Hydropower Generation

Prof. Dr. Edson C. Bortoni, L.D.
IEEE Distinguished Lecturer

Itajubá Federal University
Secretary of Science, Technology, Industry and Commerce
of Itajubá municipality

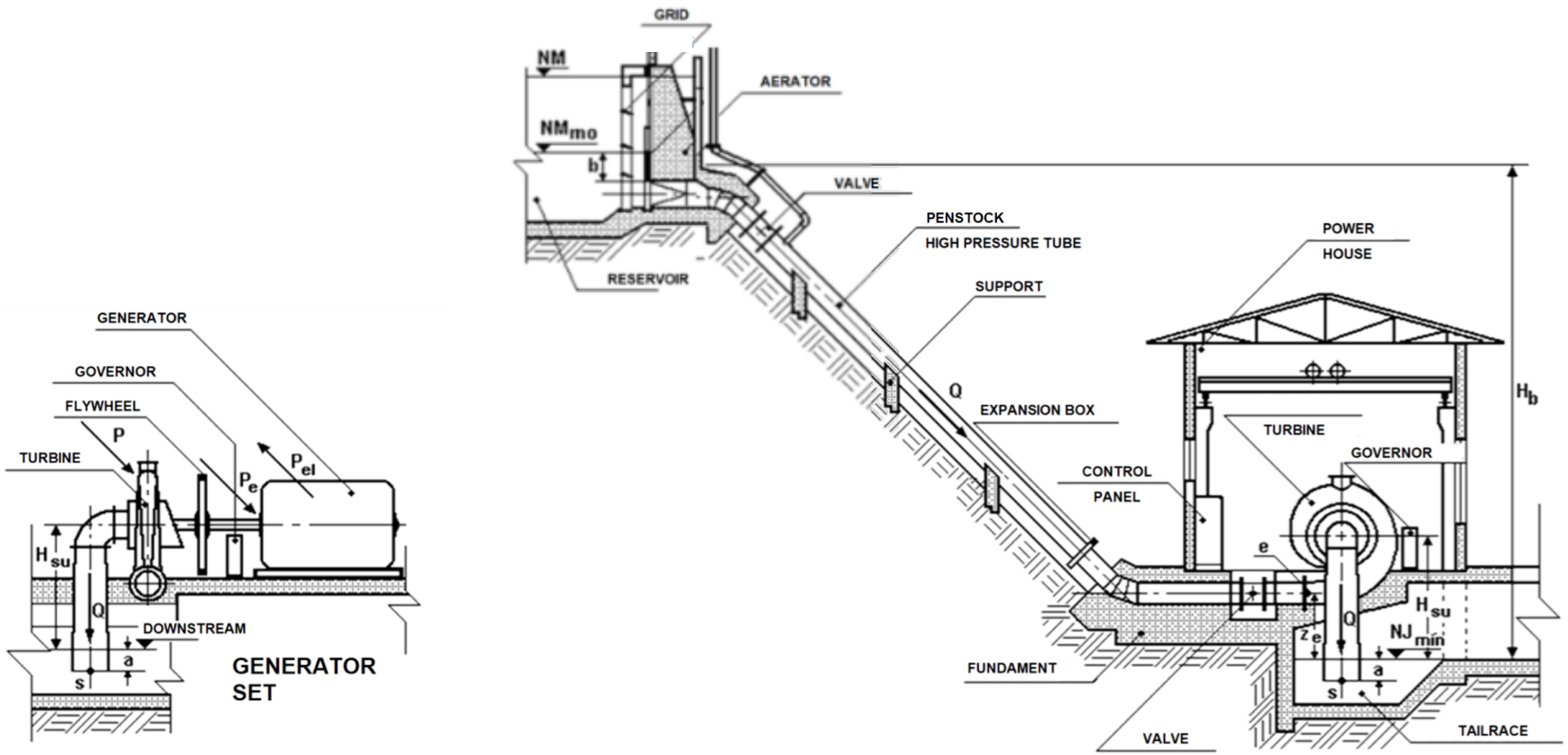
Agenda

- **Hydropower plants**
  - Common design
  - Available power
  - Hydro turbines runners
  - Hydro generators
  - Historical Costs
- **Energy transition**
  - Worldwide numbers
  - Variable-speed
  - Pumped-storage
  - Variable-speed pumped-storage

Hydropower plants

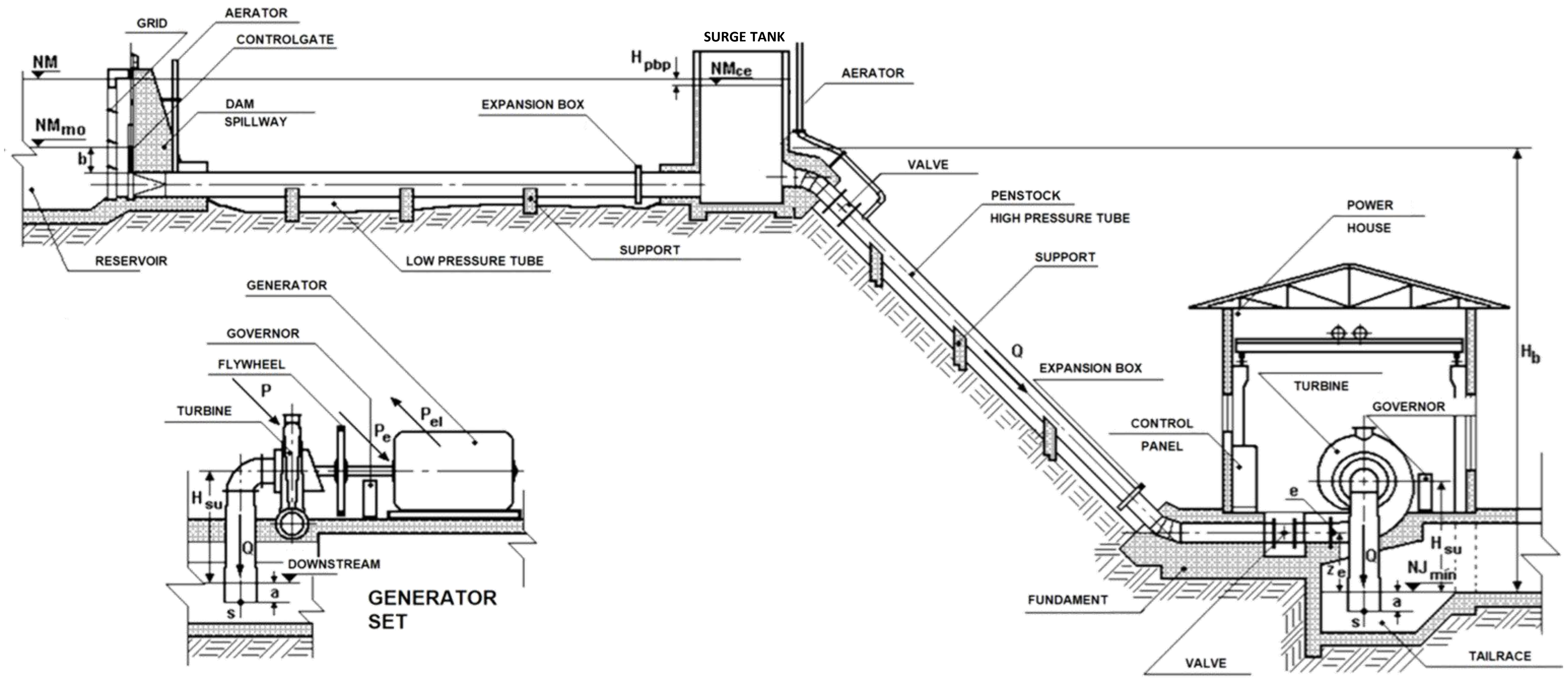
Common design

Dam hydropower plant



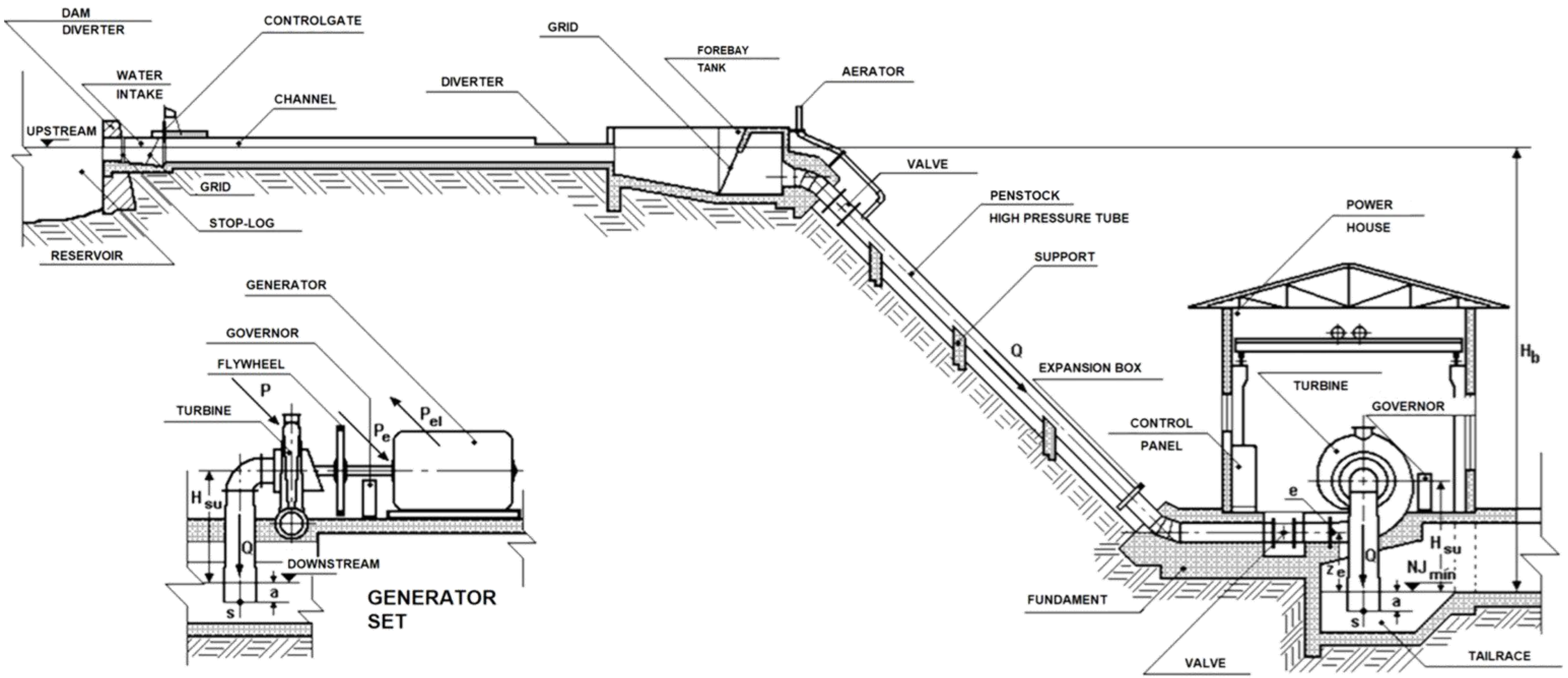
Common design

Deviation hydropower plant



Common design

Deviation hydropower plant

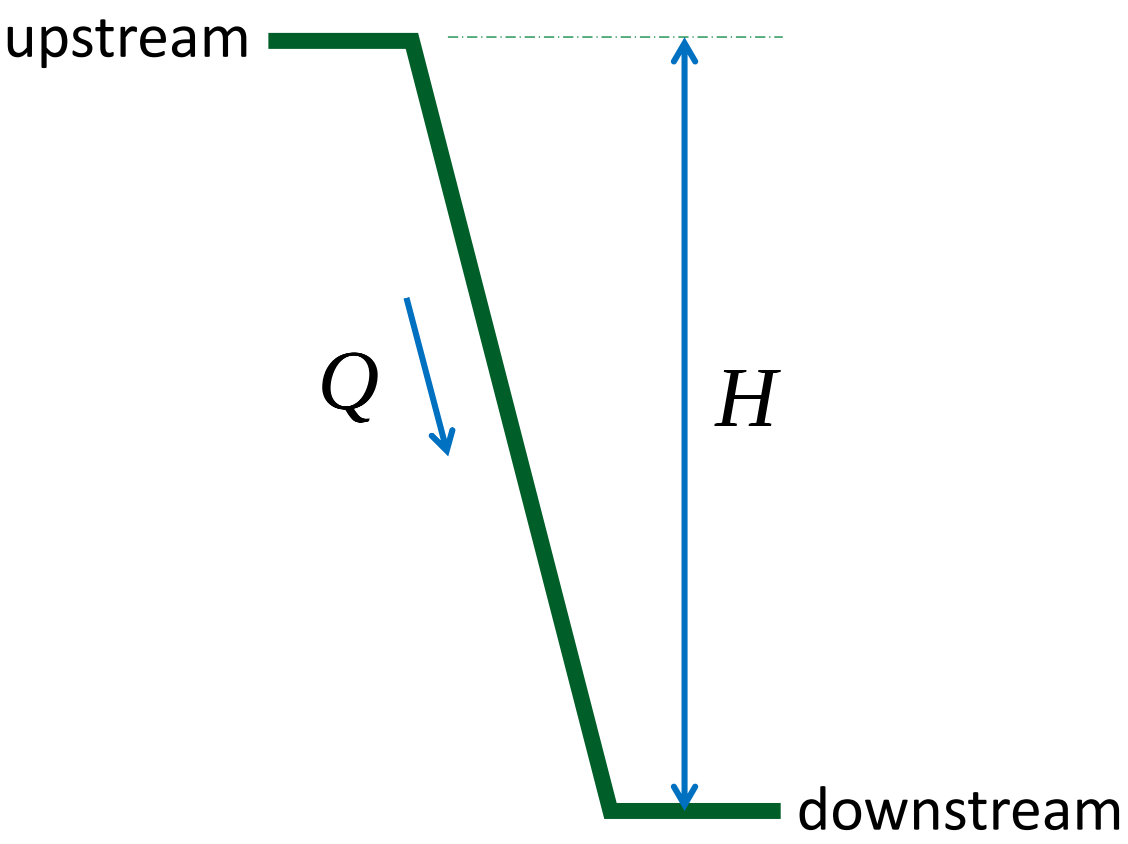


Available power

Calculation

$$P = \rho\ g\ Q\ H\ \eta_T$$

$$\eta_T = \eta_{SA}\ \eta_{TH}\ \eta_{GE}$$



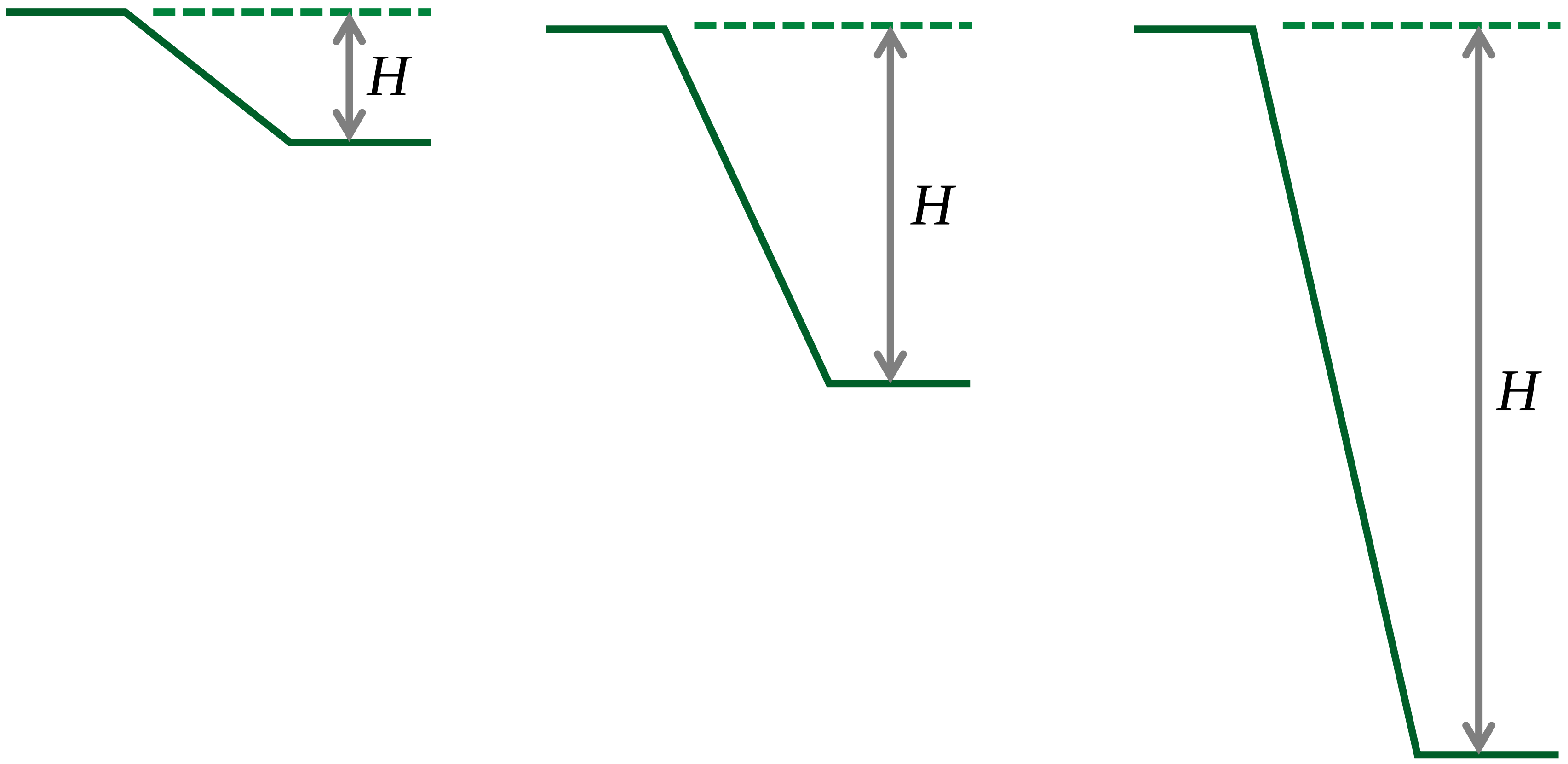
Available power

Alternatives

SIZE	FLOW	HEAD	POWER
MICRO	SMALL	SMALL	SMALL
SMALL	SMALL	AVERAGE	AVERAGE
SMALL	AVERAGE	SMALL	AVERAGE
SMALL	AVERAGE	AVERAGE	AVERAGE
LARGE	AVERAGE	HIGH	HIGH
LARGE	HIGH	AVERAGE	HIGH

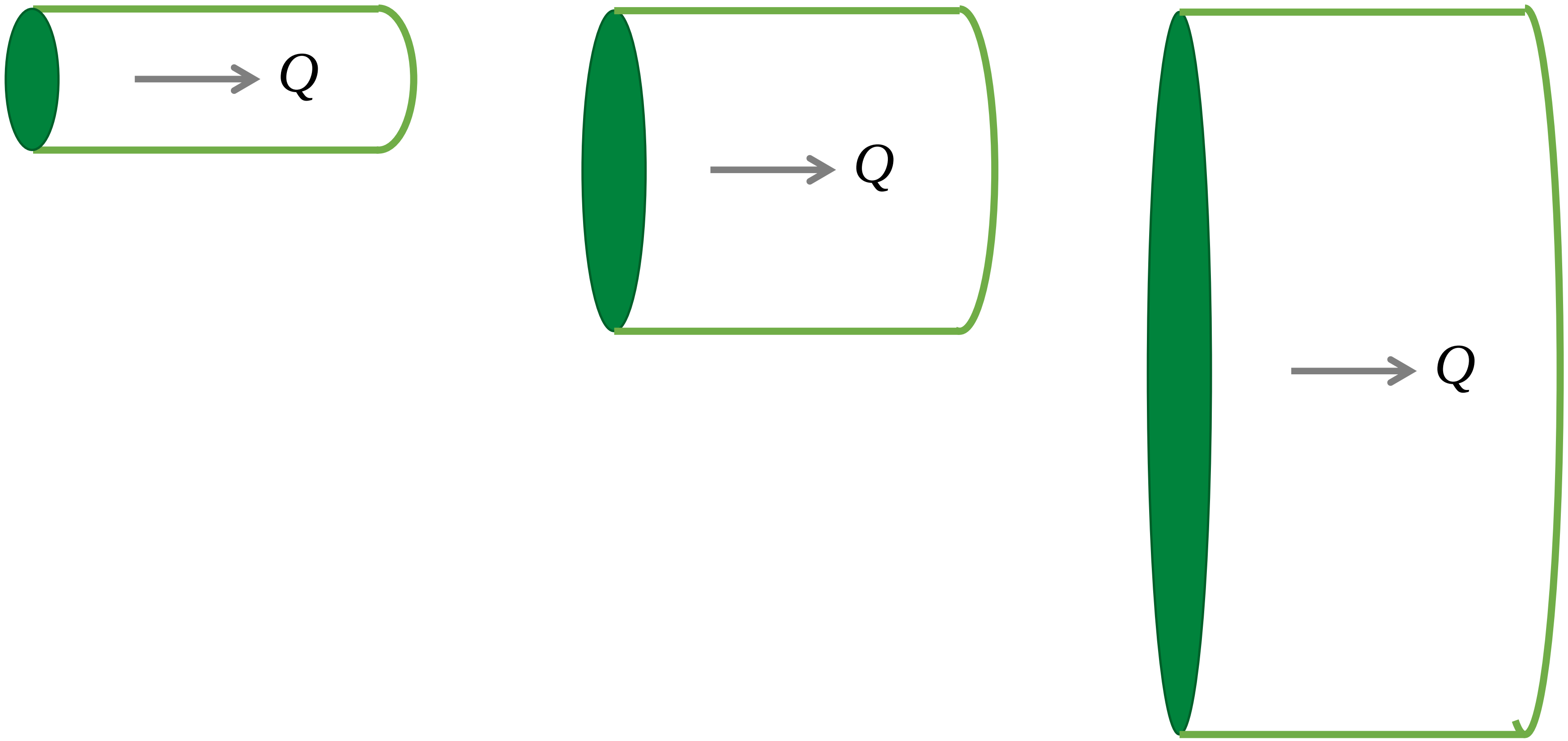
Available power

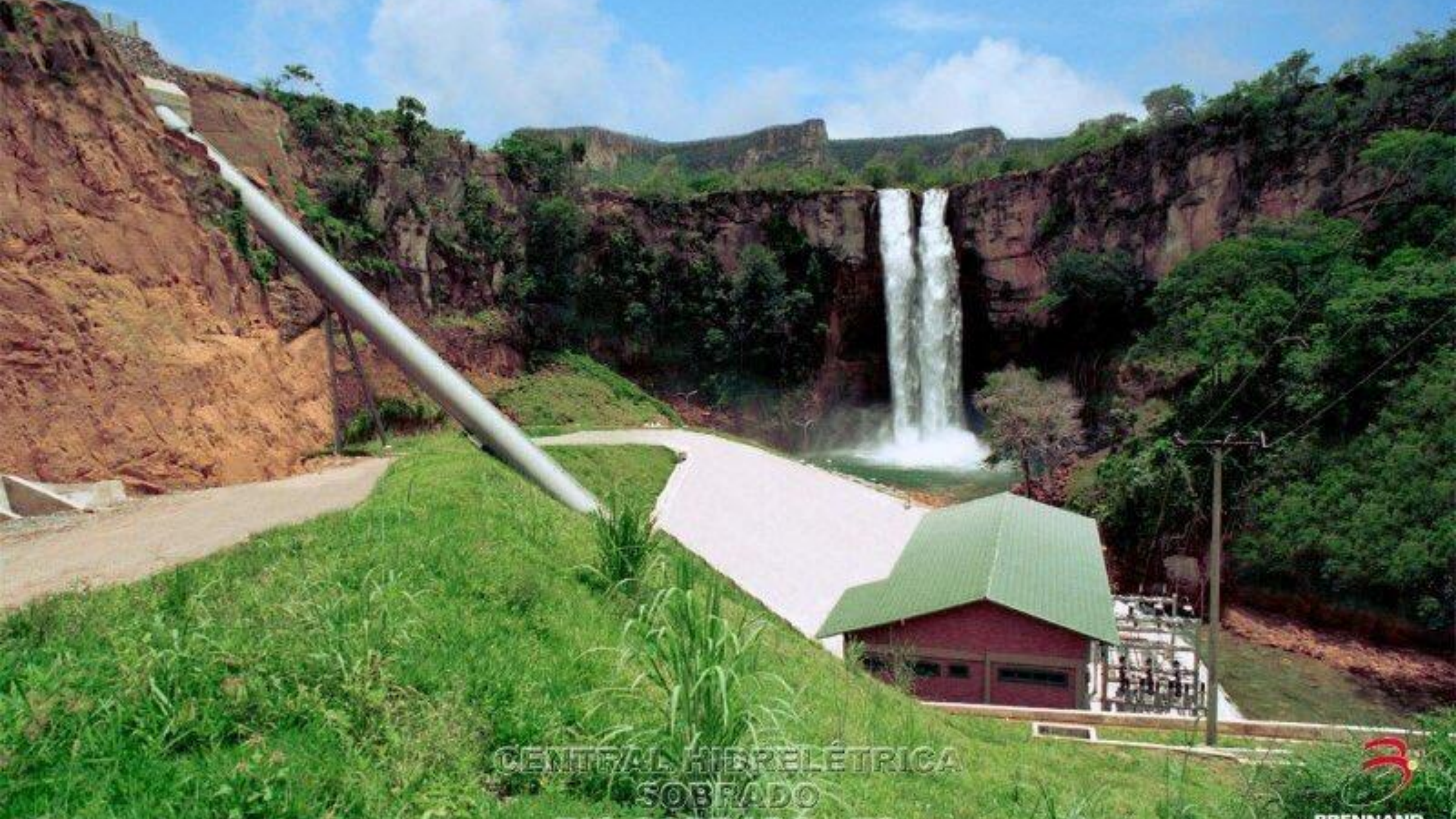
Head



Available power

Flow

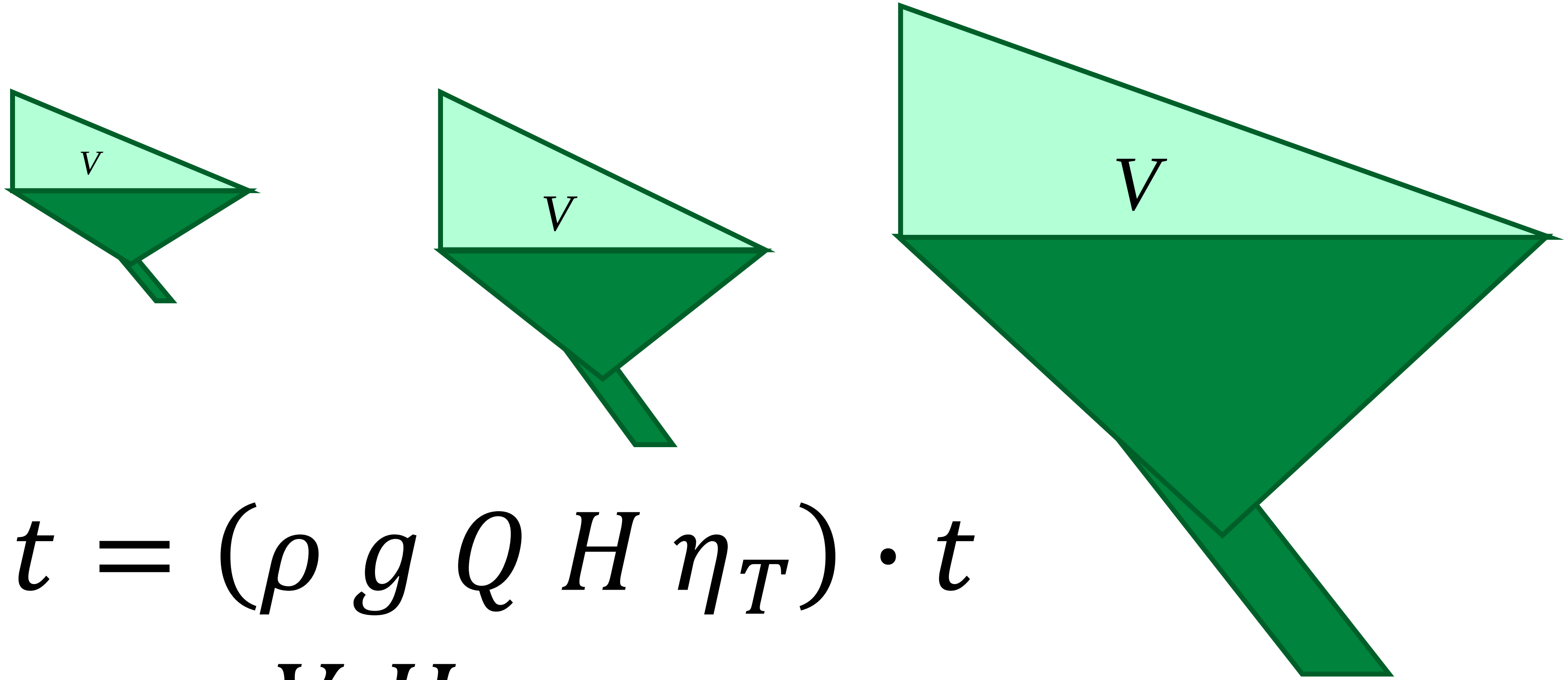



CENTRAL HIDRELÉTRICA
SOBRADO


970
MARMELEIRO-PR
F 16

Characterization

Volume

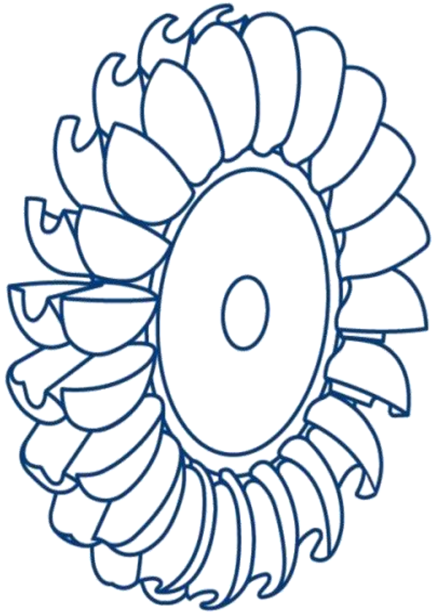


$$P \cdot t = (\rho \, g \, Q \, H \, \eta_T) \cdot t$$

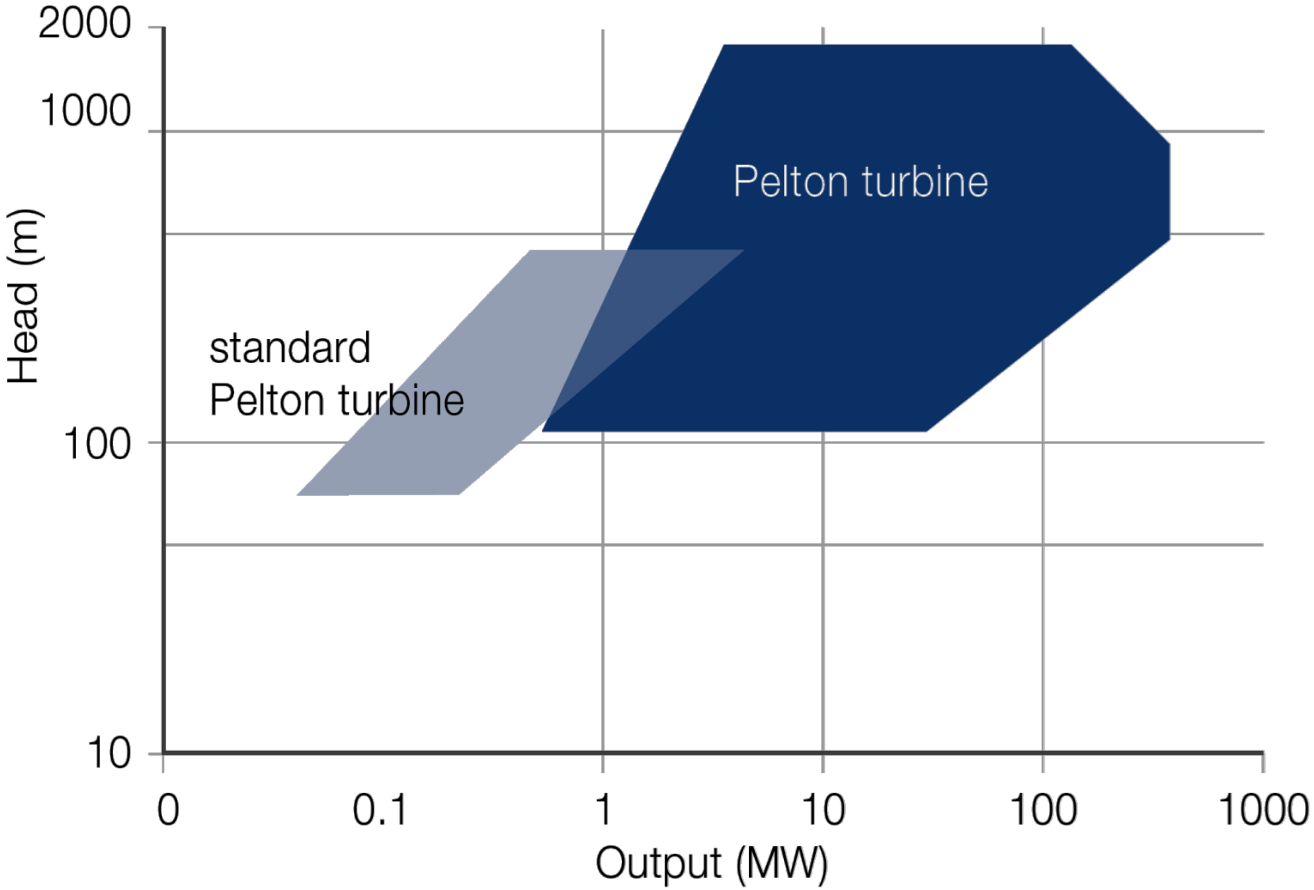
$$E = \rho \, g \, V \, H \, \eta_T$$

Hydro turbine runners

Pelton

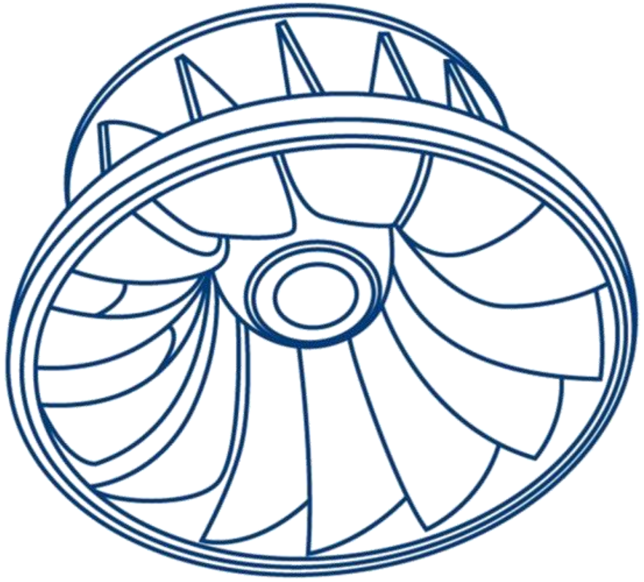


Low Flow
High Head

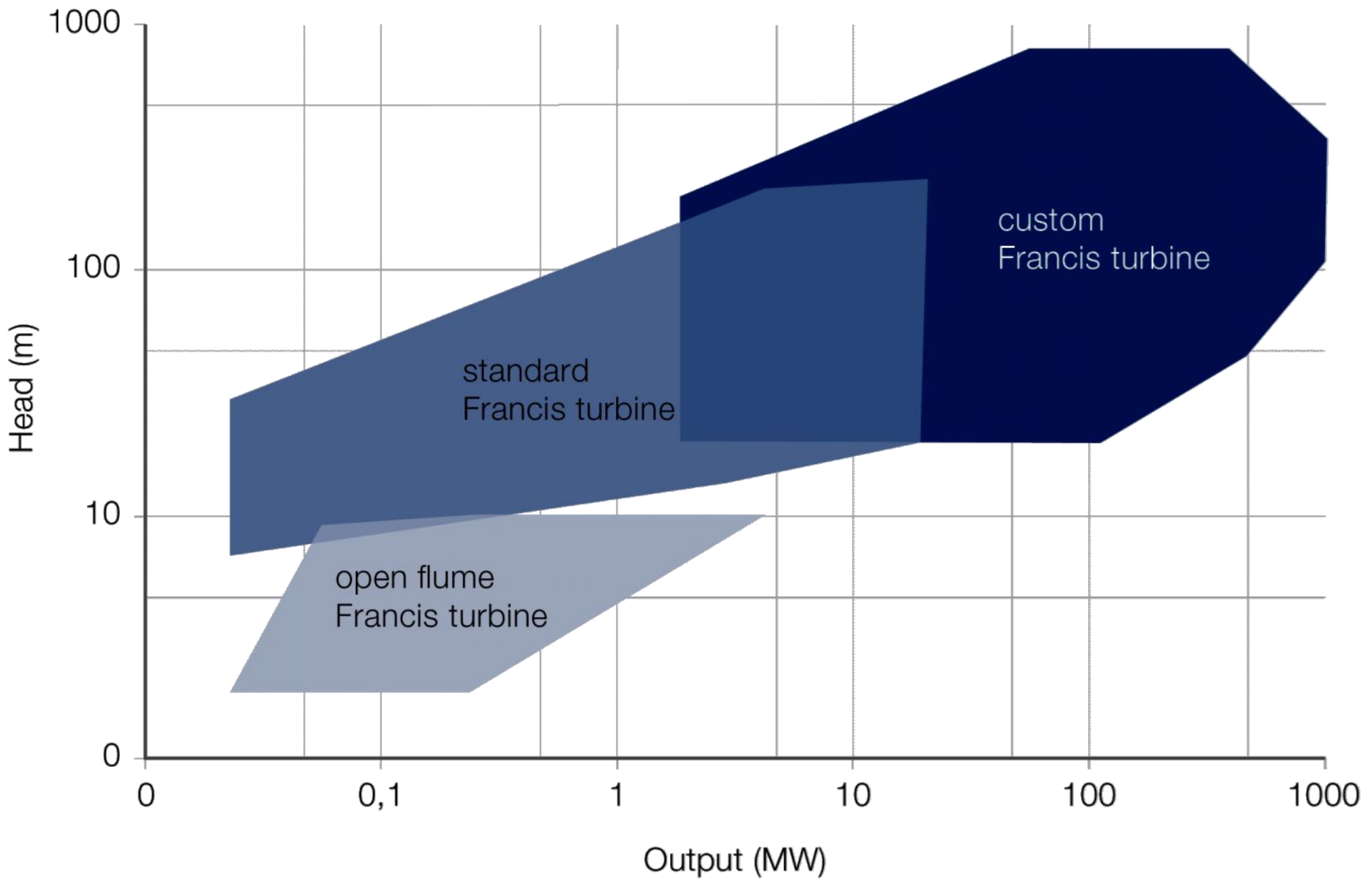


Hydro turbine runners

Francis

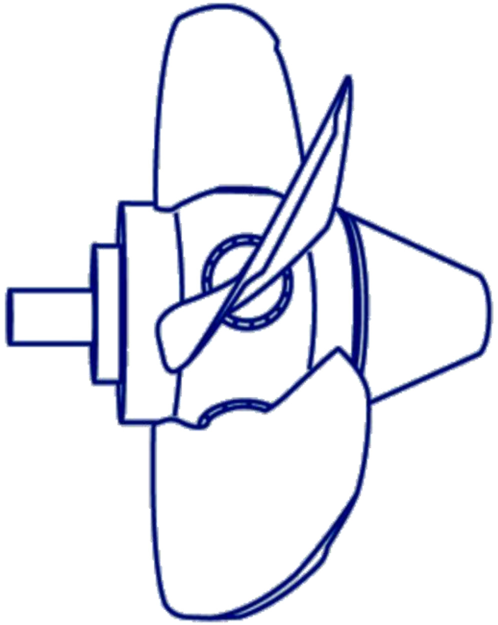


Low-High Flow
Low-High Head

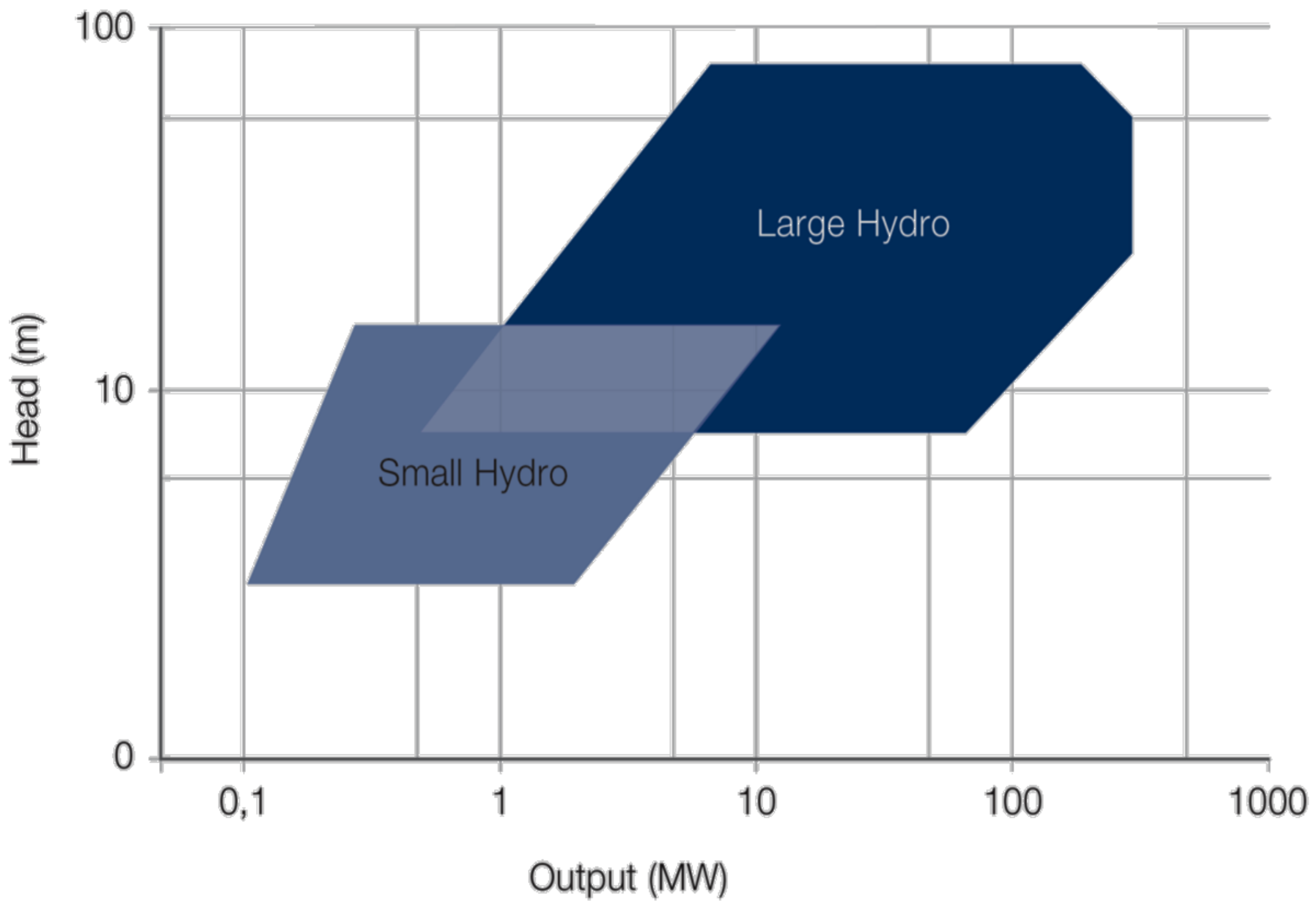


Hydro turbine runners

Kaplan



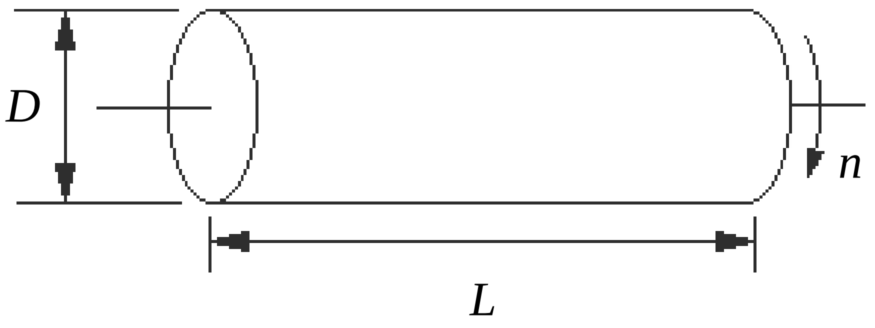
High Flow
Low Head



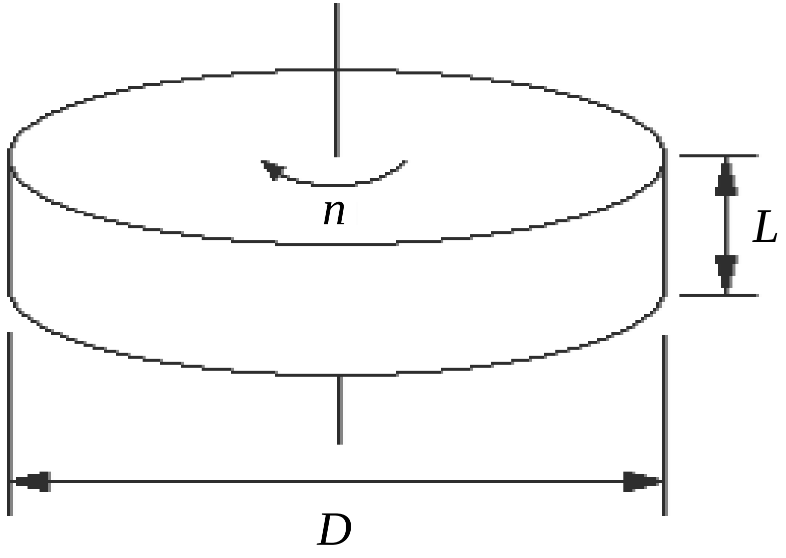
Hydro generators

Dimensional analysis

$$S = c\ D^2 L\ n$$



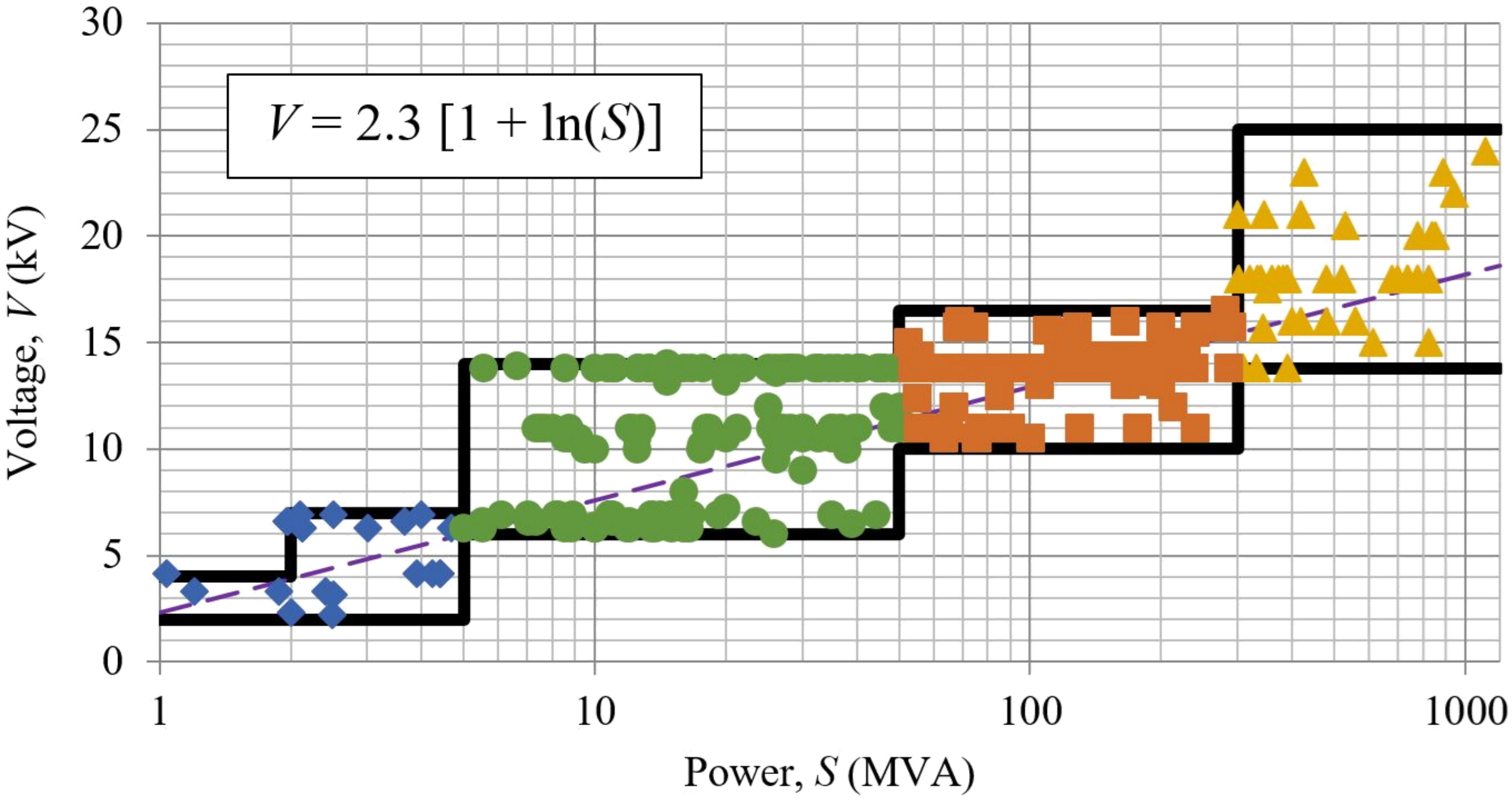
$n \geq 300$ r/min



$n < 300$ r/min

Hydro generators

Voltage vs. Power



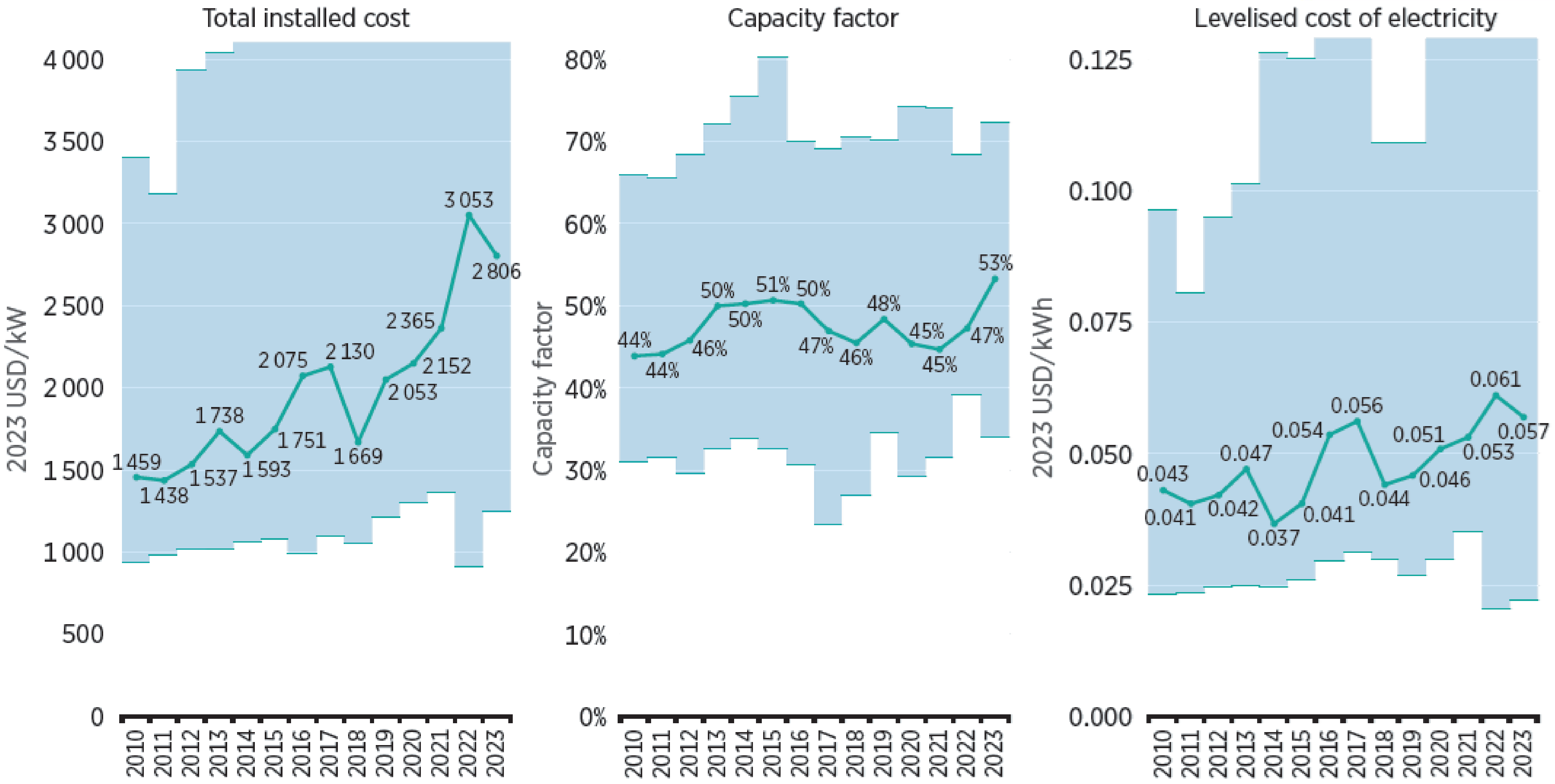
Micro hydro

Small hydro


1
2
3

Large hydro

Historic costs



Source: IRENA Renewable Cost Database

Energy transition

Worldwide numbers

Hydropower currently provides over 15% of the world's electricity.

4,185 TWh
Electricity generated from hydropower in 2023

1,416 GW
Hydropower installed capacity reached in 2023

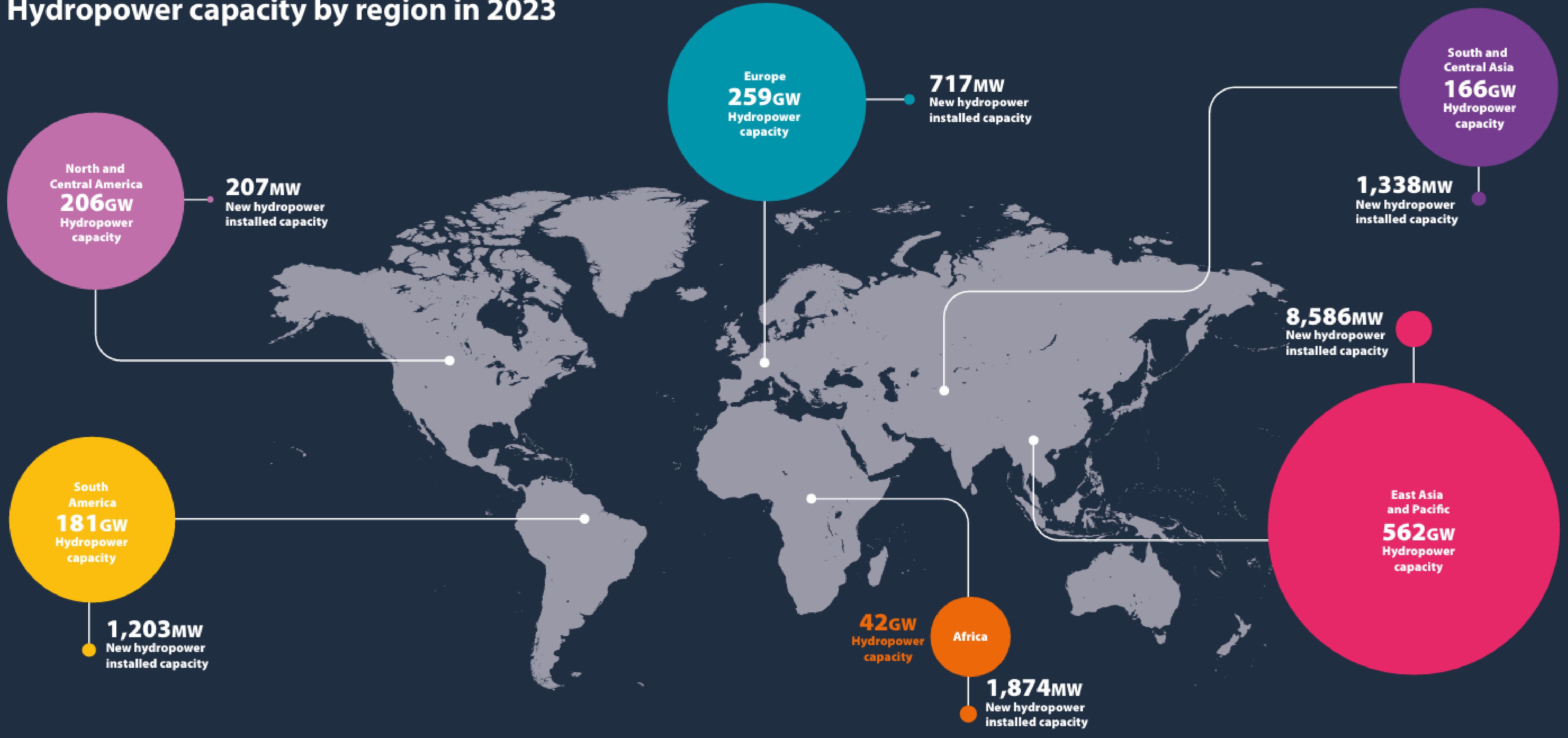
13.7 GW
Capacity added in 2023, including pumped storage

179 GW
Pumped storage installed capacity reached in 2023

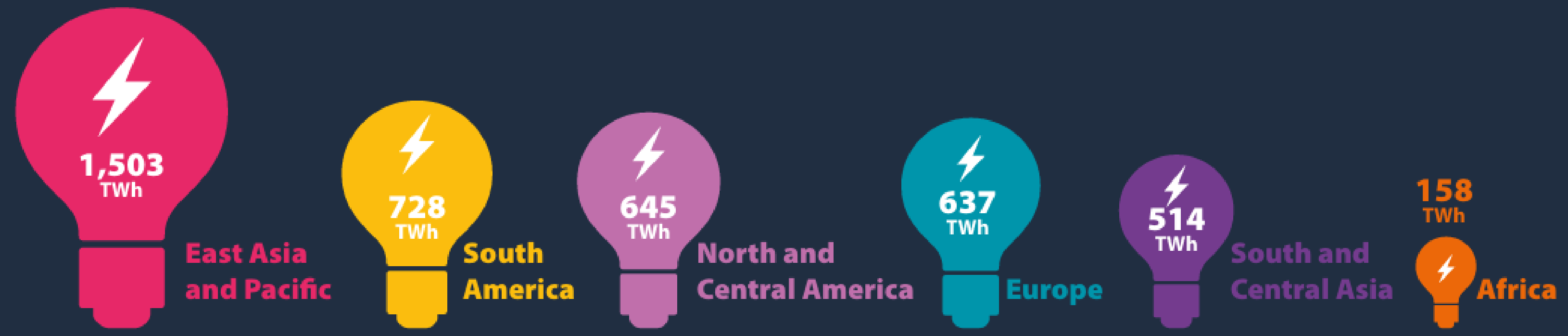
6.5 GW
Pumped storage capacity added in 2023

Source: 2023 World Hydropower Outlook (IHA)

Hydropower capacity by region in 2023



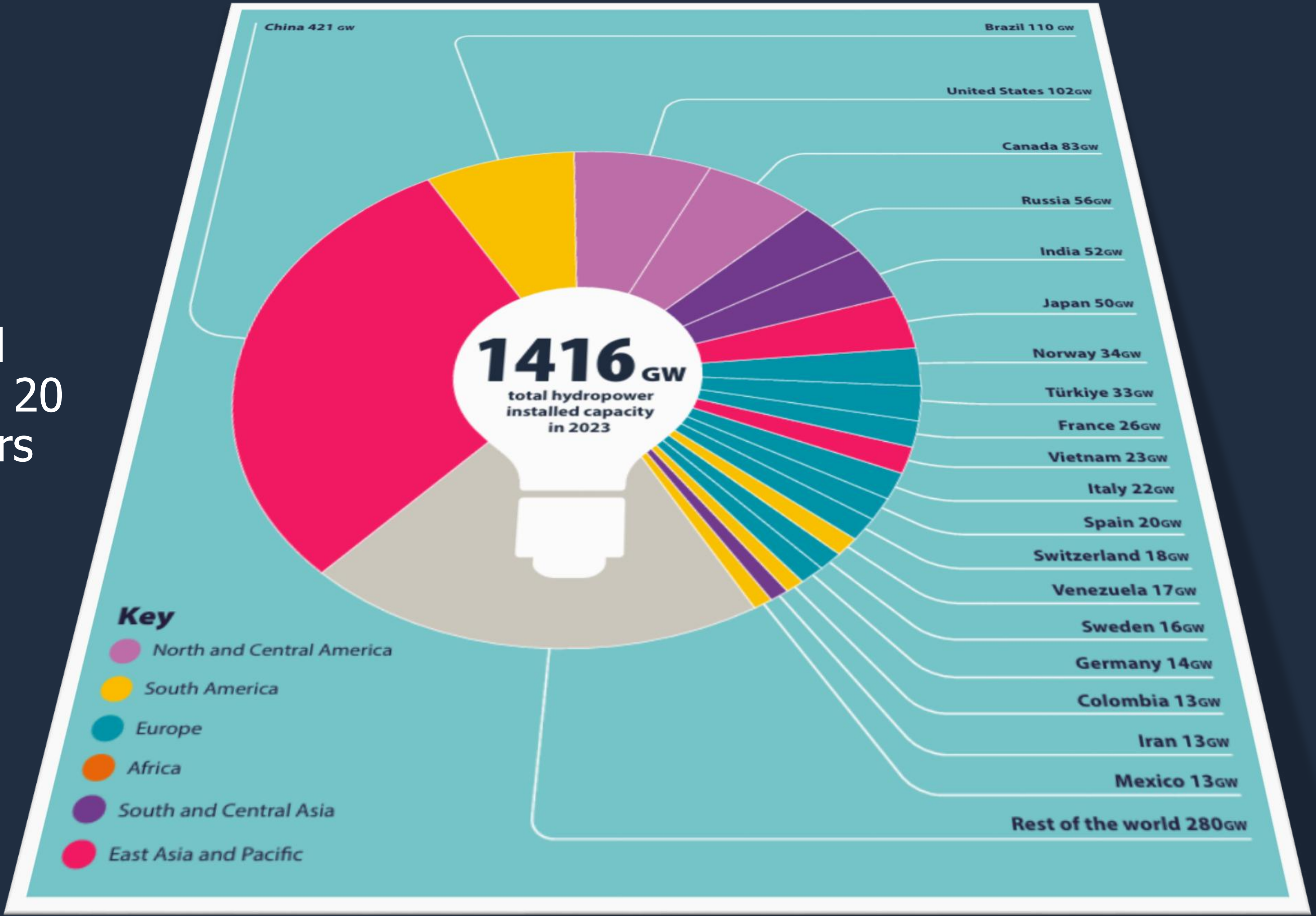
Hydropower generation by region in 2023



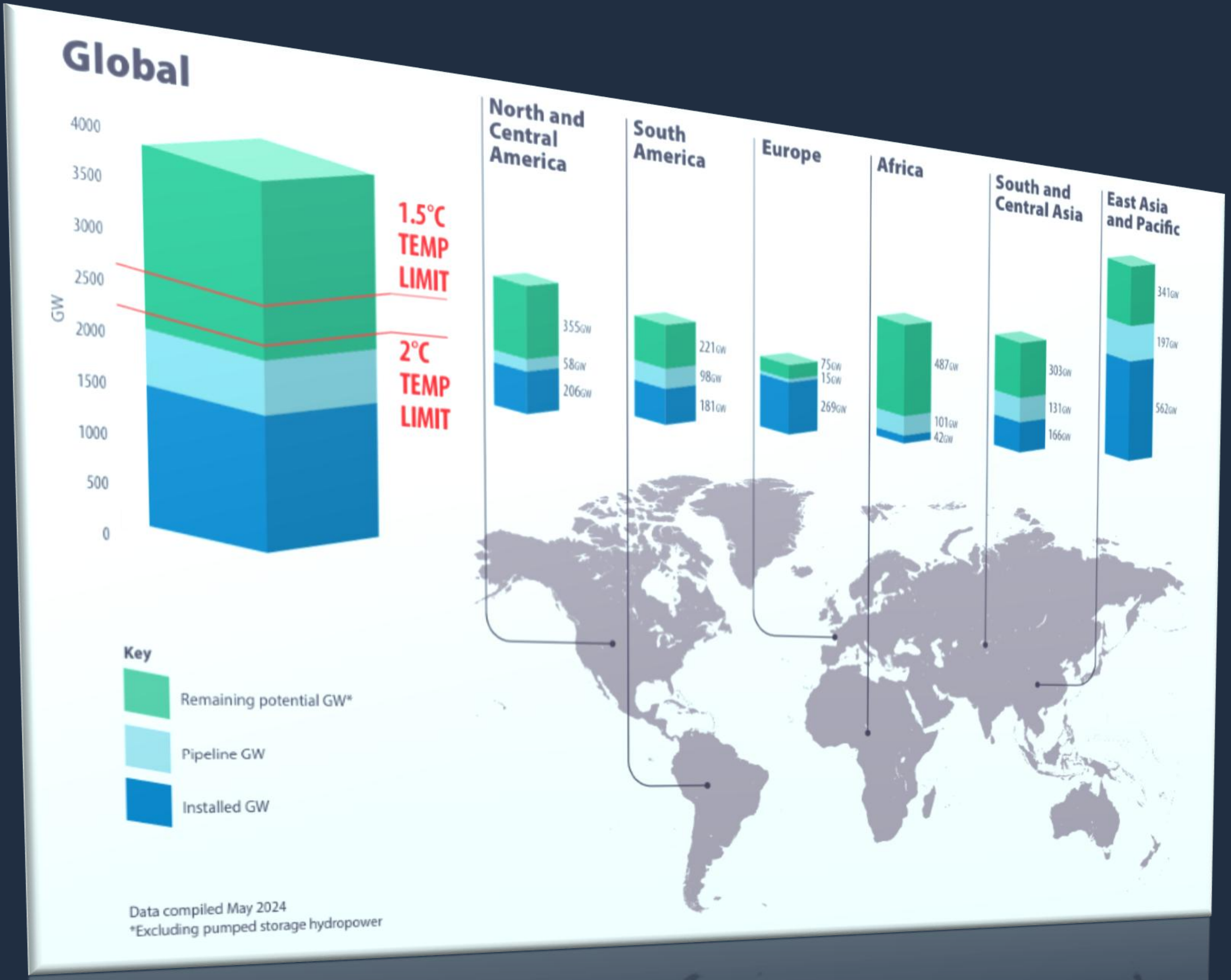
Source: 2023 World Hydropower Outlook (IHA)

HYDROPOWER CAPACITY BY COUNTRY

Hydropower installed capacity (GW) of top 20 hydropower producers and the rest of the world, including pumped.



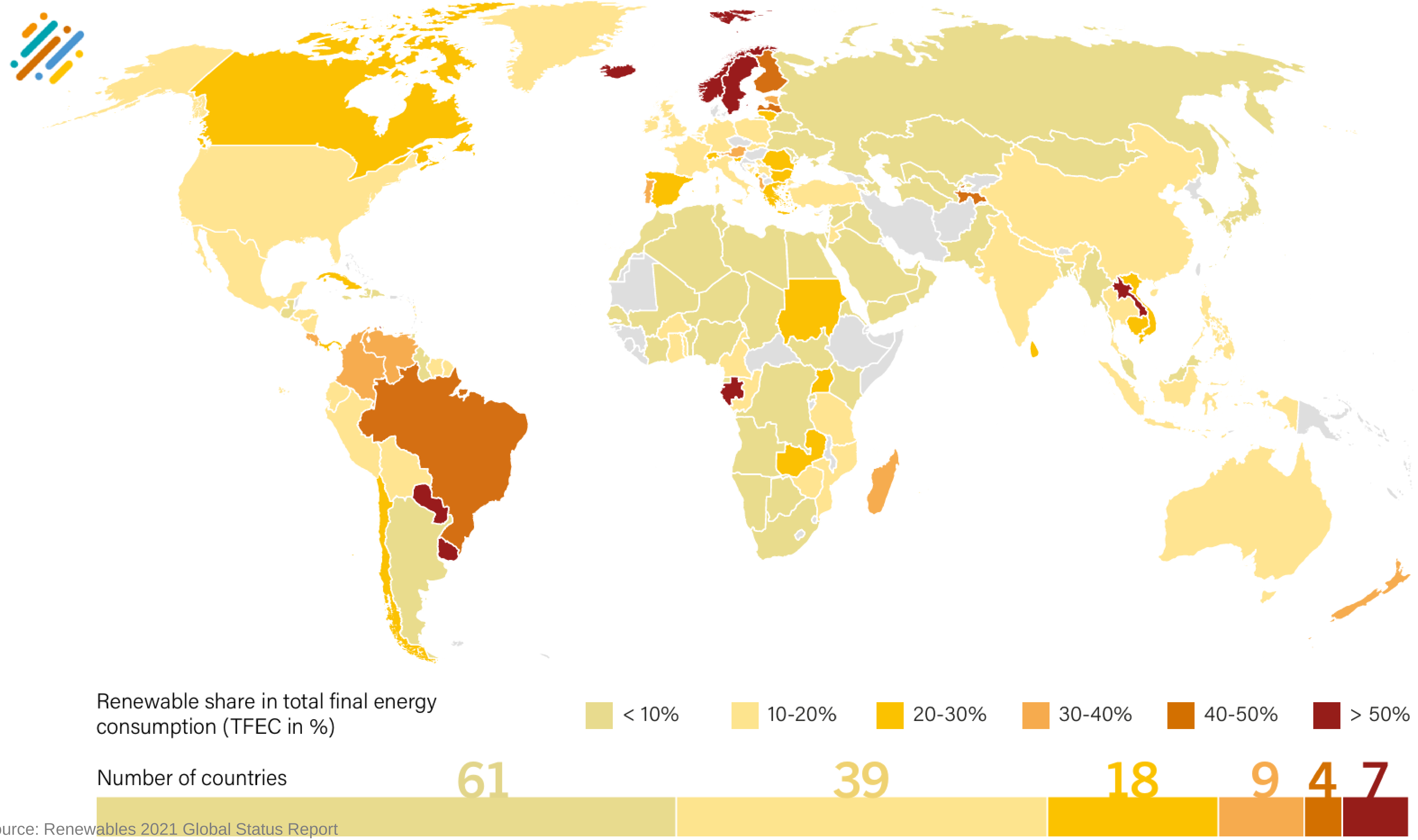
Source: 2023 World Hydropower Outlook (IHA)



Potentials

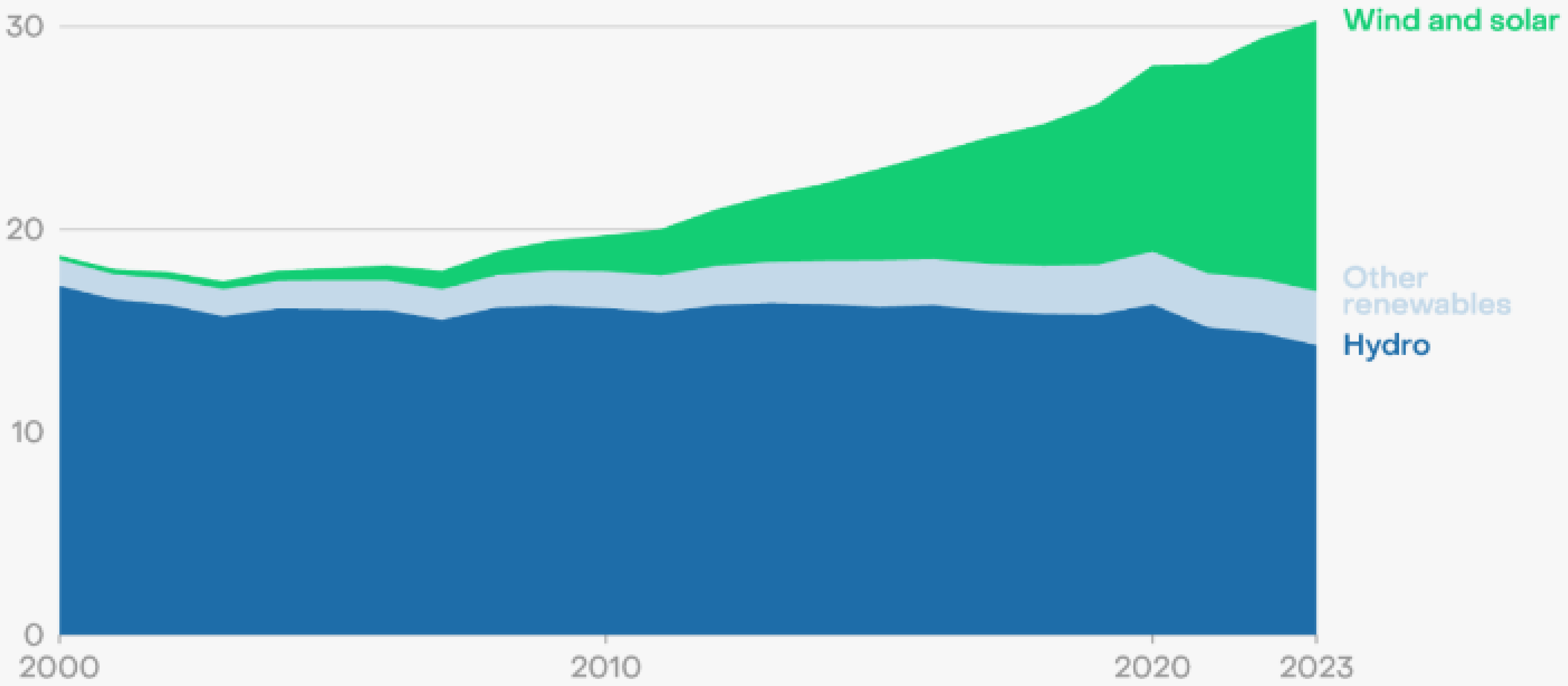
- New projects
- Uprating (repowering)
- Includes dams
- Includes run-of-river
- Excludes pumped storage

Source: 2023 World Hydropower Outlook (IHA)



Source: Renewables 2021 Global Status Report

Share of global electricity generation from renewable sources (%)



Source: Annual electricity data, Ember

EMBER

	Total installed costs (2023 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2023 USD/kWh)		
	2010	2023	Percent change	2010	2023	Percent change	2010	2023	Percent change
Bioenergy	3 010	2 730	-9%	72	72	0%	0.084	0.072	-14%
Geothermal	3 011	4 589	52%	87	82	-6%	0.054	0.071	31%
Hydropower	1 459	2 806	92%	44	53	20%	0.043	0.057	33%
Solar PV	5 310	758	-86%	14	16	14%	0.460	0.044	-90%
CSP	10 453	6 589	-37%	30	55	83%	0.393	0.117	-70%
Onshore wind	2 272	1 160	-49%	27	36	33%	0.111	0.033	-70%
Offshore wind	5 409	2 800	-48%	38	41	8%	0.203	0.075	-63%

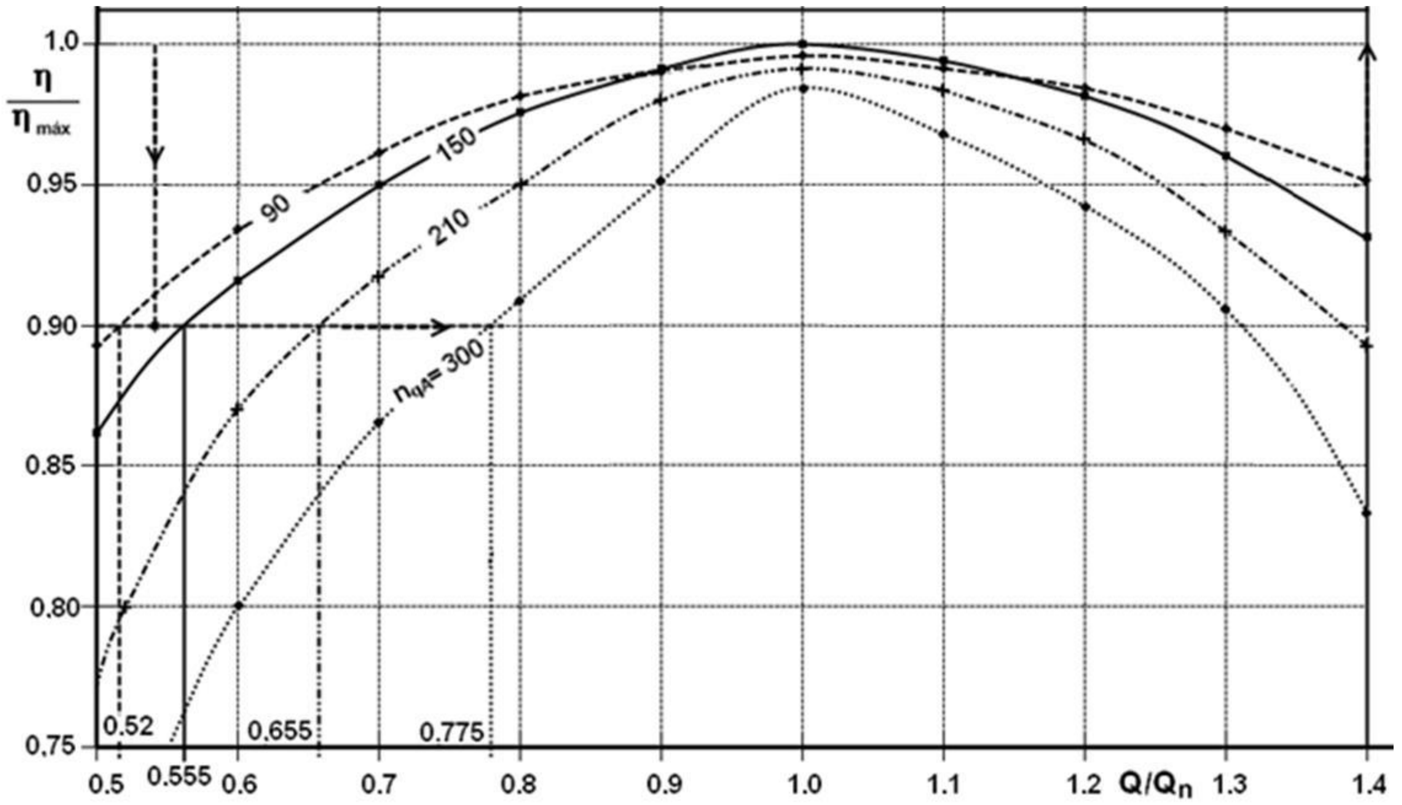
Source: IRENA Renewable Cost Database

Variable-speed

Variable-speed

Specific-speed

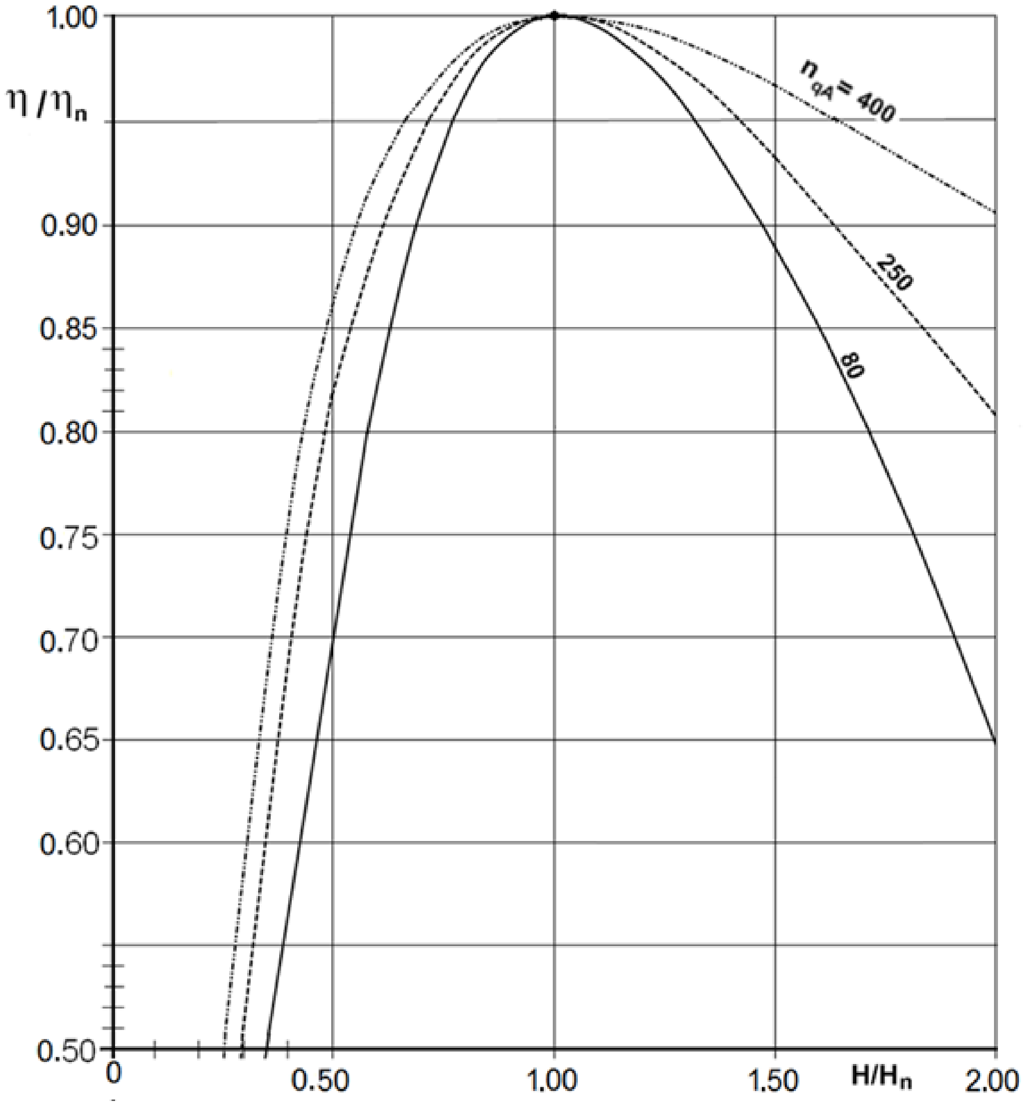
$$n_{qA} = 3\,n\,\frac{Q^{0.50}}{H^{0.75}}$$



Variable-speed

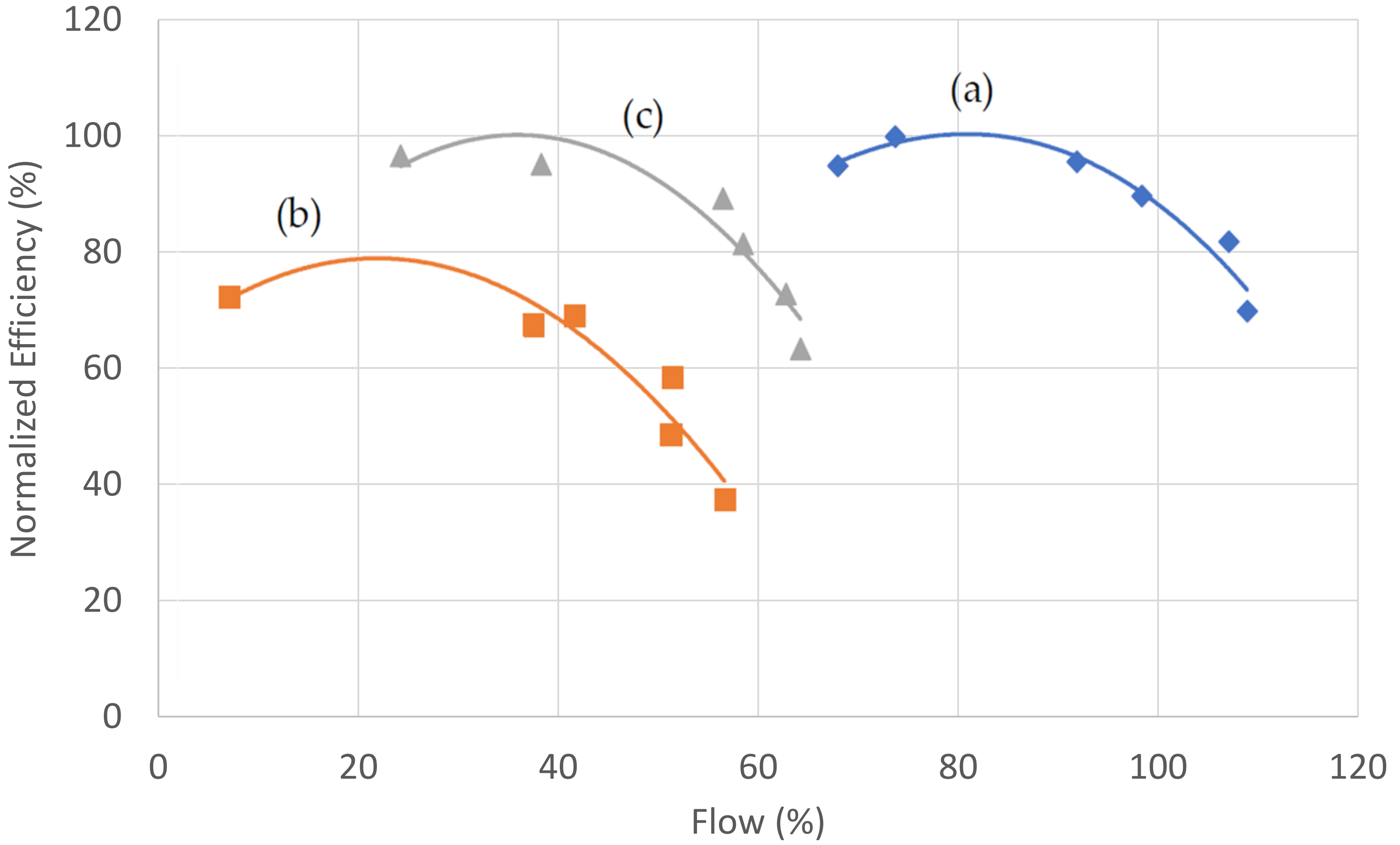
Specific-speed

$$n_{qA} = 3\,n\,\frac{Q^{0.50}}{H^{0.75}}$$



Variable-speed

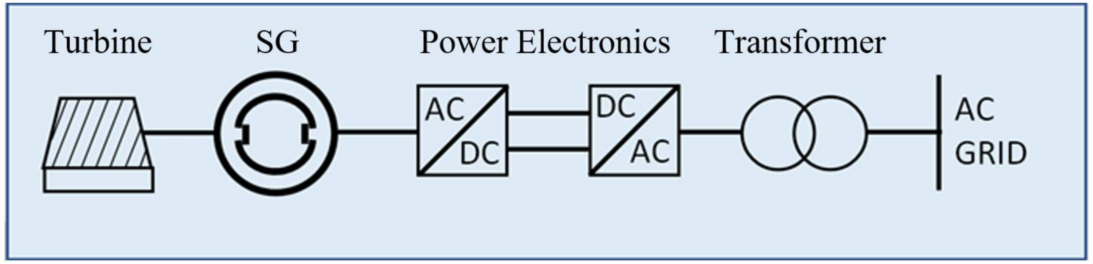
Efficiency benefits

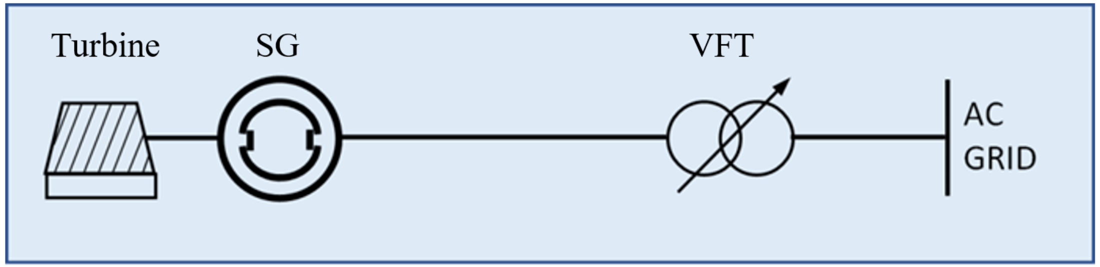


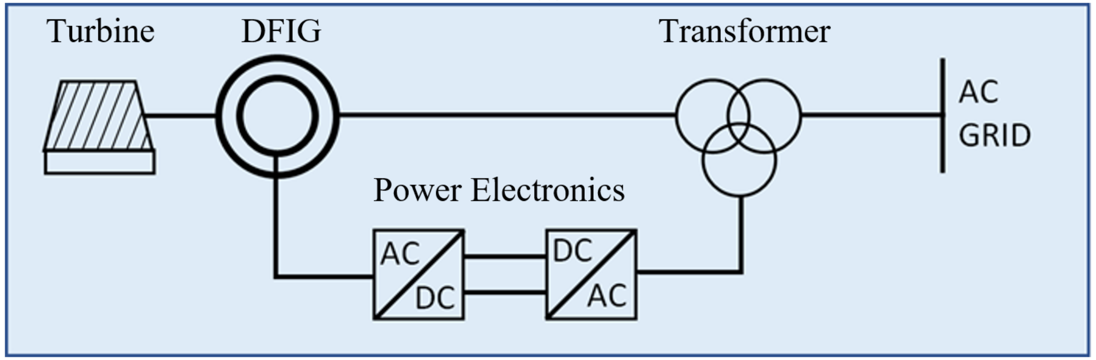
a) Rated head, rated speed
b) Reduced head, rated speed
c) Reduced head, reduced speed

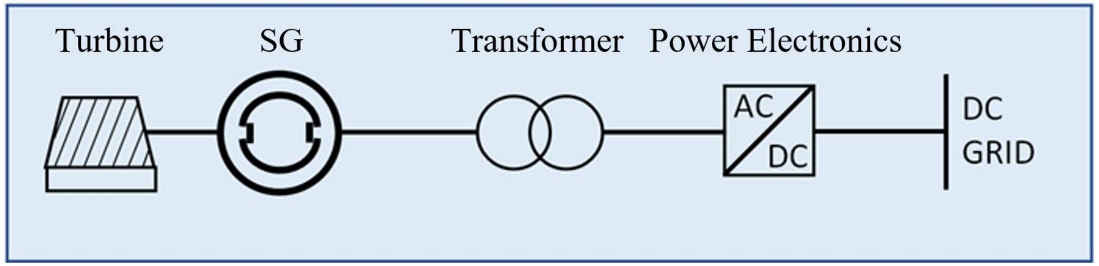
Variable-speed

Connection to the power system





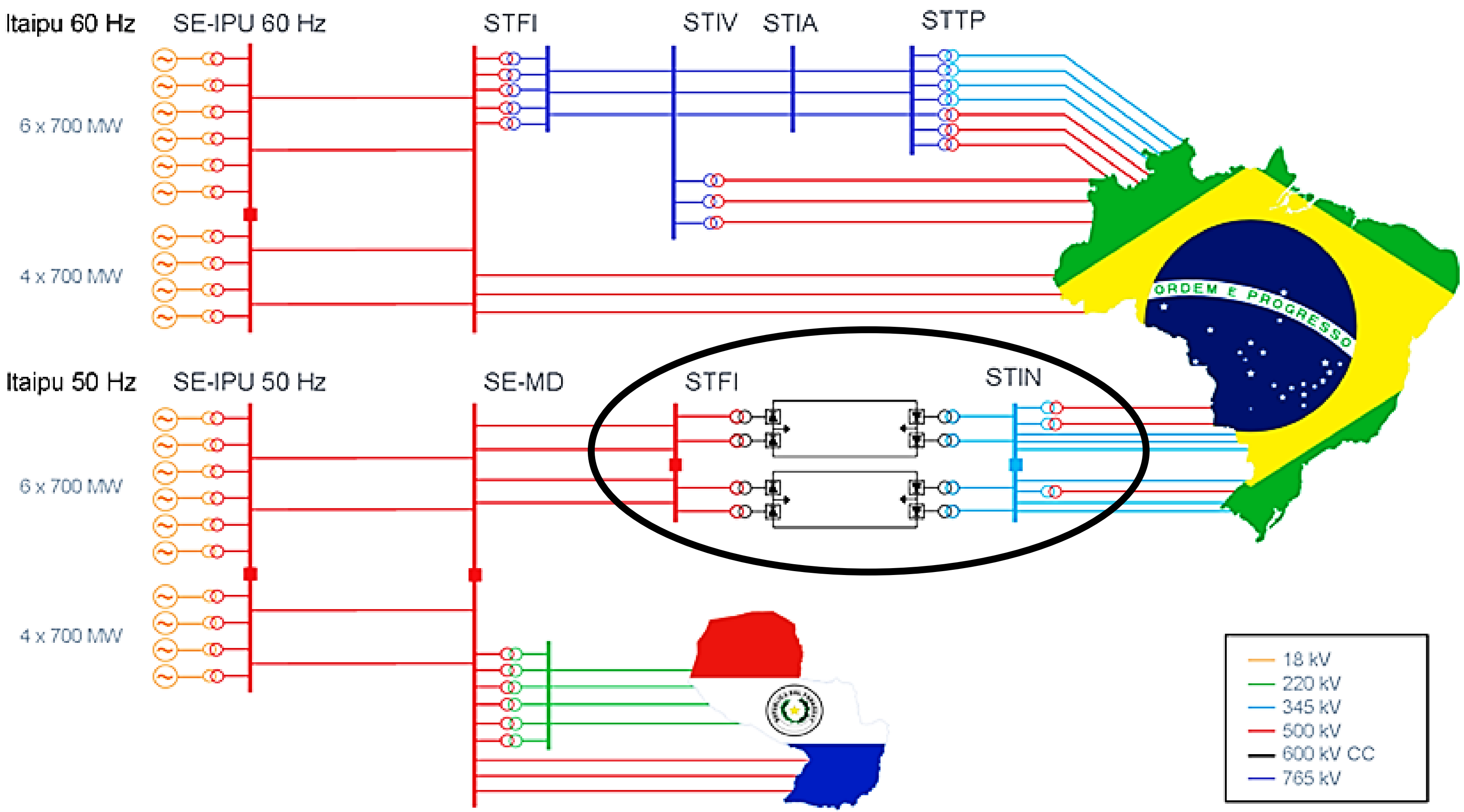




$$f = \frac{p\,n}{60}$$

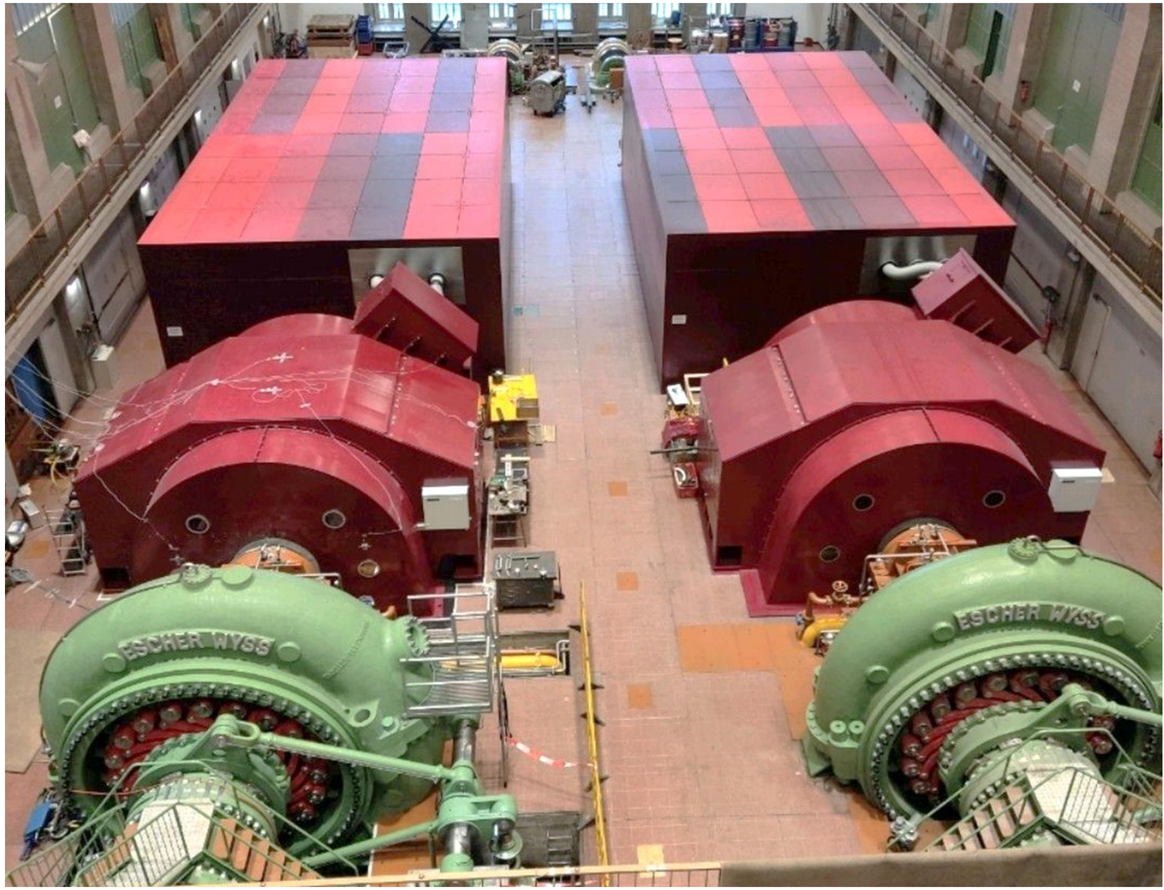
Variable-speed

Connection using a HVDC



Variable-speed

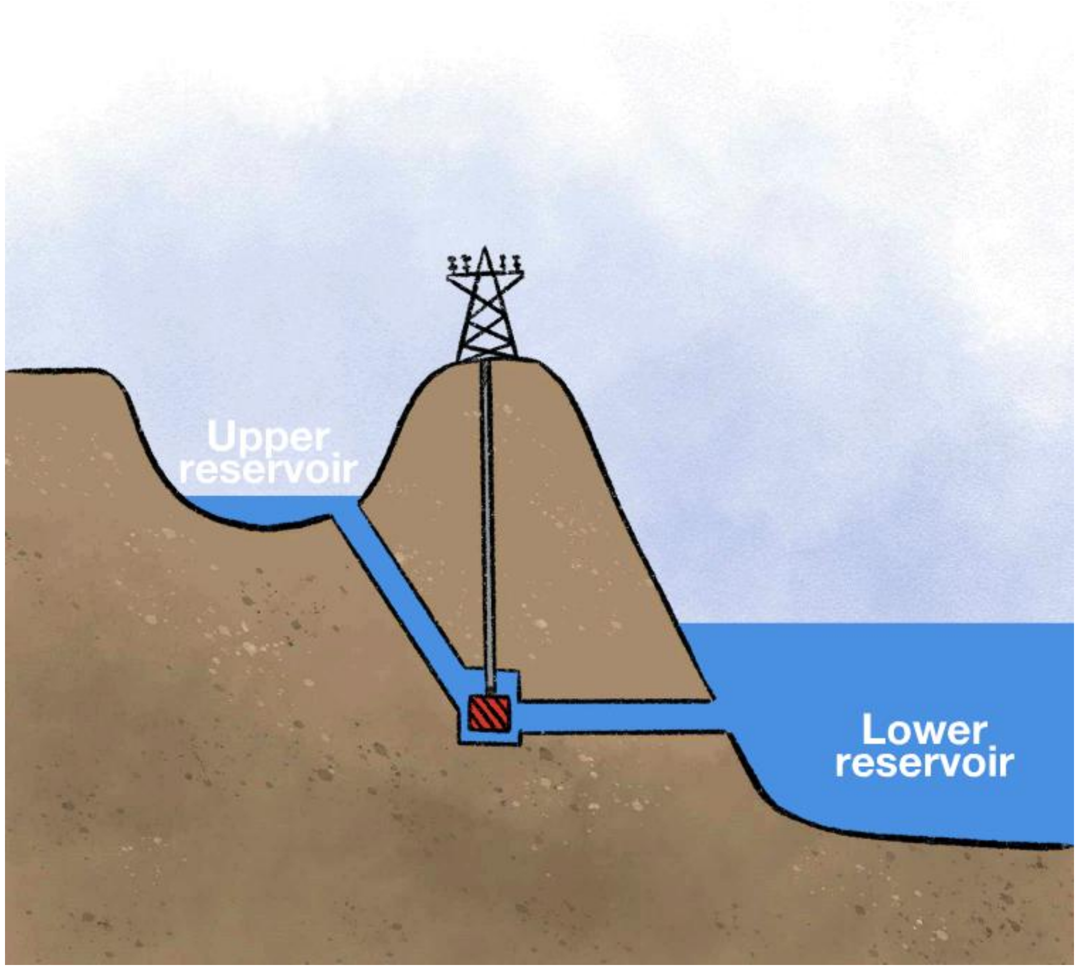
Connection using a full-converter



Pumped-storage

Pumped-Storage

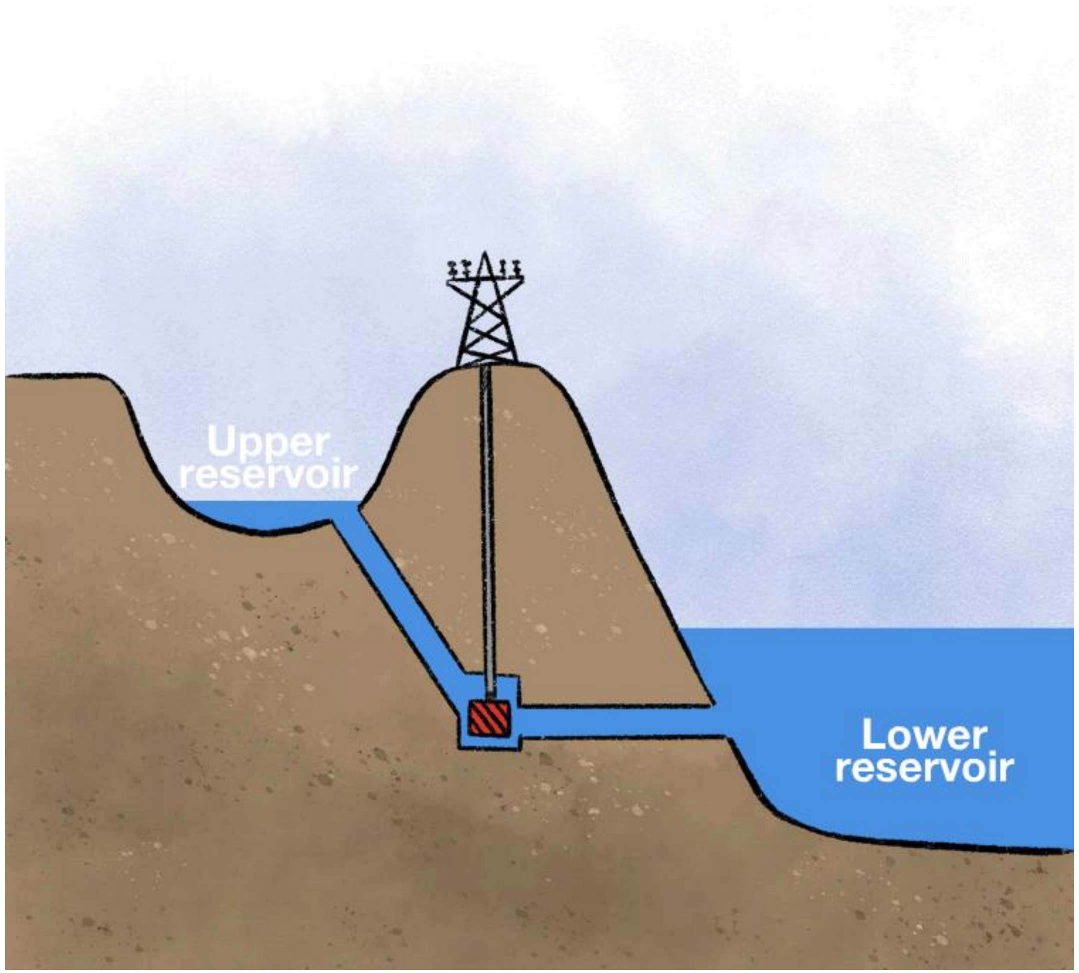
Advantages



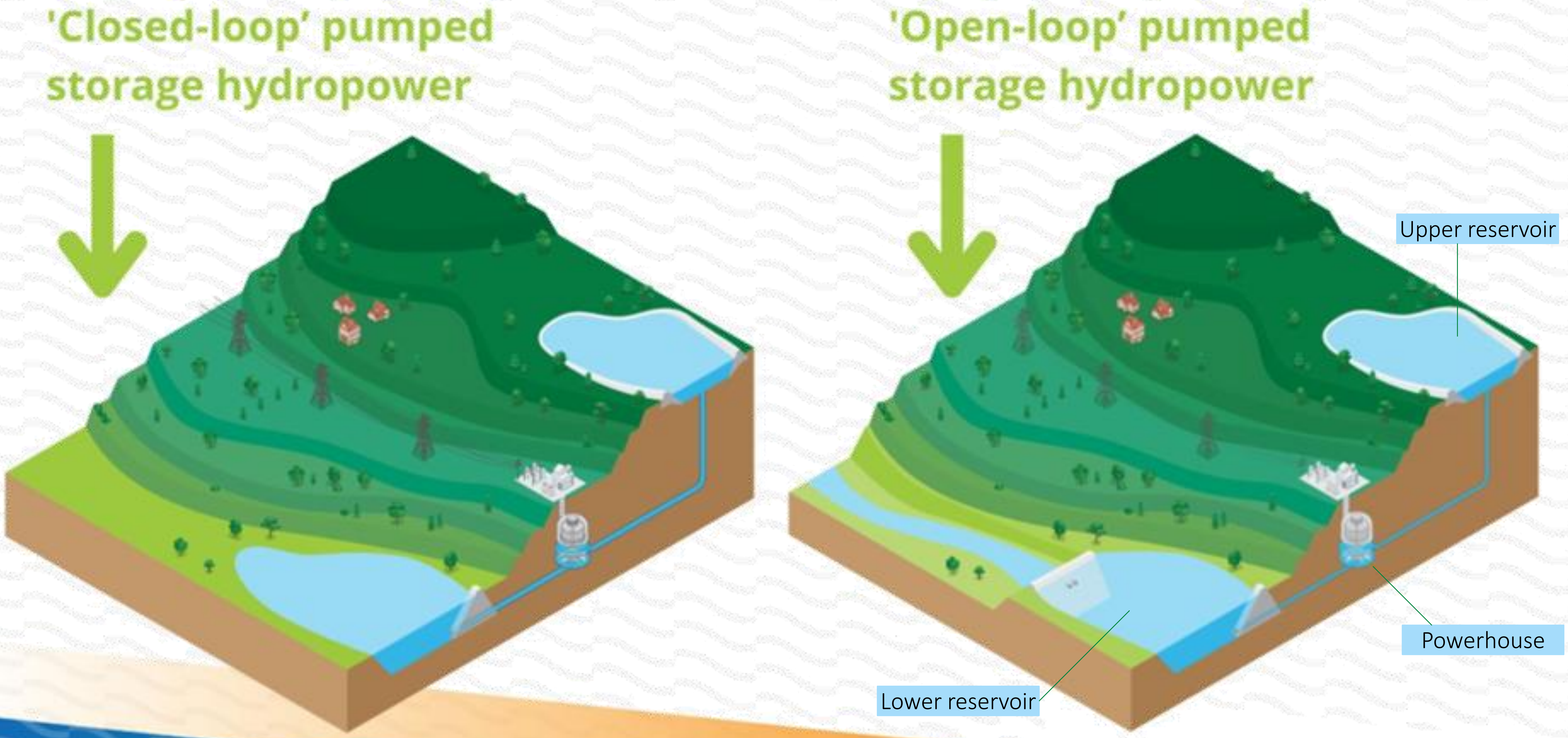
- Established technology with high technical maturity and extensive operational experience;
- Very low self-discharge;
- High round-trip efficiency;
- Large volume storage;
- Long storage periods;
- Good start/stop flexibility;
- Long life and low costs of storage.

Pumped-Storage

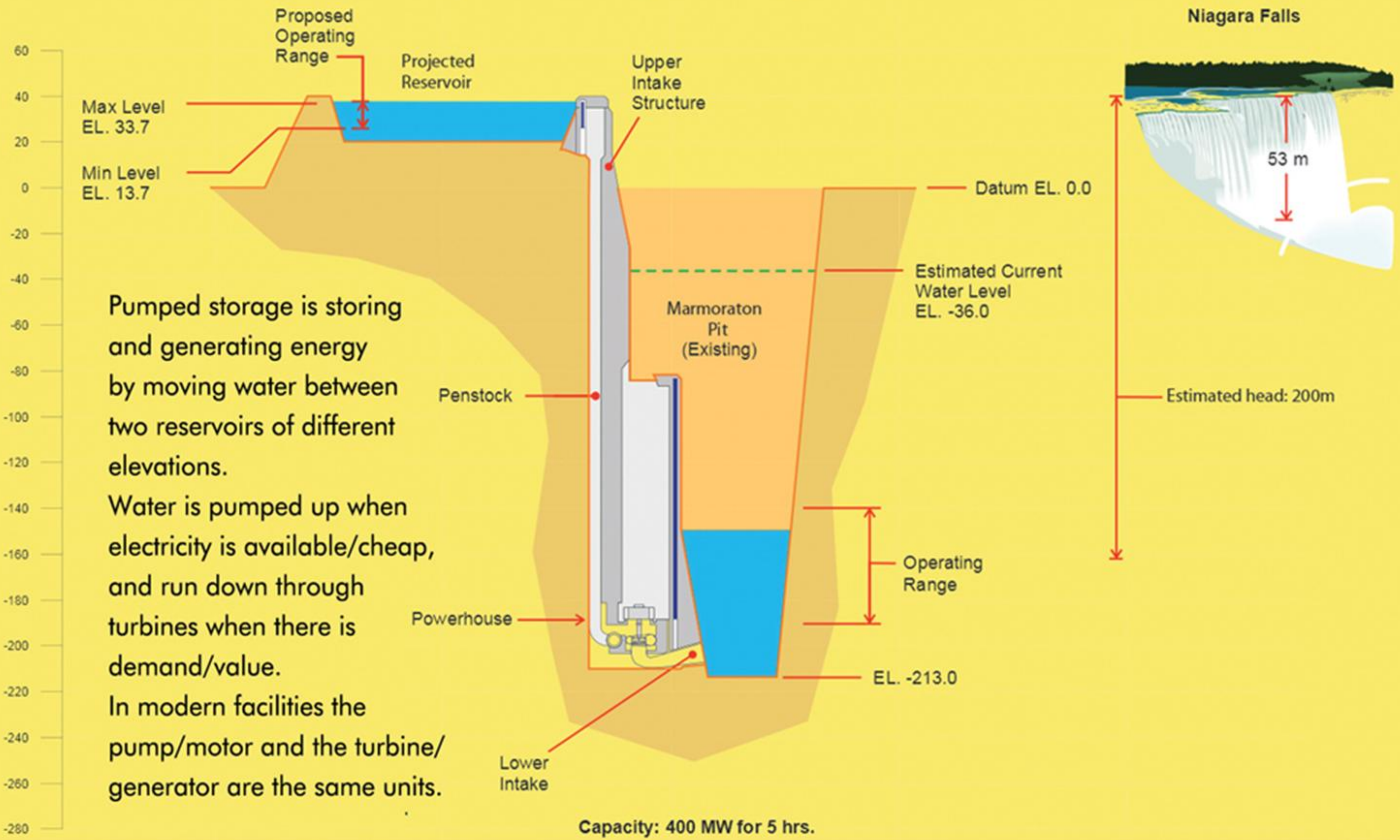
Disadvantages



- Geographic restrictions, since a suitable site with large land use is needed;
- Low energy density (large footprint);
- High initial investment costs;
- Long construction period;
- Long time to recover investment;
- Environmental concerns.


'Closed-loop' pumped storage hydropower
'Open-loop' pumped storage hydropower
Upper reservoir
Powerhouse
Lower reservoir

The Marmora Pumped Storage Design (CANADA)

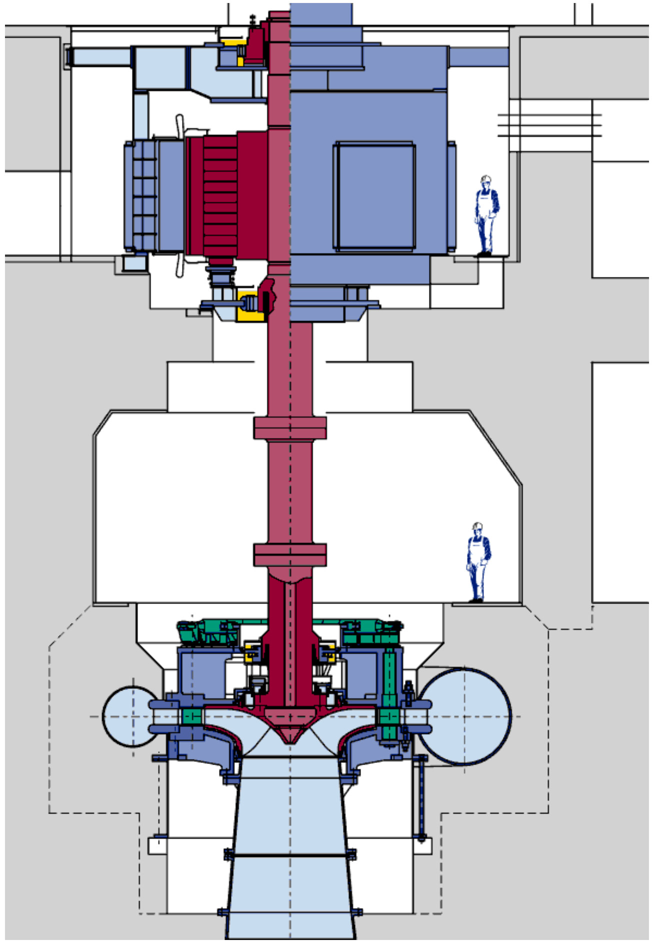


Pumped storage is storing and generating energy by moving water between two reservoirs of different elevations.
Water is pumped up when electricity is available/cheap, and run down through turbines when there is demand/value.
In modern facilities the pump/motor and the turbine/generator are the same units.

Capacity: 400 MW for 5 hrs.

Pumped-storage

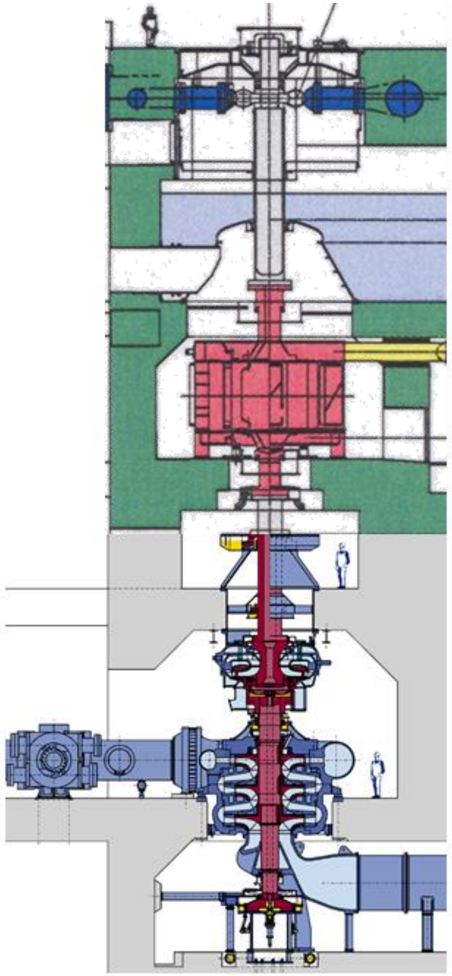
Binary arrangement (pump-turbine)



- Typical of existing fleet in the world today
- Two rotating directions
- Power control in turbine mode only
- Load range for generation: 50 -100 % power
- Proven technology

Pumped-storage

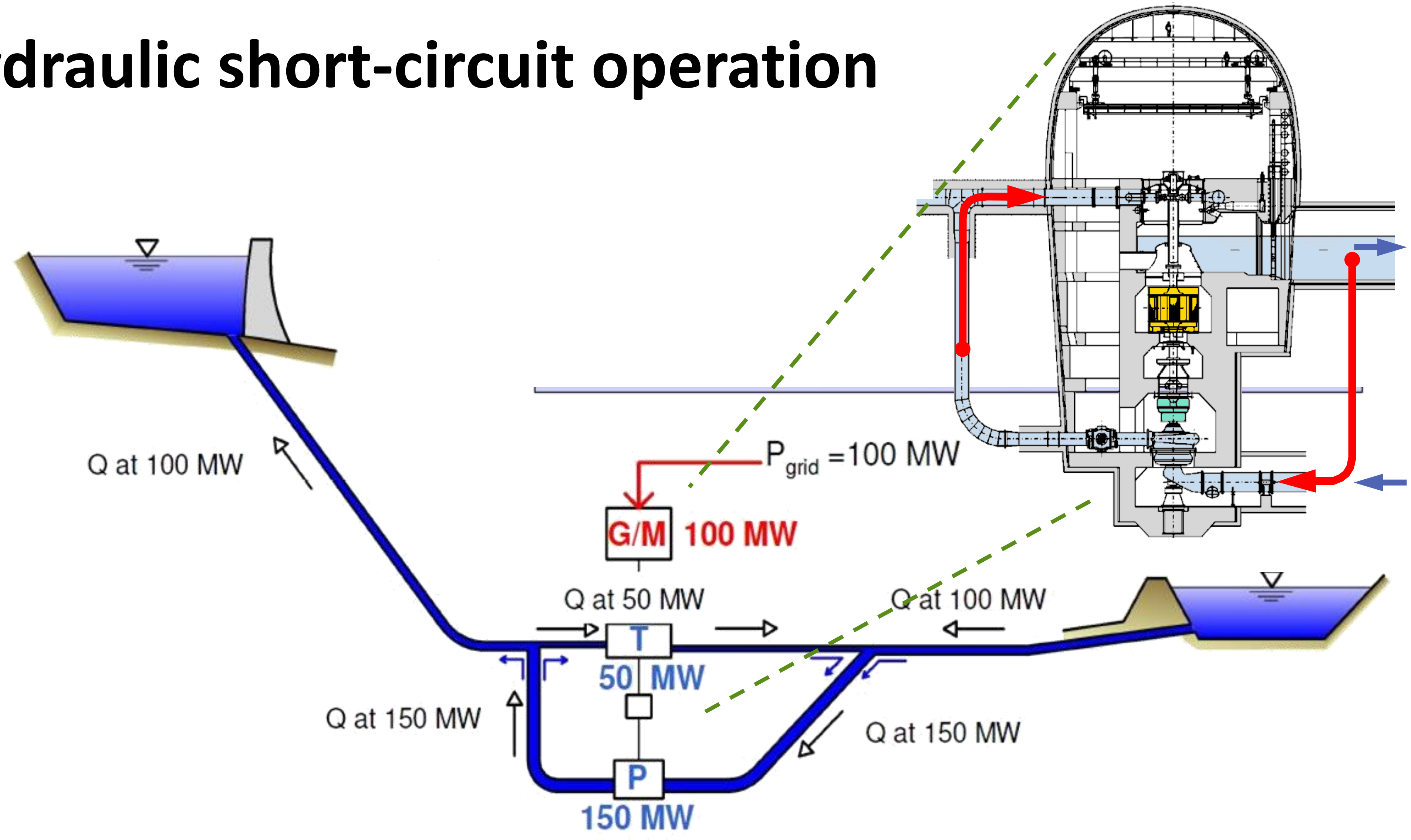
Ternary arrangement (pump+turbine)



- Regulating in turbine and pump modes with hydraulic short circuit
- No change of rotation direction
- Enables steepest load ramp
- Quickest mode changes
- Lowest losses

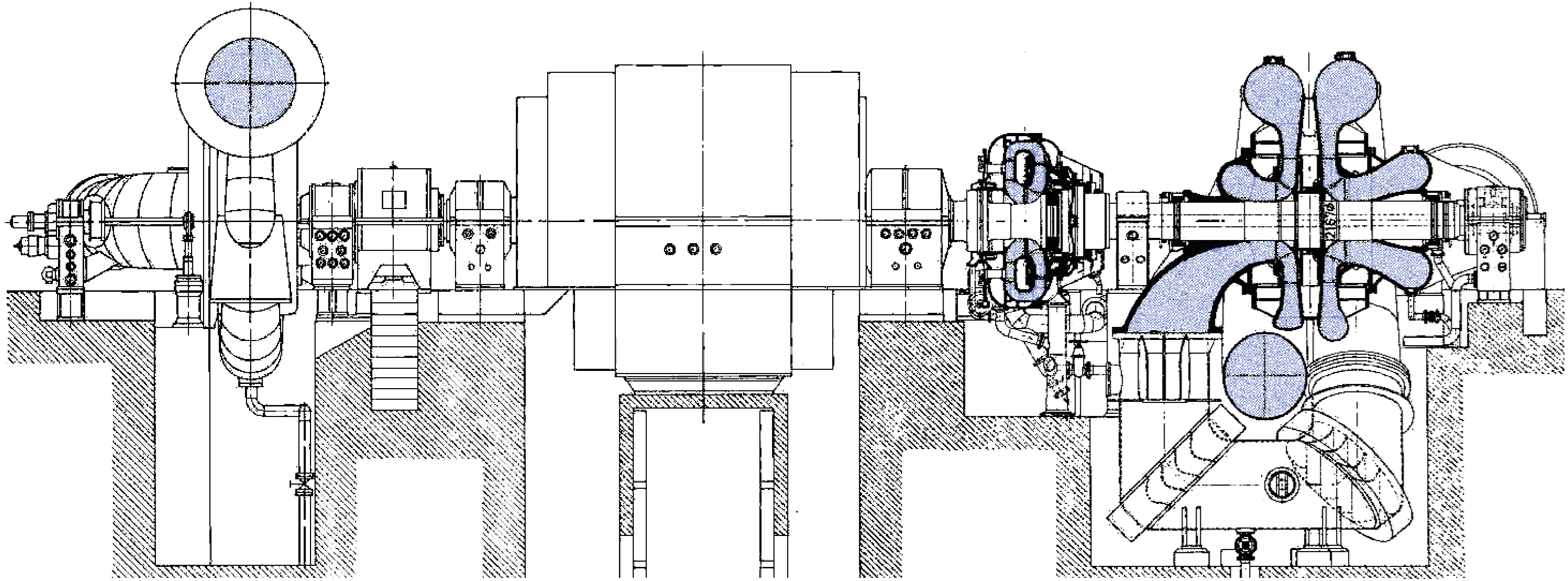
Pumped-storage

Hydraulic short-circuit operation



Pumped-storage

Ternary arrangement (horizontal mounting)




ESCHER WYSS
SIEMENS
VOITH
VOITH

Variable-speed Pumped-storage

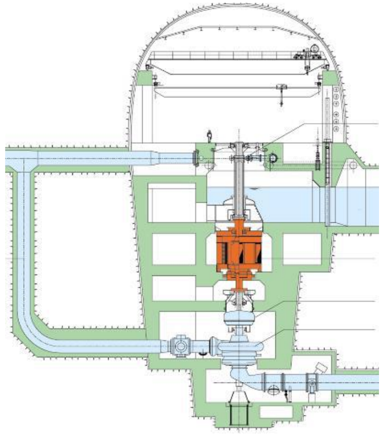
Variable-speed pumped-storage

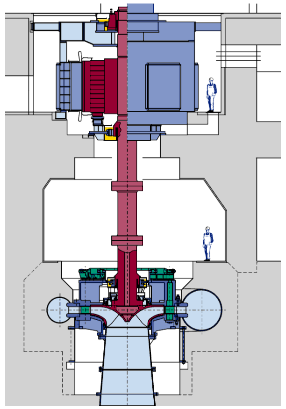
Main characteristics

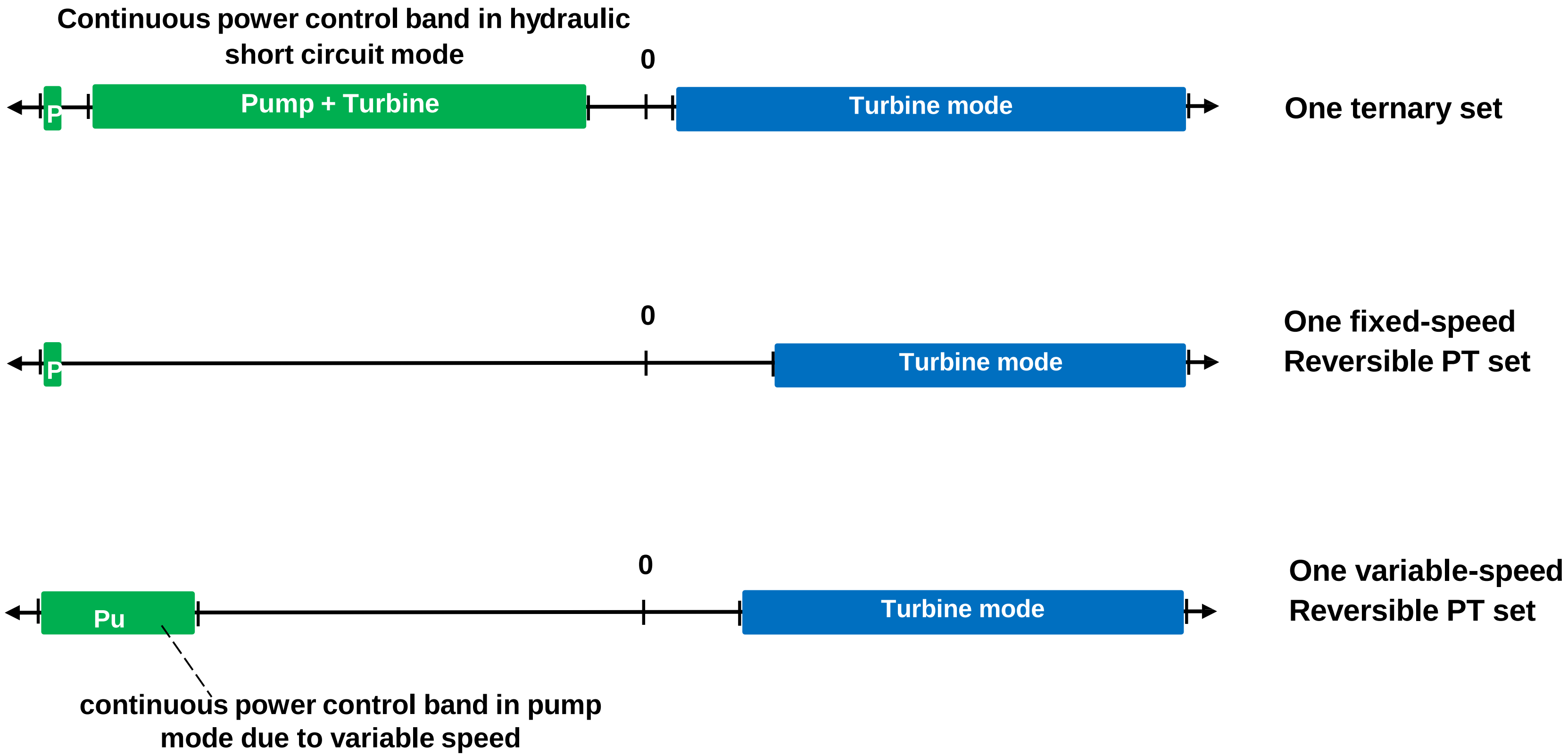
- Variable speed = motor generator adjusts turbine speed;
- Provides grid stabilization in turbine and pumping mode;
- Adjustable power in pump mode;
- Increased flexibility due to primary frequency control
- Wider operating range
- Faster power adjustment
- Increased overall efficiencies
- Improved network stability
- Synthetic inertia, not synchronous (passive)

Variable-speed pumped-storage

Ranges of operation

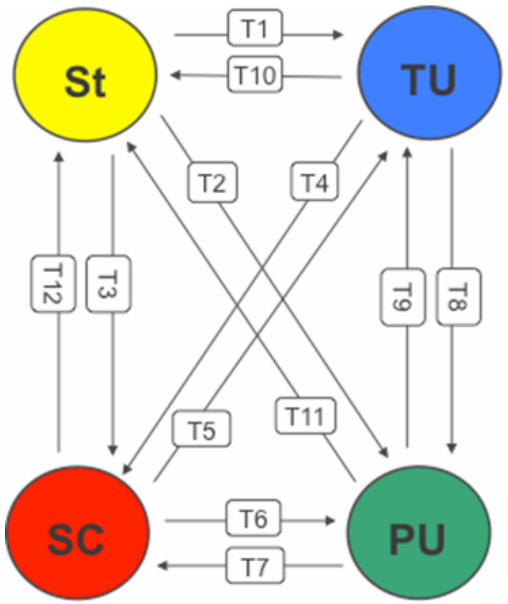






Variable-speed pumped-storage

Changing times



	Pump Turbine			time [seconds]					
T	Mode change			A	B	C_1	C_2	D	E
1	Standstill	→	TU-Mode	90	75	90	60	90	65
2	Standstill	→	PU-Mode	340	160	230	60	85	80
5	SC-Mode	→	TU-Mode	70	20	60	60	40	20
6	SC-Mode	→	PU-Mode	70	50	70	60	30	25
8	TU-Mode	→	PU-Mode	420	240	470	40	45	25
9	PU-Mode	→	TU-Mode	190	90	280	40	60	25

Reversible PT

A – conventional

B – extra fast response conventional

C_1 – VarSpeed DFIM; C_2 – VarSpeed CFSM

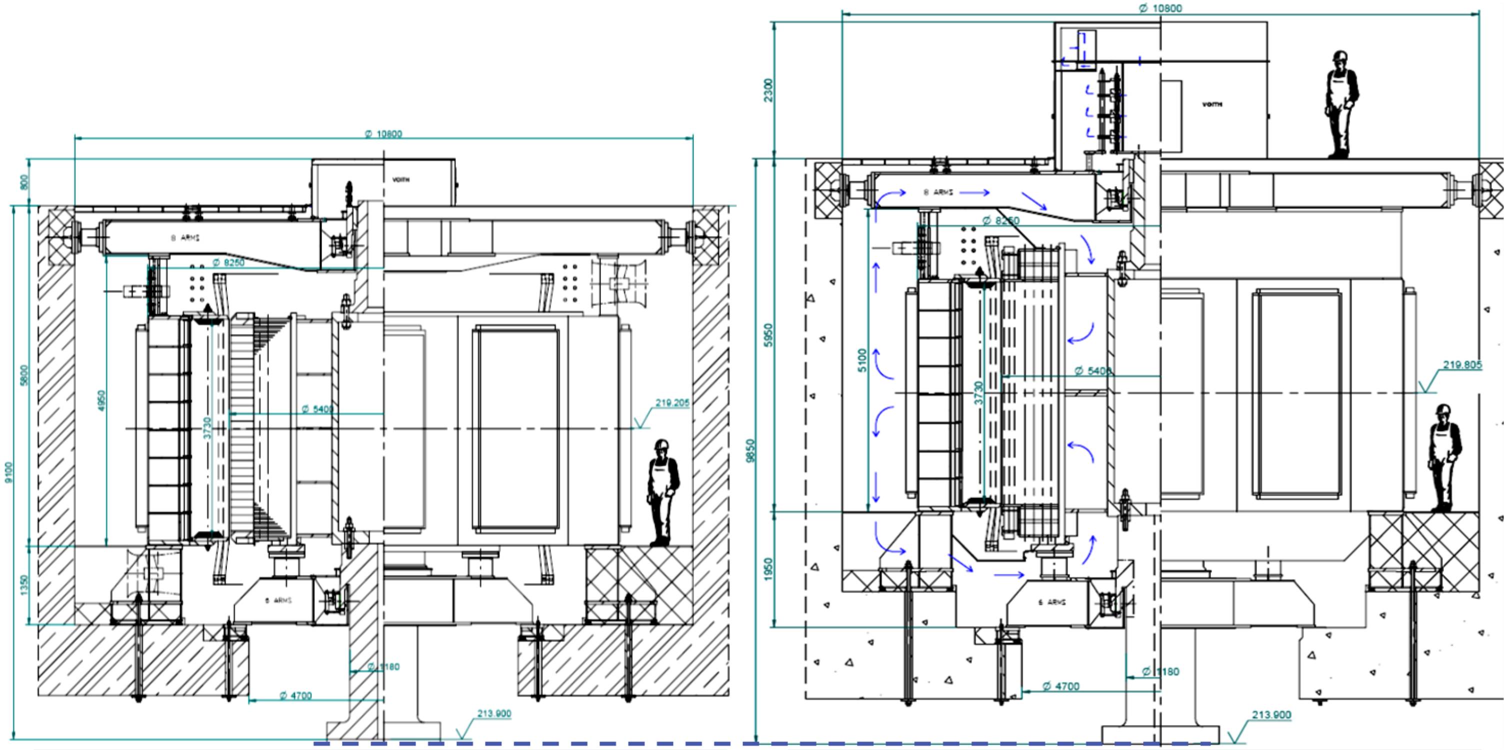
Ternary set

D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine

E – same as E but vertical with Pelton Turbine

Variable-speed pumped-storage

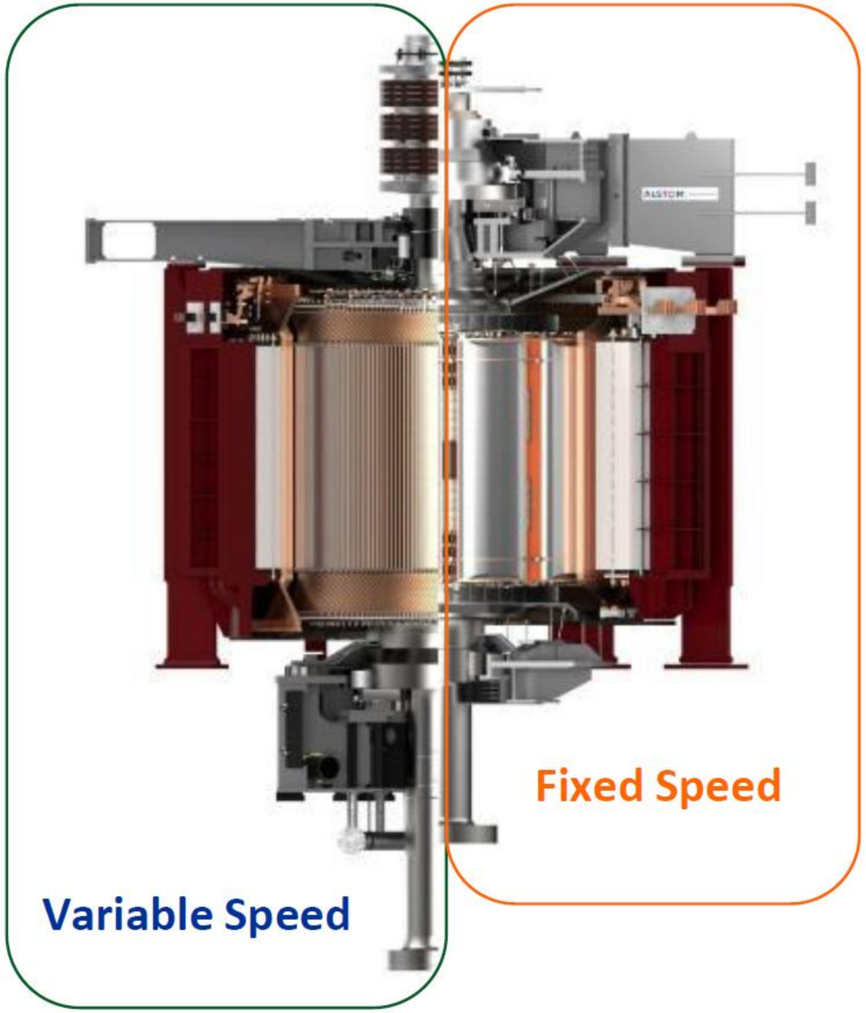
Comparison of solutions



Synchronous Machine

Double Fed Induction Machine

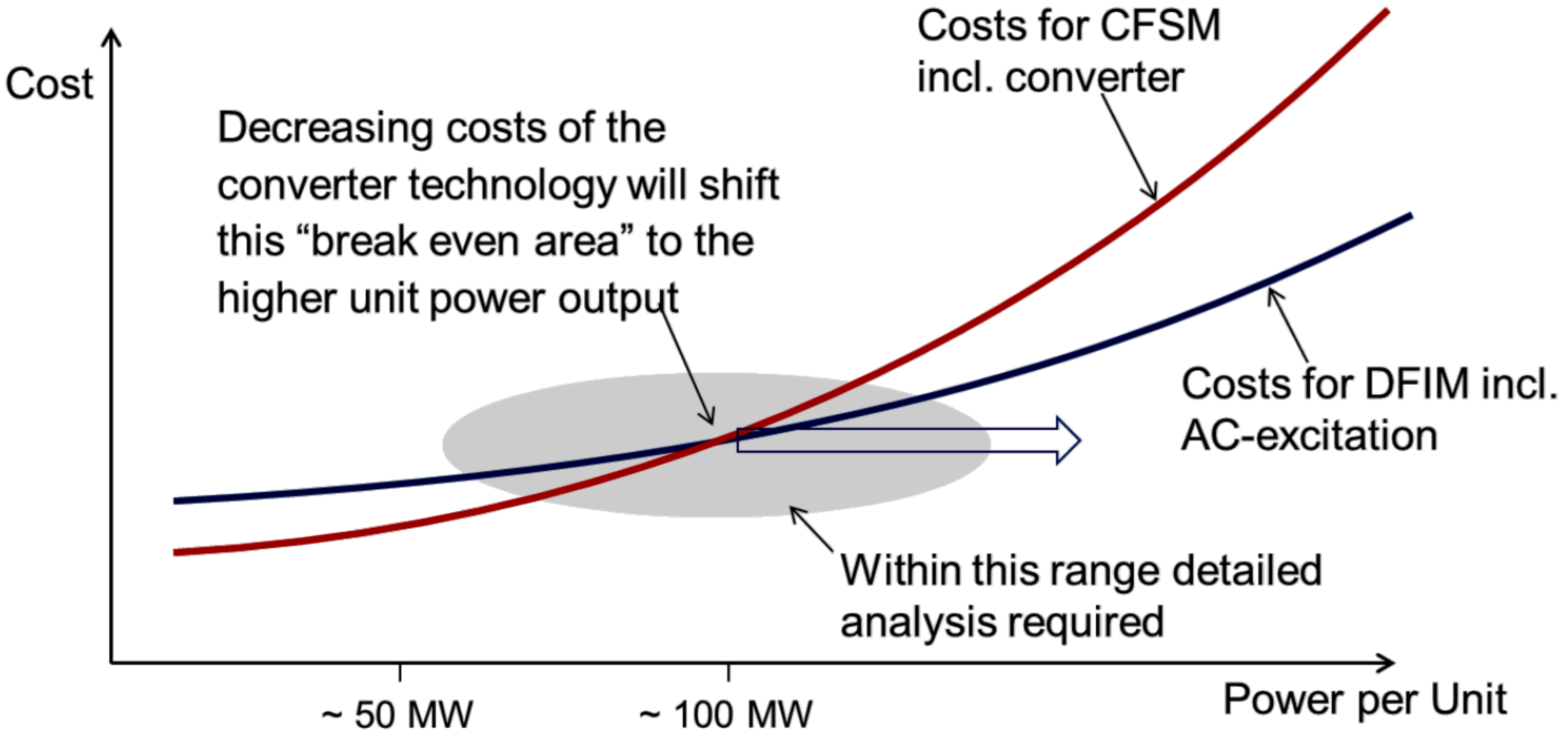
Voith



GE Vernova

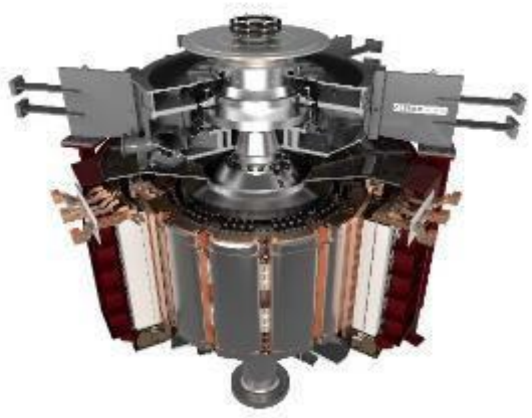
Variable-speed pumped-storage

Comparison of solutions



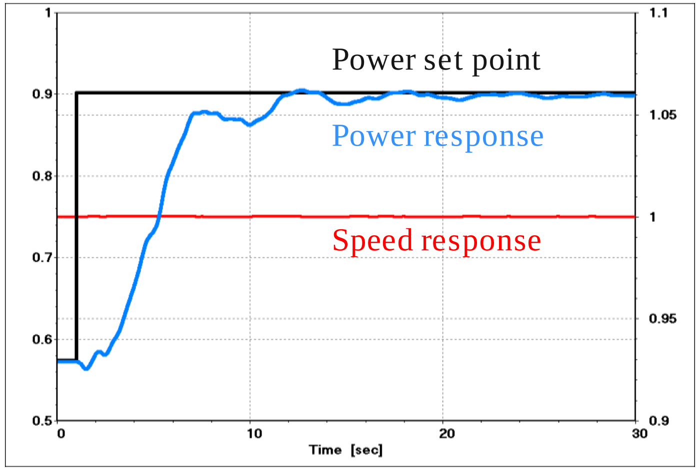
Variable-speed pumped-storage

Fast power injections



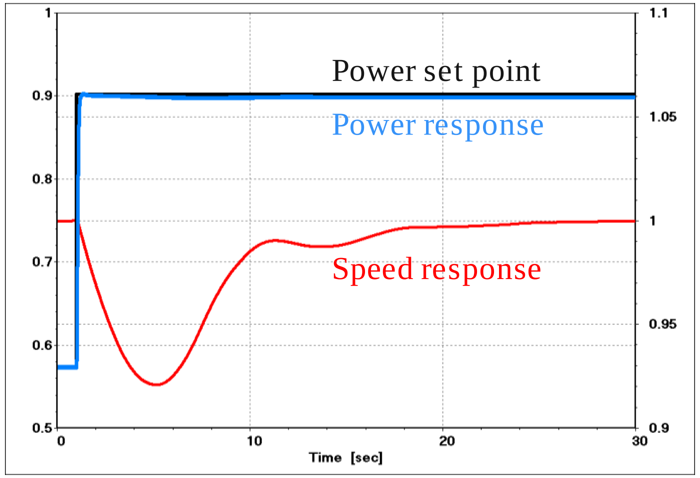
Conventional PSP

- Reaction time driven by hydraulic time constant



Variable speed PSP

- Same reaction time as batteries
- Kinetic energy converted to electrical quasi instantaneous power injection
- Turbine-governor control makes the injection sustainable



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THE END

Thank you!