

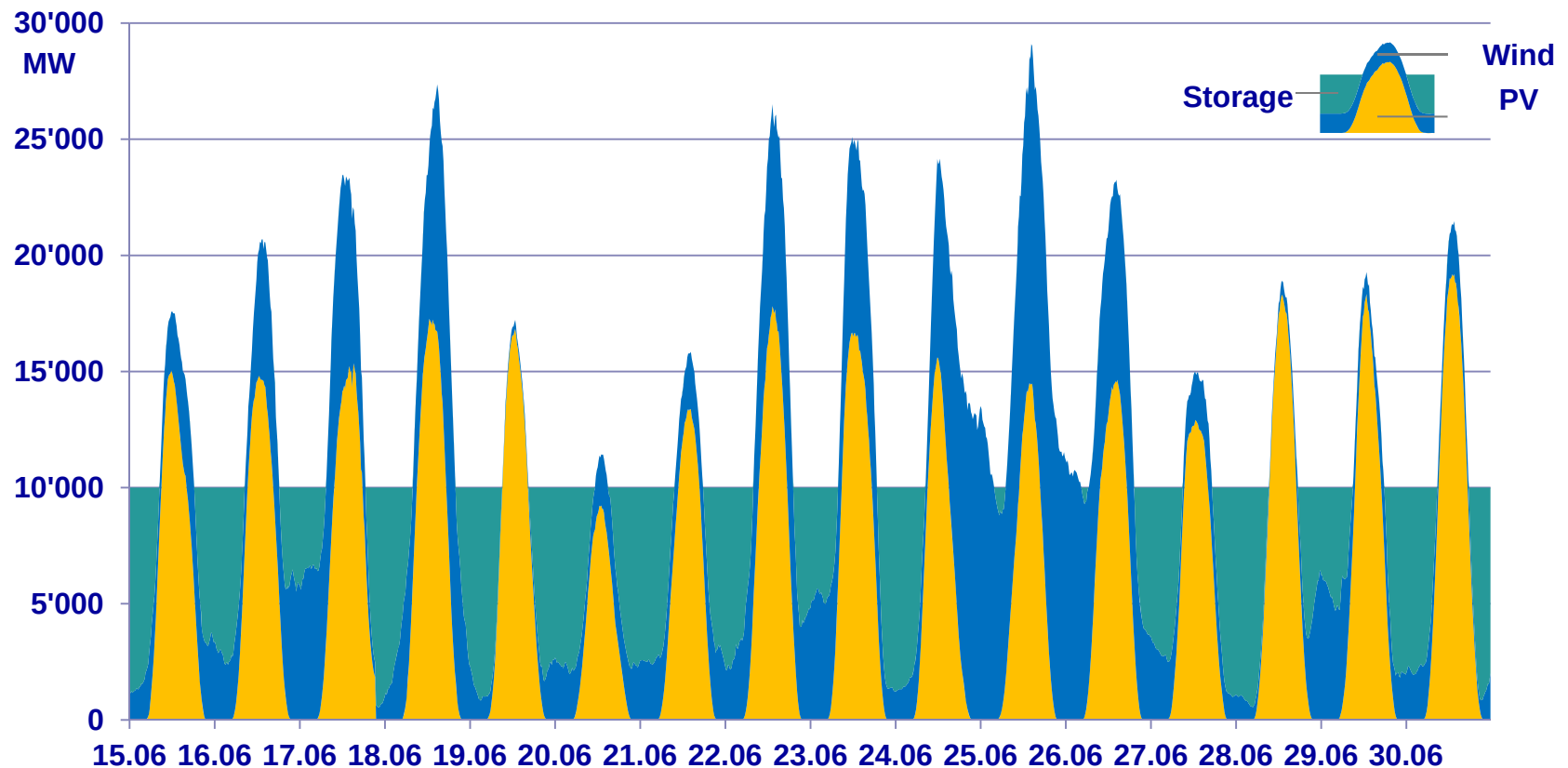
Stations de transfert d'énergie: technologie des groupes de pompage-turbinage

**Prof. François Avellan, Dr. Eng.,
EPFL School of Engineering
Institute of Mechanical Engineering**

Computing Domain of the
HYDRODYNA Pump-Turbine

Integration of New Renewable Energy Sources in Europe

○ Needs of Storage & Grid Primary and Secondary Control

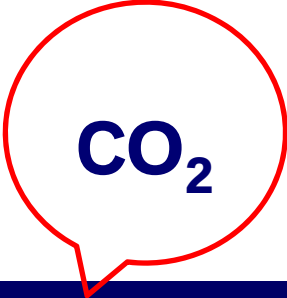


Scope

- **Facts & Figures**
- **Pumped Storage Technology**
 - ✓ **Swiss Case**
- **Scientific Challenges**
 - ✓ **Collaborative Research Program**

Challenges

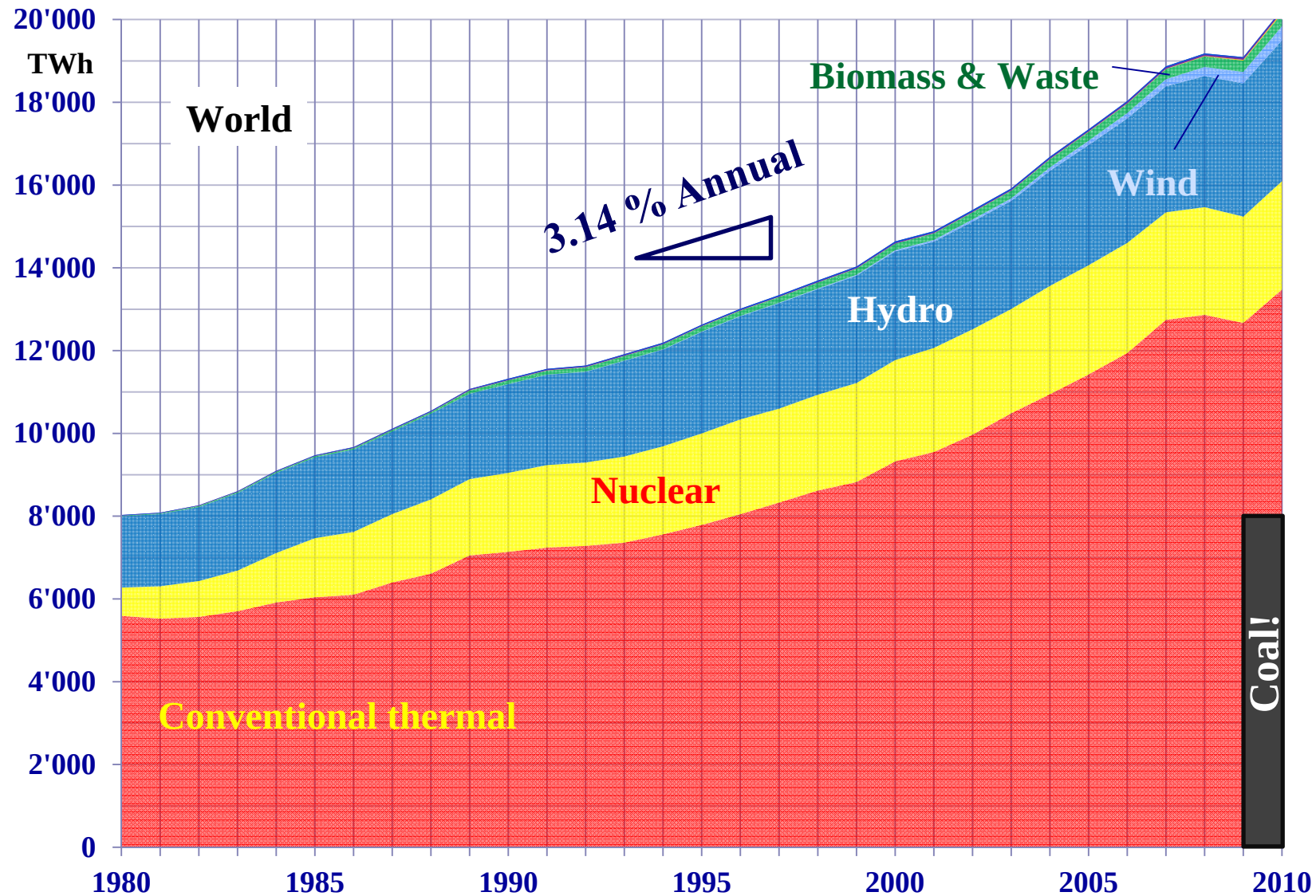
- Electricity cannot be directly stored in a practical manner on a large scale.
- Fluctuation of Demand
- NRE Development
- Electricity Market Deregulation
- Sustainability



CO₂



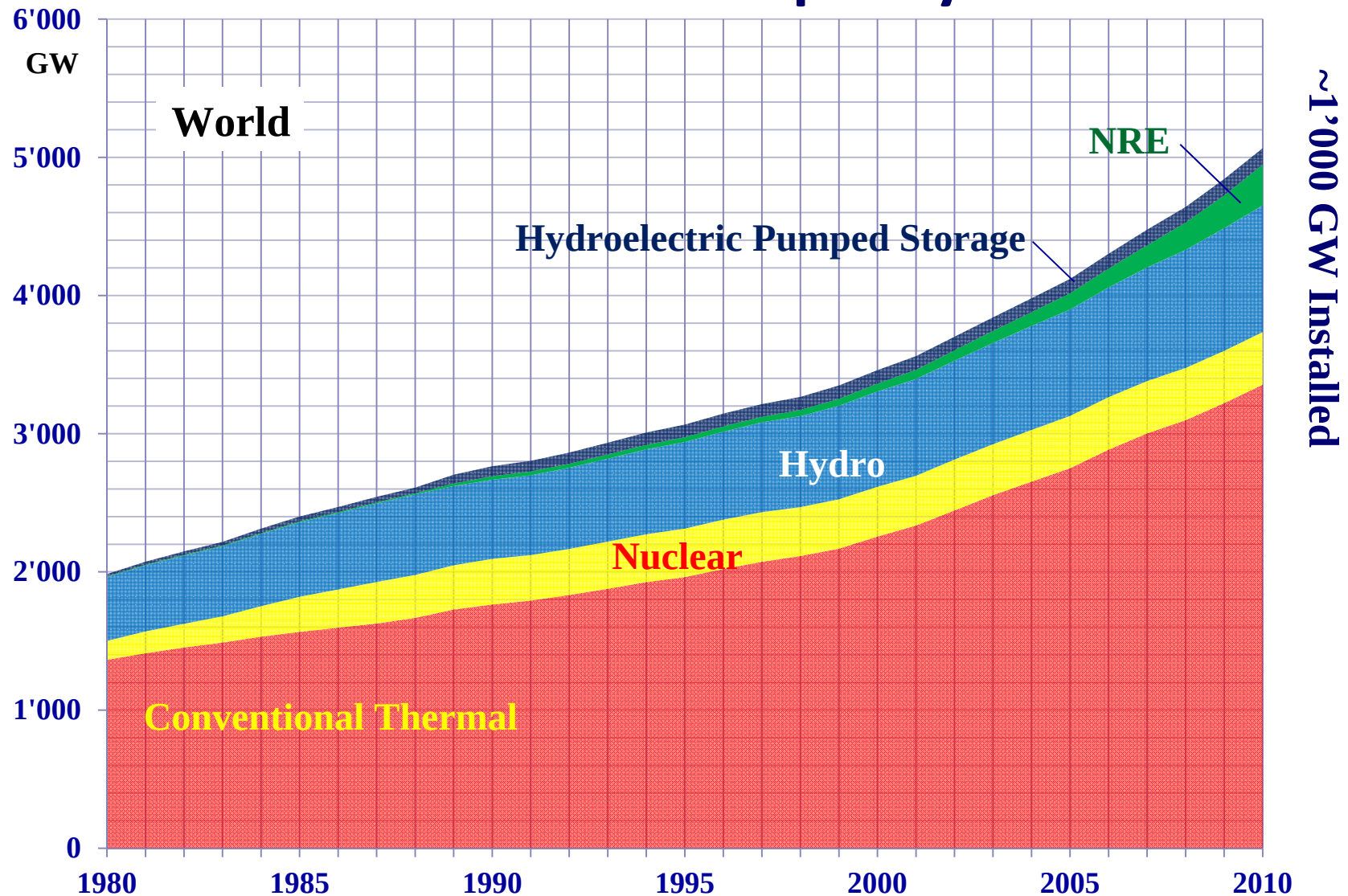
Power Generation Mix



20'225 TWh generated in 2010, 16.8 % Hydro, Source US Energy Information Administration www.eia.gov



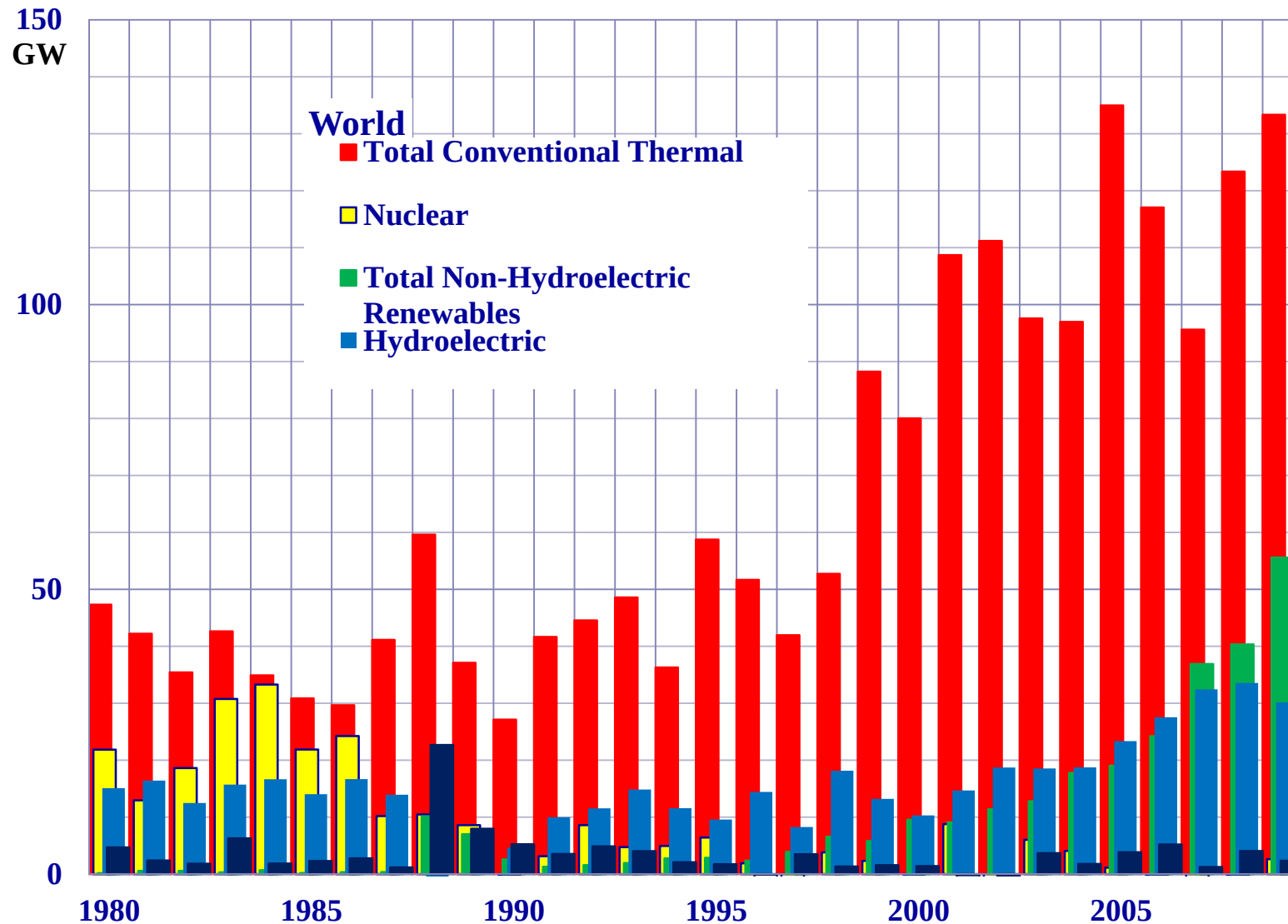
Installed Capacity



5'067 GW installed capacity in 2010, 918 GW Hydro, 121 GW Pumped Storage



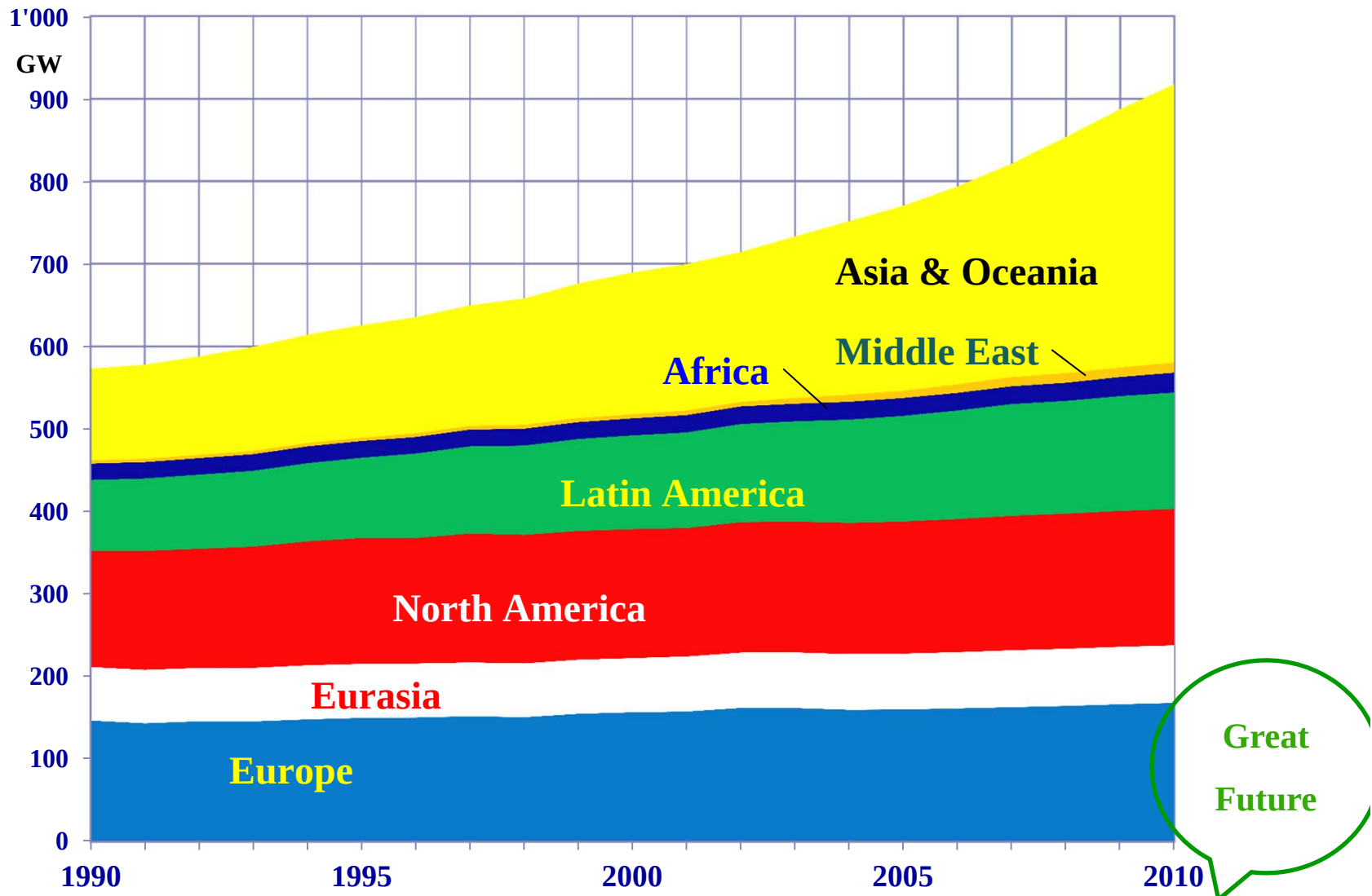
Capacity Installation



Market Development by type of fuels, Hydro over 10 GW/year since 2000



Hydro Capacity Installation



Geographical breakdown of the worldwide hydro installed capacity, 2'000 GW expected in 2050!



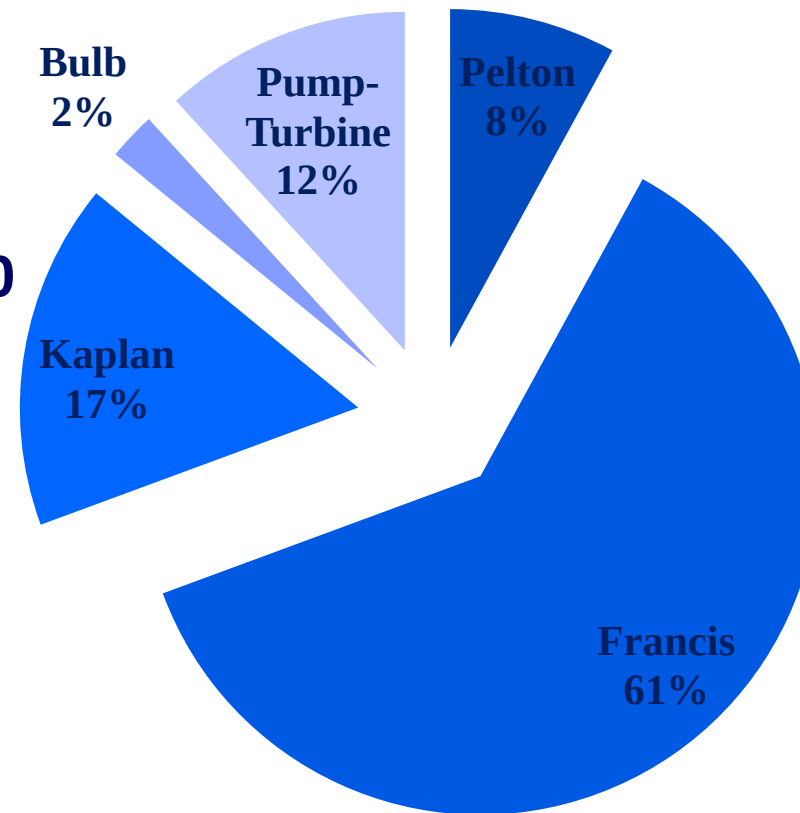
Hydro Turbines Market Outlook

○ New Projects

✓ 1'000 GW
to be build up to 2050

○ Modernization

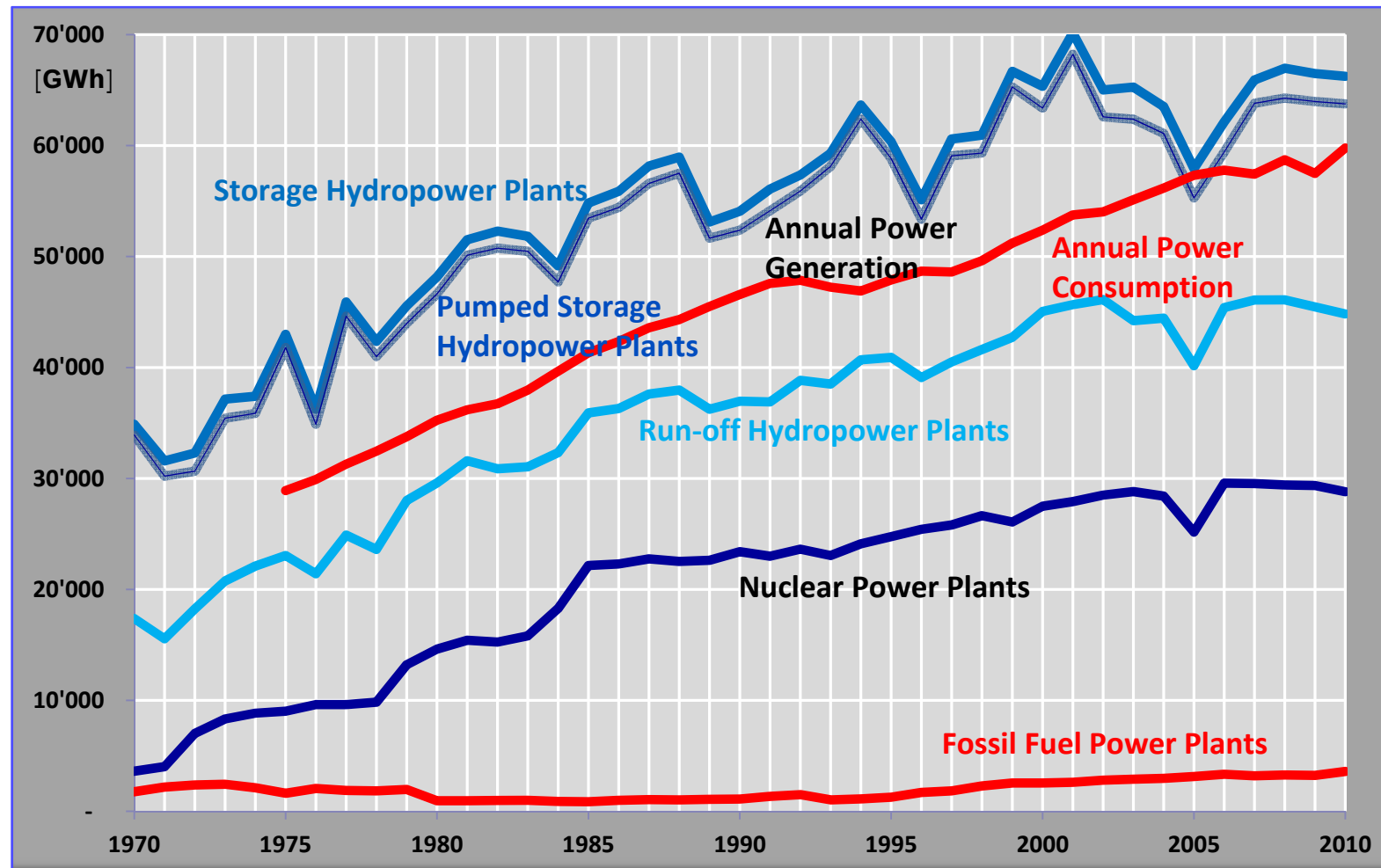
✓ 1'038 GW Installed





Domestic Power Generation Mix

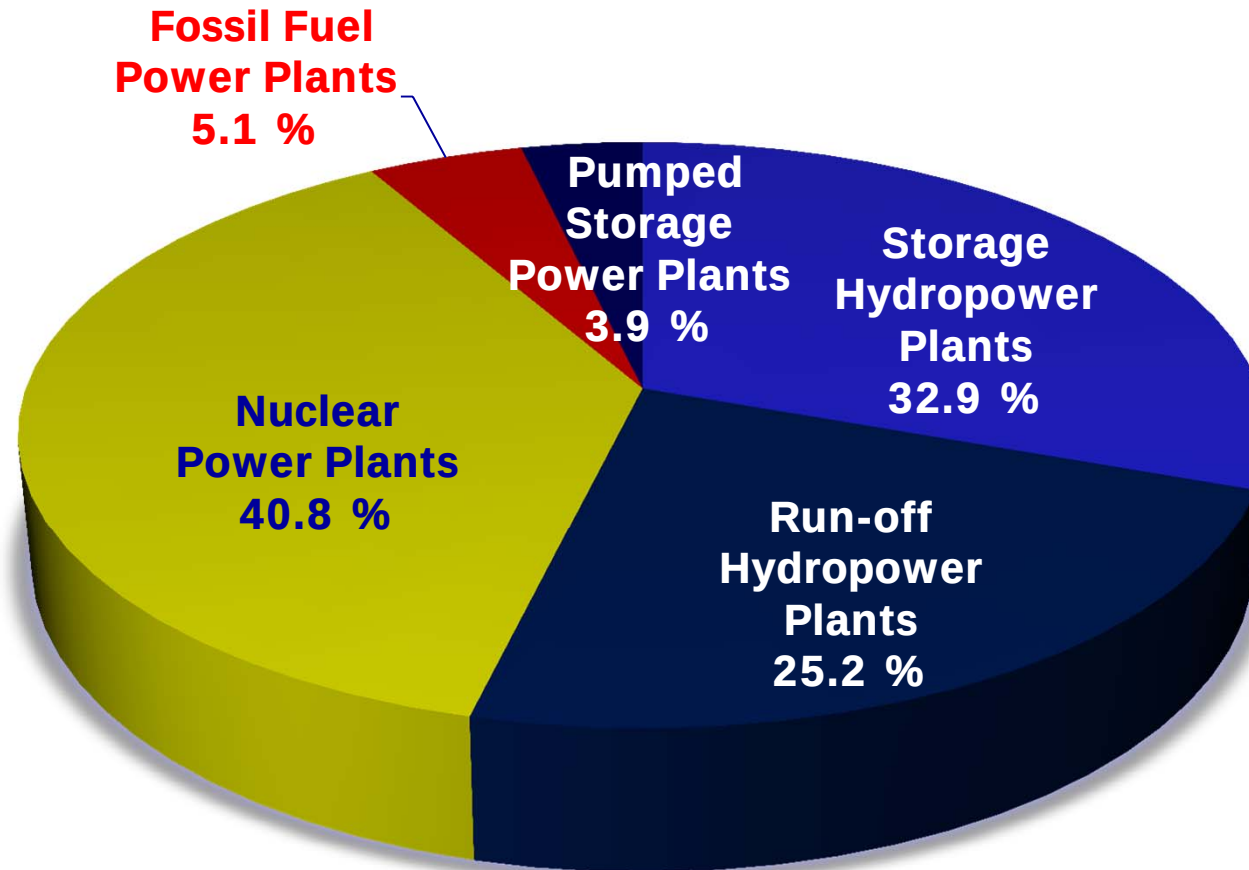
Swiss Electricity Data: 2010 Survey



Switzerland to be Proud of a Nearly CO₂-Free Power Generation Mix !



Power Generation Mix in Switzerland



63'758 GWh Power Generation in 2010 :

2009: 11'734 MW Hydropower Generating Capacity ; 1'699 MW Pumping Power Capacity



Integration of New Renewable Energy Sources

- **Storage Hydropower Plants**
 - ✓ **Mainly Pelton Turbines in Switzerland;**
- **Pumped Storage Power Plants (1'400 MW)**
 - ✓ **3'540 MW Capacity in 2016**
FMHL⁺, 240 MW; Nant de Drance, 900 MW; Linthal, 1 GW;
 - ✓ **Projects :**
Grimsel 3, 295 MW; RhôDix, 900 MW; Lago Bianco, 1 GW.
- **Gas Fired Combined Cycles Power Plants ?**
 - ✓ **Phasing out the Nuclear Power Plants;**
 - ✓ **Chavalon and/or Cornaux, 400 MW.**

Legende / Légende / Leggenda

● 10 - < 50 MW (103 Zentralen)

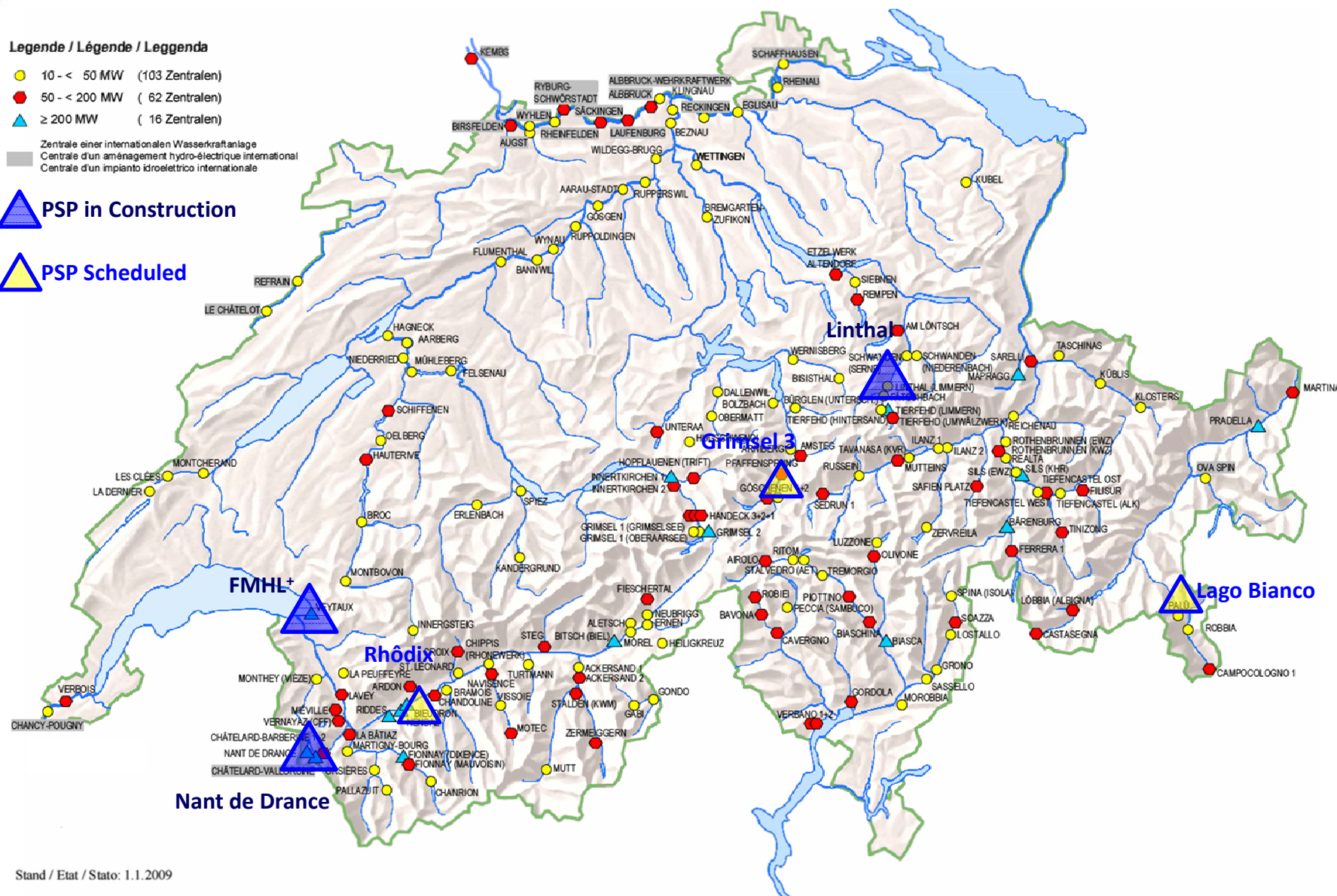
● 50 - < 200 MW (62 Zentralen)

▲ ≥ 200 MW (16 Zentralen)

■ Zentrale einer internationalen Wasserkraftanlage
Centrale d'un aménagement hydro-électrique internationale
Centrale d'un impianto idroelettrico internazionale

▲ PSP in Construction

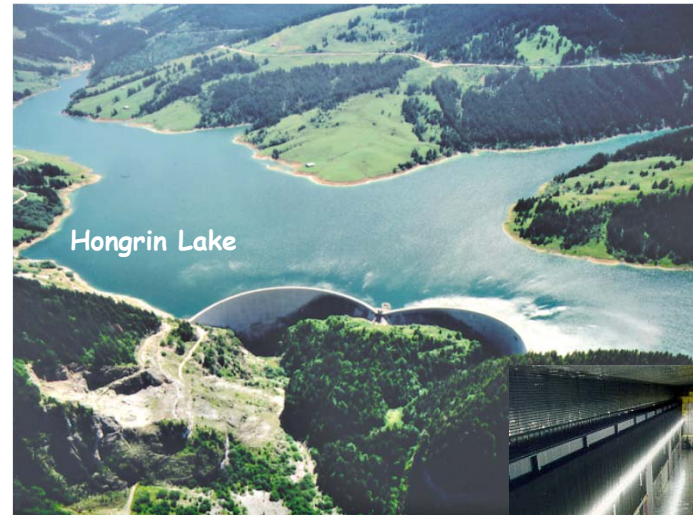
▲ PSP Scheduled



Stand / Etat / Stato: 1.1.2009

Hongrin-Léman PSP

- Hongrin Lake (1969) :
52 millions m³ Capacity
- Veytaux Power Station
(1972)
- 4 Horizontal Compound
Units
 - ✓ 256 MW Pumping Power
 - ✓ 240 MW Generating
Power
 - ✓ 850 mWC Head
 - ✓ 600 min⁻¹



Vertical Compound Units: Pelton-M/G-Pump

○ Matching both Pumping and Generating Modes

- ✓ Length of the Rotating Train;
- ✓ Speed;
- ✓ Required Submergence.

○ High Grade Control

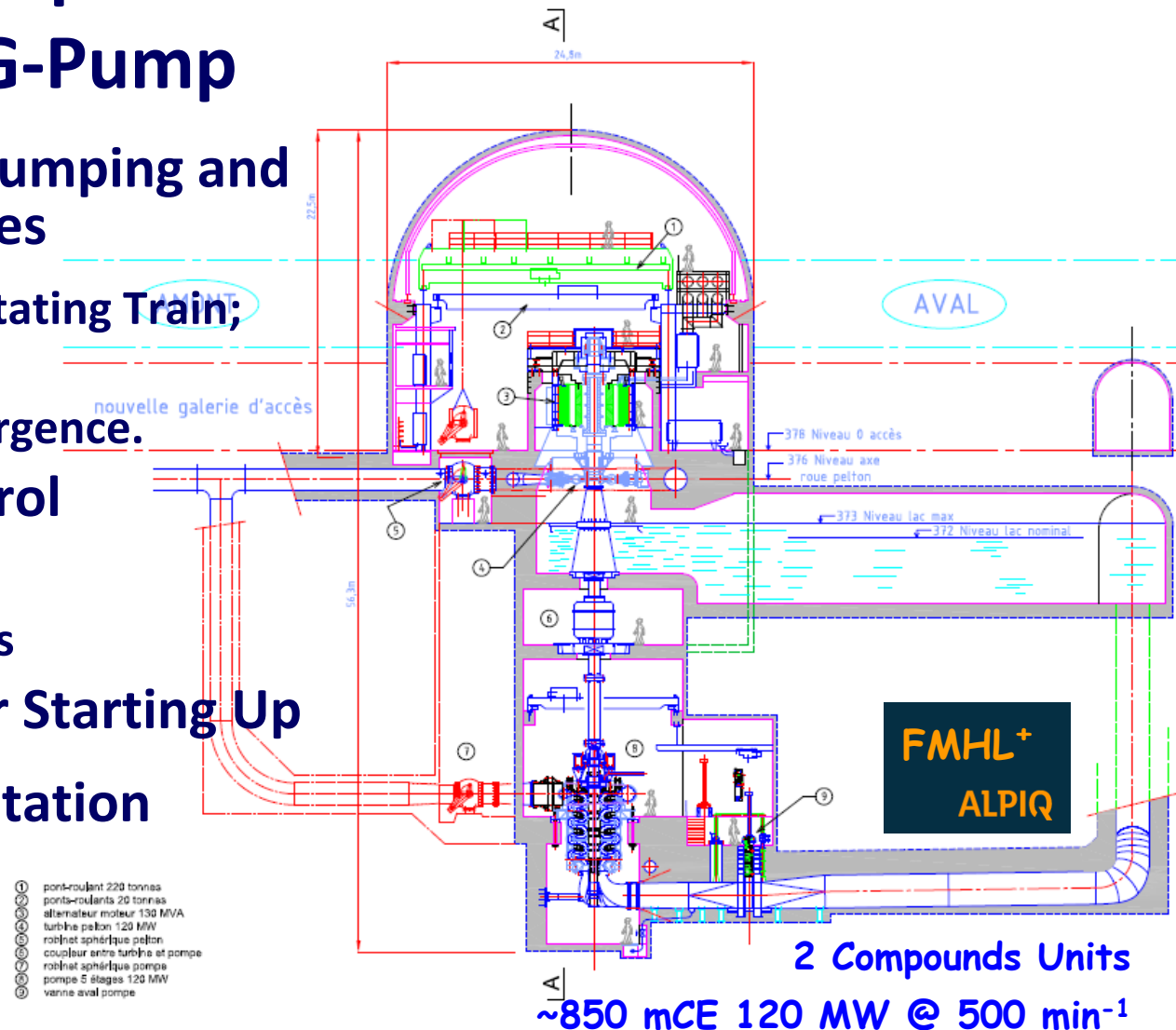
- ✓ Pelton Turbine
- ✓ Hydraulic By-Pass

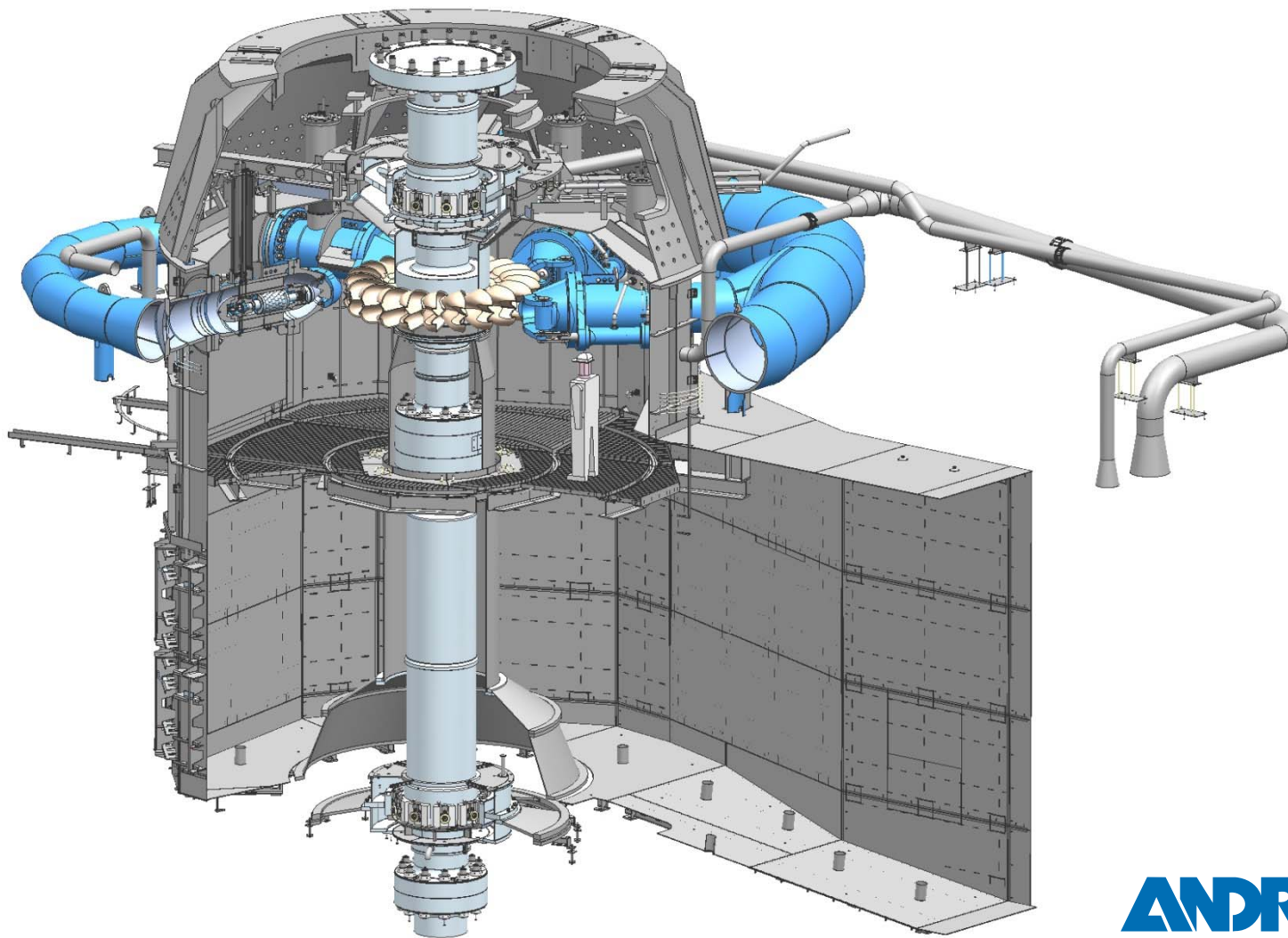
○ Turbine Drive for Starting Up

○ 1 Direction of Rotation

- ✓ Efficient Cooling

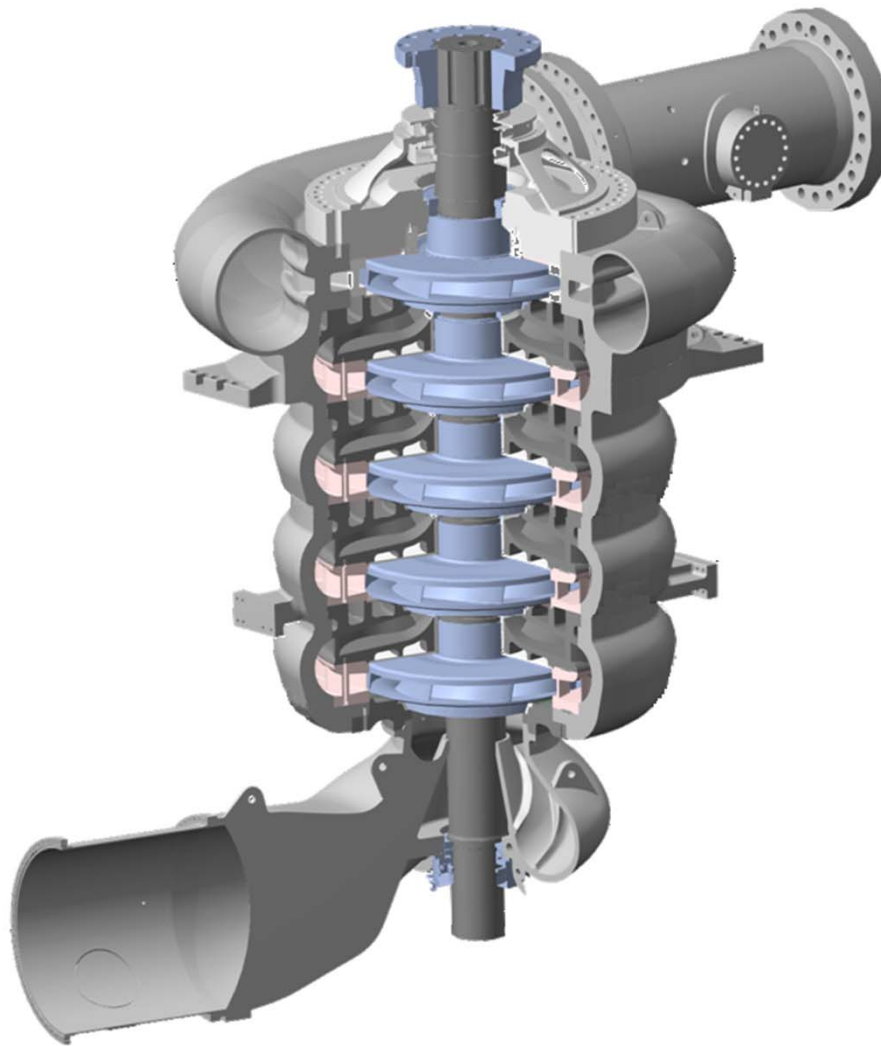
○ Safe Transients!





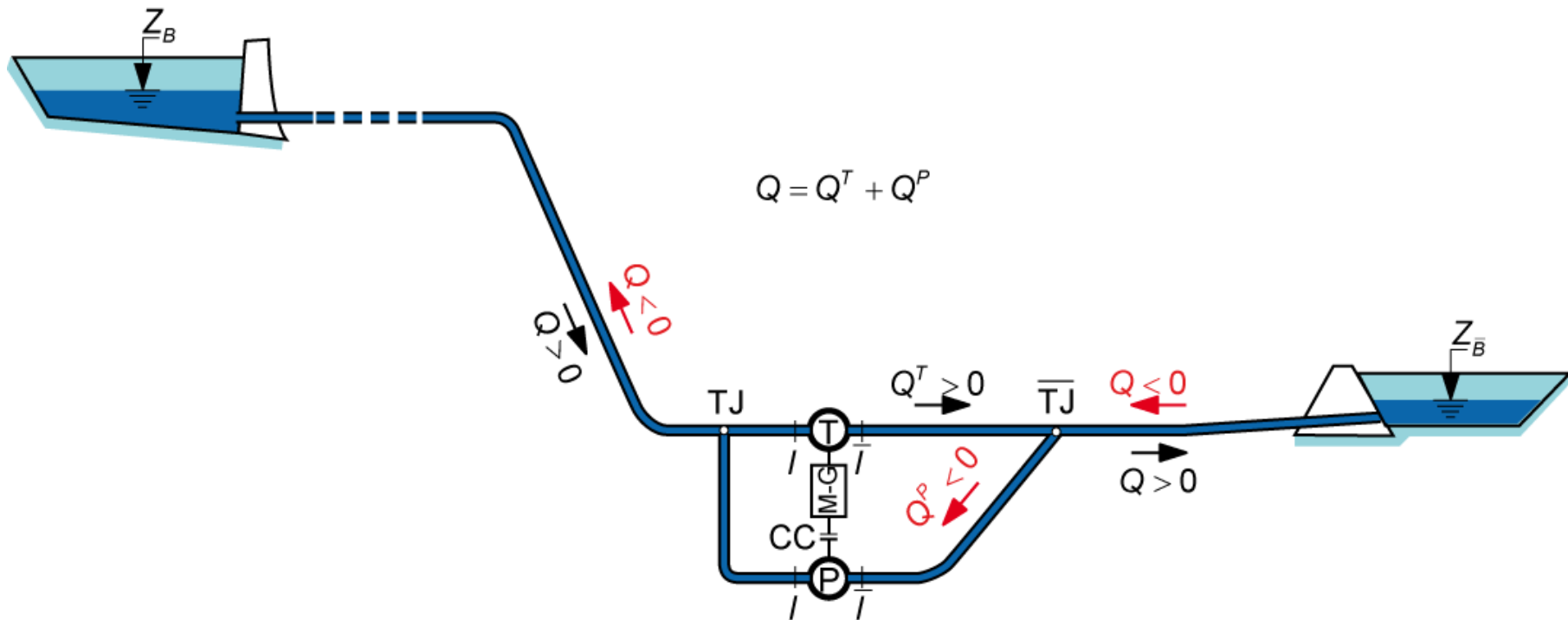
ANDRITZ
Hydro

VOITH





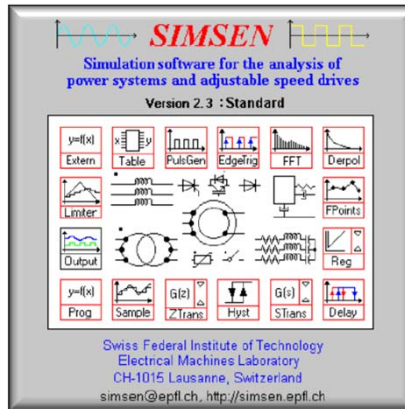
Hydraulic Bypass



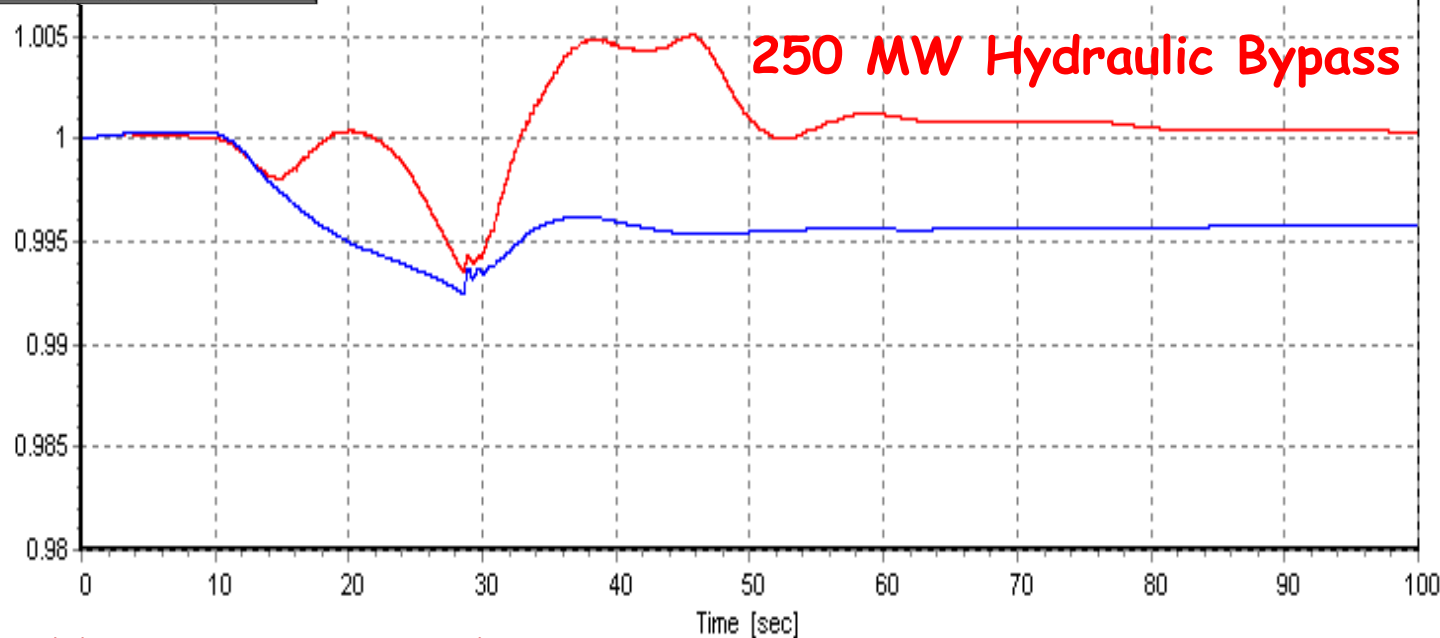
$$P^{M-G} = P^T + P^P$$



Grid Primary Control thru Hydraulic Bypass



200 MW Wind Farm Safety Tripp off
SIMSEN Numerical Simulation



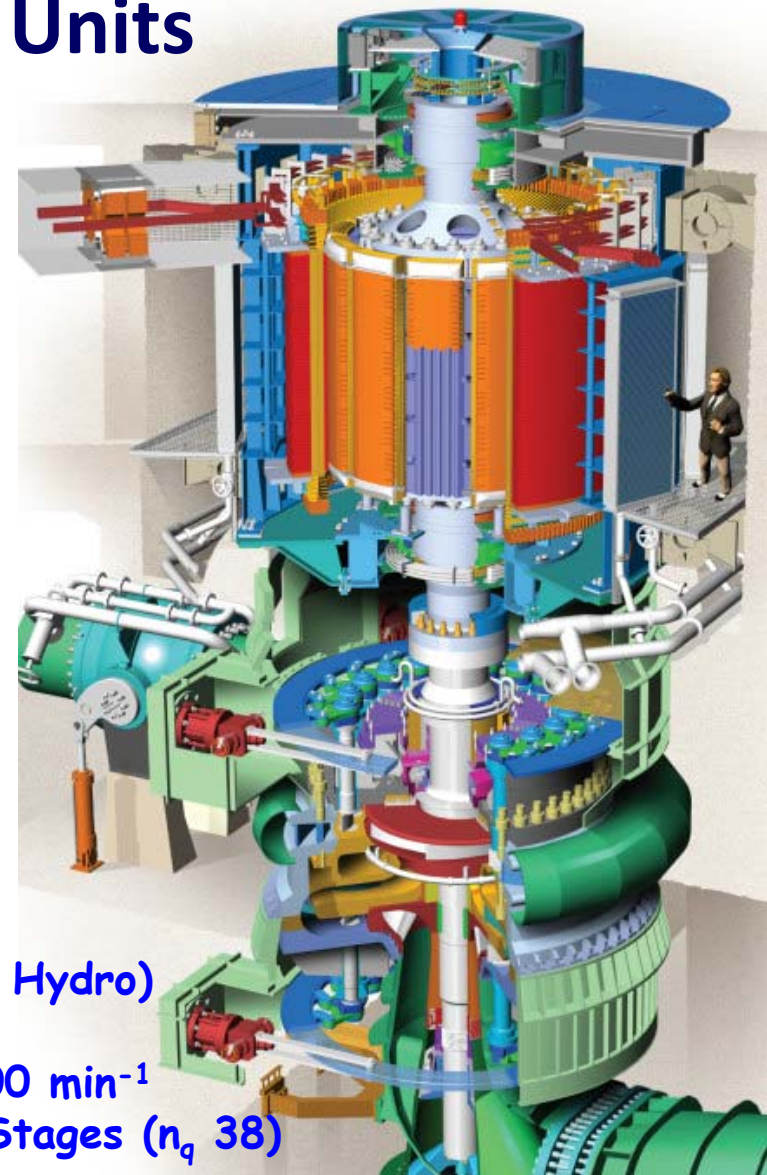
<http://simsten.epfl.ch/>

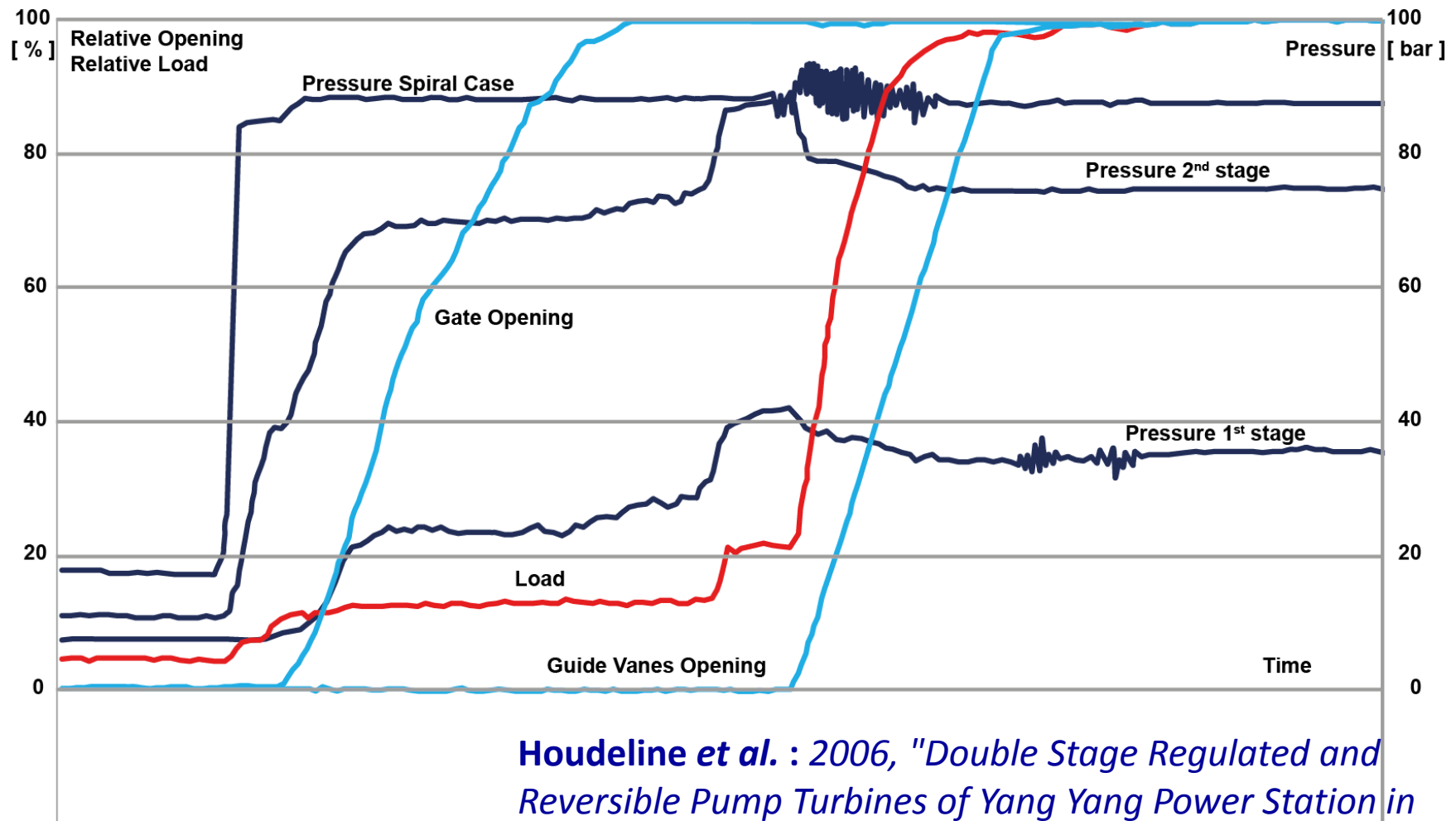
Reversible Pump-Turbine Units

Technology Challenges

- Start-Up Procedures
 - ✓ Static Frequency Converter of Limited Power
 - ✓ Back to Back arrangement
 - ✓ Turbine or Pony Motor Drive
 - ✓ Dewatering/Watering Process
- Bidirectional Motor-Generator Speed
 - ✓ Air Cooling vs. Water Cooling
- Pumping & Generating Operating Ranges Matching
 - ✓ Efficiency
 - ✓ Cavitation
 - ✓ Transients: Start-up & Load Rejection
- Grid Primary Control
 - ✓ Variable speed
 - ✓ Double Regulated Stages

Yang Yang (ALSTOM Hydro)
- 800 mWC
- 4 x 258 MW @ 600 min⁻¹
- Double Regulated Stages (η_q 38)





Houdeline et al. : 2006, "Double Stage Regulated and Reversible Pump Turbines of Yang Yang Power Station in Korea", 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama, Japan.

900 MW Nant de Drance PSP Project (VS)

Commissioning in 2015



- Emosson Lake 210 10⁶ m³ Capacity
- Vieil Emosson Lake 11 10⁶ m³ Capacity & 25.5 m Dam Height Increase
- 250 mWC to 390 mWC Head Range
- 6 x 155 MW Single Stage Pump-Turbines
- 428.6 min⁻¹ ± 7 % Variable Speed Drive

1 GW Linthal PSP Project (GL)

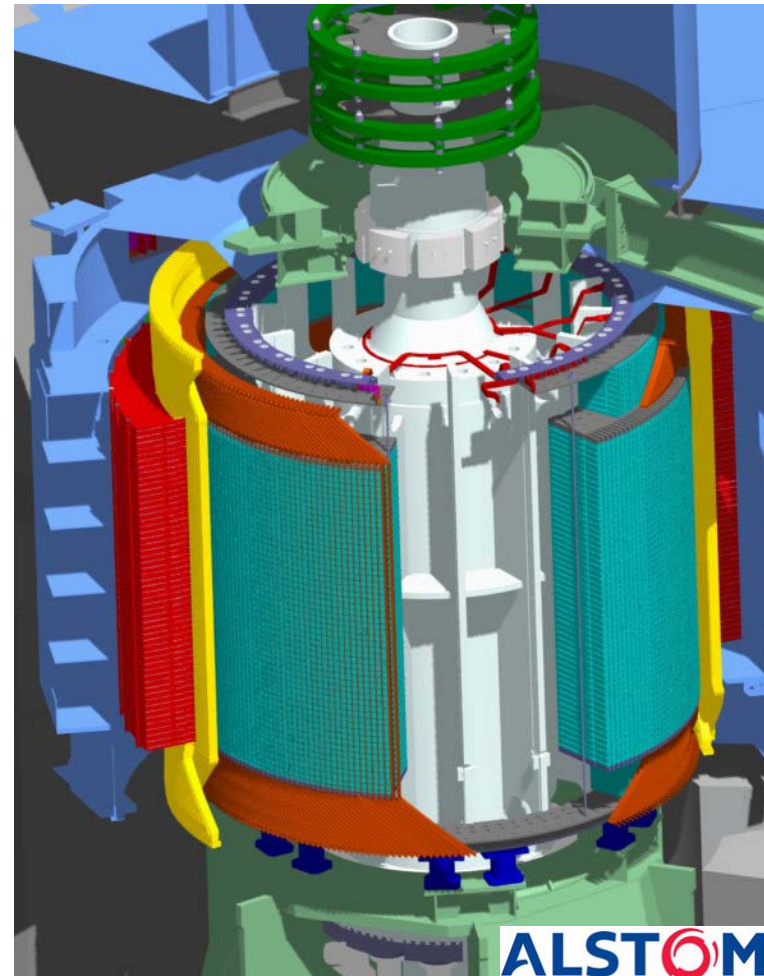
Commissioning in 2015



- Limmern 92 10⁶ m³ Capacity
- Mutt 25 10⁶ m³ Capacity
- 560 mWC to 724 mWC Head Range
- 4 x 250 MW Single Stage Pump-Turbines
- 500 rpm ± 6 % Variable Speed Drive

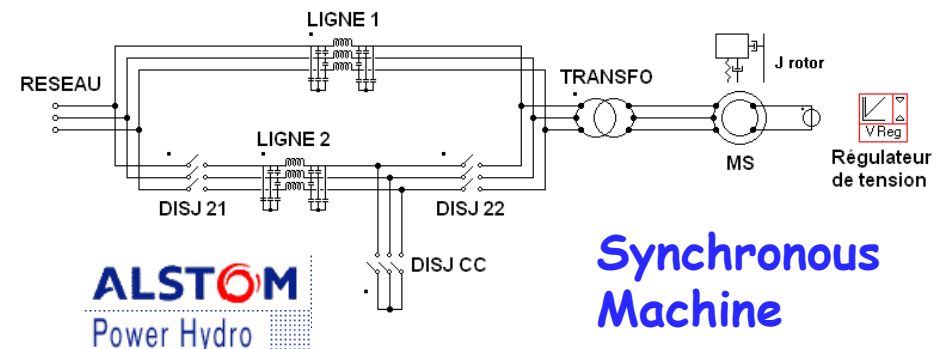
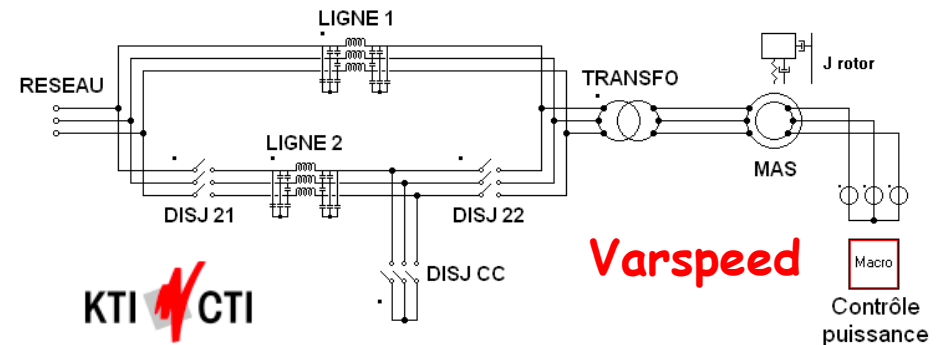
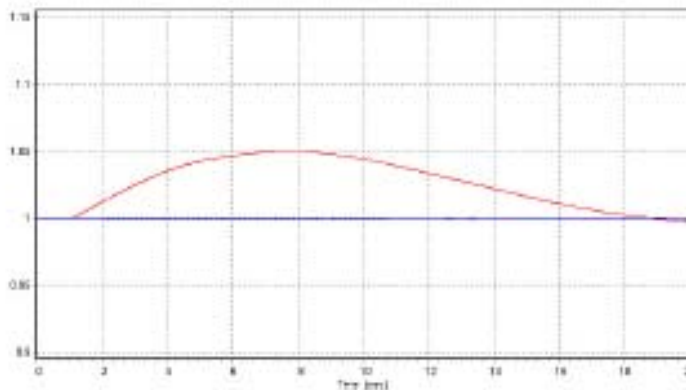
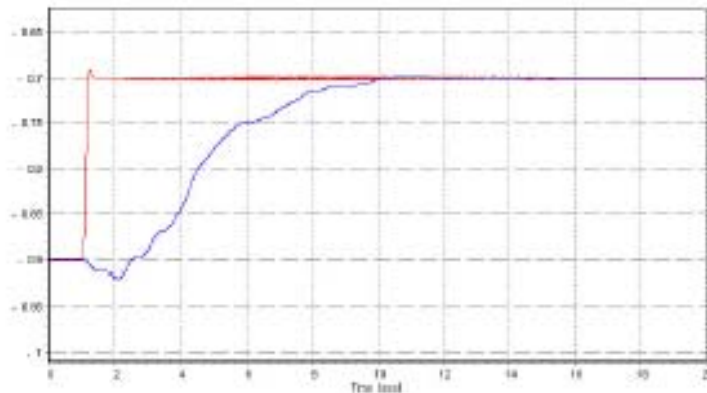
VARSPPEED Technology

- **Static Frequency Converter**
 - ✓ Voltage Source Inverter
- **Double Feed Asynchronous Machines**
 - ✓ Cylindrical Rotor with Three Phases Winding
 - ✓ Slip Rings for Excitation
- **Reversible Pump-Turbine**





Numerical Simulation of the Very Fast Change of the Power Set Point



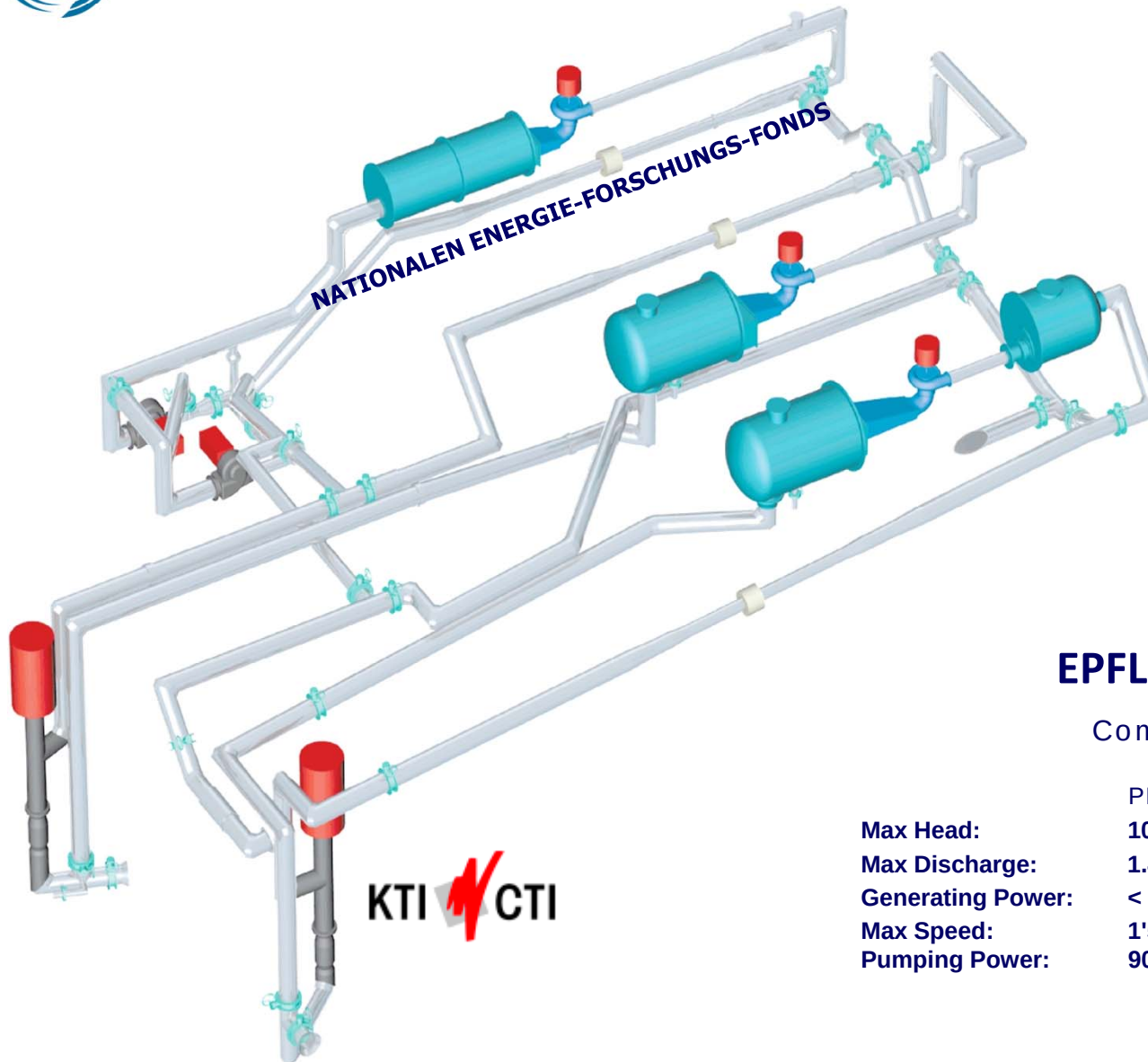
<http://simсен.epfl.ch/>

Yves Pannatier : "Optimisation des stratégies de réglage d'une installation de pompage-turbinage à vitesse variable", Thèse EPFL N° 4789, 2010.



Experimental Infrastructure

- Research
- Education
- Experimental Validation



EPFL Testing Facilities

Complying IEC 60193 Standards
Efficiency Uncertainty < 2 %

	PF 1	PF 2	PF 3
Max Head:	100 mCE	120 mCE	100 mCE
Max Discharge:	1.4 m ³ /s	1.4 m ³ /s	1.4 m ³ /s
Generating Power:	< 300 kW	< 300 kW	< 300 kW
Max Speed:	1'500 rpm	2'500 rpm	2'500 rpm
Pumping Power:	900 kW	1000 kW	2 x 400 kW

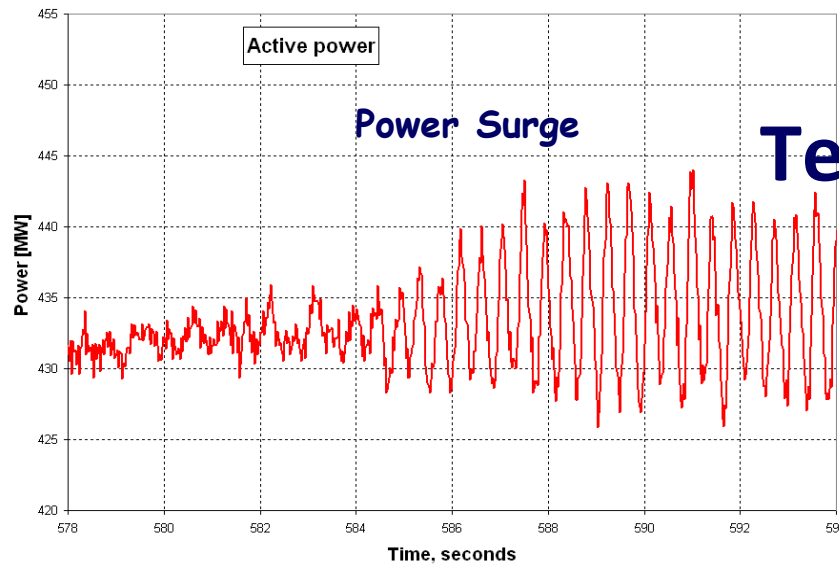
World Class Research Facilities: 3 Test Rigs for Hydraulic Turbines, Pumps and Pump-Turbines

IEC 60193 Pump-Turbine Model Testing

Pumped Storage Power Plant	Country	Owner/Manufacturer	Capacity	Year
NIU LAN GIANG	China	- /HARBIN Electrical Machinery Ltd	3 x 22 MW	2012
LI YANG	China	-/HARBIN Electrical Machinery Ltd	6 x 255 MW	2012
FRADES 2	Portugal	EDP Produção/VOITH	2 x 420 MW	2011
QINGYUAN	China	- /TOSHIBA	4 x 320 MW	2011
BAIXO SABOR Jus.	Portugal	EDP Produção/ANDRITZ Hydro	2 x 18 MW	2011
BAIXO SABOR Mont.	Portugal	EDP Produção/ANDRITZ Hydro	2 x 77 MW	2011
LUDINGTON	MI, USA	Consumers Energy/TOSHIBA	6 x 312 MW	2010
XIANYOU	China	- /DONGFANG Electrical Machinery Ltd	1'200 MW	2009
XIAN SHUI JAN	China	- /HARBIN Electrical Machinery Ltd.	4 x 370 MW	2009
Very High Head R&D	☺	- /ALSTOM Hydro	-	2007-8

IEC 60193 Pump-Turbine Model Testing (contd.)

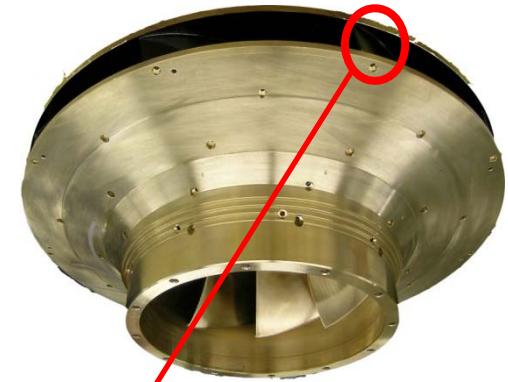
Pumped Storage Power Plant	Country	Owner/Manufacturer	Capacity	Year
ROCKY MOUNTAIN	GA, USA	Oglethorpe Power/American Hydro (WEIR)	3 x 370 MW	2005-6
BLENHEIM GILBOA	NY, USA	Rev. Eng. & Impeller Model NYPA/HITACHI	4 x 260 MW	2003
CHEONSONG	South Korea	Korea Western Power Co /GE Hydro	2 x 350 MW	2003
Nq 45 R&D	-	- /ALSTOM Hydro	-	2002
VENDA NOVE II	Portugal	EDP/VOITH Hydro	2 x 98 MW	2001
ALQUEVA	Portugal	EDIA operated by EDP/ALSTOM Hydro	2 x 130 MW	1999
TAUM SAUK*	MO, USA	Union Electric Co./AMERICAN Hydro (WEIR)	2 x 220 MW	1997



Scientific Challenges Technology Breakthrough

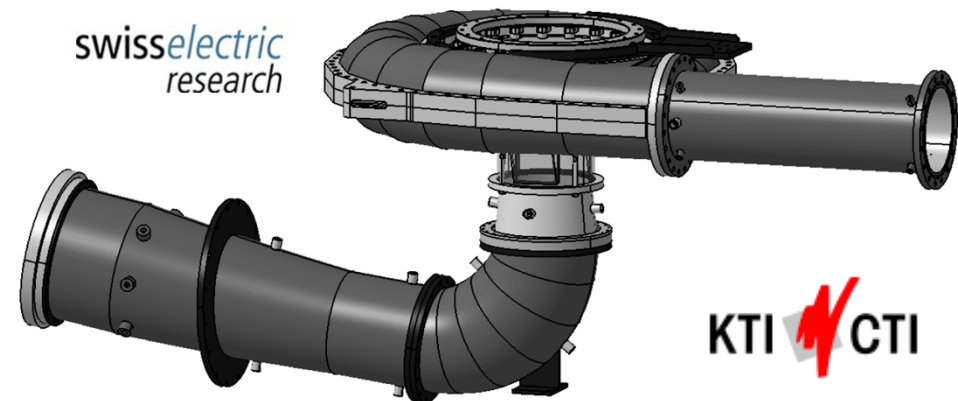
○ Integrity, Reliability and Flexibility

- ✓ Meeting Demand
- ✓ Grid Primary Control
- ✓ Frequent Mode Changes
- ✓ Extended Operating Range



HYDR DYNA Research Project **Pump-Turbine Hydrodynamics**

- Investigating, Modeling and Harnessing Unsteady Flows;
- Fluid Structure Coupling;
- Rotor-Stator Interactions;
- Performance Curve Stability;
- Off-Design Conditions.



Pompe-turbine HYDRODYNA $z_o = 20$, $z_b = 9$



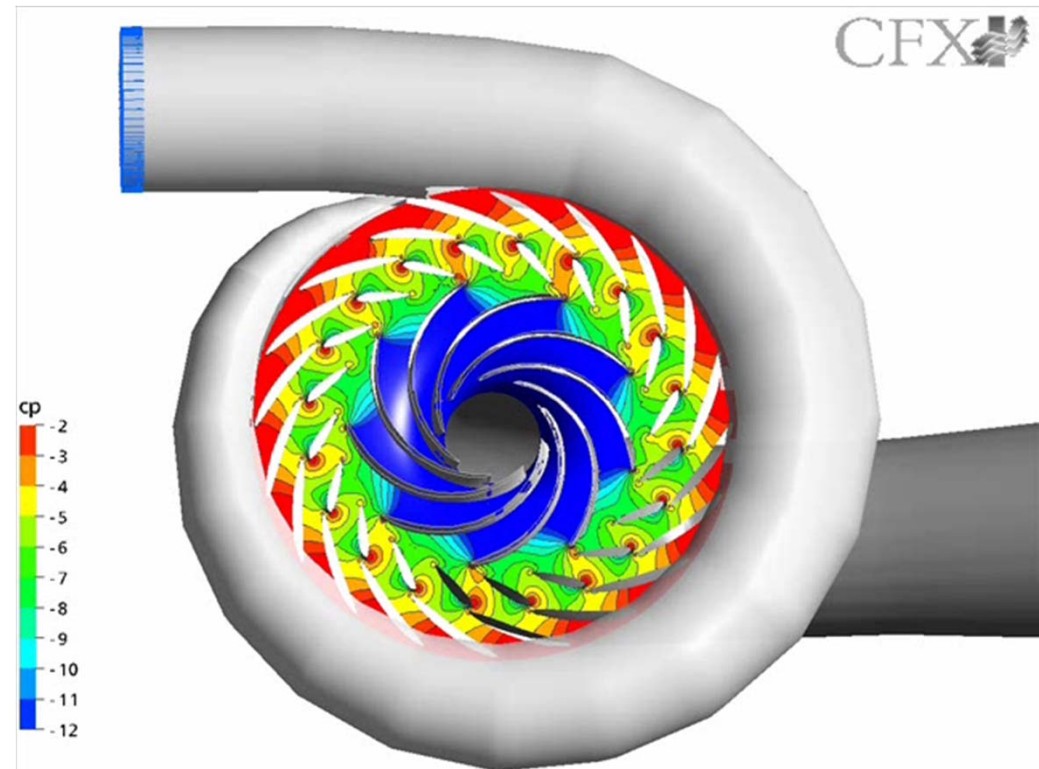
Rotor-Stator Interactions in Generating Mode

○ HYDRODYNA

Case Study

$$z_o = 20, z_b = 9$$

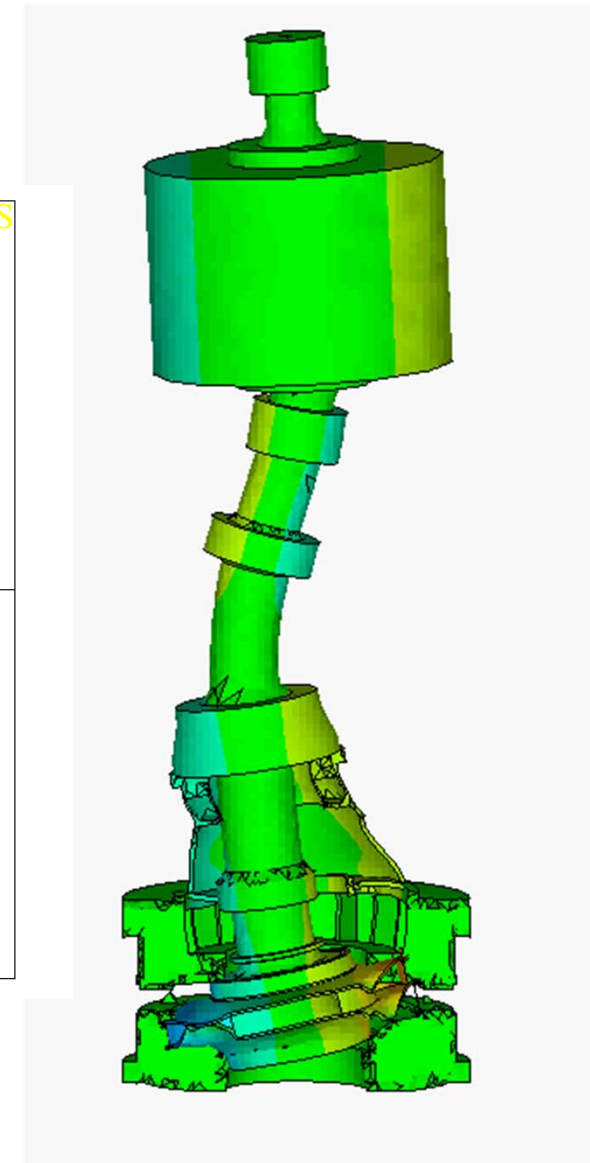
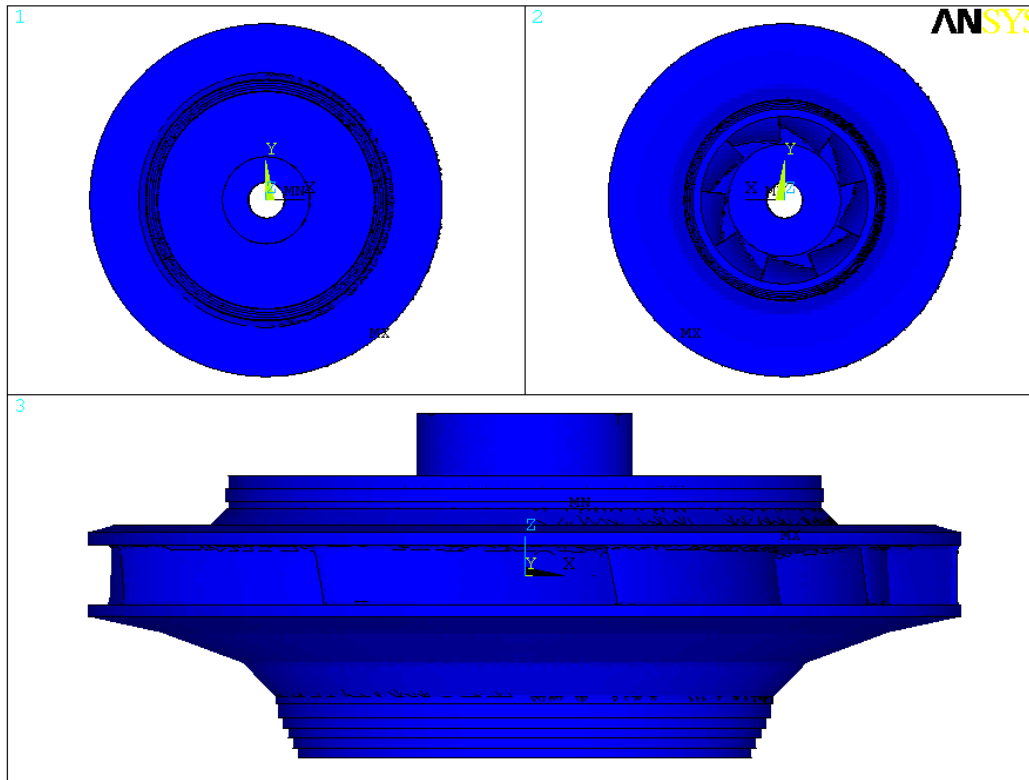
- ✓ Discovery Experiments
- ✓ Validation of Unsteady Numerical Simulations



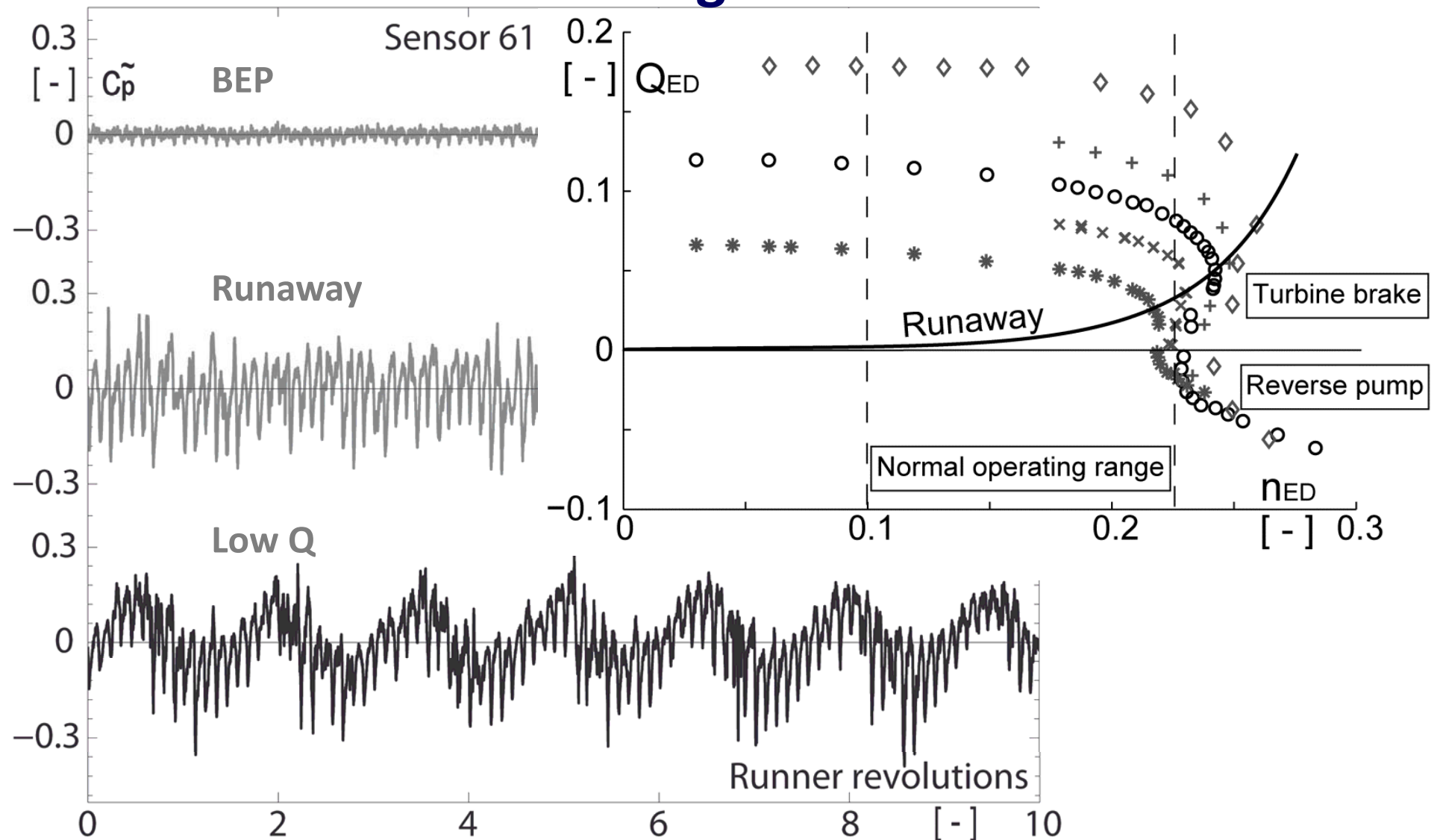
Unsteady Pressure Field
in Generating Mode
Max Discharge



Structure Dynamics Modal Analysis

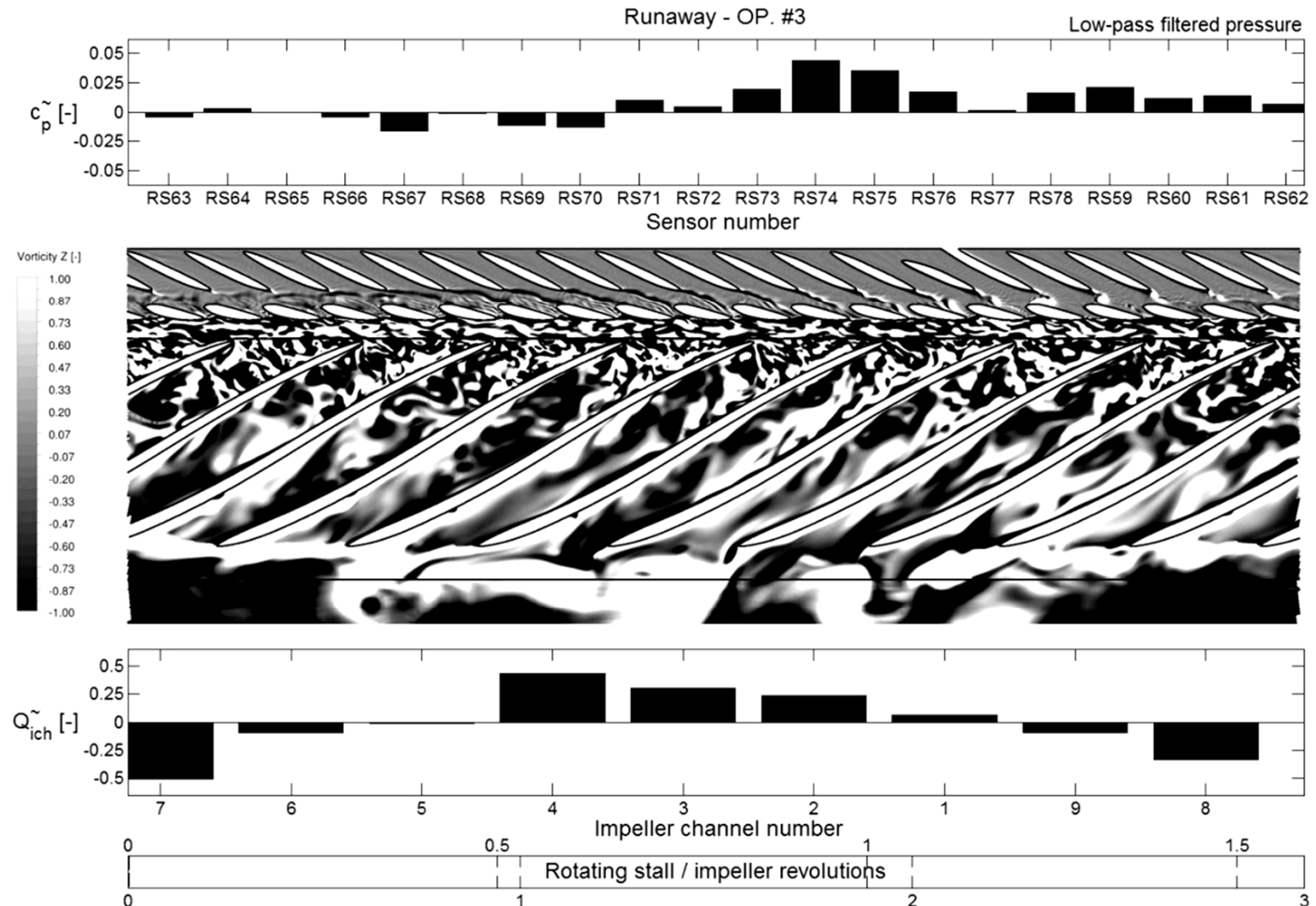


Off-Design Conditions





Rotating Stall Numerical Simulation





Conclusions

- **Pumped Storage Plants (PSP) are the key component for enabling the development and the optimum use of primary renewable energy.**
- **The development of PSP's is driven by the energy spot market, the services to the grid and public regulatory policy.**
- **The pump-turbine technology needs to be further developed to meet the market needs and to ensure and enhance the reliability, availability, maintainability and safety of the power plants. Risk analysis must be performed when utilizing existing hydraulic infrastructure.**
- **The on-going projects of PSP are an opportunity for further investigations in the field of enabling energy technology.**

Merci 😊

ALSTOM
Hydro

ANDRITZ
Hydro

VOITH




Center Industrial Diagnostics

KTI  **CTI**

swiss*electric*
research

EPFL Doctoral Thesis

- **Steven Roth:** “Fluid-Structure Coupling Effects on the Dynamic Response of Pump-Turbine Guide Vanes”, EPFL Doctoral Thesis N° 5455, 2012.
- **Vlad Hasmatuchi:** “Hydrodynamics of a Pump-Turbine Operating at Off-Design Conditions in Generating Mode”, EPFL Doctoral Thesis N° 5373, 2012.
- **Amirezza Zobeiri:** "Effect of Hydrofoil Trailing Edge Geometry on Vortex Shedding", EPFL Doctoral Thesis N° 5218, 2011.
- **Stefan Berten :** “Hydrodynamics of High Specific Power Pumps at Off-Design Operating Conditions”, EPFL Doctoral Thesis N°4642, 2010

EPFL Doctoral Theses

- **Philippe Ausoni** : " Turbulent Vortex Shedding from a Blunt Trailing Edge Hydrofoil", EPFL Doctoral Thesis N°4475, 2009.
- **Olivier Braun** : "Part load flow in radial centrifugal pumps", EPFL Doctoral Thesis N°4422, 2009.
- **Alireza Zobeiri** : "Investigations of time dependent flow phenomena in a turbine and a pump-turbine of Francis type : rotor-stator interactions and precessing vortex rope", EPFL Doctoral Thesis N°4272, 2009.
- **Christophe Nicolet** : "Hydro-acoustic modeling and numerical simulation of the unsteady operation of hydroelectric system", EPFL Doctoral Thesis N°3751, 2007.

EPFL Doctoral Theses (contd.)

- **Youcef Ait Bouziad:** "Physical modeling of leading edge cavitation: computational methodologies and application to hydraulic machinery", EPFL Doctoral Thesis N° 3353, 2006.
- **Michael Kaye:** "Cavitation monitoring of hydraulic machines by vibration analysis", EPFL Thesis N°2112, 1999
- **Roland Hirschi:** "Prediction of Partial Sheet Cavitation in Hydraulic Machines through Numerical Modeling", EPFL Thesis N° 1777. 1998
- **Francisco Pereira:** "Prediction of Cavitation Erosion: An Energetic Approach", EPFL Thesis N° 1592, 1997.
- **Mohamed Farhat:** "Contribution to Cavitation Erosion: Hydrodynamic Mechanisms and Prediction", EPFL Thesis N° 1273. 1994.