO EXISTENCE ON 7TH JULY 1948 BY AN ACT OF PARLIAMENT 'DVC ACT (XIV), 1948', WITH PRIME CORPORATE OBJECTIVES TO FULFILL.***

- ***AN AUTONOMOUS BODY OF CENTRAL AND THE STATE GOVERNMENTS OF WEST BENGAL AND BIHAR (Now JHARKHAND).***

- ***FIRST MULTIPURPOSE INTEGRATED RIVER VALLEY PROJECT OF INDEPENDENT INDIA.***

DVC : PRIME CORPORATE OBJECTIVES

- *Promotion and operation of schemes for flood control in the Damodar River and its tributaries.*
- *Promotion and operation of schemes for irrigation, water supply and drainage.*
- *Promotion and operation of schemes for the Generation, Transmission and distribution of electrical energy, both hydro-electric and thermal.*
- *Promotion and control of navigation in the Damodar river and its tributaries and channels if any.*
- *Promotion of afforestation and control of soil erosion in the valley.*
- *Promotion of public health and the agricultural, industrial, economic and general well being in the Damodar Valley and its area of operation.*



DAMODAR BASIN
GAYA
KODARMA
KTPS
TILAIYA
BARAKAR RIVER
GIRIDIH
JHARKHAND
HAZARIBAGH
KONAR
DHANBAD
GT
MAITHON
A
BTPS
B
CTPS
BOKARO RIVER
DAMODAR RIVER
RAMGARH
TENUGHAT
PANCHET
DSTPS
RTPS
Durgapur Barrage
DTPS
MTPS
GOWAI RIVER
STPS (WBSEB)
RANCHI
BURDWAN
WEST BENGAL
N
W
E
S
JAMSHEDPUR
KOLKATA
HOWRAH (DVC)
KHARAGPUR
Hydel Power Plant
Thermal Power Plant
Dam
GT

PERFORMANCE OF DVC in 58 YEARS of OPERATION (From 1959 to 2017):

➢ *FLOOD MODERATION THROUGH DVC DAMS*

- Moderation of Some Major Floods

Period	Combined Peak Inflow (In cusec)	Combined Peak Outflow (In cusec)	Flood Moderation (In cusec)
Oct. 1959	6,23,000	2,88,000	3,35,000
Oct. 1961	5,16,000	1,60,000	3,56,000
Oct. 1973	5,88,000	1,75,000	4,13.000
Sept. 1978	7,74,000	1,63,000	6,11,000
Sept. 1995	6,19,000	2,50,000	3,69,000

- Note: If the 1978 flood was allowed to pass without any moderation from DVC dams, It would have generated a flood peak of 11,80,000 cusec at Durgapur Barrage, which is more than the total design flood of DVC system i.e. 10,00,000 cusec and a total devastation could not be avoided.

IRRIGATION BY DVC WATER

- 3 crops in a year- Kharif (Monsoon), Rabi (Winter) & Boro (Summer) from DVC water.
- Supplying 1150 MCM of water on an average - for Kharif Irrigation- Area extended from 75000 Ha to 3,34,282 Ha.
- Supplying 86 MCM of water - for Rabi Irrigation
- Supplying 300 MCM of water on an average, - for non-committed Boro Irrigation
- Value of the Crop produced by DVC water has been estimated to about Rs. 500 to 700 crores annually.

MUNICIPAL & INDUSTRIAL WATER SUPPLY BY DVC

- Supplying water about 555 MCM water to 175 Municipal & Industrial agencies from Ranchi to Panagarh.

- Main Industrial consumers- Steel plants, Thermal Plants, Railways, Collieries & washeries, Fertiliser Plants etc.

- Main Domestic Consumers – Jharia Water Board Dhanbad City, Asansol, Ranigunge & Durgapur Municipalities etc.

POWER GENERATION AND DVC

- Total Present Capacity of DVC is 9305.2 MW – Thermal & Hydel both.
- Total Thermal Power Generation Capacity of DVC- 7770 MW
- Thermal Power capacities of JV companies of DVC- 1388 MW
- Total Hydel Power Generation Capacity- 147.2 MW
- Main consumers – Steel plants, Railways, Coal Industries, State Electricity boards of West Bengal, Jharkhand, Delhi, MP, Karnataka, Kerala, Punjab, Haryana etc.
- One of the major power generating units of Eastern India.

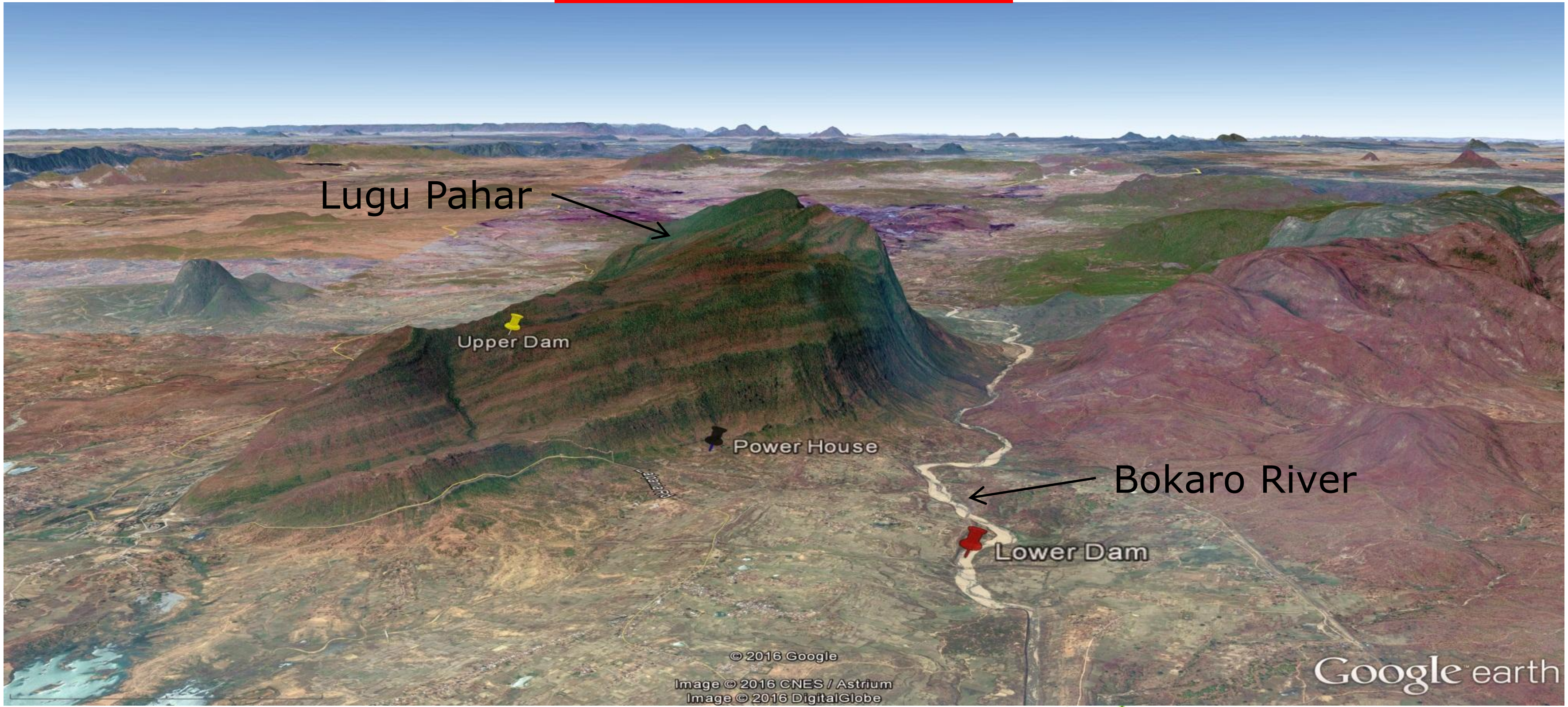
History of Pump Storage Projects in DVC

- DVC identified some *"Hydel Pumped Storage Schemes"* within the Valley area in 1970s.
- In 1978, DVC started planning of a 600 MW Hydel Pumped storage scheme at Lugu Pahar area, near Gomia in the state of Jharkhand.
- CEA advised DVC to proceed for a pumped storage scheme upto 4200 MW at the same location, considering the topographical features & availability of water.
- DVC prepared a preliminary report in 1981 for a pumped storage scheme of 3000 MW capacity at Lugu Pahar area.

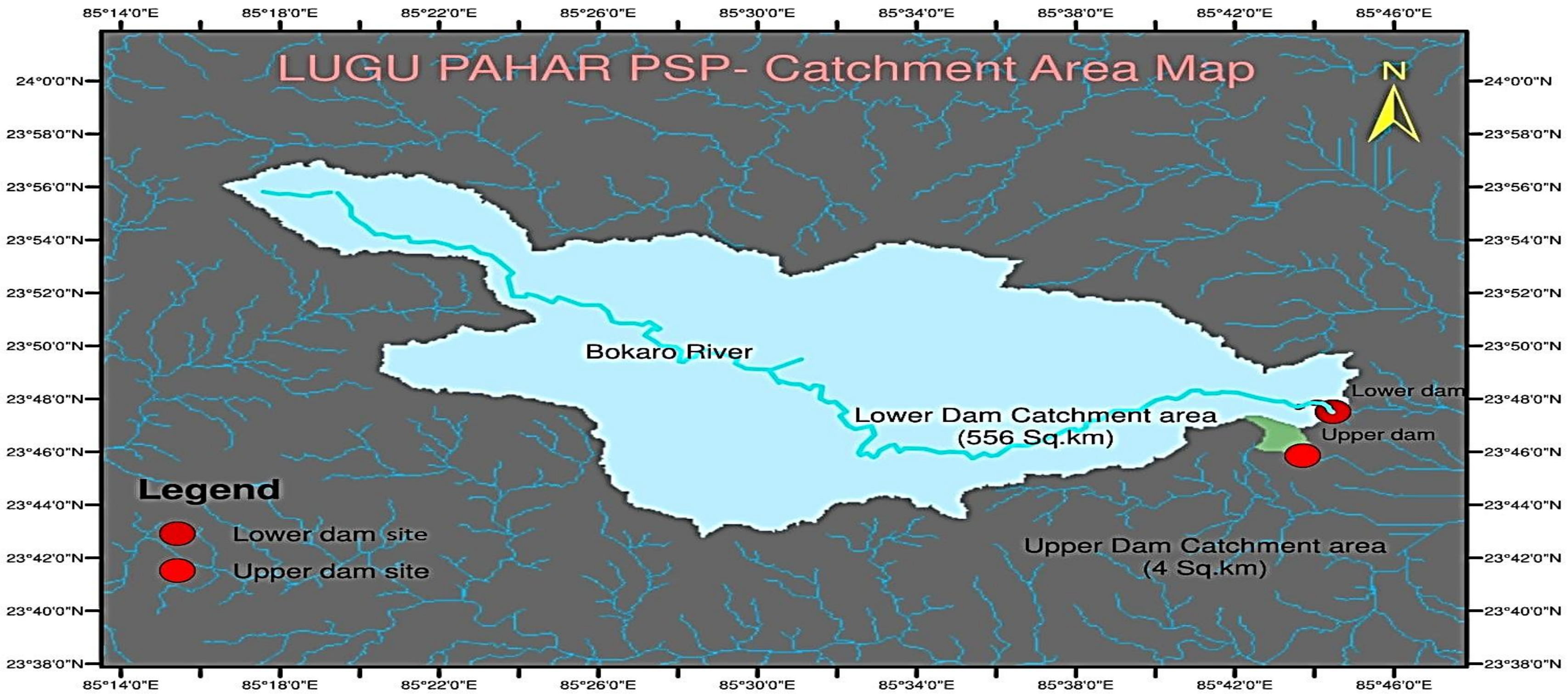
PROJECT – LOCATION & BACKGROUND

Country **State** **District**	**India** **Jharkhand** **Bokaro**
River	**Bokaro river a tributary of Damodar River**
Dam site (Upper)	**Left Bank** N-23^{0}46’30.32” , E-85^0 43’45.12” **Right Bank** N- 23˚ 46’14.4” , E- 85˚43’ 29.52”
Dam site (Lower)	**Left Bank** N- 23˚48’ 06.87” , E- 85˚ 44’ 39.47” **Right Bank** N- 23˚47’ 34.12” , E- 85˚44’ 25.9”
Access to Project	**Airport : Ranchi – 110 km** **Rail Head : Gomia**

Topography


Lugu Pahar
Upper Dam
Power House
Bokaro River
Lower Dam
© 2016 Google
Image © 2016 CNES / Astrium
Image © 2016 DigitalGlobe
Google earth

HYDROLOGY



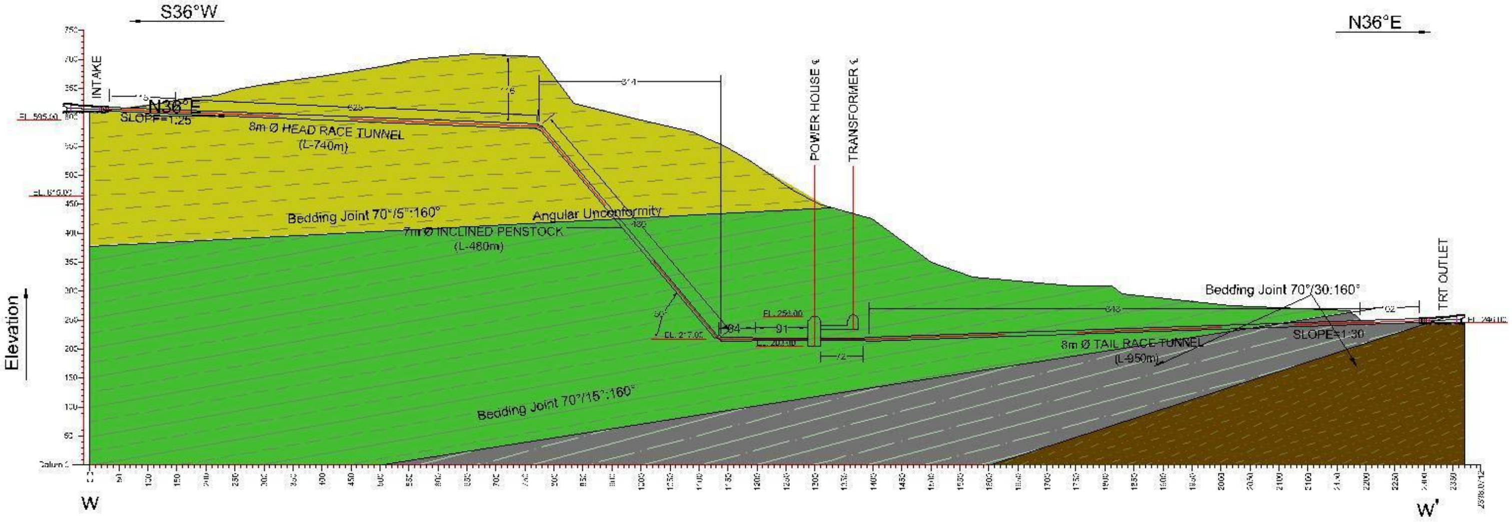
LUGU PAHAR PSP- Catchment Area Map
N
Bokaro River
Lower Dam Catchment area
(556 Sq.km)
Lower dam
Upper dam
Upper Dam Catchment area
(4 Sq.km)
Legend
Lower dam site
Upper dam site
85°14'0"E
85°18'0"E
85°22'0"E
85°26'0"E
85°30'0"E
85°34'0"E
85°38'0"E
85°42'0"E
85°46'0"E
24°0'0"N
23°58'0"N
23°56'0"N
23°54'0"N
23°52'0"N
23°50'0"N
23°48'0"N
23°46'0"N
23°44'0"N
23°42'0"N
23°40'0"N
23°38'0"N

SITE VISIT

- **Joint site visit has been conducted by DVC and WAPCOS officials on 17th August 2017.**



LAYOUT WITH GEOLOGICAL STUDIES



Legend

- Ferruginous sandstone,grit,shale (Mahadeva Fm)with/without cover of slope wash material
- Sandstone,green shale (Panchet Fm) with/without cover of slope wash material
- Sanstone,carbonaceous shale with coal (Raniganj Fm) with/without cover of slope wash material
- Sanstone, shale with ironstone bands (Barren measure Fm)with/without cover of slope wash material
- Trace of Bedding Plane/Joint

PROJECT LAYOUT

HRT- 740M (2 NOS)
DIA- 8M
PRESSURE SHAFT- 7M
LENGTH 544M
TRT-
DIA 8M
LENGTH-950M

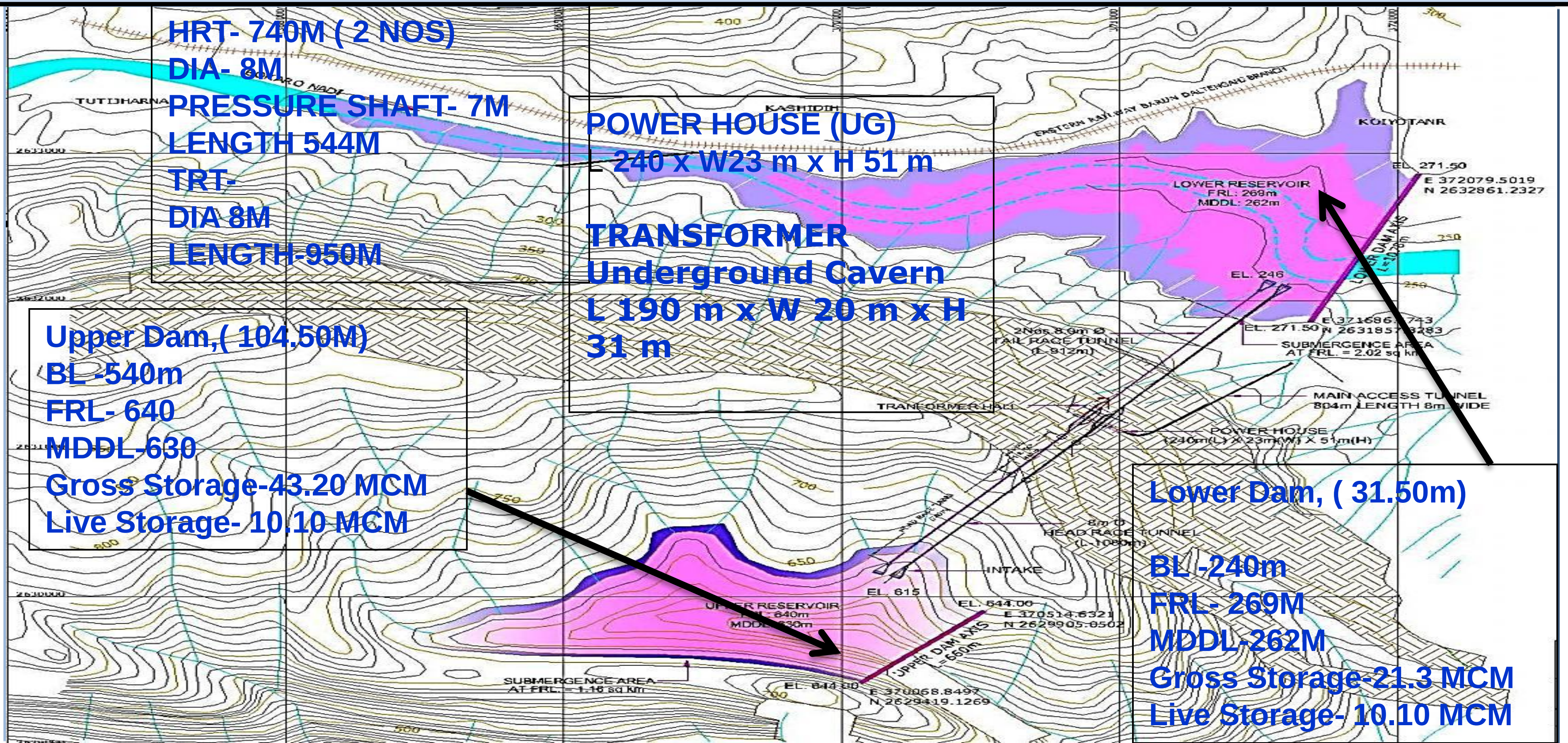
POWER HOUSE (UG)
L 240 x W23 m x H 51 m

TRANSFORMER Underground Cavern
L 190 m x W 20 m x H 31 m

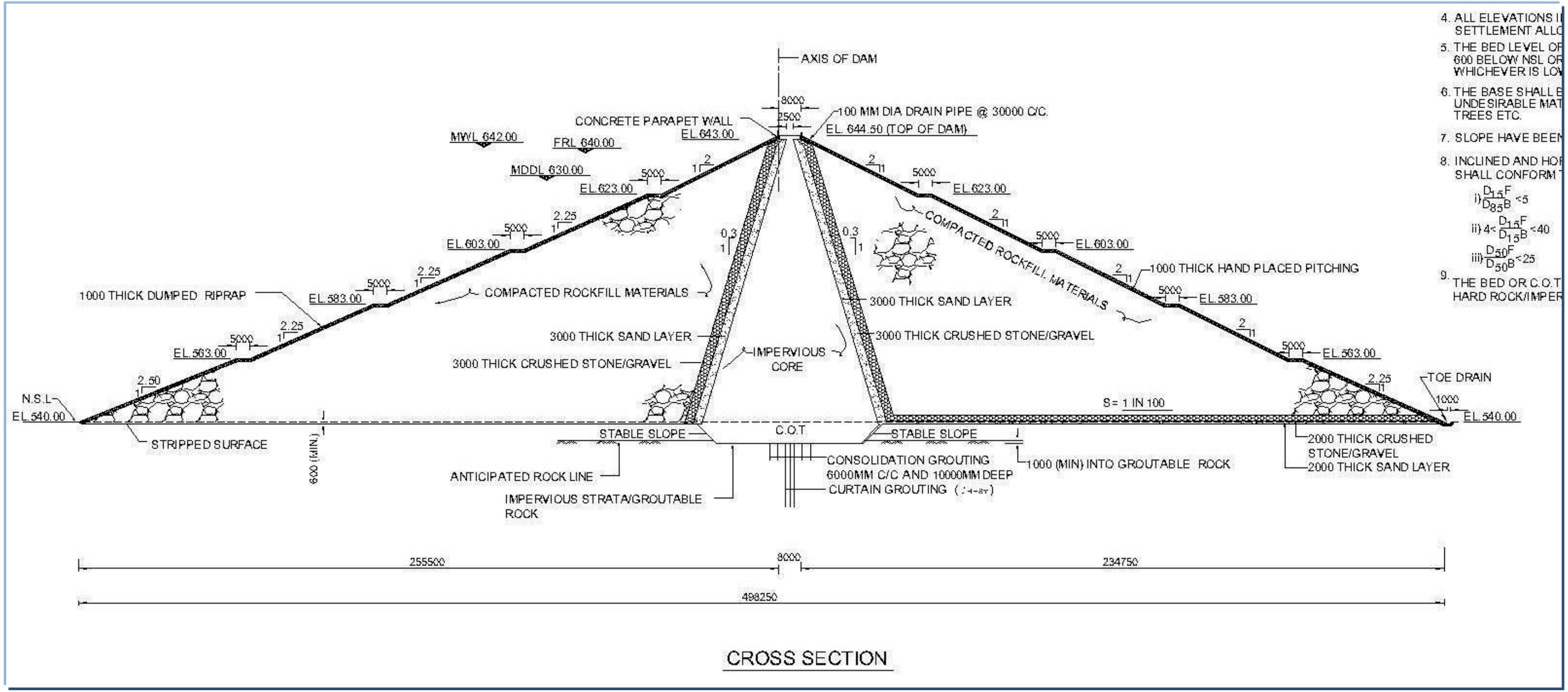
Upper Dam,(104.50M)
BL -540m
FRL- 640
MDDL-630
Gross Storage-43.20 MCM
Live Storage- 10.10 MCM

Lower Dam, (31.50m)

BL -240m
FRL- 269M
MDDL-262M
Gross Storage-21.3 MCM
Live Storage- 10.10 MCM

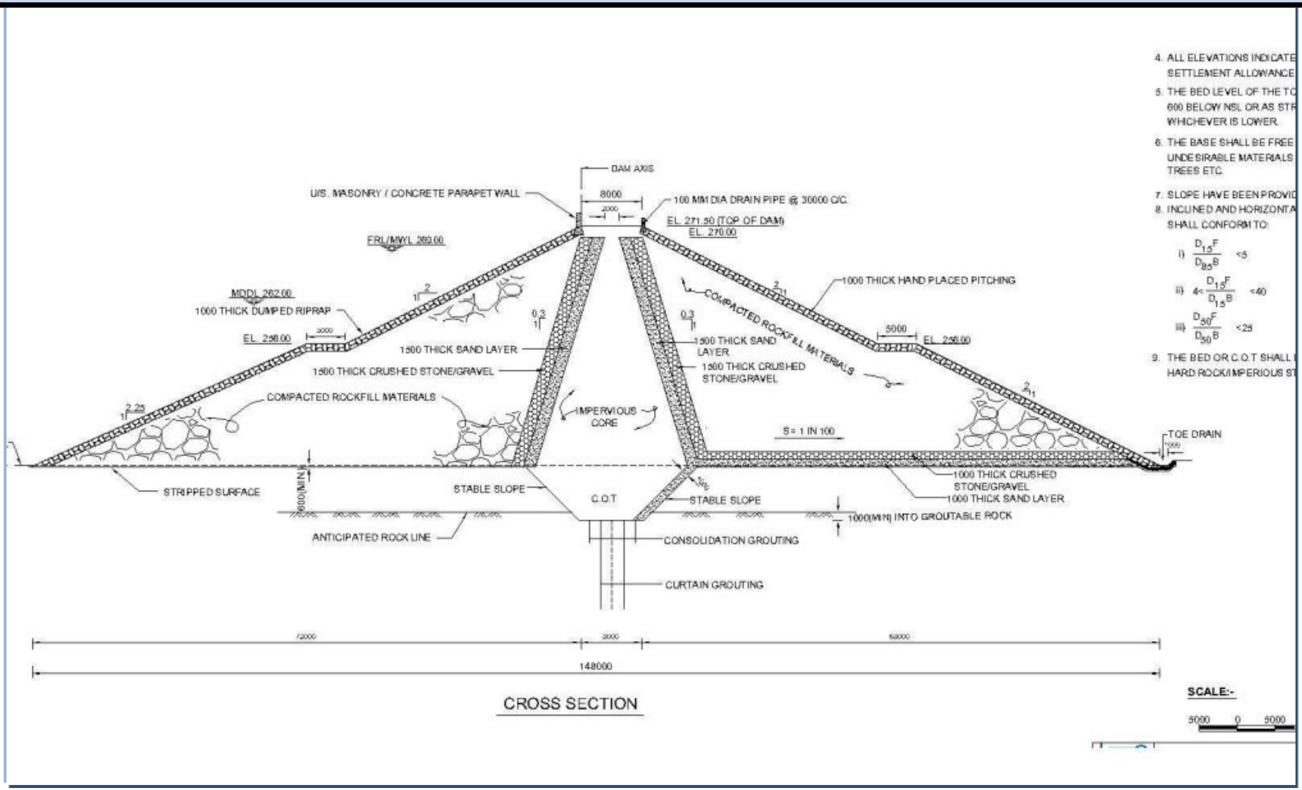


DRAWINGS- UPPER DAM



C/S UPPER DAM

DRAWINGS- LOWER DAM



C/S LOWER DAM

RESRVOIR SIMULATION-RESULTS

- The Upper Pond with FRL at **640** m and MDDL **630.64** m has a live storage capacity of 10.10 mcum.
- The head during generating mode would vary from a minimum of **346 m** to a maximum of 364m. The discharge during generating cycle caries from 440 cumec to 480 cumecs.
- The FRL of lower Pond is 269 m and MDDL 262 m
- The head during pumping cycle varies from a minimum of 352m to a maximum of **368m** .
- The ratio of Maximum to Minimum head is **1.05.**
- Pumping duration during off peak is **7.4**hours.
- The pumping energy requirement is **11000 Mwh.**
- The cycle efficiency is **81.82%**.

ELECTROMECHANICAL ASPECTS

Type	Francis type, vertical shaft reversible pump-turbine
Number of unit	Six (6) units
Rated Turbine Head	362 m
Turbine Output at Rated Head	253 MW
Rated Pump Head	378 m
Pump Input at Rated Head	285 MW
Rated Turbine Discharge	79.00 m^3/s
Rated Pump Discharge	71 m^3/s
Synchronous Speed	333.3 rpm

ELECTROMECHANICAL ASPECTS

Generator-Motor	
Type	Three (3) phase, alternating current synchronous, generator-motor, vertical shaft, rotating field, enclosed housing, rim-duct air-cooled and suspended type
Number of unit	Six (6) units
Rated Capacity	Generator; 250 MW , Motor; 300 MW
Rated Voltage	18.0kV
Rated Frequency	50 Hz
Rated Speed	333.3 rpm
Over Load Capacity	110 % rated capacity

CONCLUSIONS

- The project involves minimum civil works with availability of local construction material.
- **No geological** surprise is envisaged. Geological setup is conducive for underground works.
- No interference with hydrological regime of the river project being **close loop Pumped storage project**.
- Minimum land requirement of **496 Ha.**
- The majority of land is **forest and minimum private land is** envisaged.
- No **R&R issues seems to be** involved.

CONCLUSIONS

- The per MW cost is **2.98 Cr.** Only.
- The generation per ha of forest land is **10.2 Mu /Ha** which is much more than the **required 2 Mu /Ha** as per latest Guidelines. Hence eligible for preferential consideration.
- DVC and state of West Bengal ,Jharkhand do not have **realisable Hydro Potential of this Scale. Hence, Lugu Pahar Pumped Storage is the only feasible alternative available**.
- West Bengal has already constructed Purulia PSP(900 MW) and Turga PSP(1000 MW) is now under pre-construction. **Other states** are also going for PSP in an accelerated manner.
- In view of mandatory large injection of Renewables , DVC needs advance planning to integrate it.
- Considering the over all trend of generation planning and demand , DVC would be needing source to generate peak power to improve Hydro: Thermal Mix and provide much needed balance to renewable in year 2025-26 .
- Lugu Pahar can address all above issues .
- **PFR Establishes that scheme has merits for detailed Investigation and preparation of DPR.**


Thank you

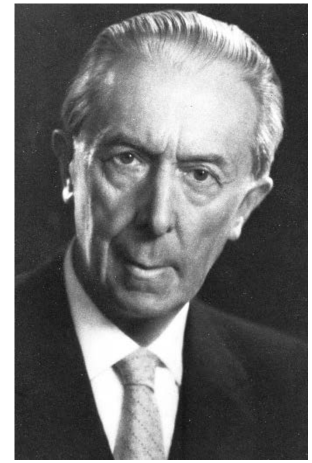
VOITH

Overview of Pump Storage Plants

India, 2018-02-09/08

VOITH

One of the Biggest Family-Owned Companies in Europe



1867

1971

Johann Matthäus Voith 1803 – 1874

Friedrich Voith 1840 – 1913

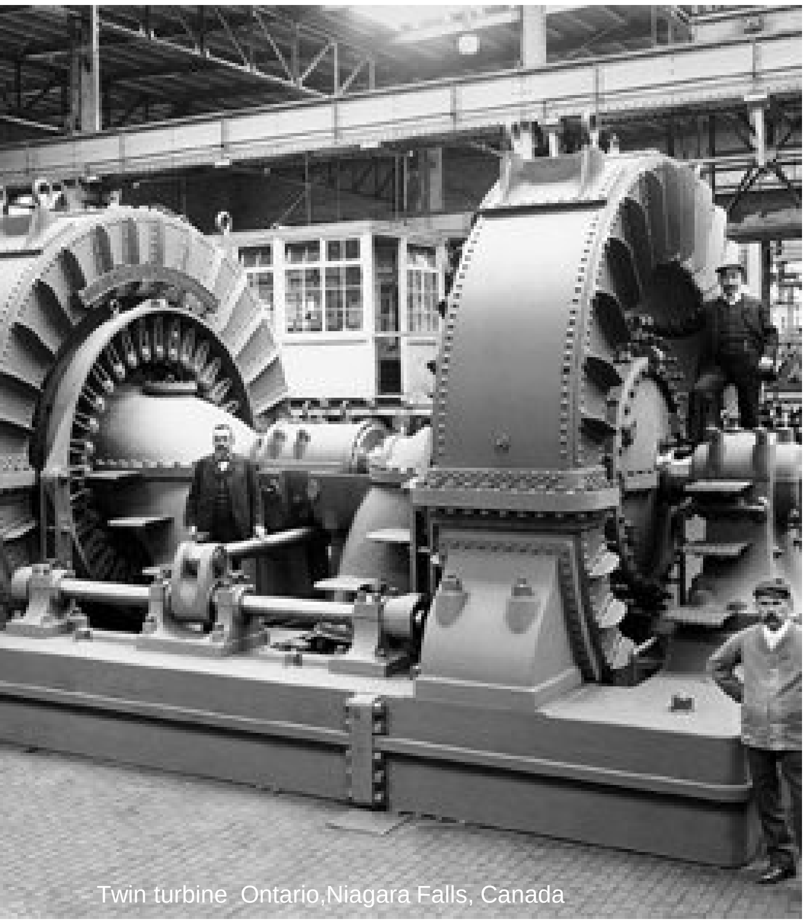
Walther, Hermann and Hanns Voith

Hanns Voith

All shares are owned by the Voith family.

Management and Supervisory Boards are staffed by external executives.

150 years experience in hydropower



1873	First Voith Francis turbine
1903	First Pelton turbine
1912	Niagara Falls, Canada: Twin Francis turbines with 12 MW output
1934	Pedreira, Brazil: World's first reversible pump-turbine, 5.3 MW output
...	

Global Projects

Total Number of Powerhouses with Voith Hydro Participation: 6,730

1,660
North America

1,100	130	2,900	940
South America	Africa	Europe	Asia-Pacific

Source: Go2Hydro (1900 – 2011-20-04)

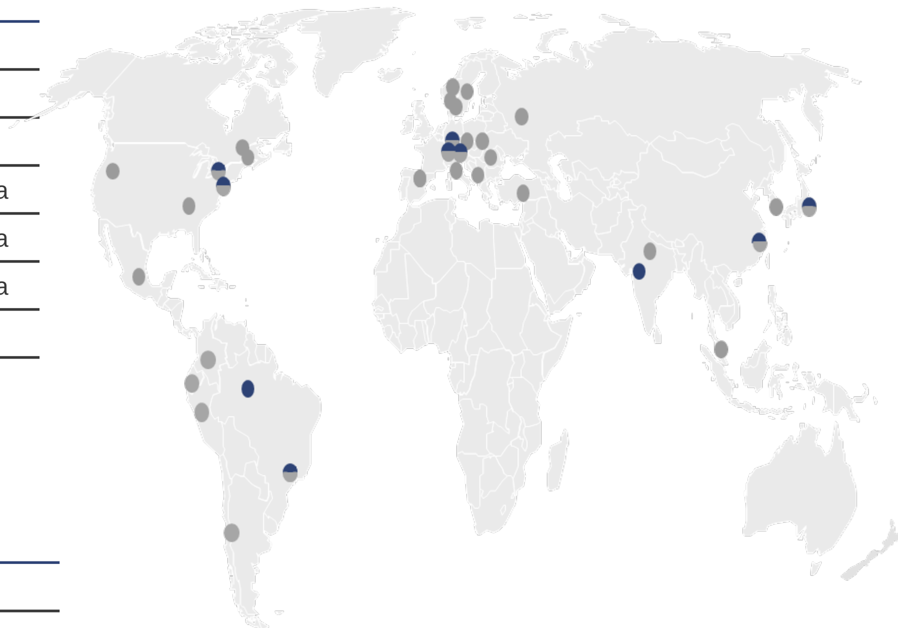
Voith Hydro - Global Locations

North America

York (PA)	USA
Chattanooga (TN)	USA
Springfield (OR)	USA
Mississauga (ON)	Canada
Montreal (Brossard, QC)	Canada
Granby (QC)	Canada
Ciudad de Mexiko	Mexico

Latin America

São Paulo	Brazil
Manaus	Brazil
Lima	Peru
Santiago	Chile
Cuenca	Ecuador
Medellín	Columbia



- Production
- Sales/ Engineering/ Service-Shop

Asia

Shanghai	China
Noida	India
Vadodara	India
Kawasaki	Japan
Seoul	Korea
Kuala Lumpur	Malaysia

Europe

Heidenheim	Germany
St. Pölten	Austria
St. Georgen	Austria
Tolosa (Ibarra)	Spain
Cinisello Balsamo (Milano)	Italy
Oslo	Norway
Trondheim	Norway
Gamle Fredrikstad	Norway
Västeras	Sweden
Pilsen	Czech
Ankara	Turkey
Moscow	Russia
Podgorica	Montenegro
Bukarest	Romania
Trebisov	Slovakia

Voith Hydro Presence in India

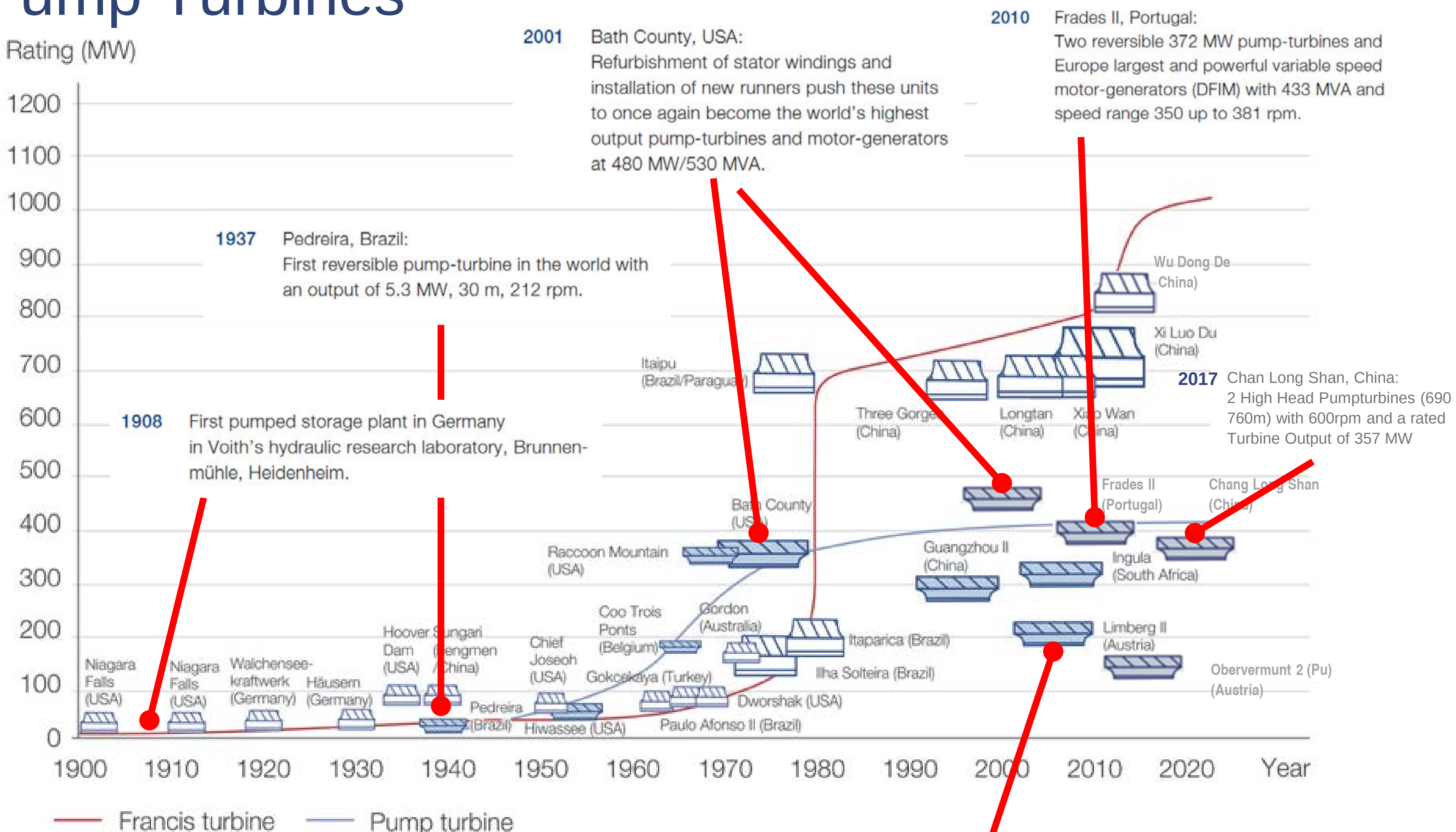
- **Manufacturing facility in Vadodara**
- Distance from important places :
  - Air Port : 21 Kms (Vadodara)
  - Railway Station : 24 Kms (Vadodara)
  - Port : 450 Kms (Mumbai)

- **Head Office at Noida**

- Design
- Project Management
- Supply Management
- Automation Workbench
- Small Hydro Product Development Centre
- Digital Solutions
- Finance

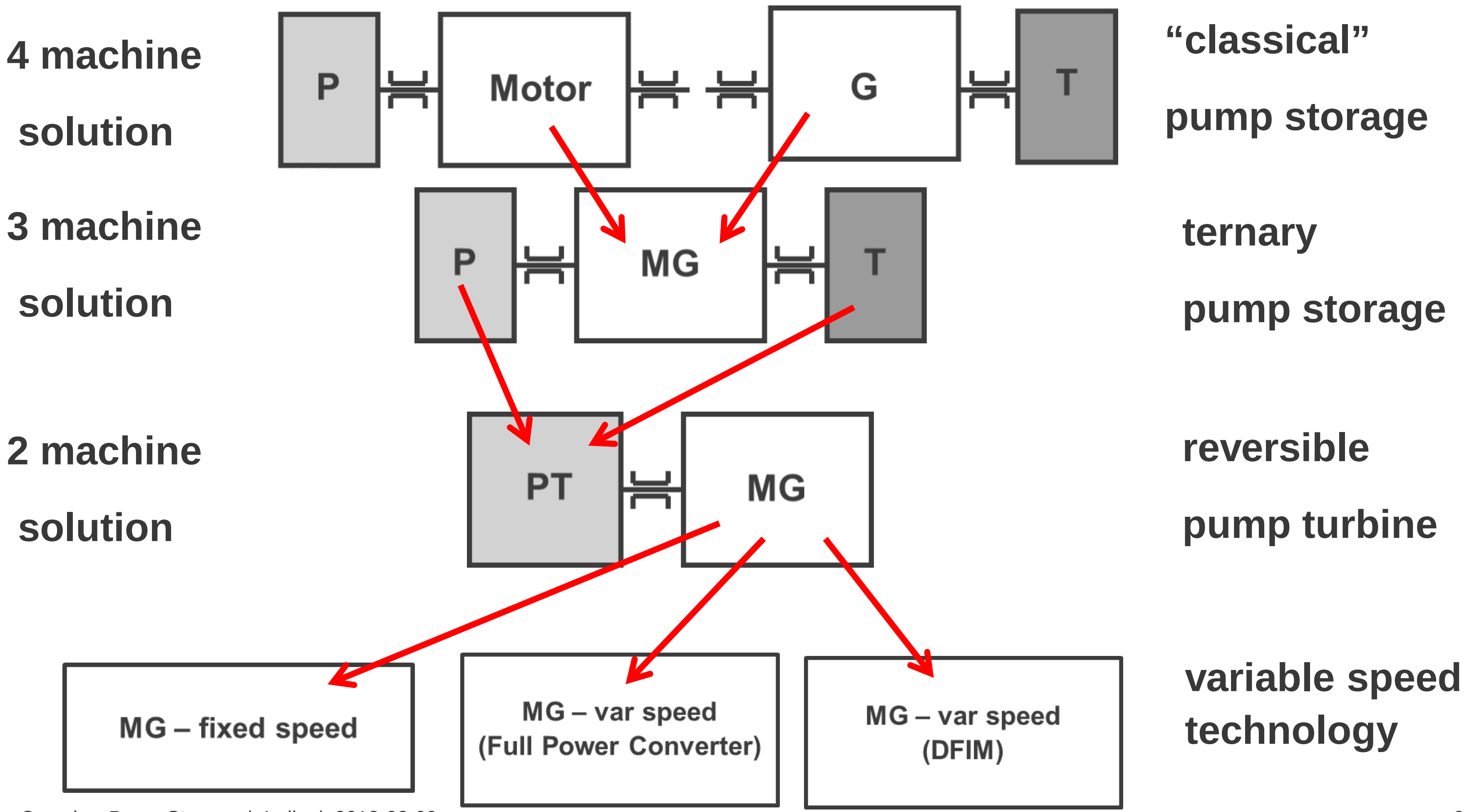
Pump Storage Concept

Development of power outputs for Francis and Pump Turbines

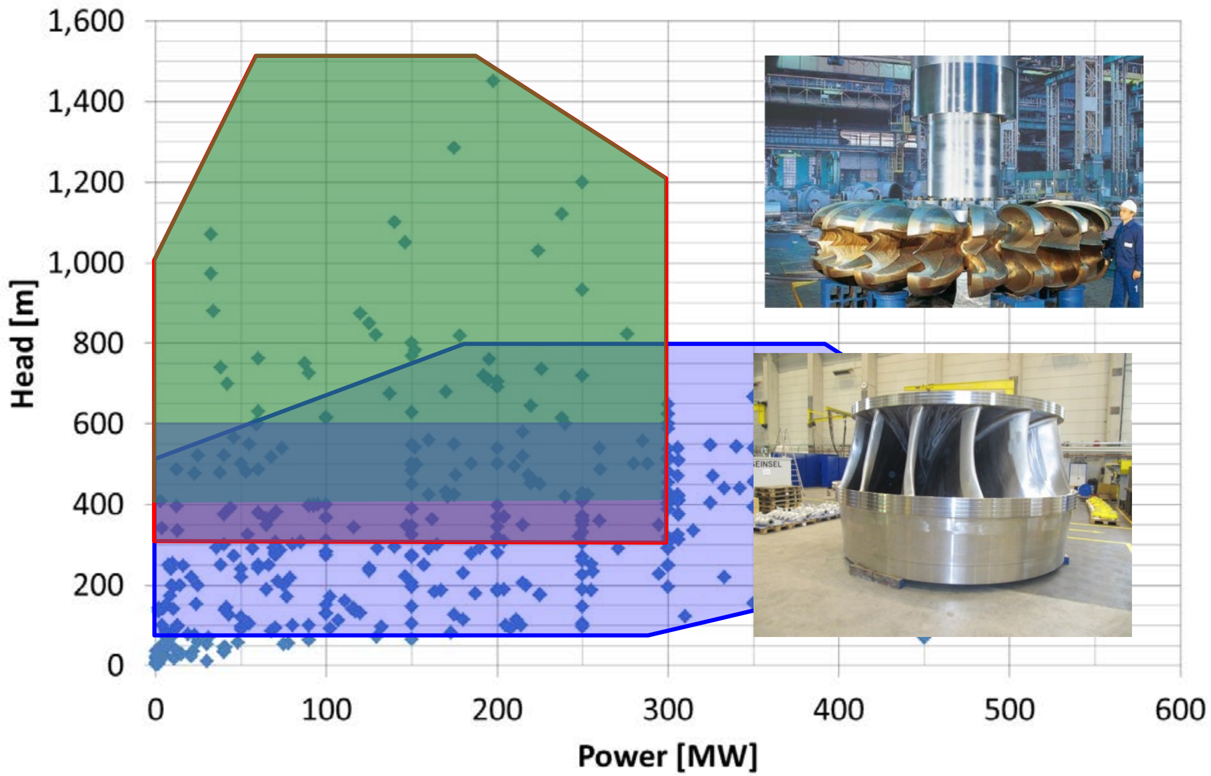


2006 Limberg II, Austria:
Two 240 MW pump-turbines with optimum design to meet wide head range application.

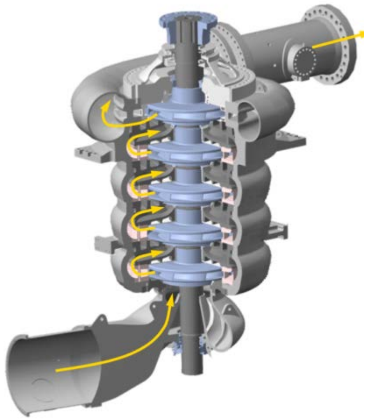
Pump Storage Plants – Development of Power Unit Arrangement

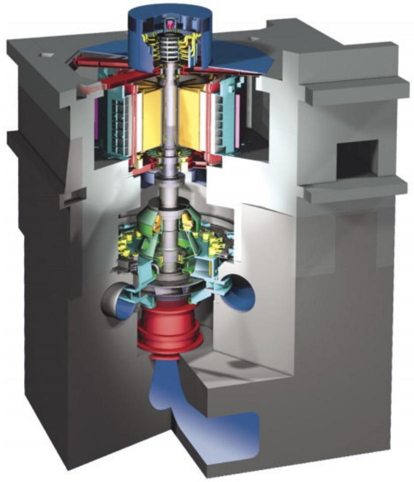


Application areas of different solutions for the hydraulic machine with respect to head and power

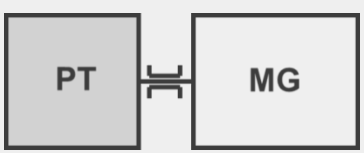


source: Voith Hydro – PSP Market Overview

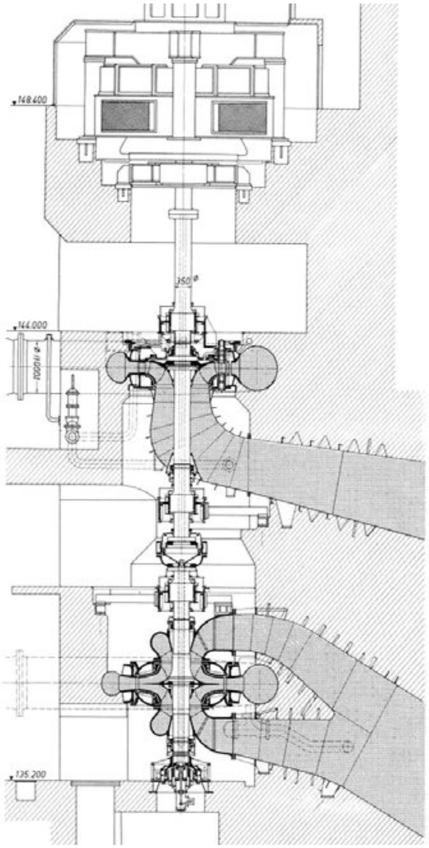




Power Unit Concepts

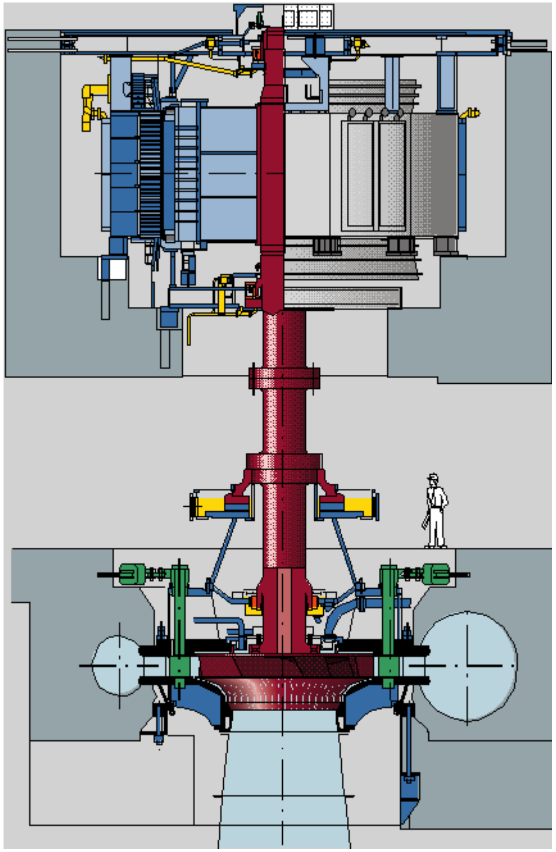
	MG – fixed speed	MG – var speed (Full Power Converter)	MG – var speed (DFIM)
 up to 1500m or more	application for high heads / fast mode changes	-	-
 up to 600m	fast mode changes	-	-
 up to 800m	most common application in the past	mainly for grid stabilization (low power)	mainly for grid stabilization (high power)

Pump Storage Plants – Turbine Arrangement



Ternary

Pump / Turbine

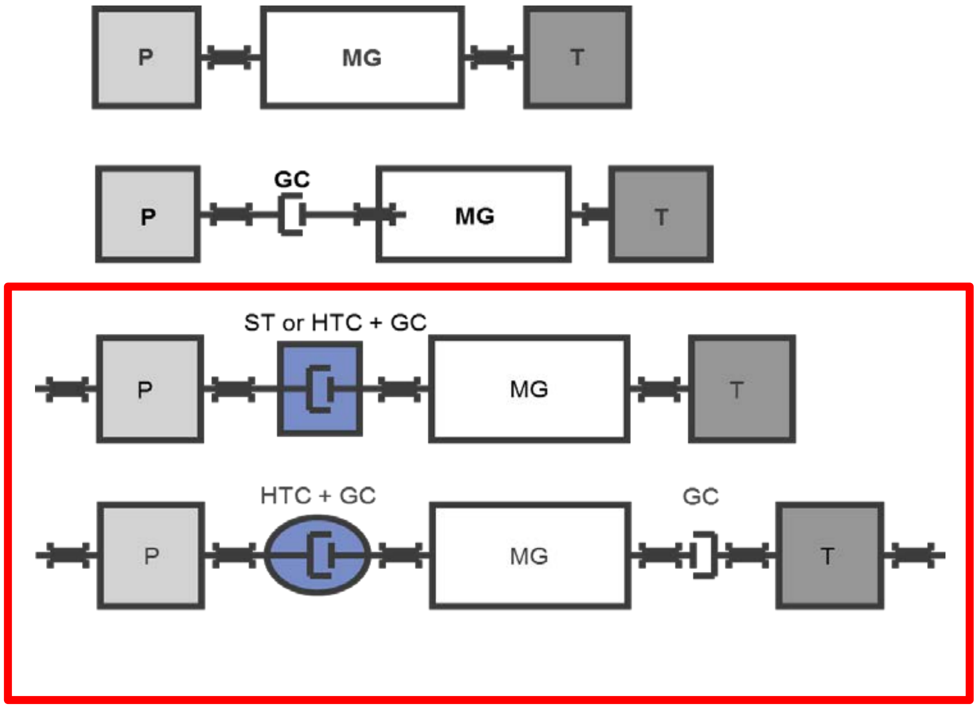


Reversible

Pump Turbine

Ternary Units

1. Unit Arrangements

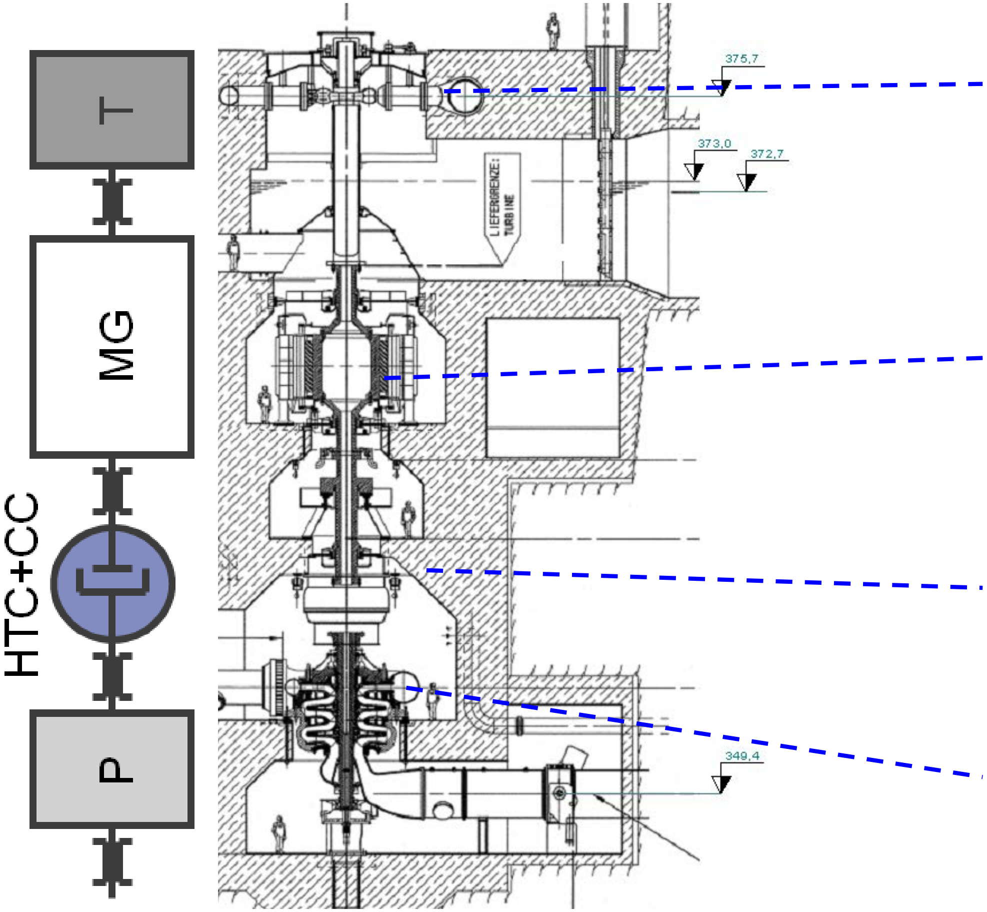


Possible configurations

MG	Motorgenerator
GC	Gear coupling
ST	Starting turbine
HTC	Hydr. torque converter

for horizontal and vertical arrangement

Main components of a vertical ternary unit with a Pelton turbine (Kops II, Austria)



Pelton turbine

(2 bar air-pressurized)

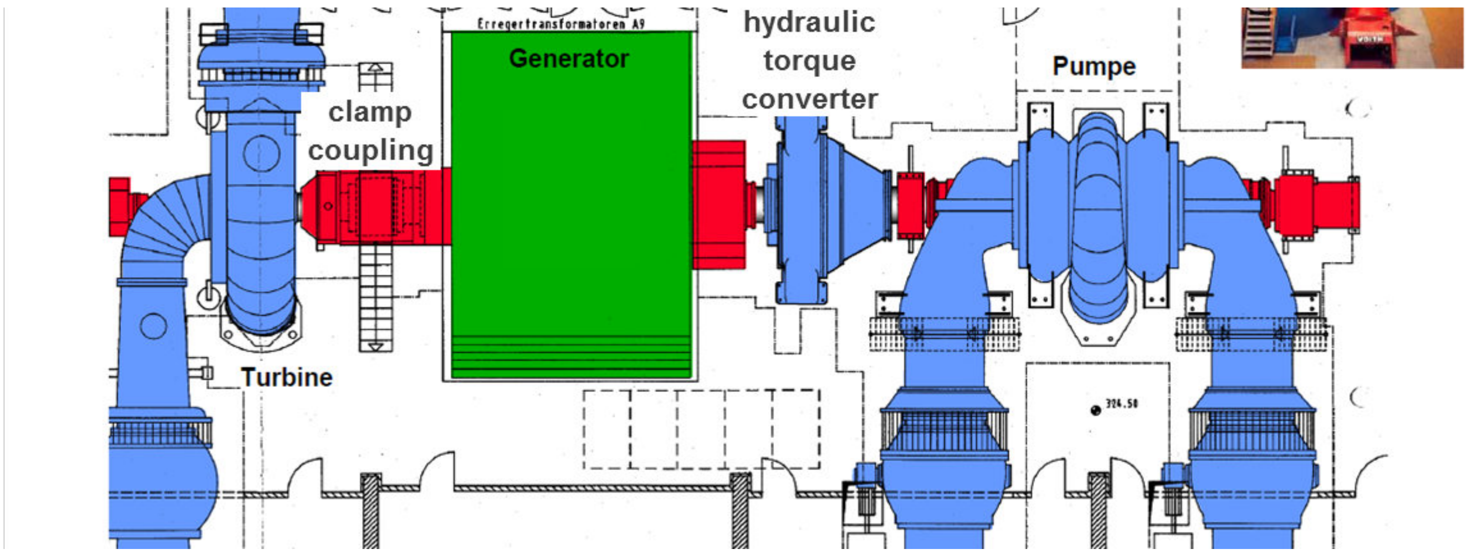
Motor Generator

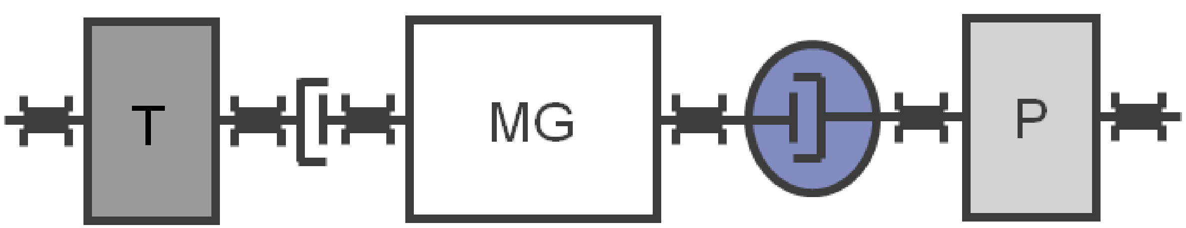
Hydraulic torque converter

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

Ternary unit arrangement with a horizontal shaft configuration

(Wehr, Germany) 4 x 227 MW T/ 4 x 245 MW P

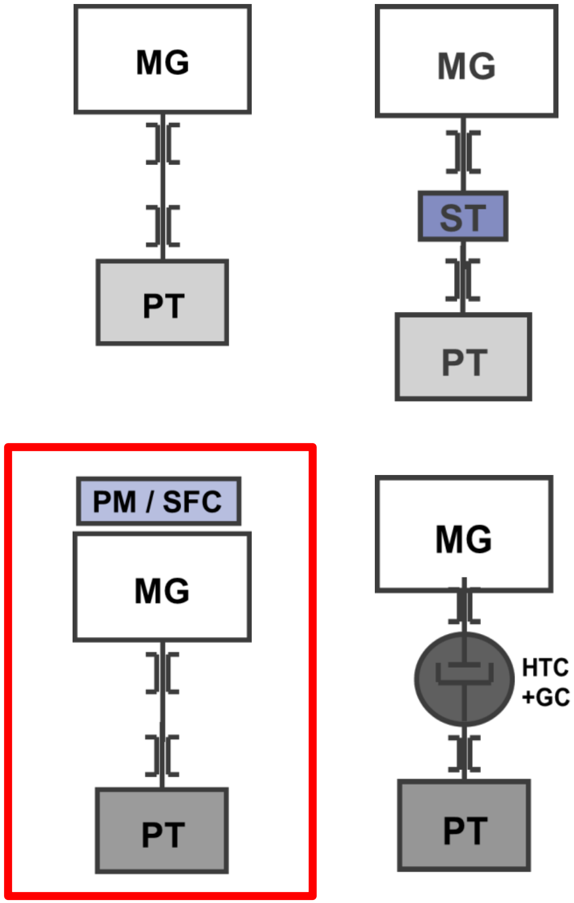




Reversible Pump Turbines

PSW La Muela II (SP 80 km far away from Valencia) , 852 MW, under construction

1. Unit Arrangements

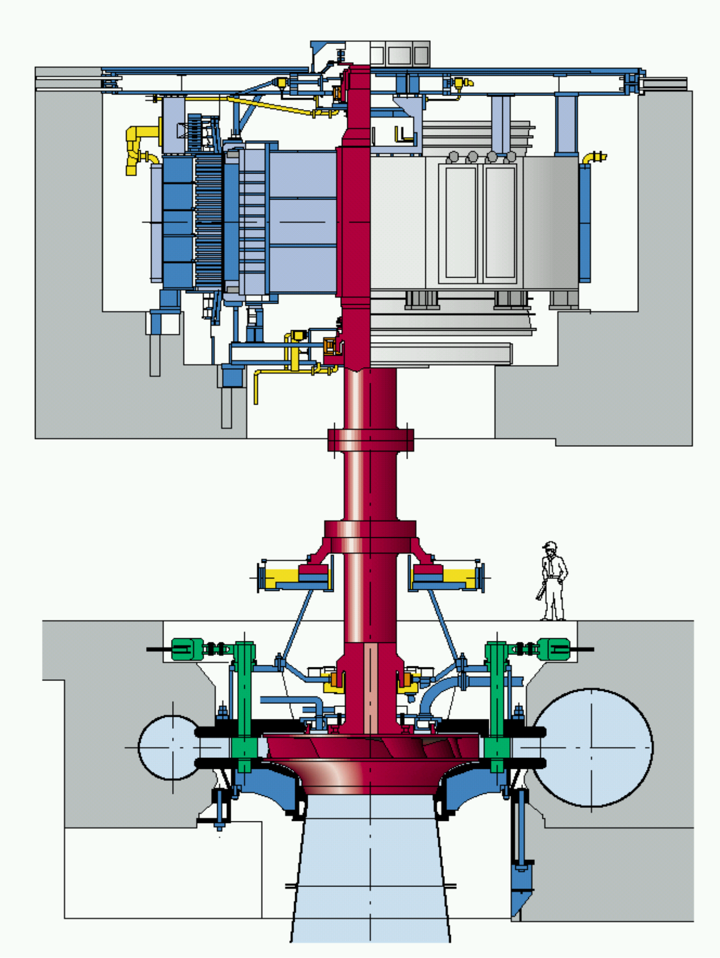


Possible configurations

MG	Motorgenerator
GC	Gear coupling
ST	Starting turbine
HTC	Hydr. torque converter
PM	Pony Motor
SFC	Static Frequency Converter
PT	Pump Turbine

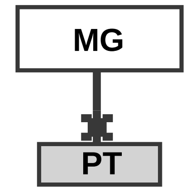
for horizontal and vertical arrangement

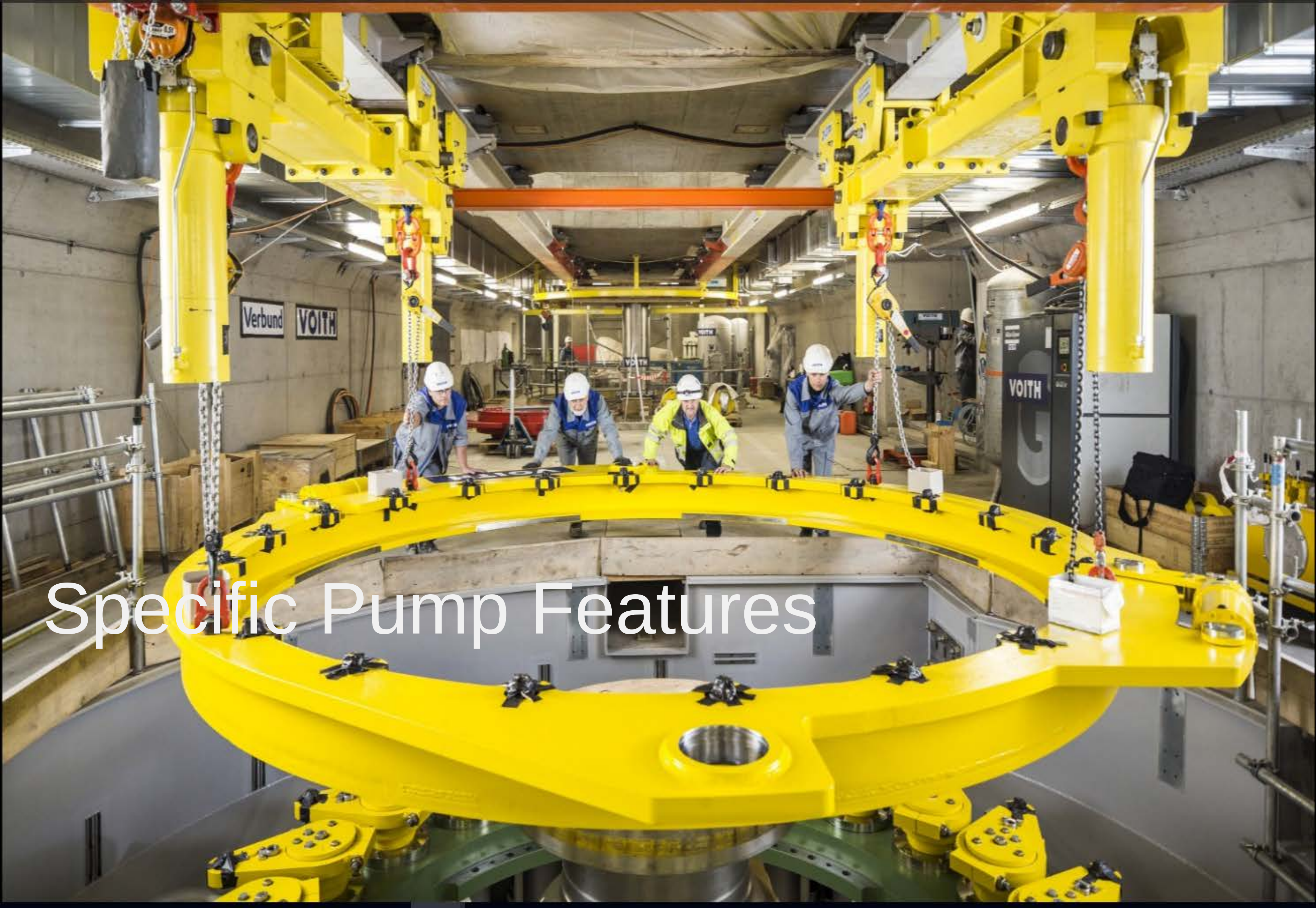
Conventional Reversible Unit (PT + MG)



- Typical of existing fleet in world today
- Two rotating directions
- Power control in turbine mode only
- Load range for generation: 50% - 100% power.
- Input cannot be controlled in pump mode
- Hydraulic circuit possible in case of 2 units (1 unit operates as pump 1 unit operats as turbine)

Arrangement of machines: comparison P+T/PT

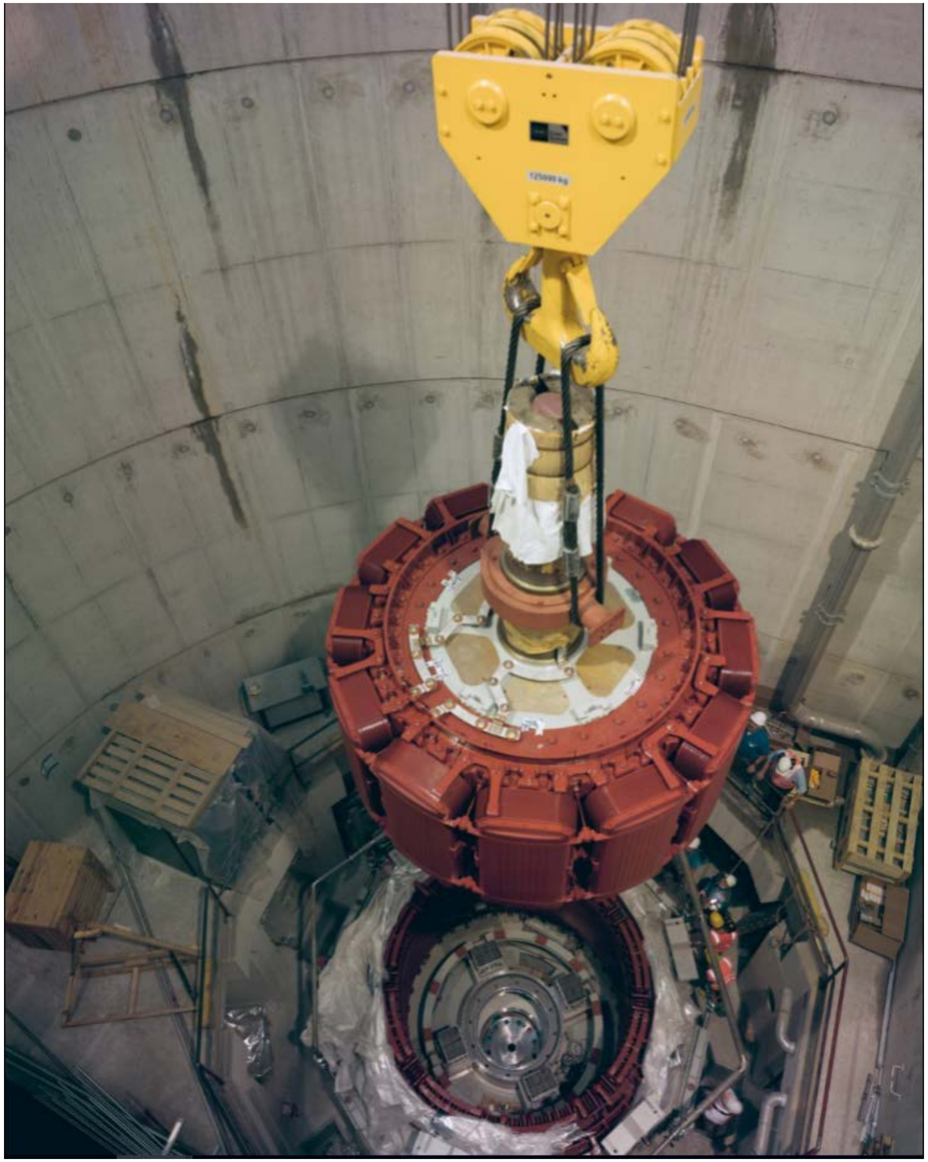
Type of machine			
Investments	−		+
Space requirements	−		+
Efficiency	+		−
Setting	+		−
Transition time: P ⇒ T / T ⇒ P	+	(with HTC)	−
Hydraulic short circuit	+		−
High heads	+		−
Operation costs	−		+
Technical risks	−		+
Maintenance efforts	−		+



Specific Pump Features

PSP Features

- Hydraulic Torque Converter
- Start Up“ Pump Mode
- Black Start – Back to Back
- Servo Motor Control
- Runner Removal
- Variable Speed

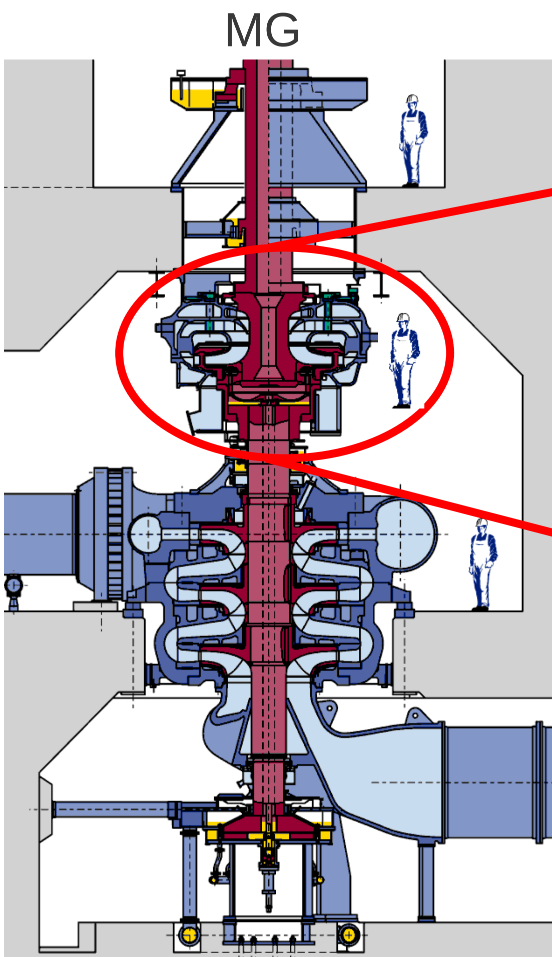


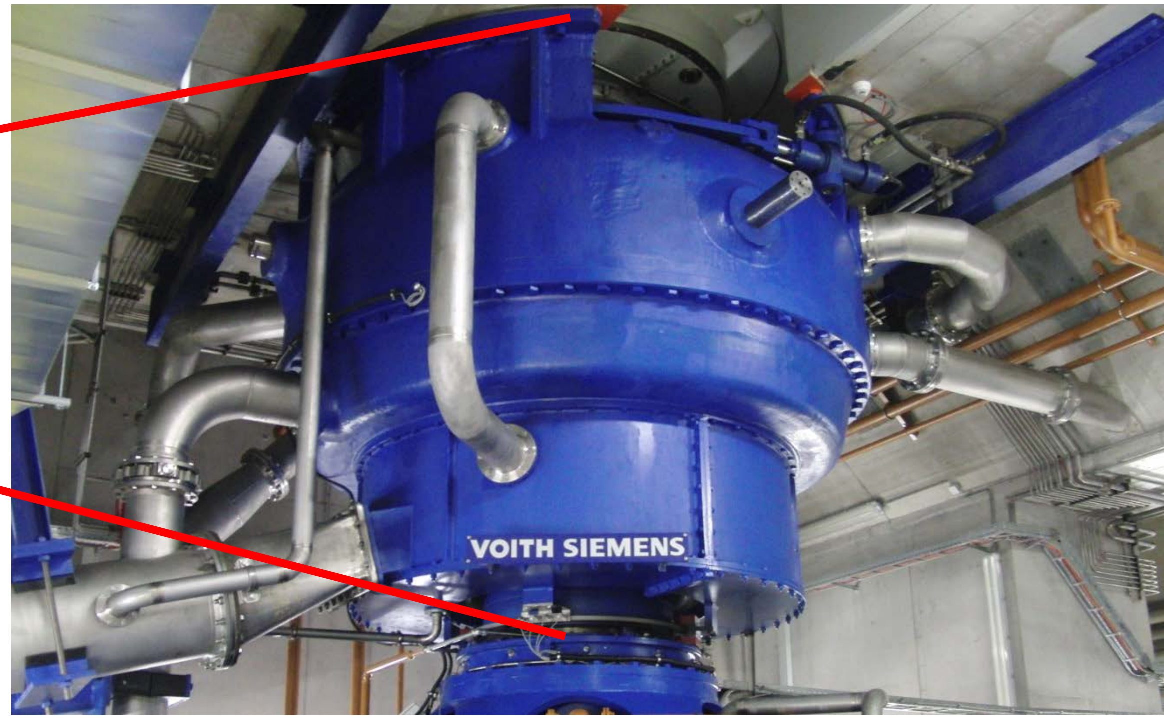
PSP Features

- **Hydraulic Torque Converter**
- „Start Up“ Pump Mode
- Black Start – Back to Back
- Single Servo Motor Control
- Runner Removal
- Variable Speed

Hydraulic Torque Converter

VOITH





KOPS II / VIW

3 - Stage Pump + Torque Converter

VOITH

Hydraulic Torque Converter - References

Plant	units	head [m]	speed [1/min]	pump input [MW]	converter [MW]	year
Lünersee	5	1000	750	43	33	1954
Säckingen	4	410	600	70	40	1964
Roßhag	2	690	750	52	31	1967
Hornbergstufe	4	640	600	248	150	1970
Malta	2	1100	500	144	87	1973
Häusling	2	725	600	170	96	1982
Kops 2	3	840	500	165	90	2007

HTC for Obervermunt II project is under construction

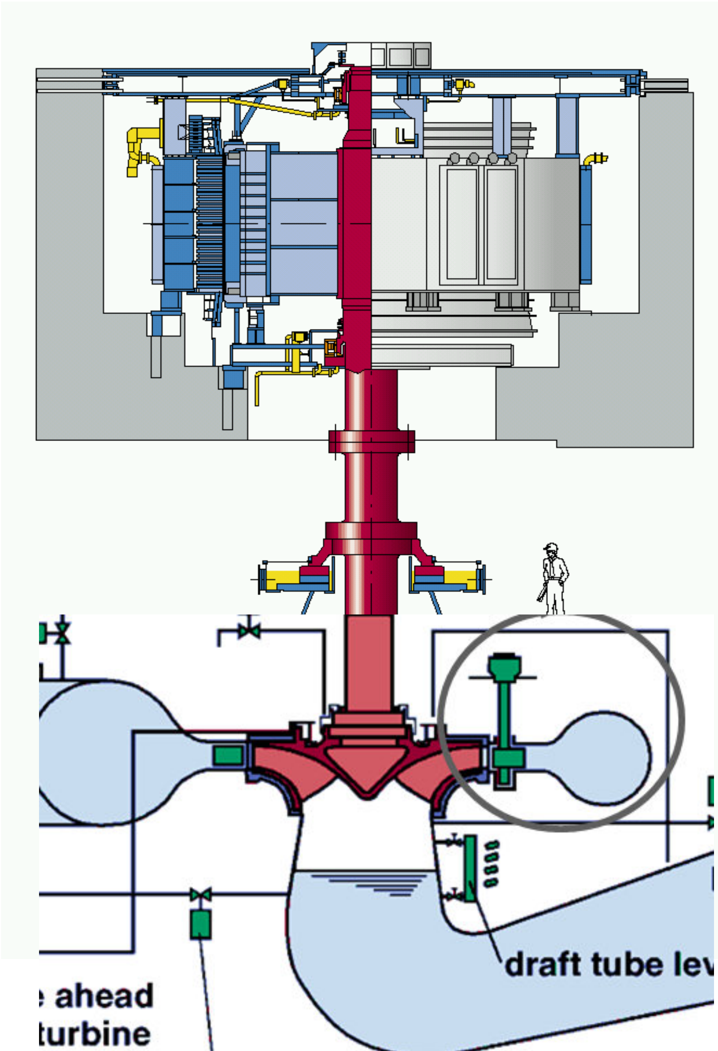
Advantages of the hydraulic torque converter

- Very short startup time of the storage pump (soft start + no air in the waterways especially in multi stage pumps)
- The consumption of electricity starts already with the filling stage of the hydraulic torque converter, in about 10 seconds 60% of the storage pump power are suitable.
- Minor no-load losses of the hydraulic torque converter (< 0,05 % of the rated power) compared to a connected starting pump
- Self-control into synchronisation, no additional speed control is required.
- Lowest water consumption / water is taken from the tail water side, i.e. no storage water from the upper reservoir (< = > startup turbine).
- Very good operational experience since 1954.
- Voith Hydro is the only company with references.

PSP Features

- Hydraulic Torque Tonverter
- **„Start Up“ Pump Mode**
- Black Start – Back to Back
- Servo Motor Control
- Runner Removal
- Variable Speed

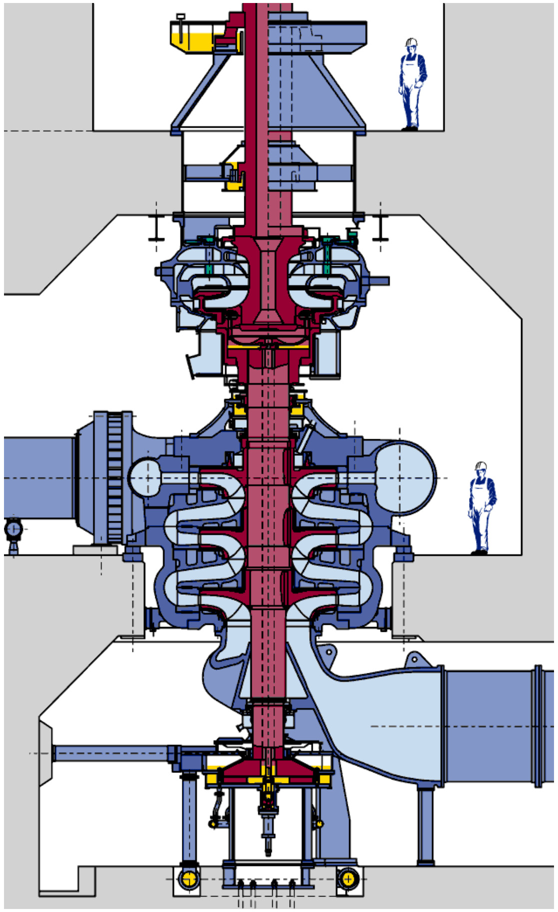
Required Power to “start up” in Pump Mode



- Required power to rotate the runner in water at rated speed about 20% of rated pump input

- Required power to rotate the runner in air at rated speed about 3...5% of rated pump input (blow down equipment necessary)

Required Power to “start up” in Pump Mode



- Required power to rotate the runner in water at rated speed about 60% of rated pump input
- Start in air not technically feasible (large volume to be blow down at a high pressure level)

VOITH

“Start Up” in Pump Mode - Devices

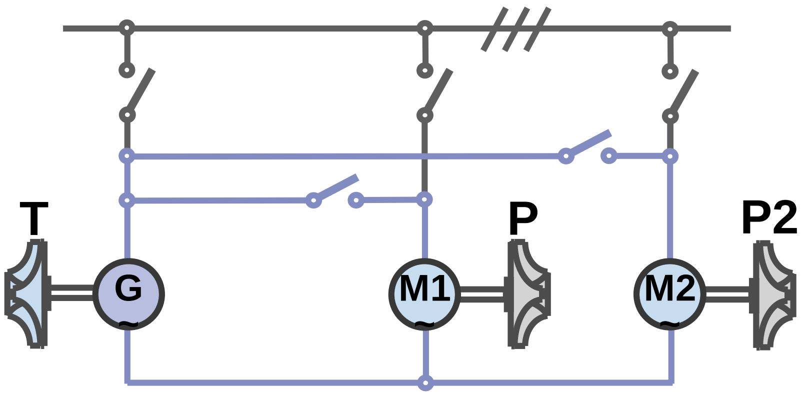
	pump „in water“	pump „in air“	single stage	multi stage
Starting Turbine	yes	yes	yes	yes
Pony Motor	no	yes	yes	no
SFC	no	yes	yes	no
HTC	yes	yes	yes	yes

<u>Common Practice:</u>

Single stage pumps / reversible Pump turbines ➔ in air by SFC
multi stage pumps ➔ in water by HTC

PSP Features

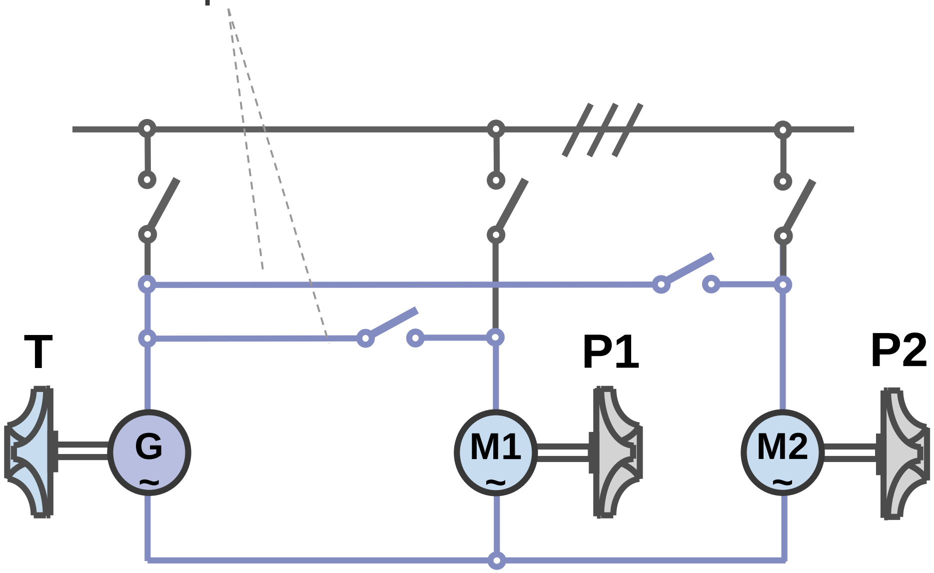
- Hydraulic Torque Tonverter
- „Start Up“ Pump Mode
- **Black Start – Back to Back**
- SCO Mode
- Single Servo Motor Control
- Runner Removal
- Draft Tube Gates
- Variable Speed



VOITH

Start Up in Pump Mode - Back to Back

additionally start-up switching line arrangements + circuit breakers + protection criteria



P1 and P2 can be started by the turbine T one by one using dedicated electrical connections between the motor-generators since the frequency during the start-up is different from the grid frequency.

Full-frequency starting: The motor of the pump to be started gets excited during the standstill and after starting of the runs synchronically with the generator.

Partial-frequency starting: At first the motor gets started asynchronically and after reaching the generator‘s speed it is excited and runs synchronically with the generator.

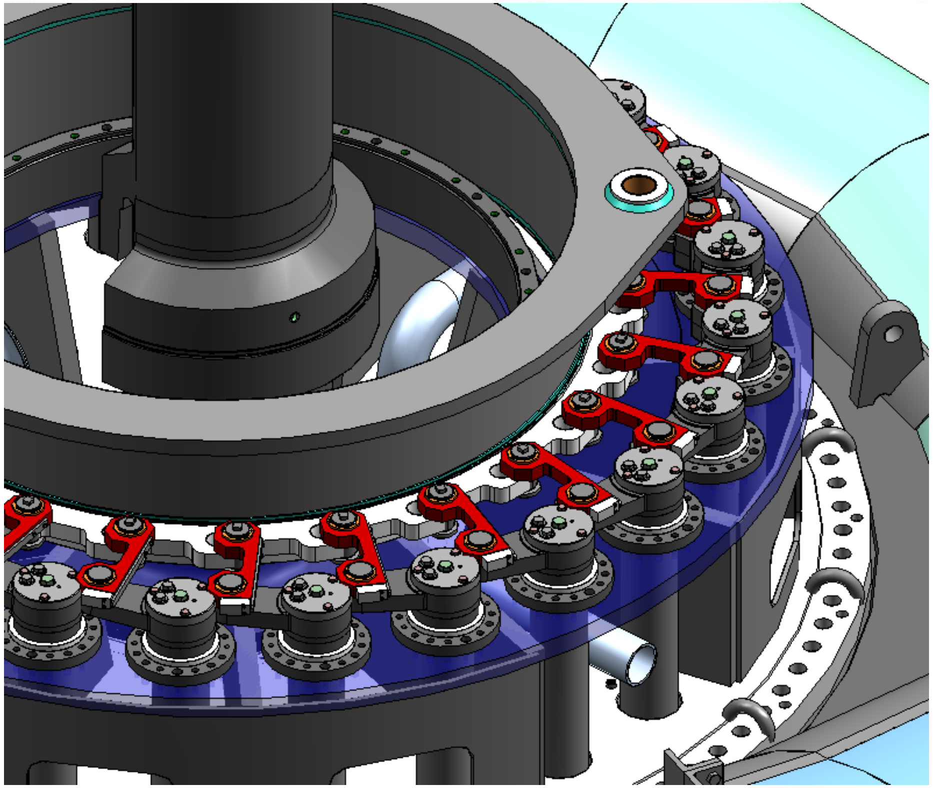
PSP Features

- Hydraulic Torque Tonverter
- „Start Up“ Pump Mode
- Black Start – Back to Back
- **Servo Motor Control**
- Runner Removal
- Variable Speed

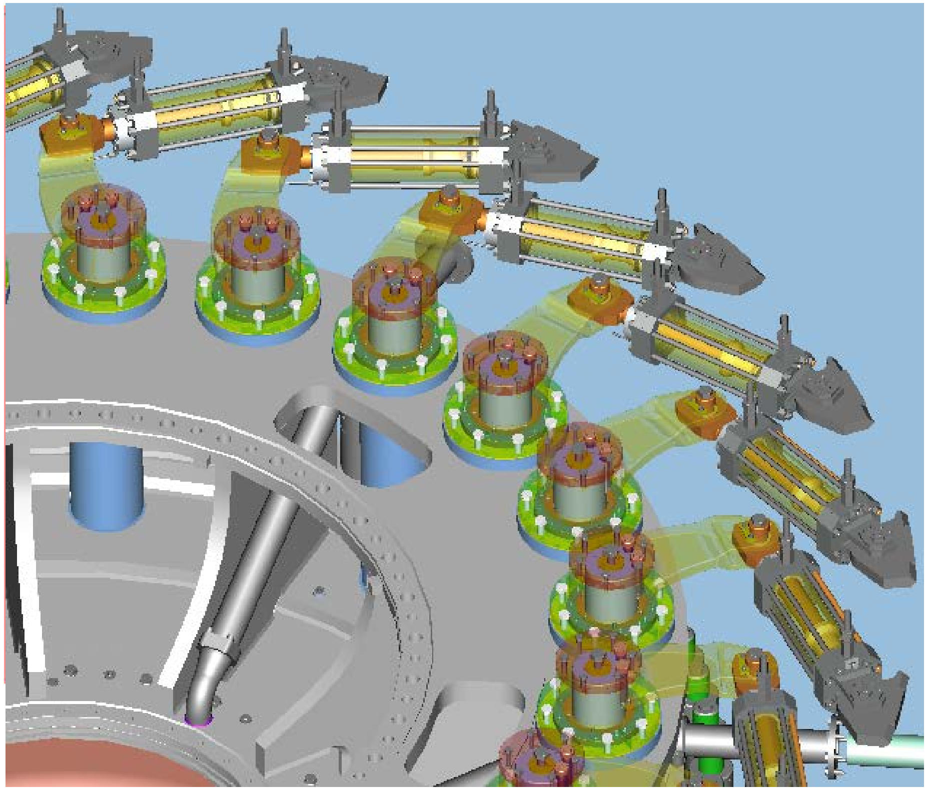
VOITH

Project Details – Distributor Mechanism

Standard kinematics with operating ring



Individual Servomotors



Project Details – Distributor Mechanism

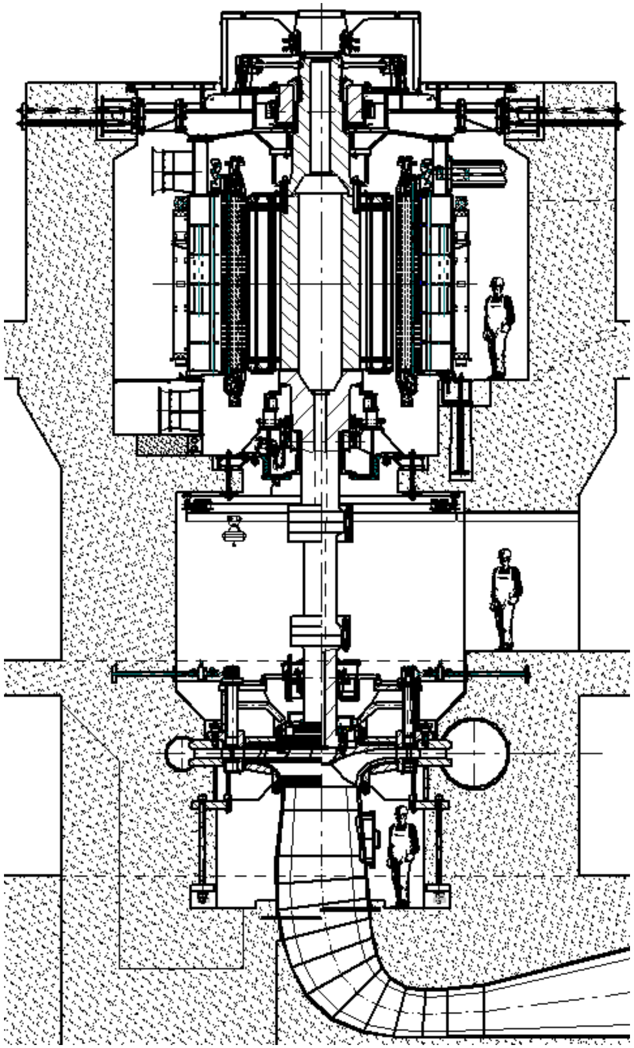
Individual Servomotors offer several advantages compared to standard kinematics with operating ring, links and levers.

- Smooth machine start by individual opening of wicket gates
- Better control of transient machine behavior
- Easier maintenance (shorter period) and access to turbine components

PSP Features

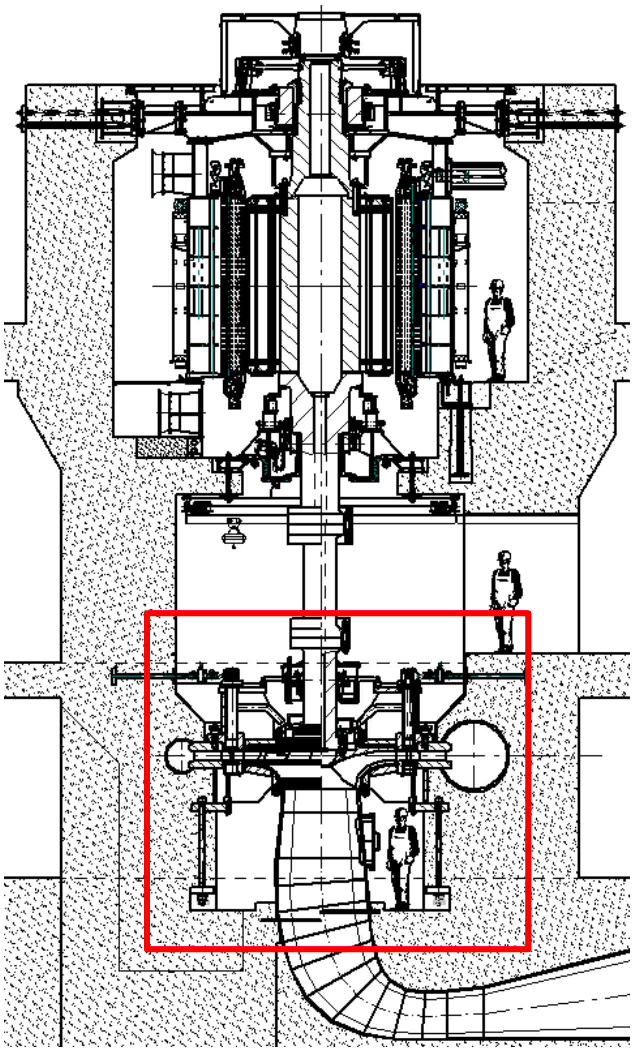
VOITH

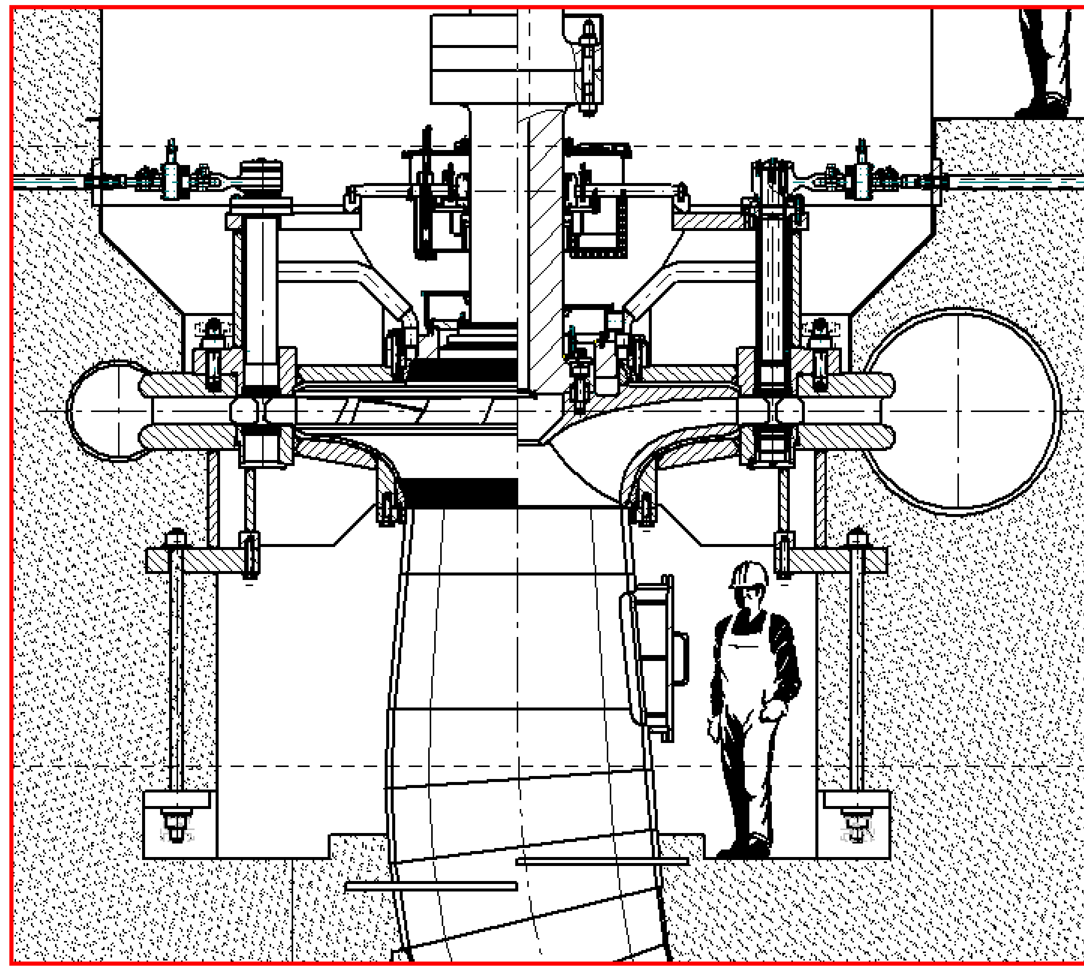
- Hydraulic Torque Tonverter
- „Start Up“ Pump Mode
- Black Start – Back to Back
- Single Servo Motor Control
- **Runner Removal**
- Variable Speed



VOITH

Power Unit Cross Section



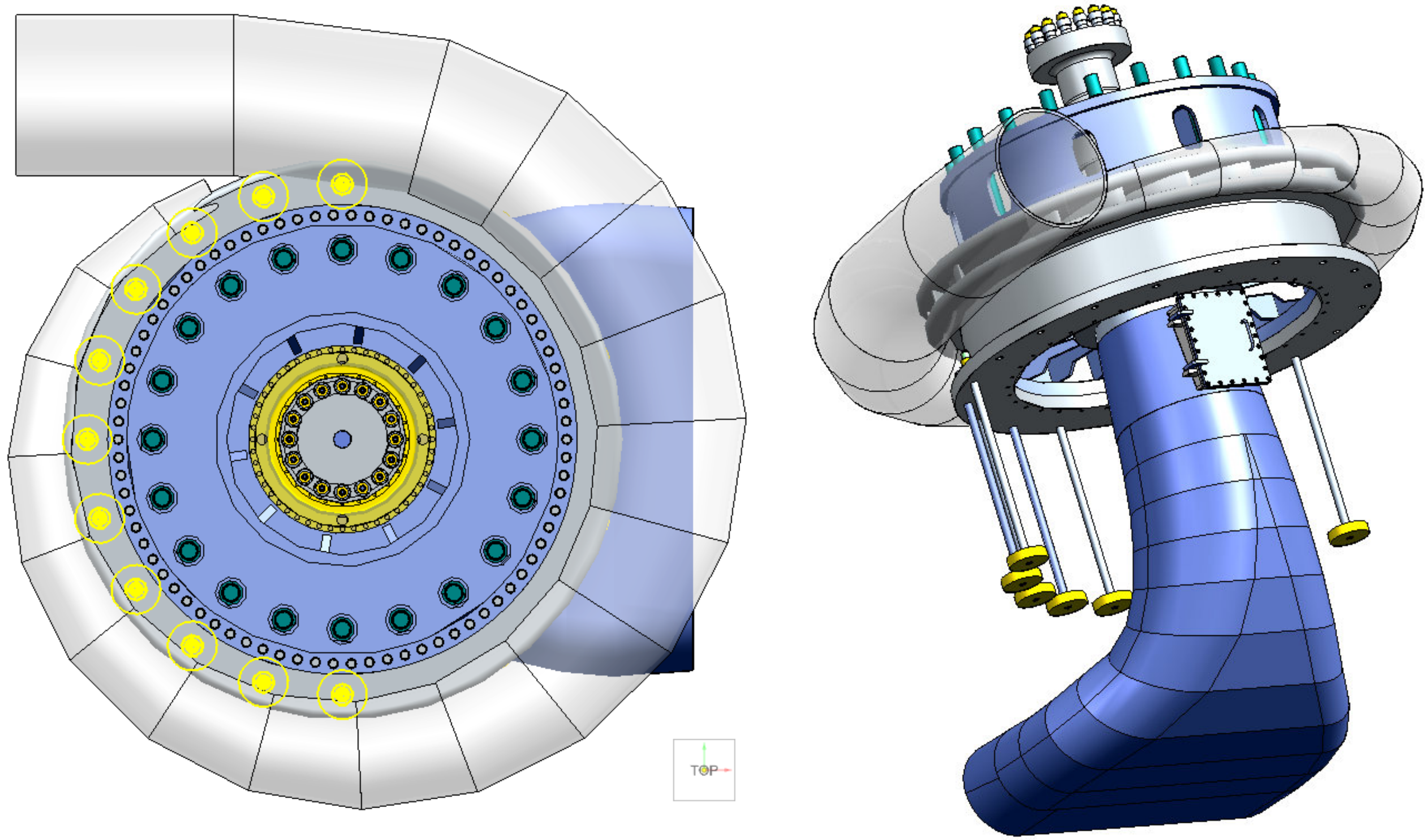


VOITH

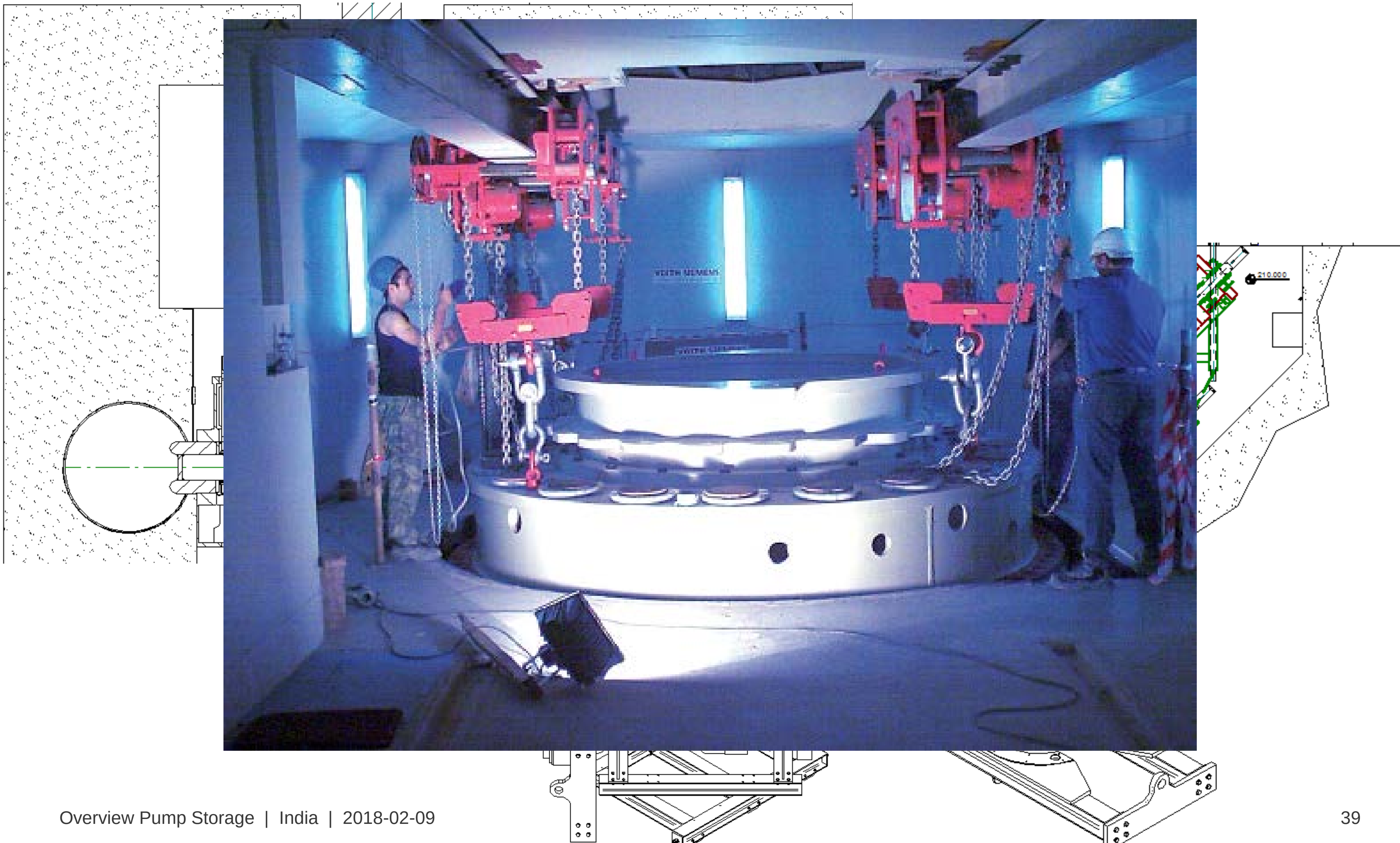
Project Details – Runner Removal

The runner removal by the draft tube access is not possible due to the interferance with anchor tie rods.

Anchor tie rods

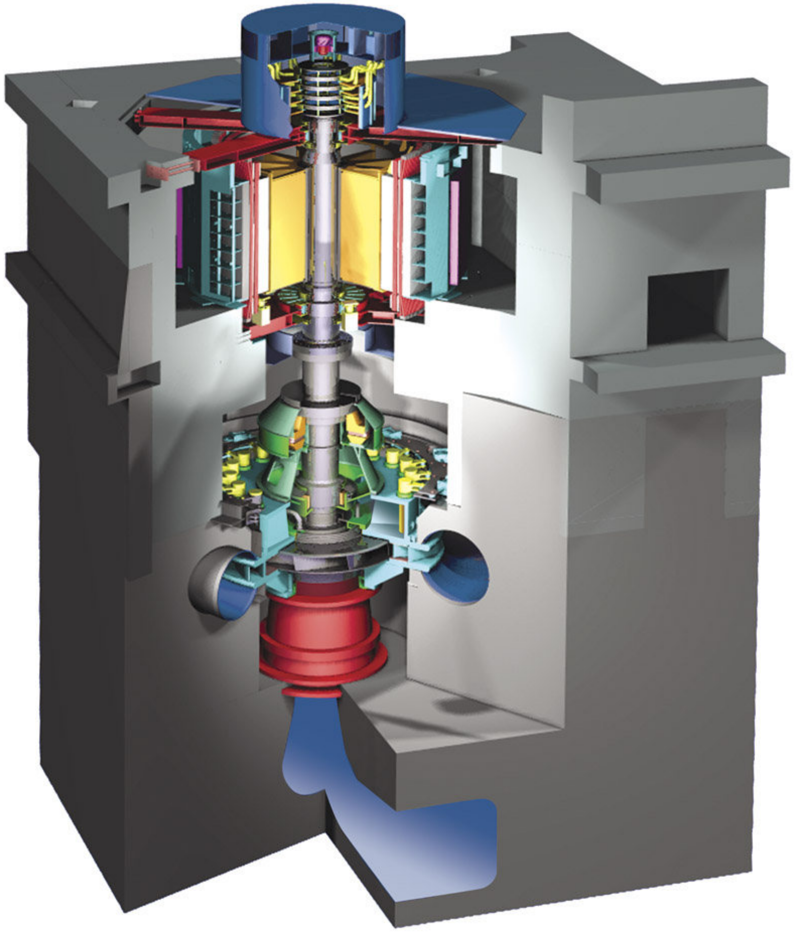


Project Details – Runner Removal



PSP Features

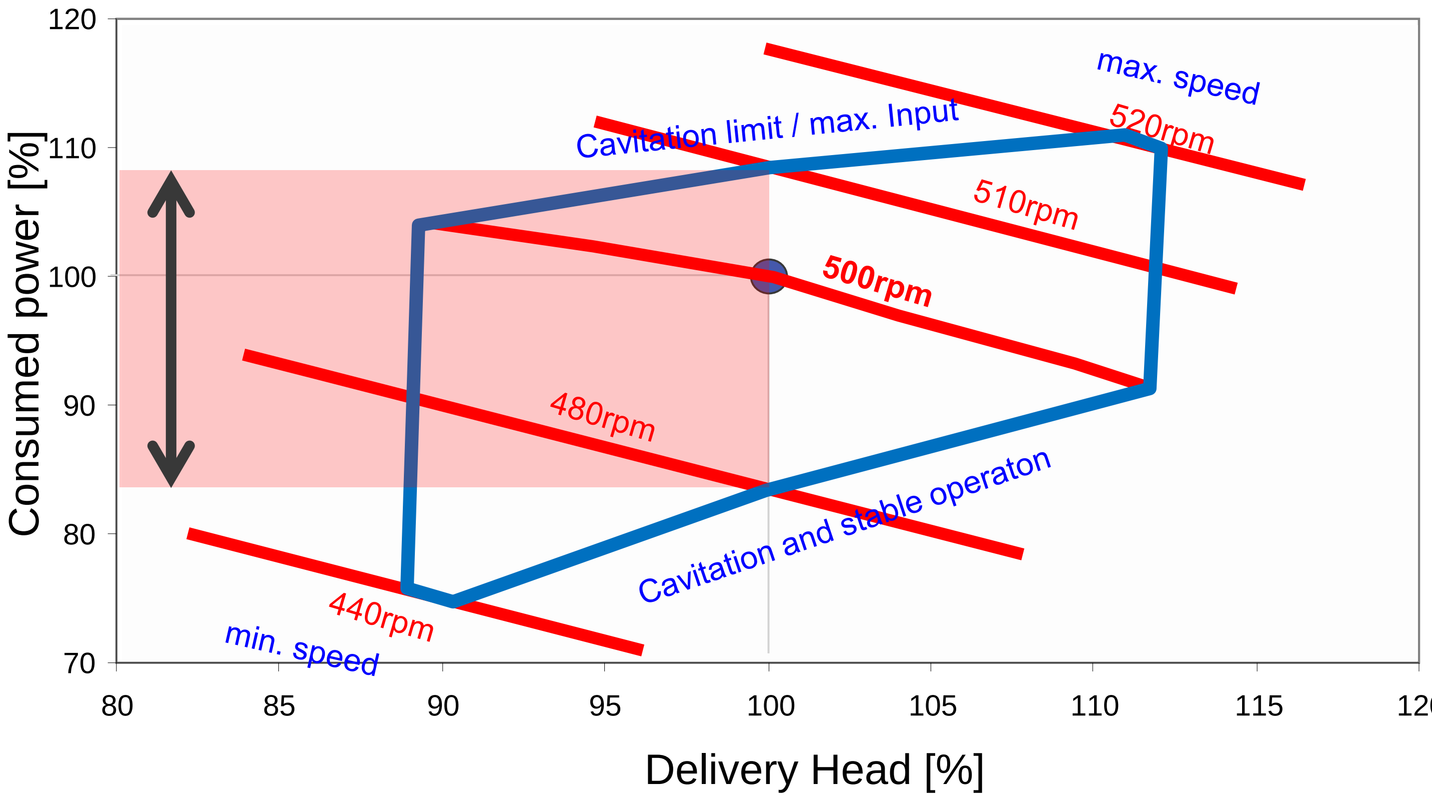
- Hydraulic Torque Converter
- „Start Up“ Pump Mode
- Black Start – Back to Back
- Single Servo Motor Control
- Runner Removal
- **Variable Speed**



Motivation for variable - speed Applications

- Power Control in Pump Mode
- Large Head Variation of the Reservoirs
- Performance Optimization
- Extended Turbine Operating Range
- Features for grid stability

Motivation - Power Control in Pump Mode



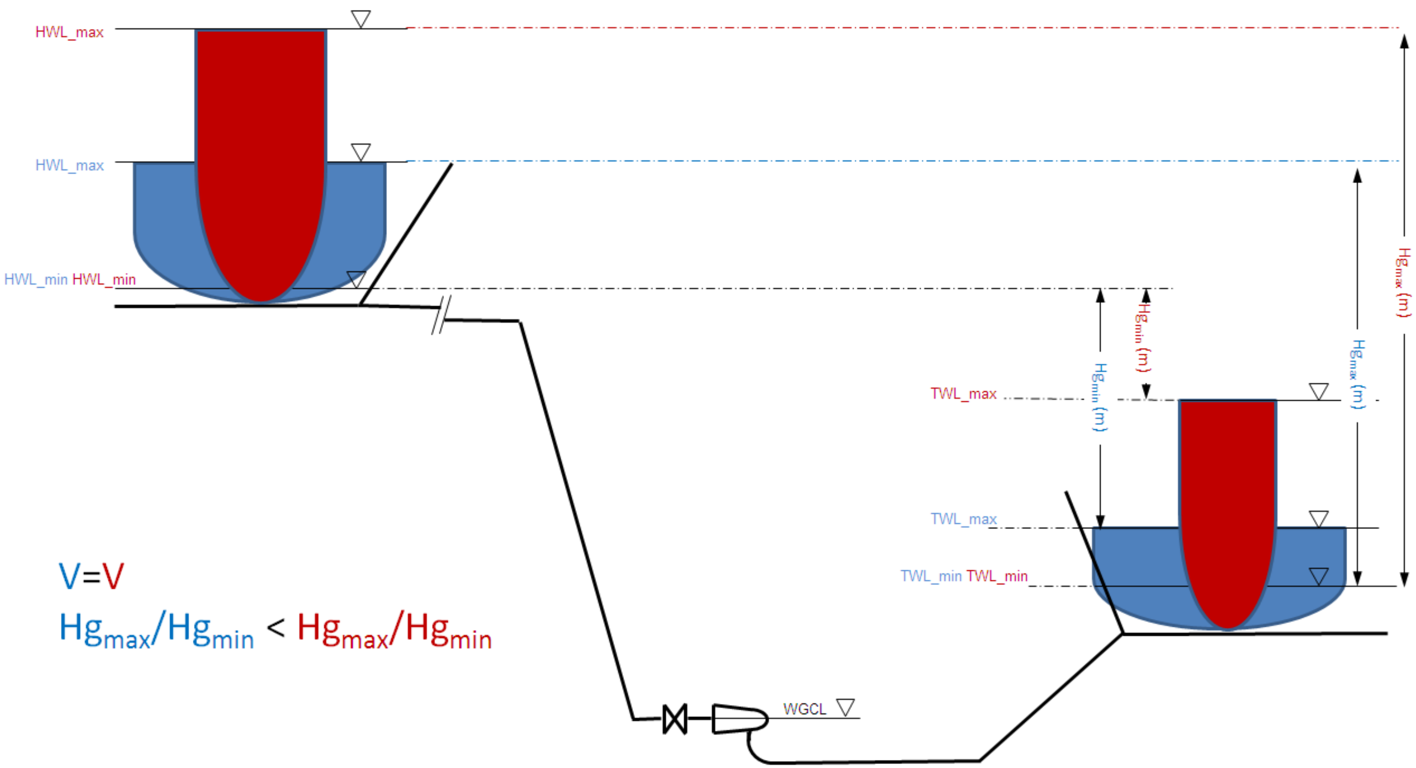
pump input = f (runner diameter; hydr. geometry) ➔ fixed at the prototype

pump input = f (head) ➔ can hardly be influenced at the prototype

pump input = f (speed) ➔ can be changed by a nvar-M/G + BoP

VOITH

Motivation – Large Head Variation of the Reservoirs

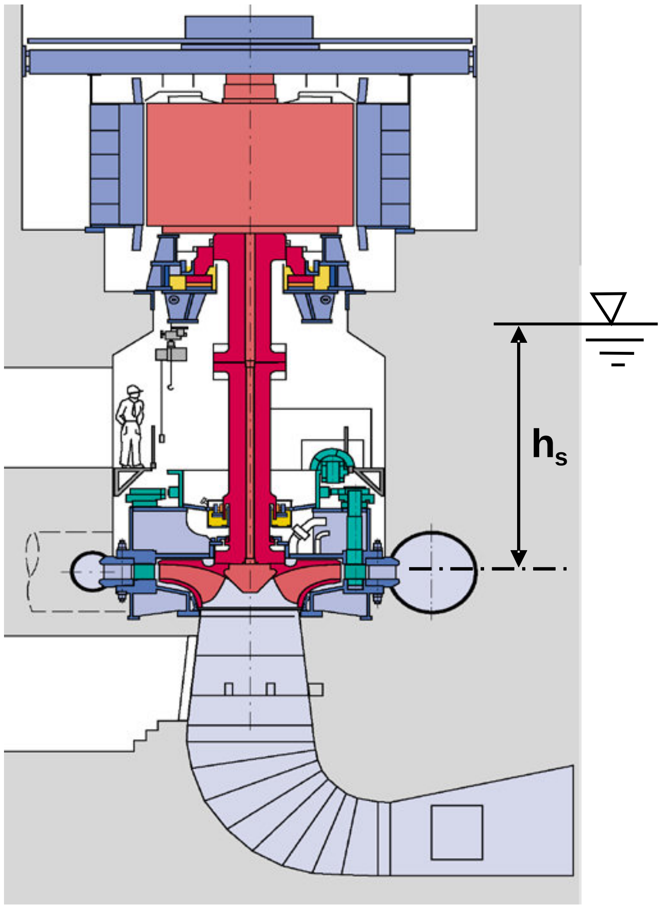


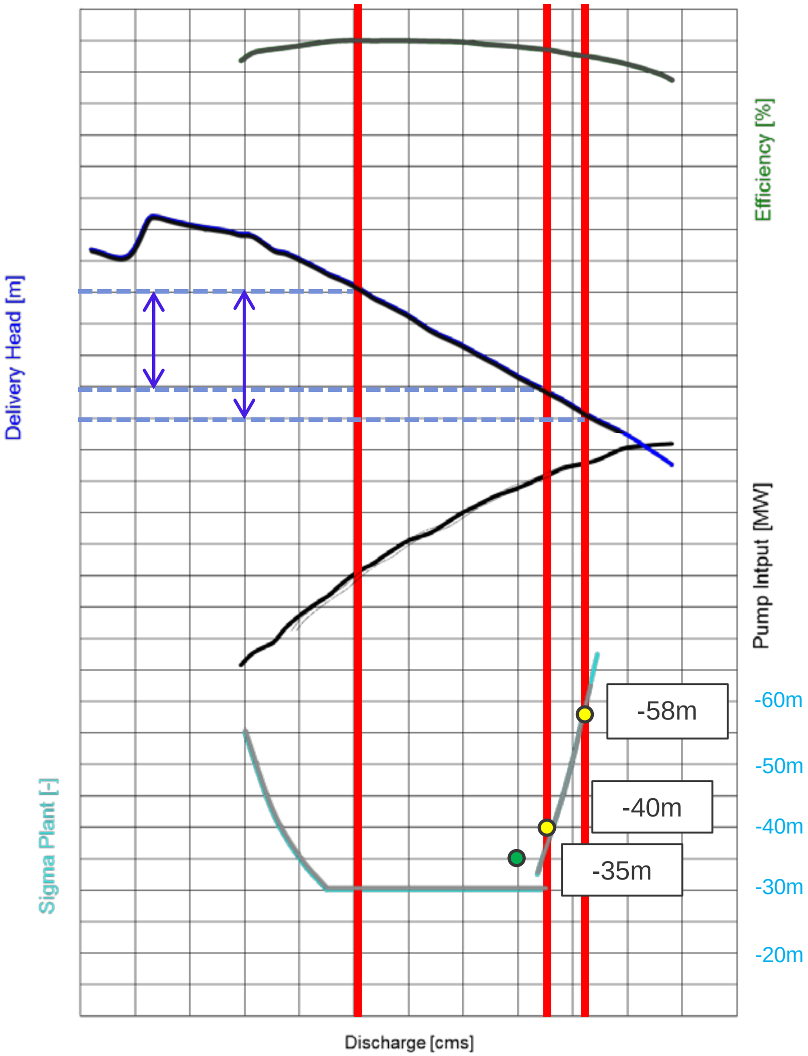
V=V

Hg_{max}/Hg_{min} < Hg_{max}/Hg_{min}

VOITH

Motivation – Large Head Variation of the Reservoirs

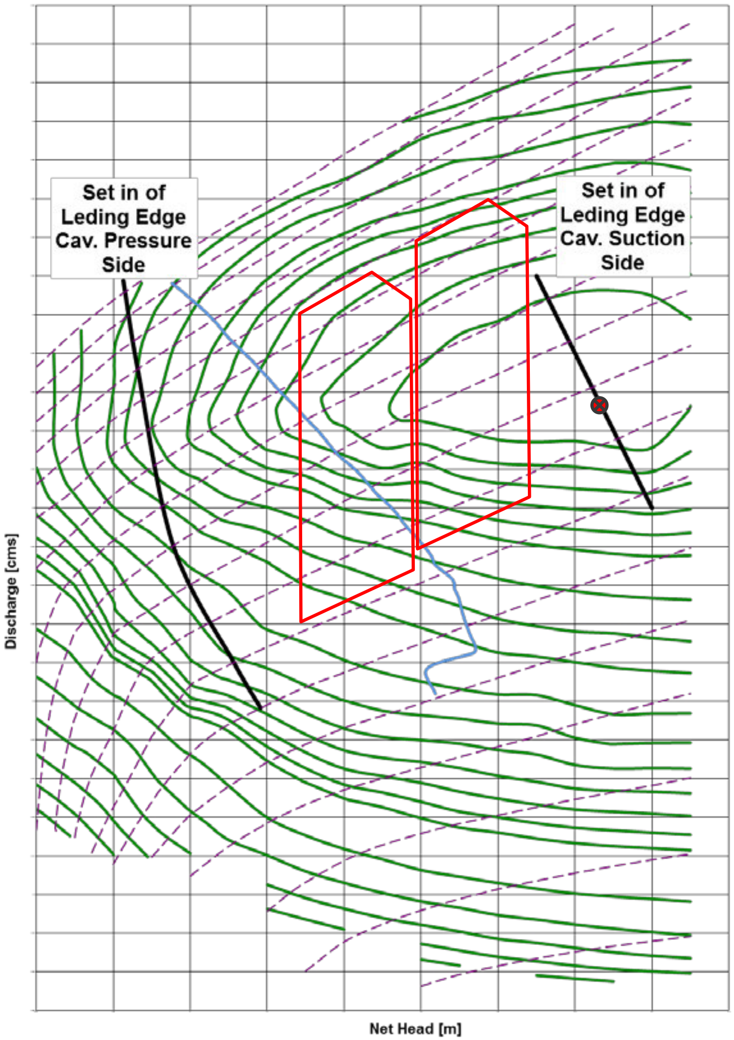




VOITH

Motivation – Performance Optimization (Tu Mode)

- Runner diameter and speed are selected to have a stable pump mode operation
- Turbine mode operation will have therefore some constrains

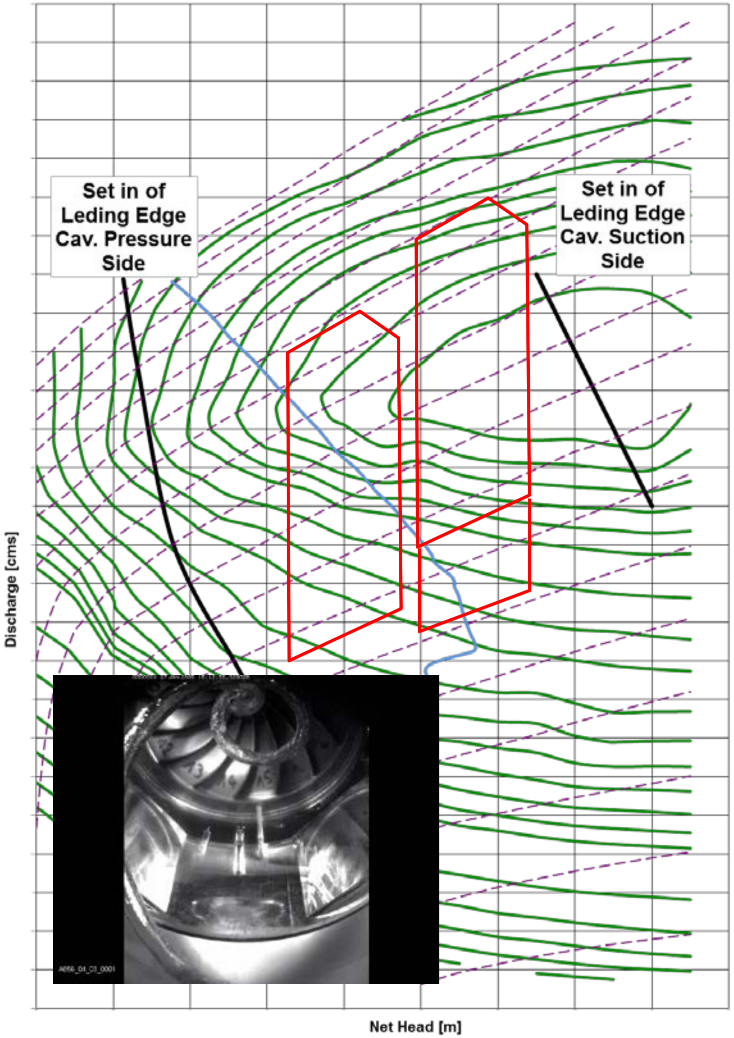


Motivation – Extended Turbine Operating Range

Lower speed improves

- Pressure Pulsations
- Noise
- Vibration
- Efficiency at low part load

This effect can be used to decrease the lower operating limit.



Motivation – Features for Grid Stability

- 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 – low voltage ride through, sustain longer in a 3 phase short circuit) by injecting fast active and reactive power in both modes (pump & turbine mode).

Line up of all Solutions

	Fix speed SM	DFIM - AC-Excitation	CFSM
MG Power	... 500 MVA (nearly no limitations)	... 500 MVA (limited by speed)	... 500 MVA (limited by speed)
Converter Power	6 % to 12 % (depending on machine size)	up to 30 % (of MG Power, depending on slip)	100 % (of MG Power)
Speed Range	Not applicable	+/- 10 % (typical)	+/- 20 % (typical)
Power Range MG	Not applicable	70 ... 100 % (typical)	40 ... 100 % (typical)
Power Factor Stator	0,9 (typical)	0,9 (typical)	0,9 (controlled to unity)
Power Factor Grid	0,9 (typical)	0,9 (typical)	0,9 (typical)
Generator Efficiency	synch. MG	less than synch. MG	synch. MG
Converter Efficiency	not applicable for normal operation	Approx. 96% - 98% of converter power incl. transformer (typical)	Approx. 96% - 98% of converter / MG power
Rotor Voltage / Current	acc. to best fit for MG / as needed	3,3 or 6,6 kV / up to 7,5 kA	acc. to best fit for MG as needed
Phase reversal switch	necessary	necessary	not necessary
Starting Time	medium	medium	short
Head Variation	no adaptation	medium	high
Costs MG	lower (approx. 100 %)	higher (approx. 130 %)	lower (approx. 100 %)
Costs converter system	low	high (approx. 5 times SFC - system costs)	higher (approx. 10 times SFC - system costs)
Availability	with converter or in case of two units BtB possible	operation only with converter	turb. operation w/o converter (bypass)
Blow Down	necessary	necessary	not necessary

VH References – Pump Storage

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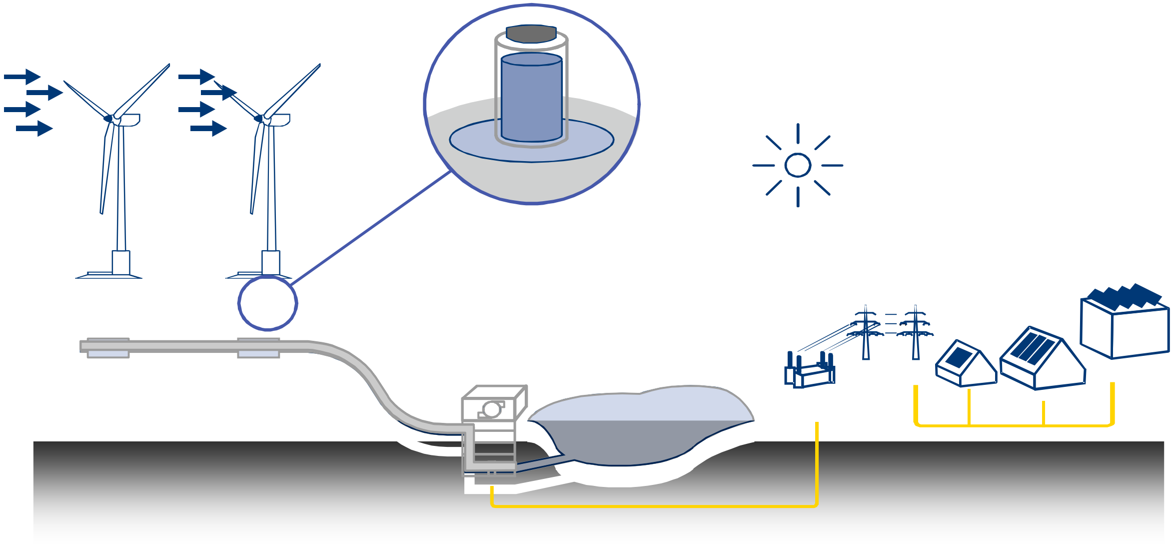
Year of Commissioning	Project	Details
1937	Pedreira, Brazil	First reversible pump turbine in the world with 5.3 MW unit output, 30 m, 212 rpm
1954	Luenersee, Austria	First pump with head exceeding 1000 m
2001	Bath County, USA	World's highest output pump turbine of unit power 480MW
2010	Frades II, Portugal	372 MW pump turbine, Europe's most powerful variable speed motor generator with speed range from 350 rpm to 381 rpm
2011	Hongrin Leman,Switzerland	5 stage radial pumps, P :118 MW, H : 865 m
2017	Chan Long Shan, China	357 MW pump turbine, H : from 690 m to 760 m

Innovative, scalable small size pumped storage – Gaildorf, Germany



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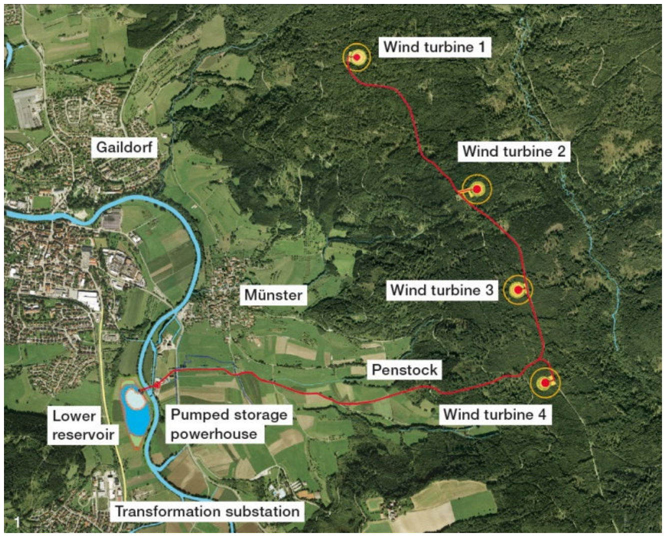
Gaildorf – Combination of Wind and Water



Wind Turbine Capacity	4 x 3.4 MW		Pump Storage Capacity (speed variable; hydraulic circuit operation)	3 x 5.3 MW
Rotor Diameter	137m		Runner Diameter	1.150m
Wind Power (~ 6.2 m/s)	42 GWh		Storage Capacity	70 MWh
Installation Height (Hub)	155 – 157m		Net Head	200m

Source: Brochure Naturstrom EN, Naturstromspeicher GmBH

Advantages for on-site integration of PSP with wind farm in Gaildorf (I)

- CO_2 emissions are zero during operation since generation with wind & storage in pumped mode & generation in turbine mode are CO_2-free
- Complete coverage of the electrical energy consumption of the city of Gaildorf with 12,000 inhabitants
- Savings of approximately 10,000 tons of black coal or 25,000 tons of lignite coal & corresponding CO_2 emissions
- Standardized pumped storage power plants (16/24/32 MW)
- Several project synergies PSP with a wind farm: substation, access roads, planning, land use, project & operation management, project volume, ...

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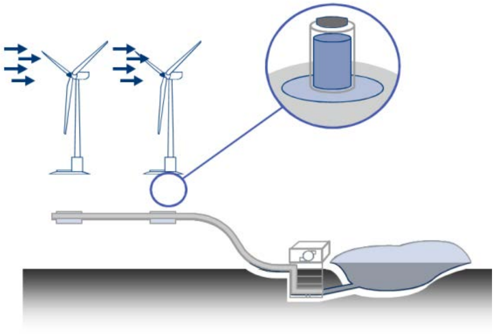
Advantages for on-site integration of PSP with wind farm in Gaildorf (II)



- In Germany a fast & easy approval process for windfarms is in place, otherwise very massive public interventions due to the artificial upper reservoir
- Integration of the upper reservoir in the towers of the wind turbines reduces the interference in the natural areas significantly
- Short project implementation (3-5 years versus 10-15 years for large pumped storage power plants)
- Easily bankable power plant solution
- Smoothening effects of the wind volatility regarding over-all power output

Summary

- Todays pump storage power plant concepts are reversible pump turbines or ternary units (Pu+Tu)
- Input regulation during pump mode requires speed variable units or the possibitly to operate in hydraulic circuit
- Speed variable units are equipped with synchronous motor-generator with a full power convertor between grid and stator or double feed induction machine with AC-excitation for the rotor
- Operating scheme including grid services of a modern pump storage plant must be well known to consider the necessary features at the E/M equipment, BoP and civil works

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Contact:

Sanjai Dhar Dwivedi
Assistant Vice President – Turbine and Valve Engg

Tel. +91 120 30 74 242

Mobile +91 9910097647
sanjaidhar.dwivedi@voith.com

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