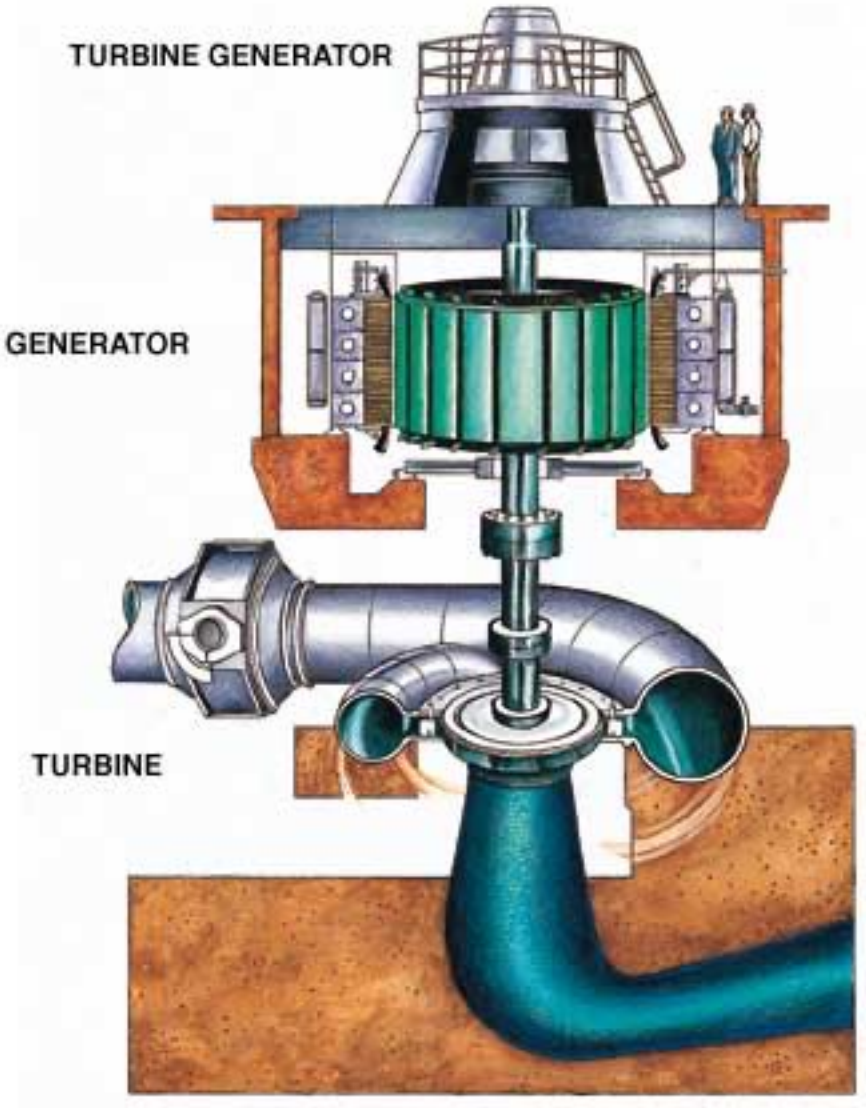
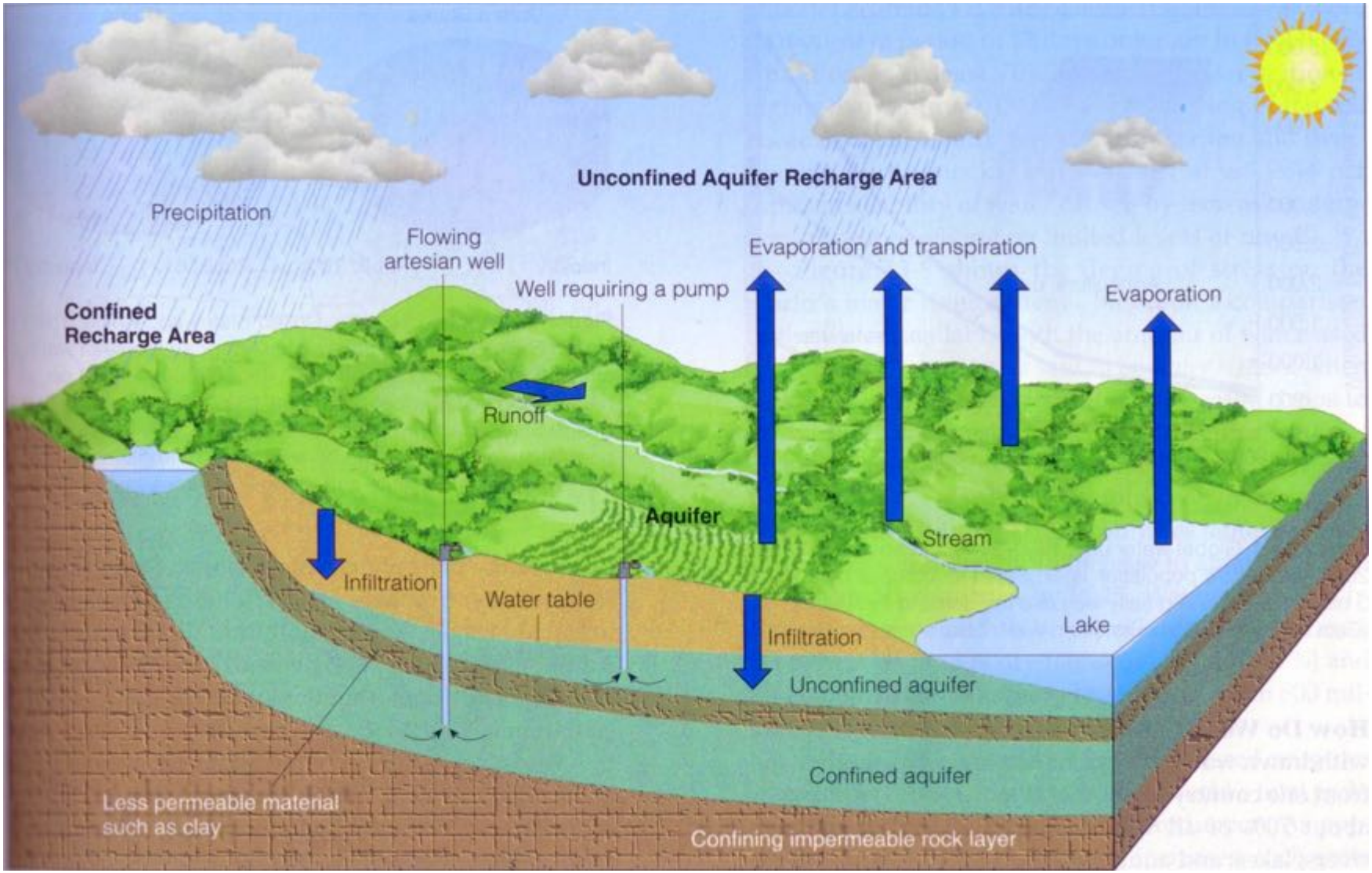
Thermodynamics of energy conversion

9) HYDROPOWER

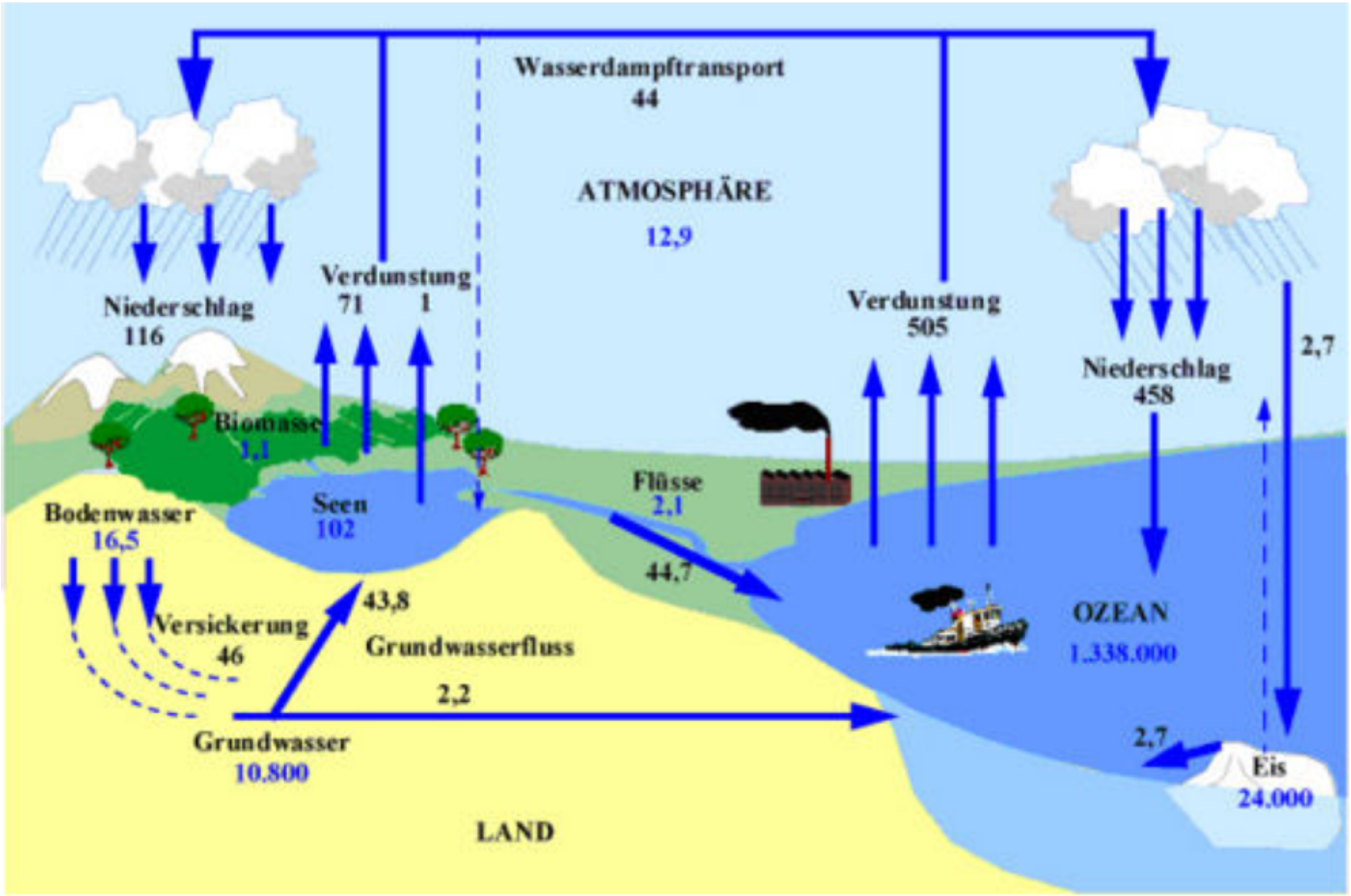


9) HYDROPOWER

9.1. WATER EVAPORATION & PRECIPITATION



9.1.1. WATER CYCLE



The global water flow: Reservoirs (blue numbers) in 1'000 km^3, Flows in 1'000 km^3/year (black numbers)

QUESTION

How often is the water in the atmosphere exchanged?

Estimate the power in the cycle?

QUESTION

How often is the water in the atmosphere exchanged?

Evaporation from ocean: 505·1000 km^3 /year
Evaporation from lakes, plants: 73.1·1000 km^3/year

Water in the atmosphere: 12.9·1000 km^3

12.9/(578.1) = 0.223 year = 8 days

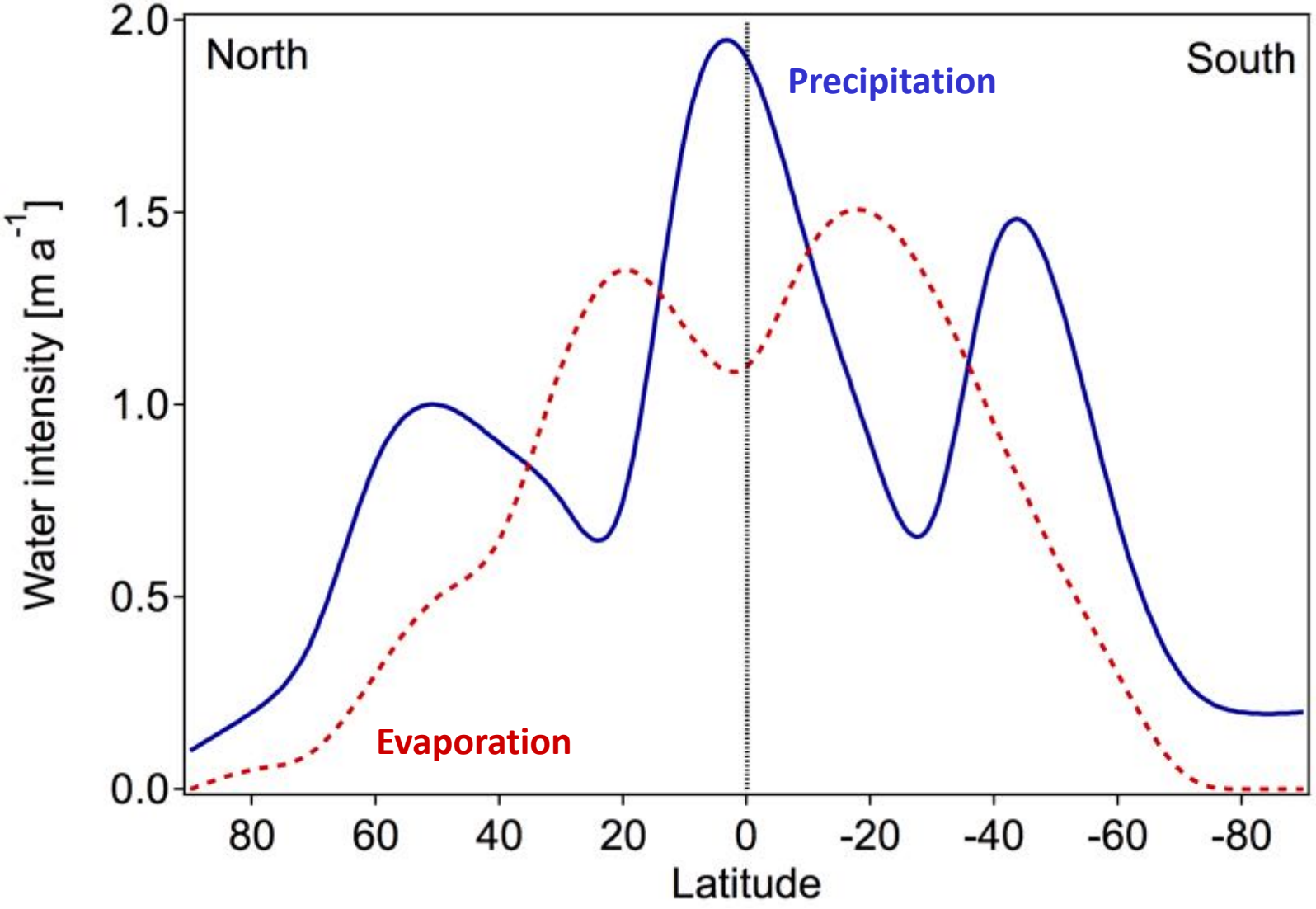
Estimate the power in the cycle?

$W = m \cdot g \cdot \Delta h$
$P = m \cdot g \cdot \Delta h / t$

$P = 578.1 \cdot 1000\ km^3 \cdot 10^{12} kg \cdot 10 m/s^2 \cdot 2500m/(8days \cdot 24h/day \cdot 3600s/h)$

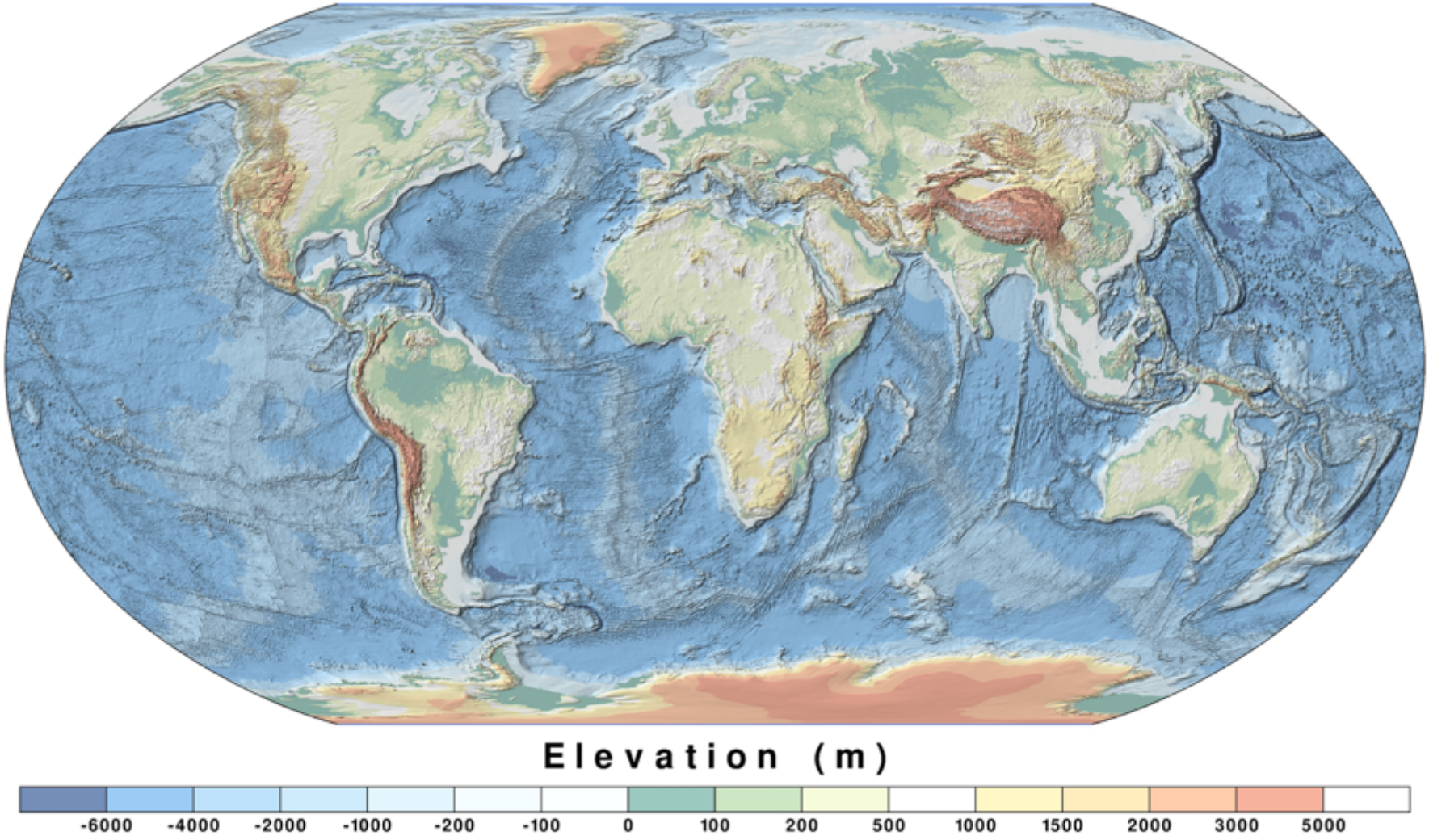
P = 21’000 TW

9.1.2. PRECIPITATION & EVAPORATION



9.1.3. ELEVATION IN CENTRAL EUROPE: ALPS

9.1.4. AVERAGE ELEVATION



Ref.: http://ian.macky.net/pat/map/world/world_etopo2v2.jpg

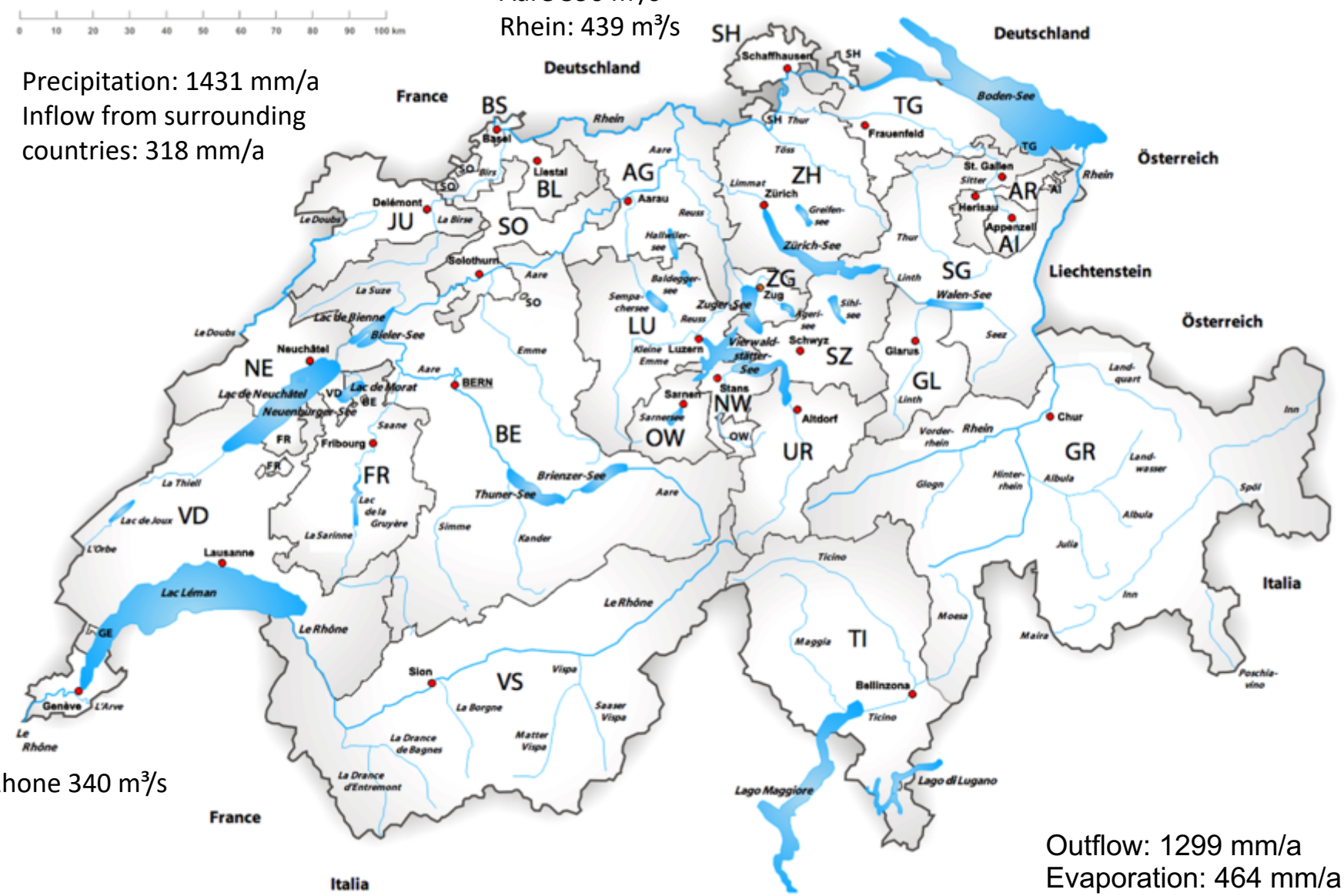
9.1.5. AVERAGE ELEVATION IN SWITZERLAND

Ref.: http://www.lahistoriaconmapas.com/atlas/country-map01/switzerland-elevation-map.htm

9.1.6. WATER FLOWS IN SWITZERLAND

Aare 590 m³/s
Rhein: 439 m³/s

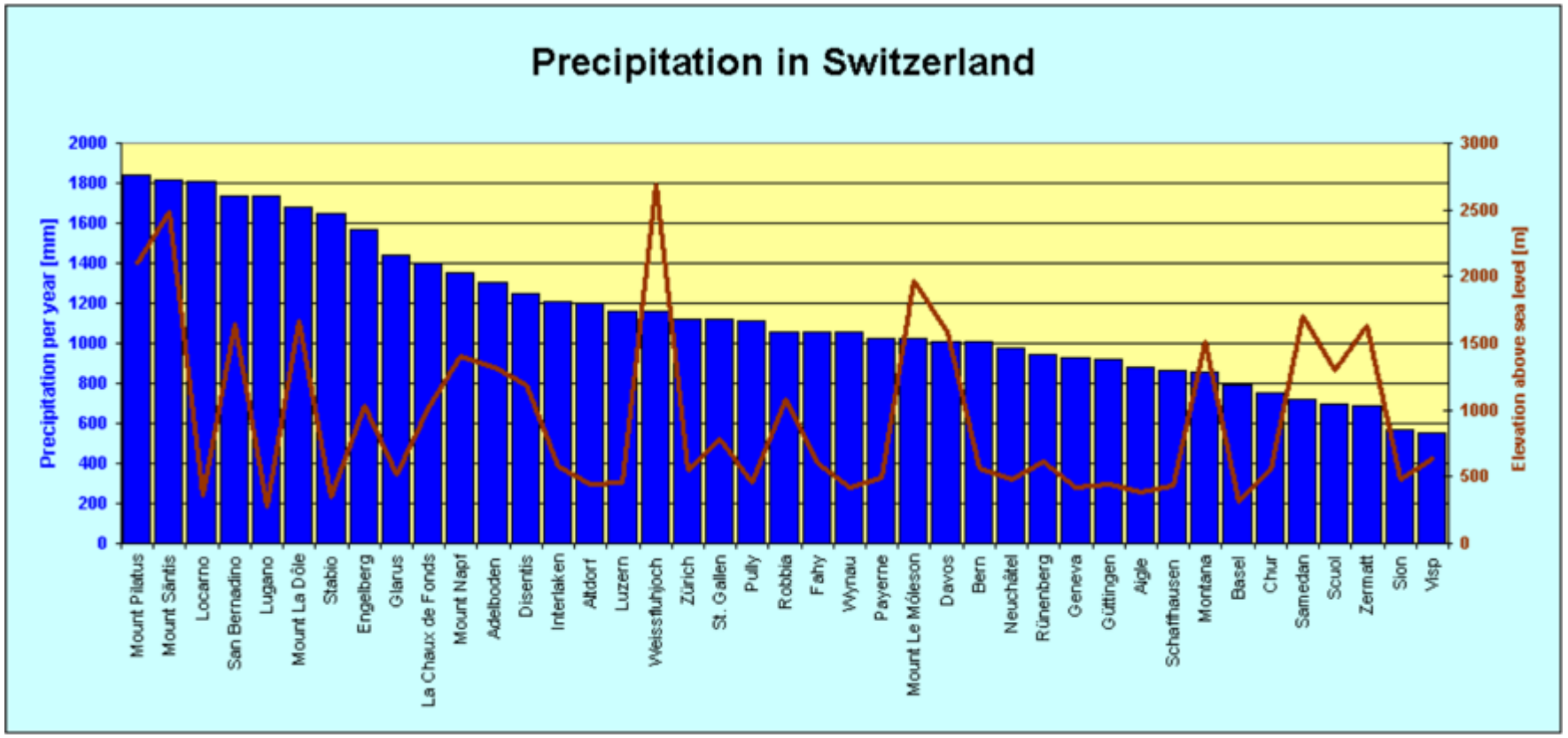
Precipitation: 1431 mm/a
Inflow from surrounding countries: 318 mm/a



Rhone 340 m³/s

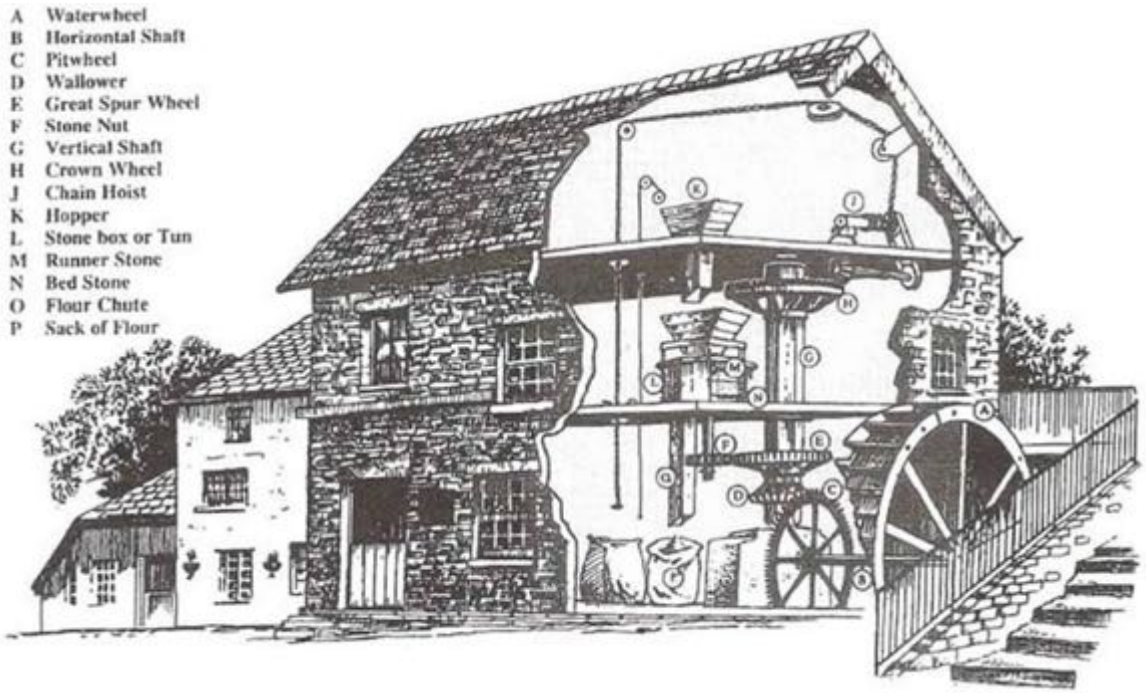
Outflow: 1299 mm/a
Evaporation: 464 mm/a

9.1.7. PRECIPITATION AND ELEVATION



Ref.: http://www.about.ch/geography/climate/index.html

9.1.8. HYDROPOWER HISTORY



Hydropower station (Lonza) in Gampel 1897

Oberer Murgsee 1880

Mühleberg 1920

http://www.hydro-bpt.eu/hydropower.php.en

9.1.9. HYDROPOWER POTENTIAL IN CH

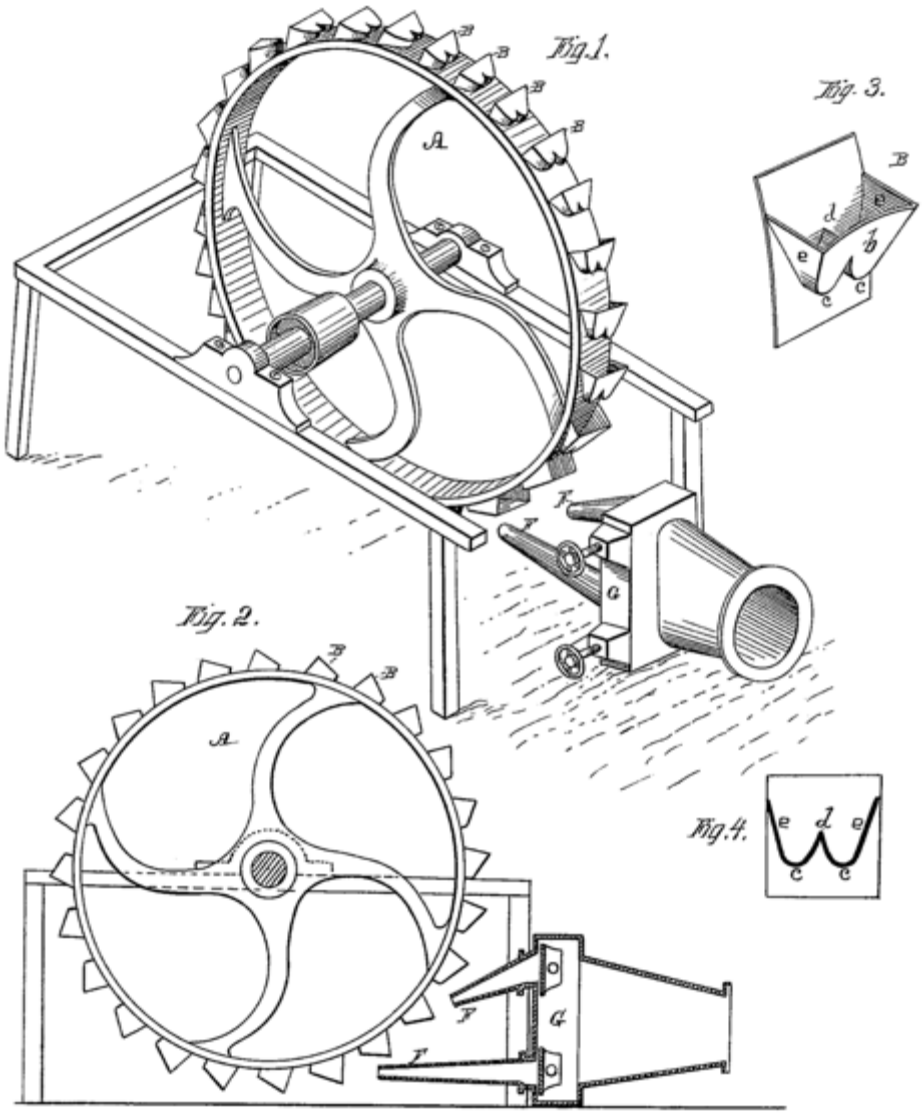
$$P = \dot{V} \cdot \rho \cdot g \cdot h$$

Switzerland:
Precipitation 1431 mm/a
(Average of periode 1901-2000)
Average elevation 1‘500 m
for 1/3 of the surface area: 41'285 km²

dV/dt = 4500 m^3/s

P = 41000km^2/3·1.431m/a ·9.81m/s^2
·(1700-200)m·1000kg/m^3 = 2.8·10^{17}
Ws/a = 80'000 GWh/a = 9 GW

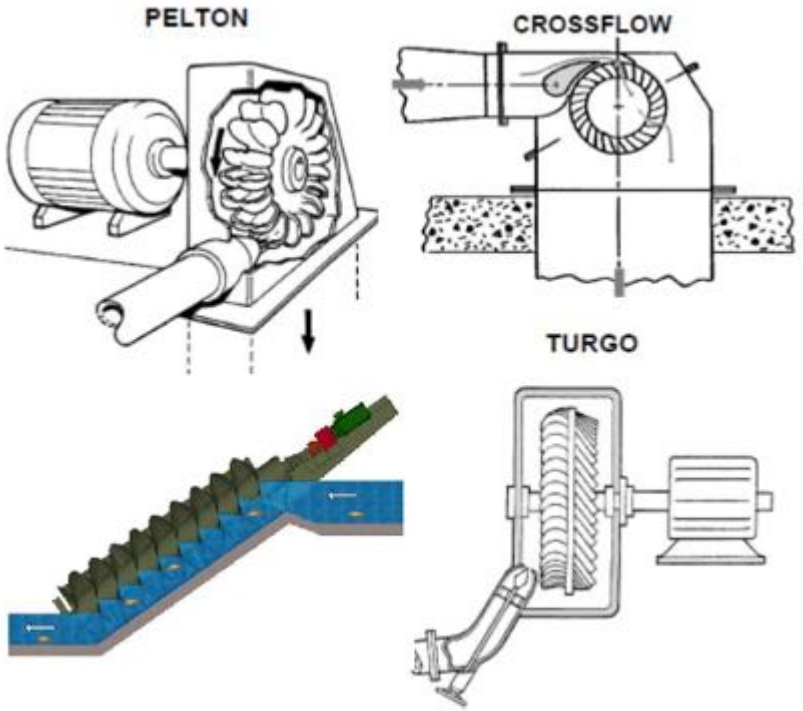
Currently: 4.5 GW used



9.2. Hydropower Turbines

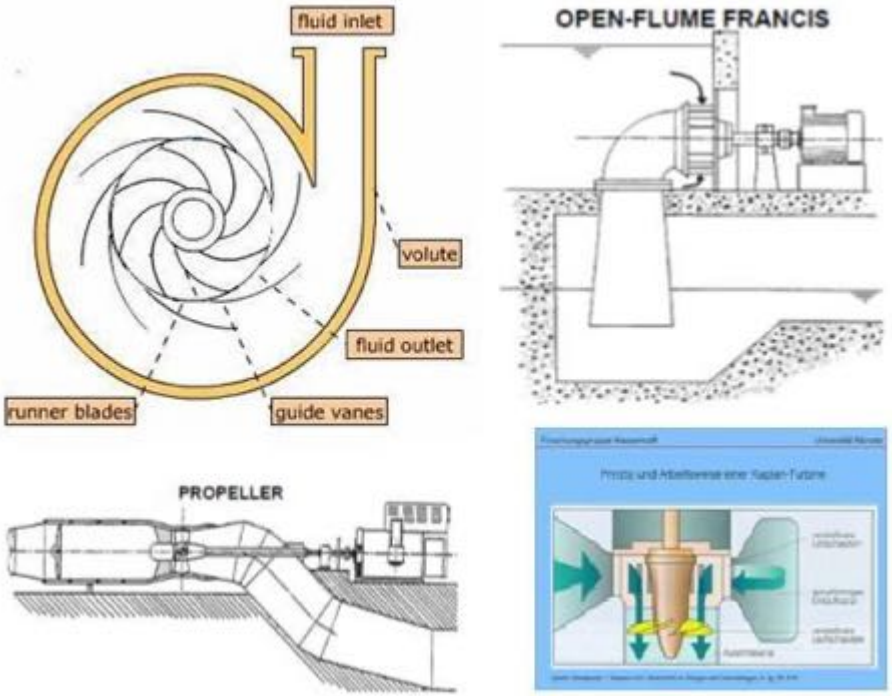
Impulse Turbine

The Pelton, Turgo, Crossflow and Archimedes are types of impulse turbines and work under the principle of a jet of water acting upon buckets or runners on a wheel, which is rotated due to the force of the moving water.

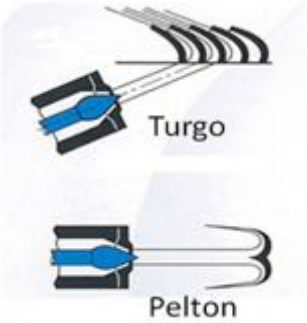


Reaction Turbine

The main types of reaction turbines include; the Francis turbine, the Propeller/Kaplan turbine, the Tyson, Gorlov and China turbines. the development of reverse pumps or pump as turbines (PaT's) are used as reaction turbines.

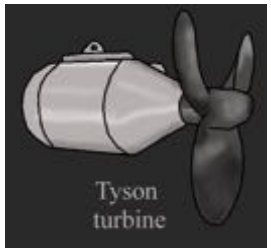


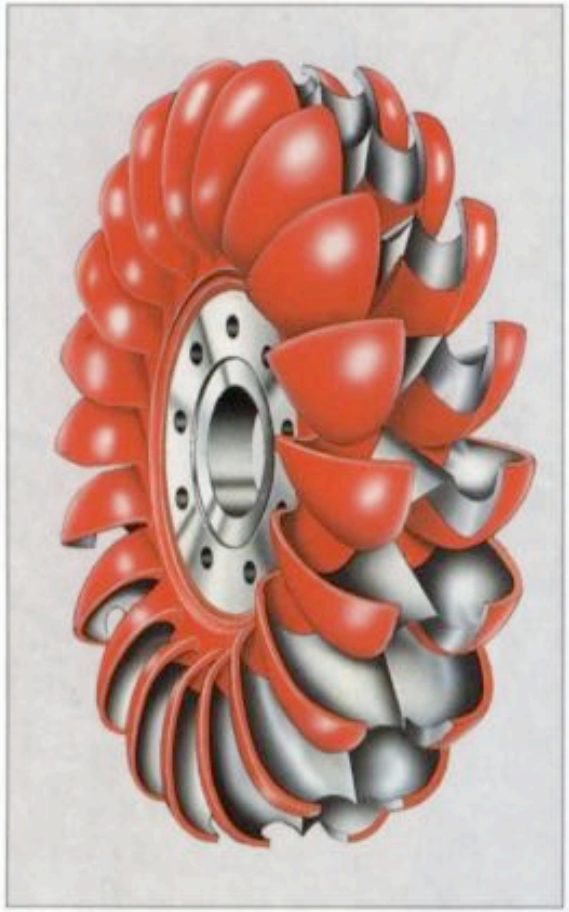
9.2.1. TURBINES



crossflow

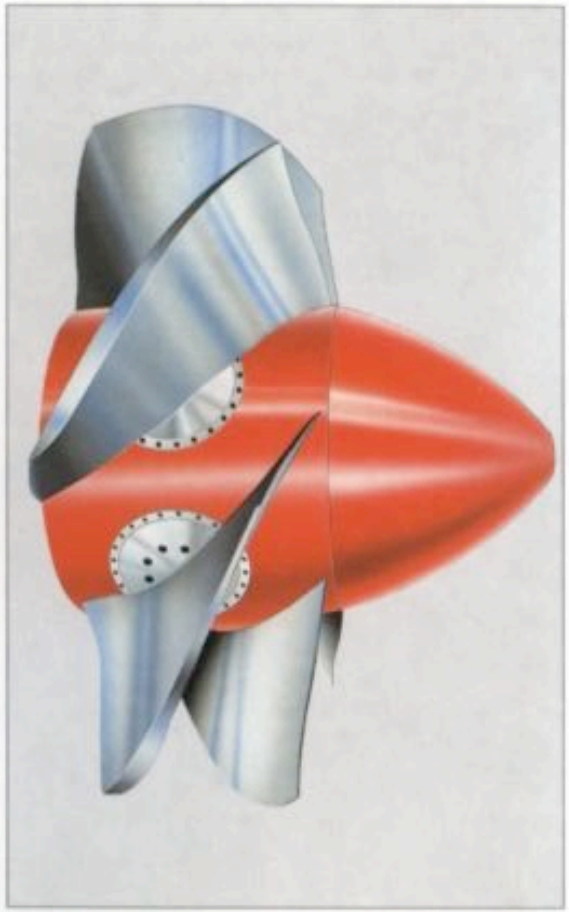
Gorlov





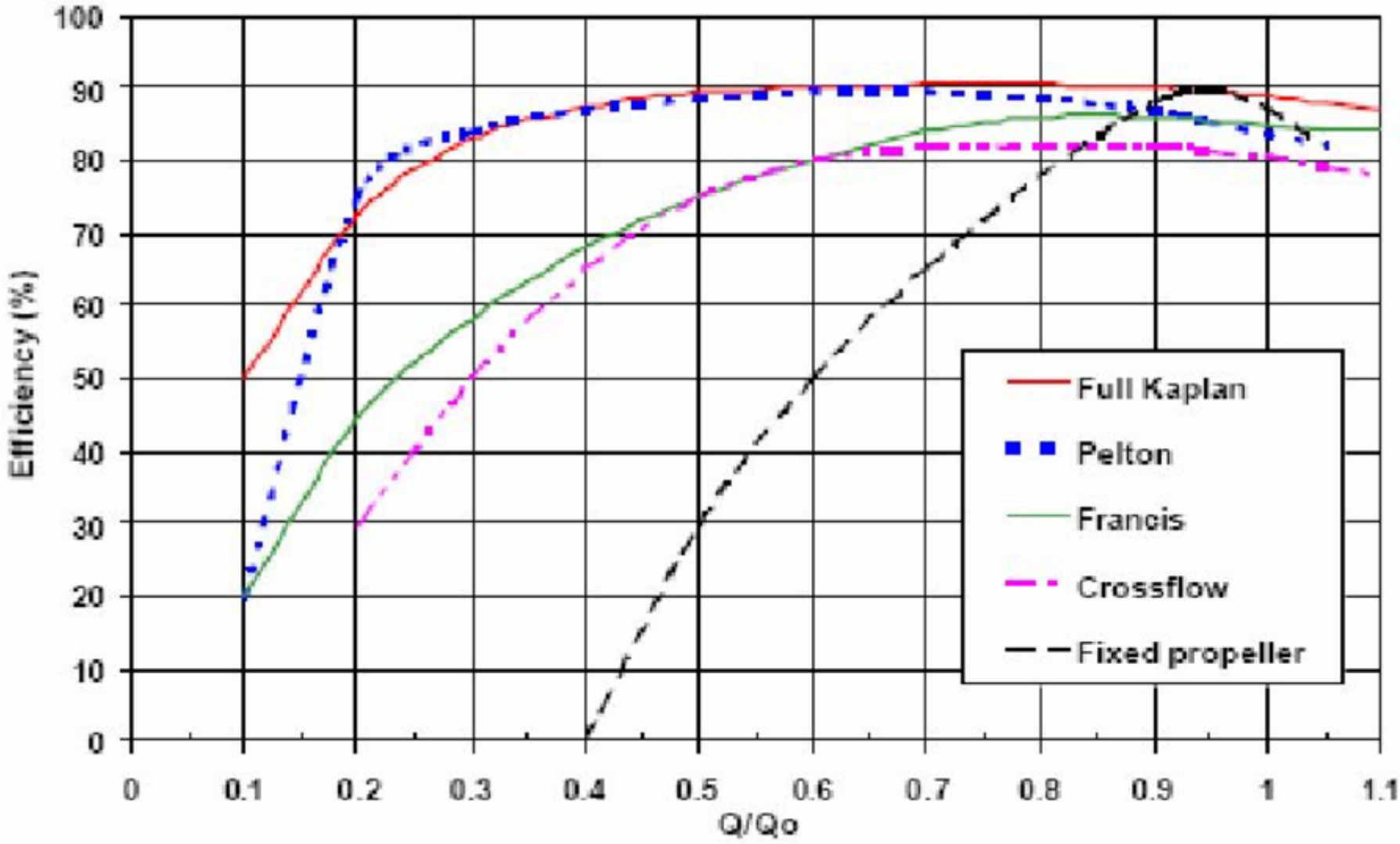
Pelton turbine

Francis turbine

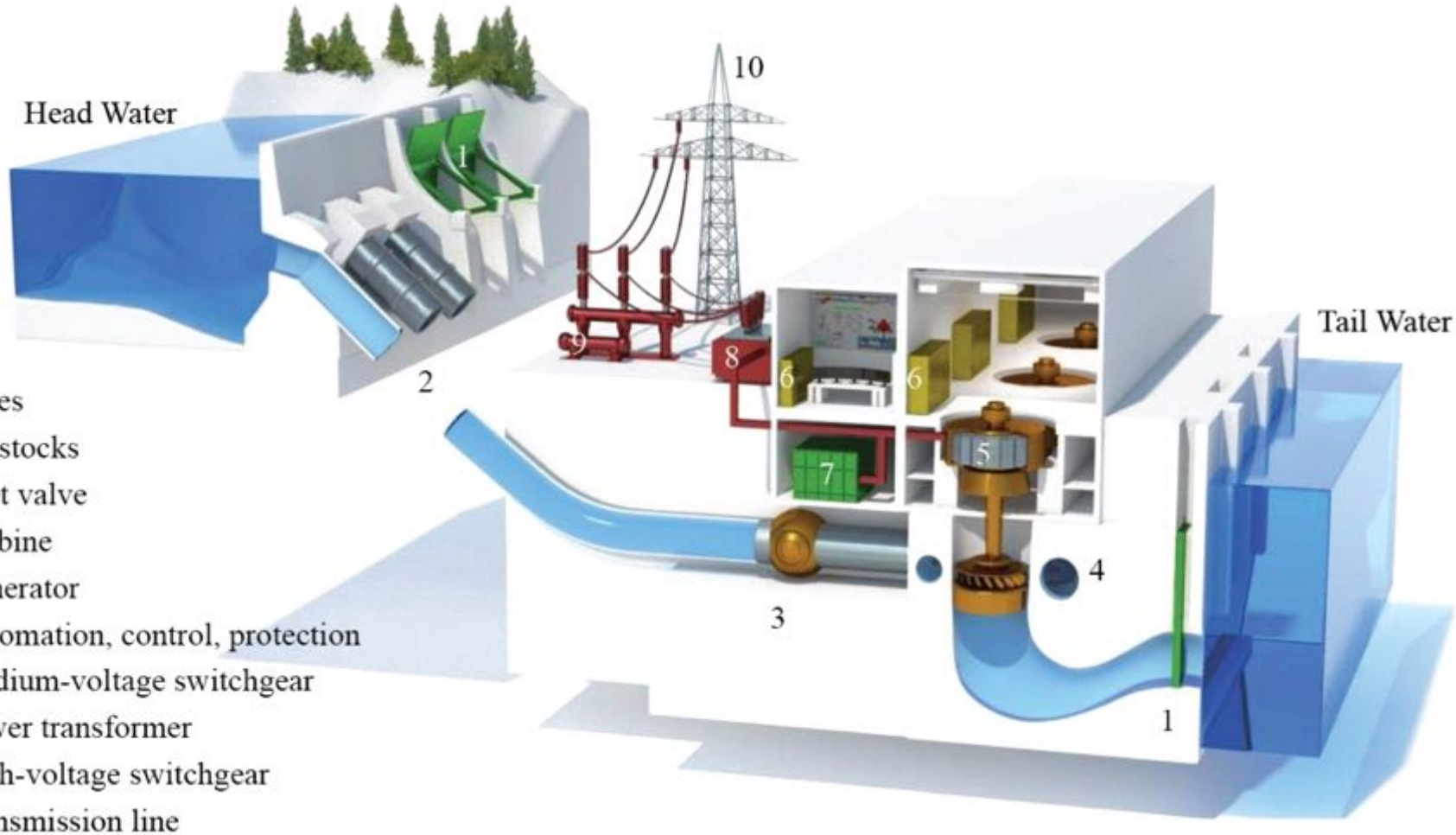


Kaplan turbine

9.2.2. TURBINE EFFICIENCY

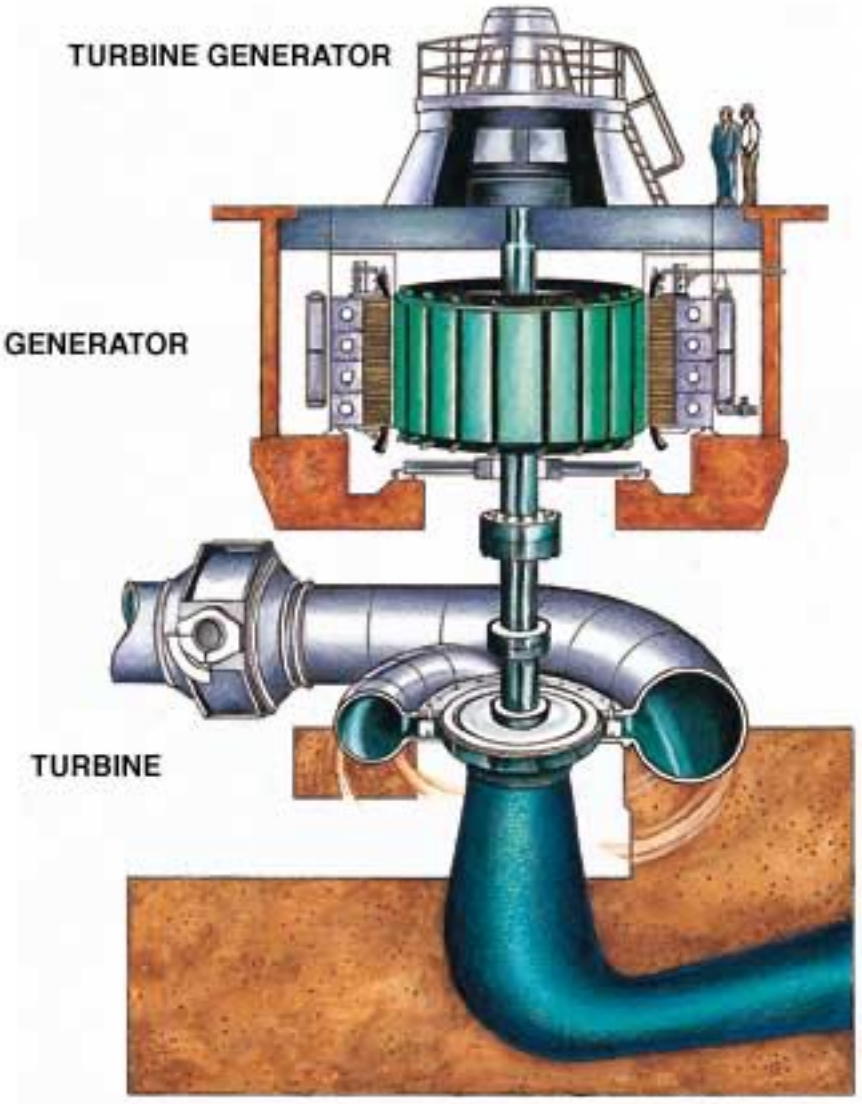


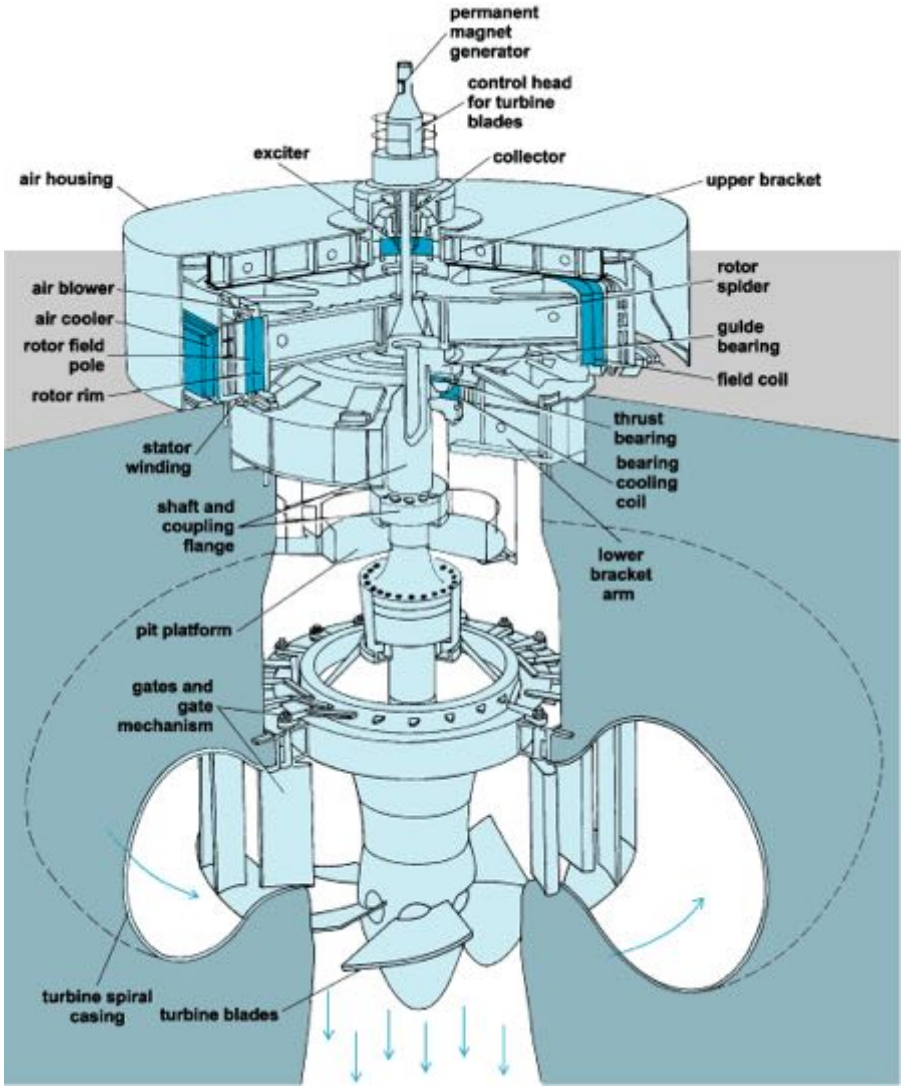
9.3. HIGH PRESSURE HYDROPOWER PLANT



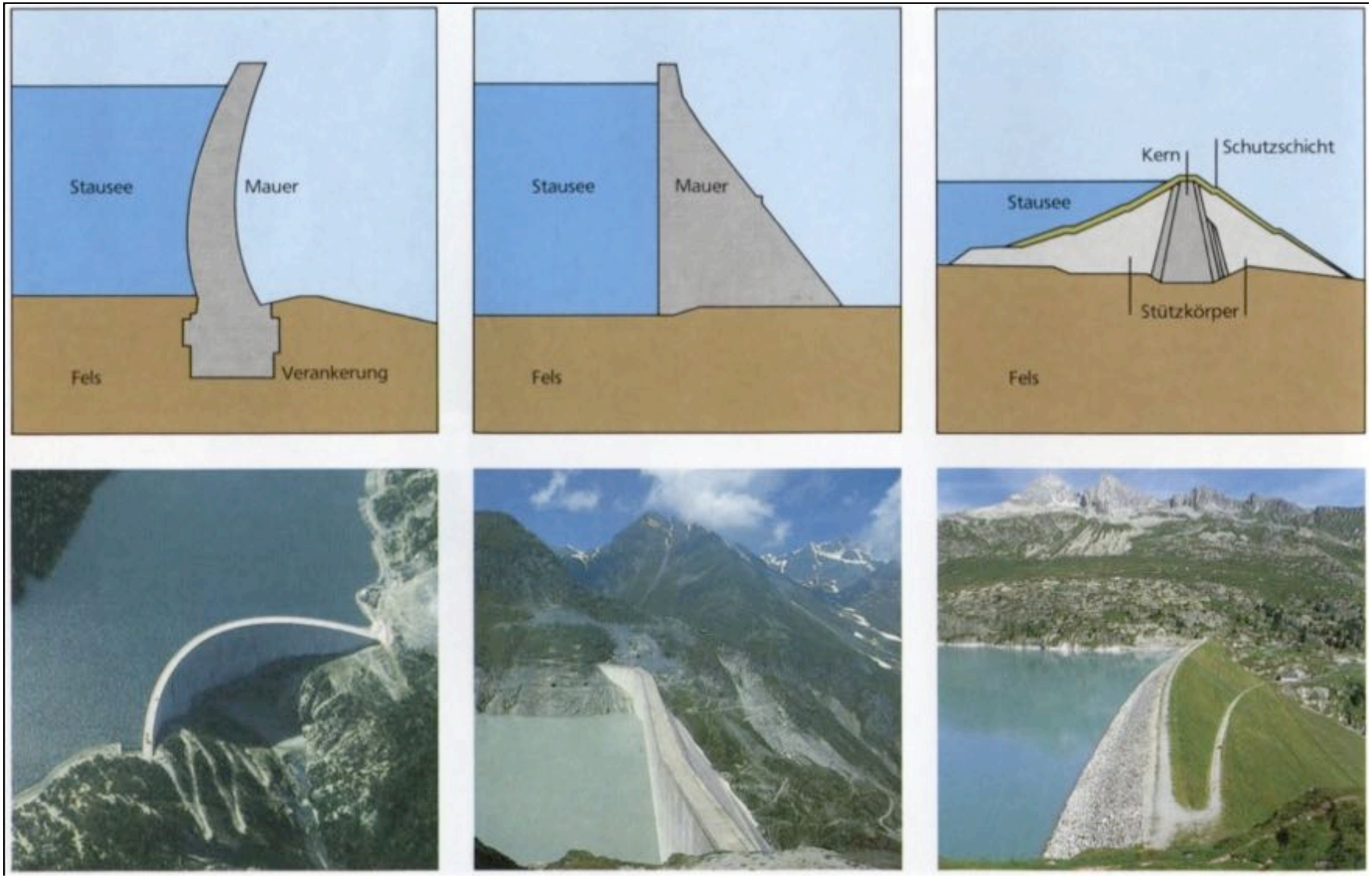
1 Gates
2 Penstocks
3 Inlet valve
4 Turbine
5 Generator
6 Automation, control, protection
7 Medium-voltage switchgear
8 Power transformer
9 High-voltage switchgear
10 Transmission line

9.3.1. HIGH PRESSURE TURBINE

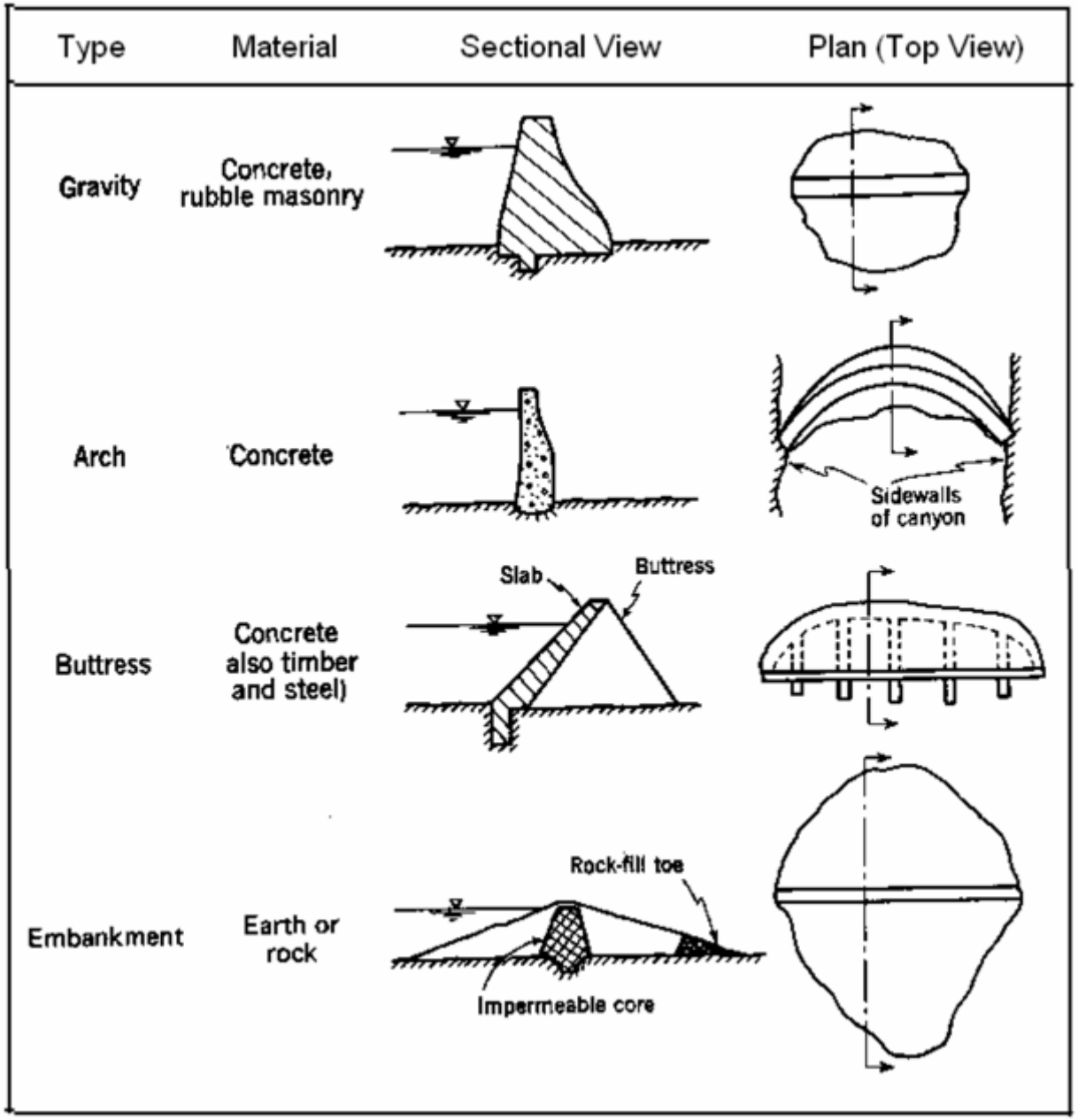




9.4. TYPES OF DAMS

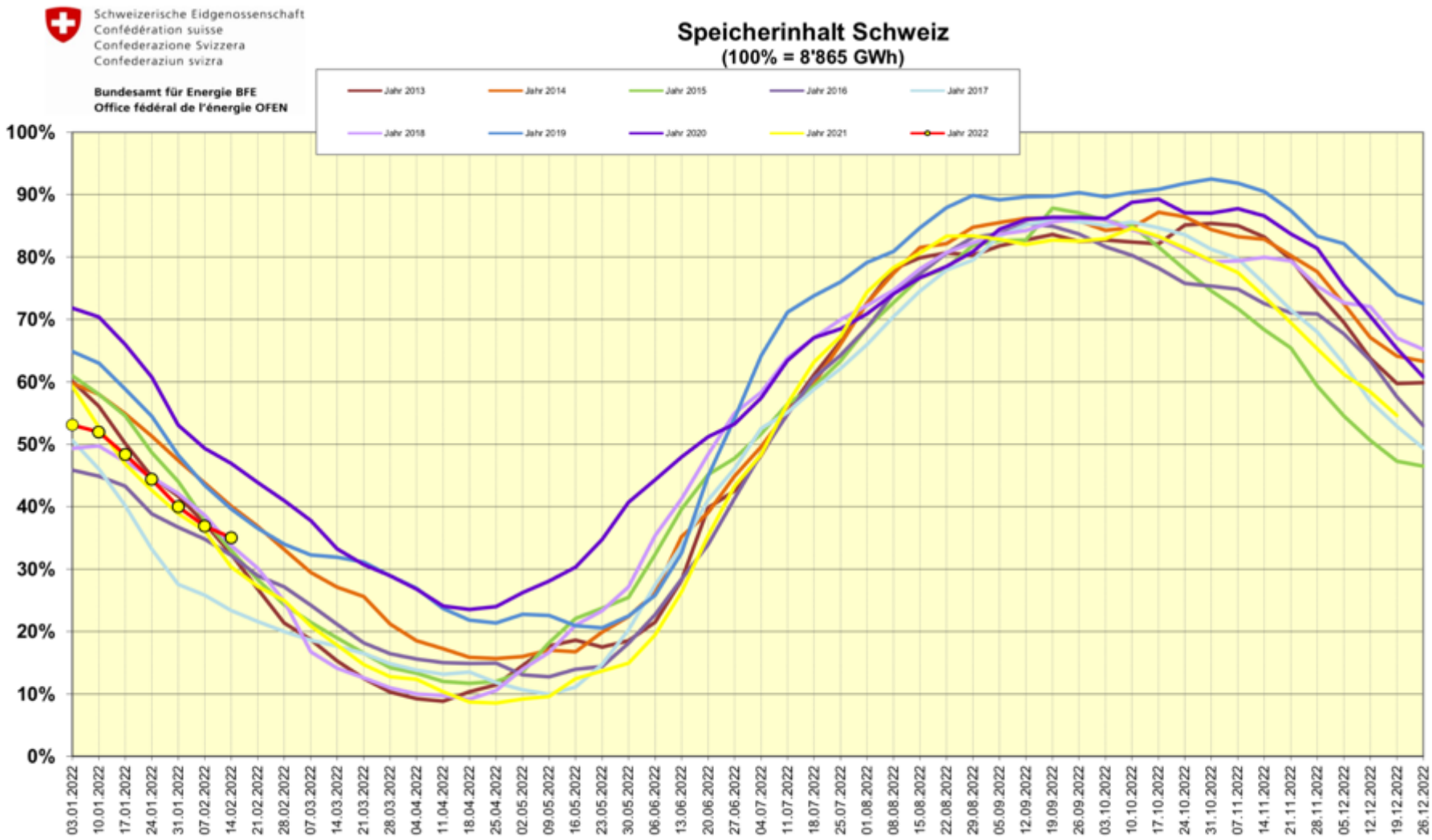


9.4.1. CONSTRUCTION OF DAMS



9.4.2. WATER COLLECTION SYSTEM

9.4.3. WATER LEVEL IN SWISS STORAGE LAKES



9.4.4. SPECIFICATIONS OF HYDROPOWER STORAGE STATIONS

Table A1. Hydropower plants 2018 and water fees 2016 in Switzerland.

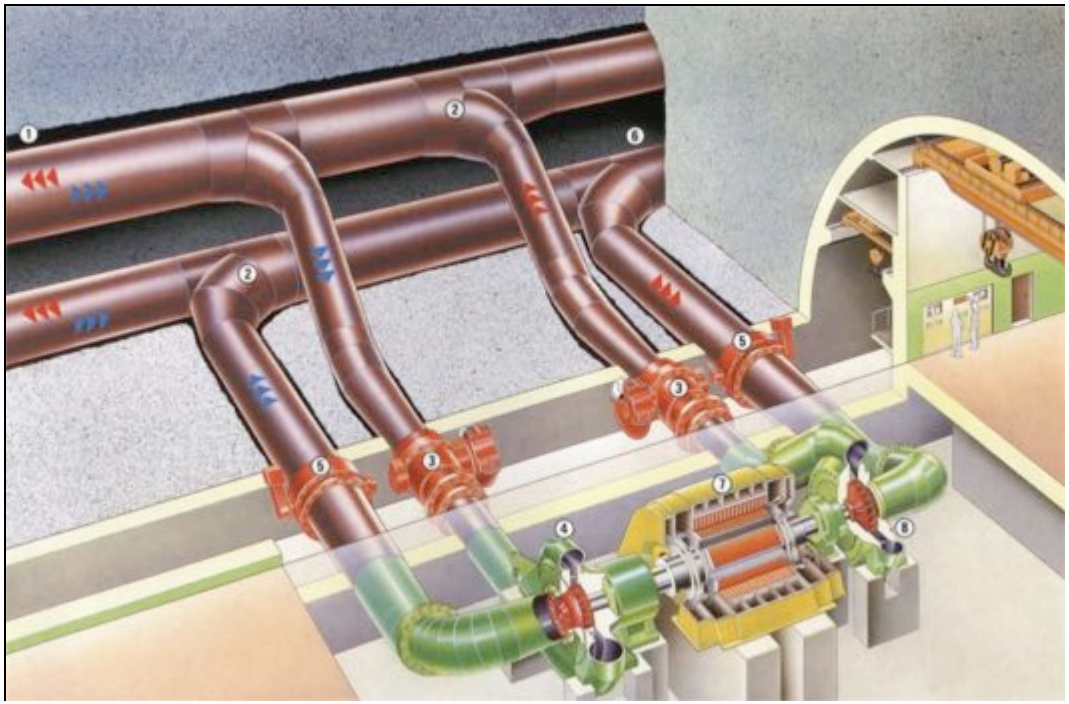
Region	Canton [a]	No. of Plants	Maximum Capacity (MW)				Average Expected Production (GWh/a)				Water Fees (million CHF/a)
			Run-of-River Plants	Storage Plants	Pumped-Storage Plants	TOTAL	Run-of-River Plants	Storage Plants	Pumped-Storage Plants	TOTAL	
Alps	GR	108	636.7	1910.6	172.5	**2719.7**	2333.8	5303.5	300.2	**7937.5**	124.4
	TI	34	279.9	960.7	209.0	**1449.6**	950.1	2481.2	115.8	**3547.1**	55.1
	UR	25	300.7	204.7		**505.3**	1174.5	383.2		**1557.7**	26.3
	VS	125	917.4	3443.1	250.7	**4611.2**	3326.1	5954.4	444.9	**9725.3**	148.4
	Subtotal	**292**	2134.6	6519.1	632.2	**9285.8**	7784.4	14,122.3	860.9	**22,767.6**	**354.2**
	share CH	*46%*	*53%*	*80%*	*20%*	***61%***	*46%*	*82%*	*55%*	***64%***	***65%***
Pre-Alps	SZ	15	64.2	48.0	118.1	**230.3**	238.2	60.0	181.4	**479.6**	6.6
	OW	12	36.2	80.8		**116.9**	152.0	140.7		**292.7**	4.1
	NW	6	31.7	14.4		**46.1**	124.0	31.3		**155.3**	2.4
	GL	38	108.5	382.0	1140.0	**1630.5**	426.9	523.9	7.8	**958.6**	12.3
	ZG	7	7.9		14.5	**22.4**	40.2		30.4	**70.6**	0.5
	FR	13	49.3	124.3	164.4	**338.0**	157.5	388.4	62.5	**608.4**	10.7
	AI	1	1.7	2.5		**4.2**	3.1	7.7		**10.8**	0
	Subtotal	**92**	**299.4**	**652.0**	**1437.0**	**2388.4**	**1142.0**	**1152.0**	**282.1**	**2576.1**	**36.6**
	share CH	*14%*	*7%*	*8%*	*47%*	***16%***	*7%*	*7%*	*18%*	***7%***	***7%***
Bern and Vaud	BE	71	315.1	863.5	437.0	**1615.6**	1563.2	1729.9	39.3	**3332.3**	44.1
	VD	24	173.3	28.9	255.6	**457.9**	709.2	36.7	97.2	**843.0**	9.8
	Subtotal	**95**	**488.4**	**892.4**	**692.6**	**2073.5**	**2272.3**	**1766.5**	**136.5**	**4175.3**	**53.9**
	share CH	*15%*	*12%*	*11%*	*22%*	***14%***	*13%*	*10%*	*9%*	***12%***	***10%***
Plateau and Jura	ZH	14	79.7		48.4	**128.1**	491.91		101.2	**101.2**	8.9
	LU	9	8.5			**8.5**	52.7			**52.7**	0.7
	SO	9	87.7			**87.7**	545.2			**545.2**	8.2
	BS	0	49.5			**49.5**	269.6			**269.6**	3.6
	BL	10	53.6			**53.6**	303.0			**303.0**	3.4
	SH	4	42.5		5.0	**47.5**	279.6			**279.6**	4.1
	AR	3	10.8			**10.8**	23.4			**23.4**	0.5
	SG	49	66.8	88.2	274.3	**429.3**	260.9	179.8	175.9	**616.6**	8
	AG	29	542.2			**542.2**	3242.6			**3242.6**	49.6
	TG	12	12.1			**12.1**	69.3			**69.3**	0.2
	NE	11	33.5			**33.5**	128.8			**128.8**	1.9
	GE	4	136.5			**136.5**	647.6			**647.6**	9.7
	JU	5	7.4			**7.4**	36.4			**36.4**	0.1
	Subtotal	**159**	**1130.8**	**88.2**	**327.7**	**1546.7**	**5859.2**	**179.8**	**277.1**	**6316.1**	**98.9**
	share CH	*25%*	*28%*	*1%*	*11%*	***10%***	*34%*	*1%*	*18%*	***18%***	***18%***
TOTAL	**CH**	**638**	**4053.2**	**8151.7**	**3089.5**	**15,294.4**	**17,057.8**	**17,220.6**	**1556.6**	**35,835.1**	**543.6**
	% share		*27%*	*53%*	*20%*	***100%***	*48%*	*48%*	*4%*	***100%***	

Storage capacity 8'835 GWh

Note: The cantons of Bern (BE) and Vaud (VD) are separated here, since they both cover areas belonging to the Alps, Pre-Alps, Plateau and Jura. Data source: [15,42]. [a] For the abbreviations of the cantons (official signs), see Table A2.

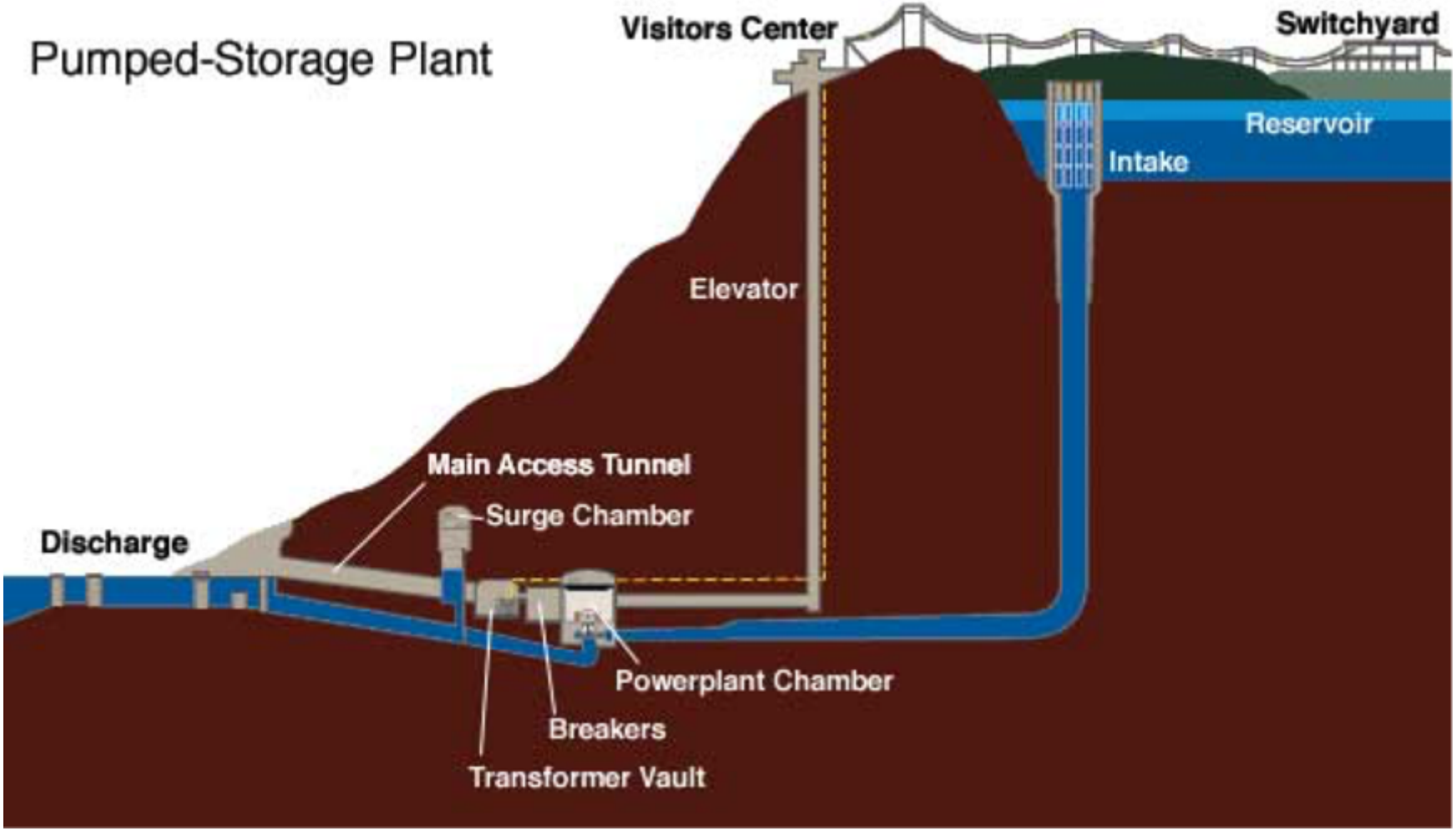
9.5. PUMPED STORAGE HYDROPOWER PLANT

Pumping station Oberaar-Grimsel:
4 Turbine with each 75 MW water flow 90 m^3/s
4 Pumps with each 83 MW water flow 78 m^3/s

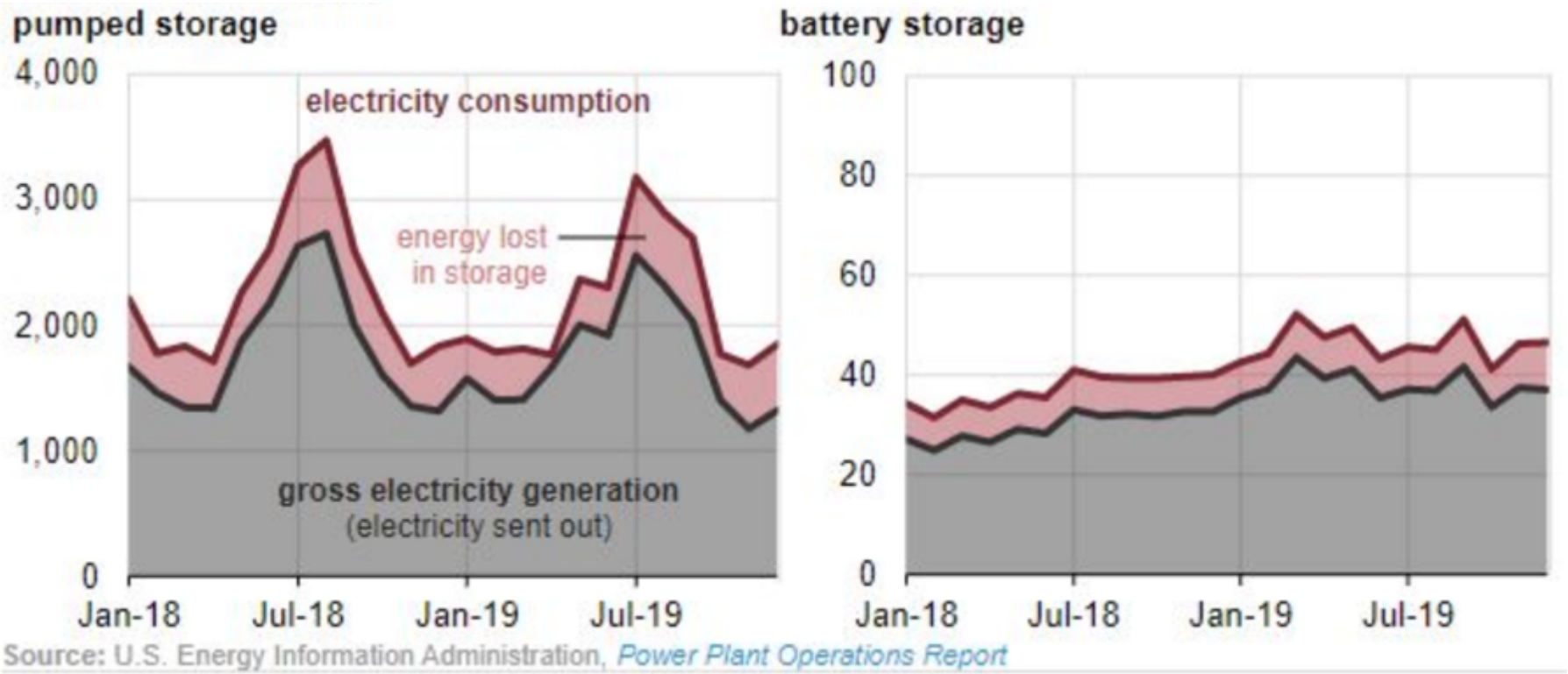


1 From and to pressure tube (Oberaarsee),
2 Distribution tube,
3 Ball valve,
4 Francis turbine,
5 Reduction valve,
6 From and to the storage lake (Grimselsee),
7 Motor-Generator
8 Pumps

9.5.1. PUMPED STORAGE HYDROPOWER PLANT



9.5.2. EFFICIENCY OF PUMPED HYDROPOWER



Monthly round-trip efficiency, by selected energy storage technology (Jan 2018-Dec 2019) in GWh. Pumped-storage hydroelectric facilities in the U.S. operated with an average monthly round-trip efficiency of 79%, and the utility-scale battery fleet operated at 82%, according to 2019 data from the U.S. Energy Information Administration (EIA).

Ref.: https://www.hydroreview.com/technology-and-equipment/eia-monthly-net-generation-utility-scale-wind-rushes-to-11-percent-of-u-s-mix/

Question:

Calculate the amount of water to be stored for 1 kWh of electricity in a pumped hydropower plant $\Delta h = 500m$. What is the gravimetric and volumetric energy density.

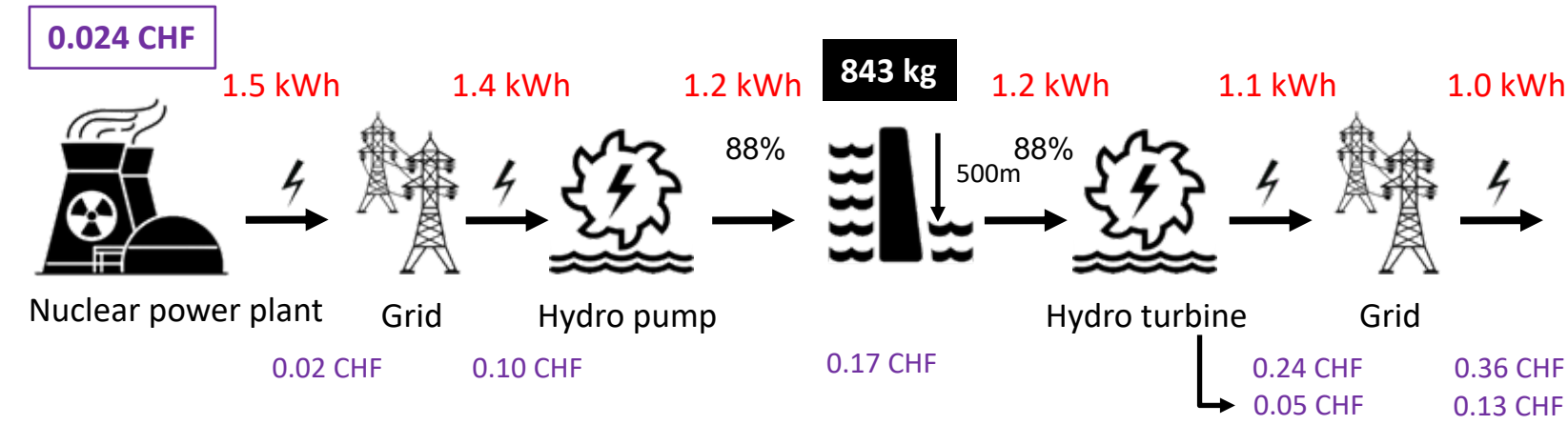
Question:

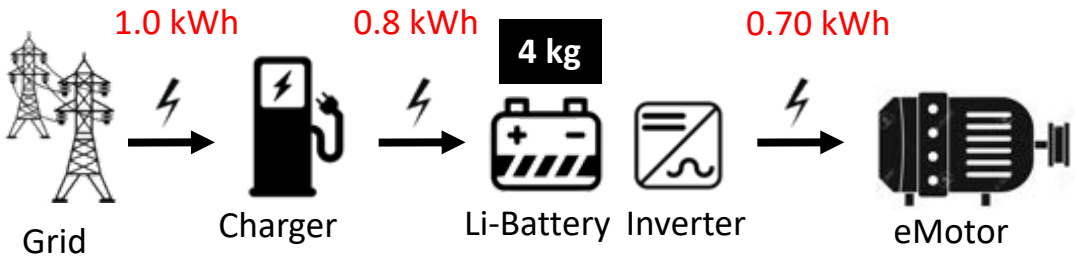
Calculate the amount of water to be stored for 1 kWh of electricity in a pumped hydropower plant. What is the gravimetric and volumetric energy density.

$W = \eta \cdot m \cdot g \cdot \Delta h$ ->
$m = W/(88\% \cdot 9.81 m/s^2 \cdot 500m) = 1000\ J \cdot 3600/(88\% \cdot 9.81 m/s^2 \cdot 500m)$
$m = 834\ kg$

Gravimetric energy density = 1000 Wh/834 kg = 1.2 Wh/kg
Volumetric energy density = 1.2 Wh/L

9.5.3. NUCLEAR POWER STORED BY PUMPED HYDROPOWER



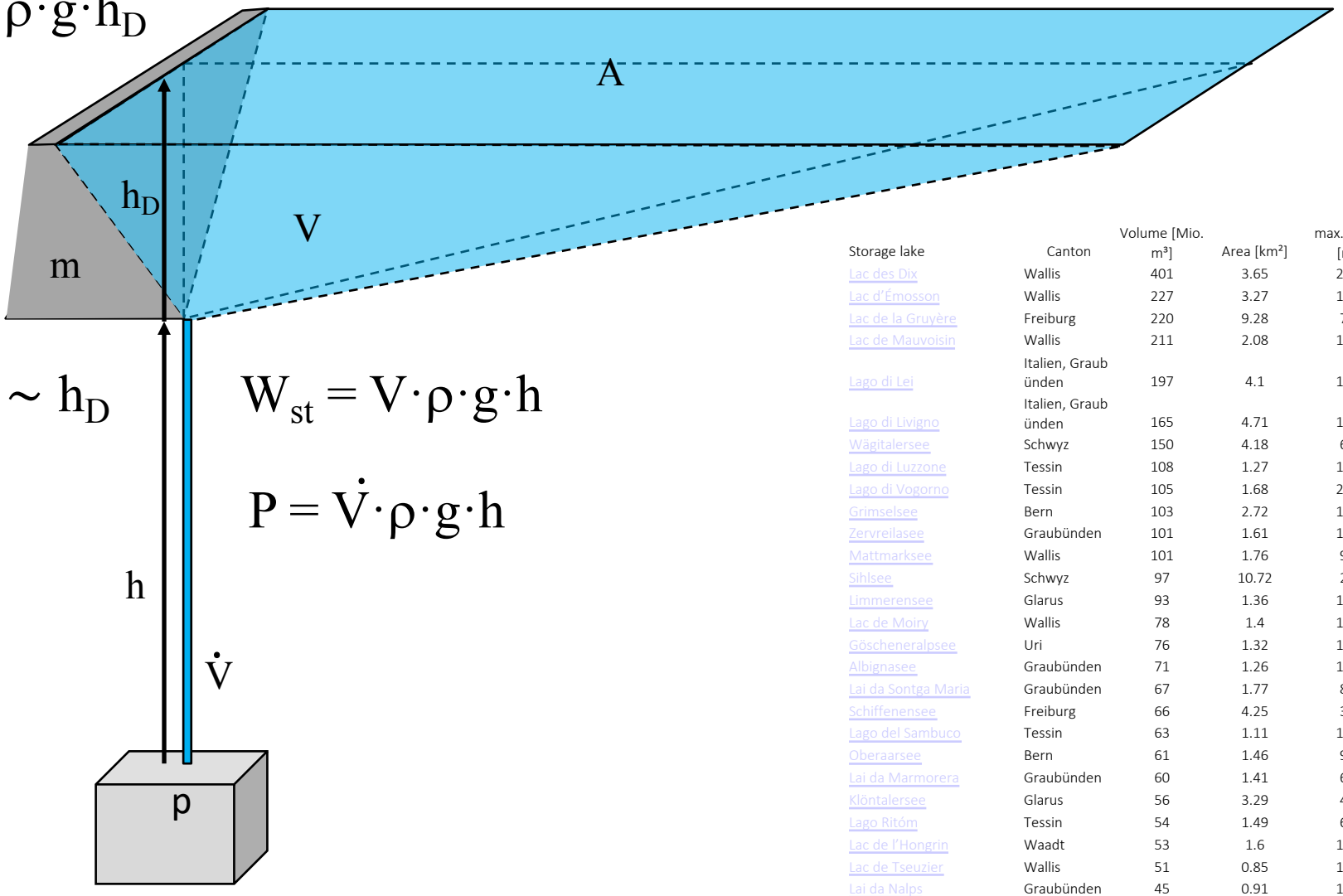


Electricity from Nuc.	0.024 CHF/kWh
Electricity from Nuc. Grid	0.10 CHF/kWh
Electricity Hydro Grid	0.13 CHF/kWh
Electricity Nuc. & Hydro	0.36 CHF/kWh

9.5.4. ENERGY STORAGE, SURFACE AREA AND DAM WEIGHT

$$P_S = I \cdot A \cdot \eta$$

$$p = \rho \cdot g \cdot h_D$$



$$m \sim h_D$$

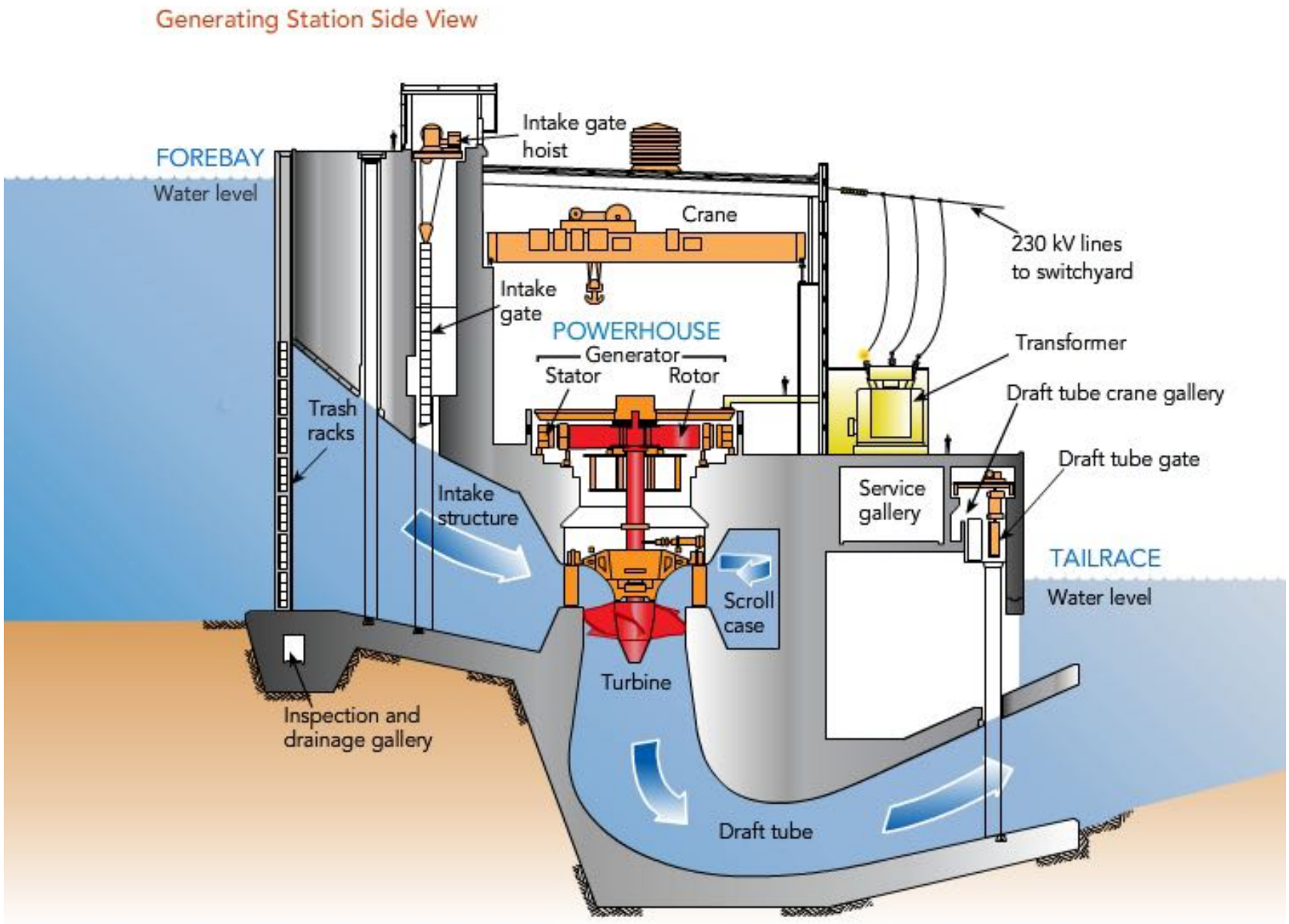
$$W_{st} = V \cdot \rho \cdot g \cdot h$$

$$P = \dot{V} \cdot \rho \cdot g \cdot h$$

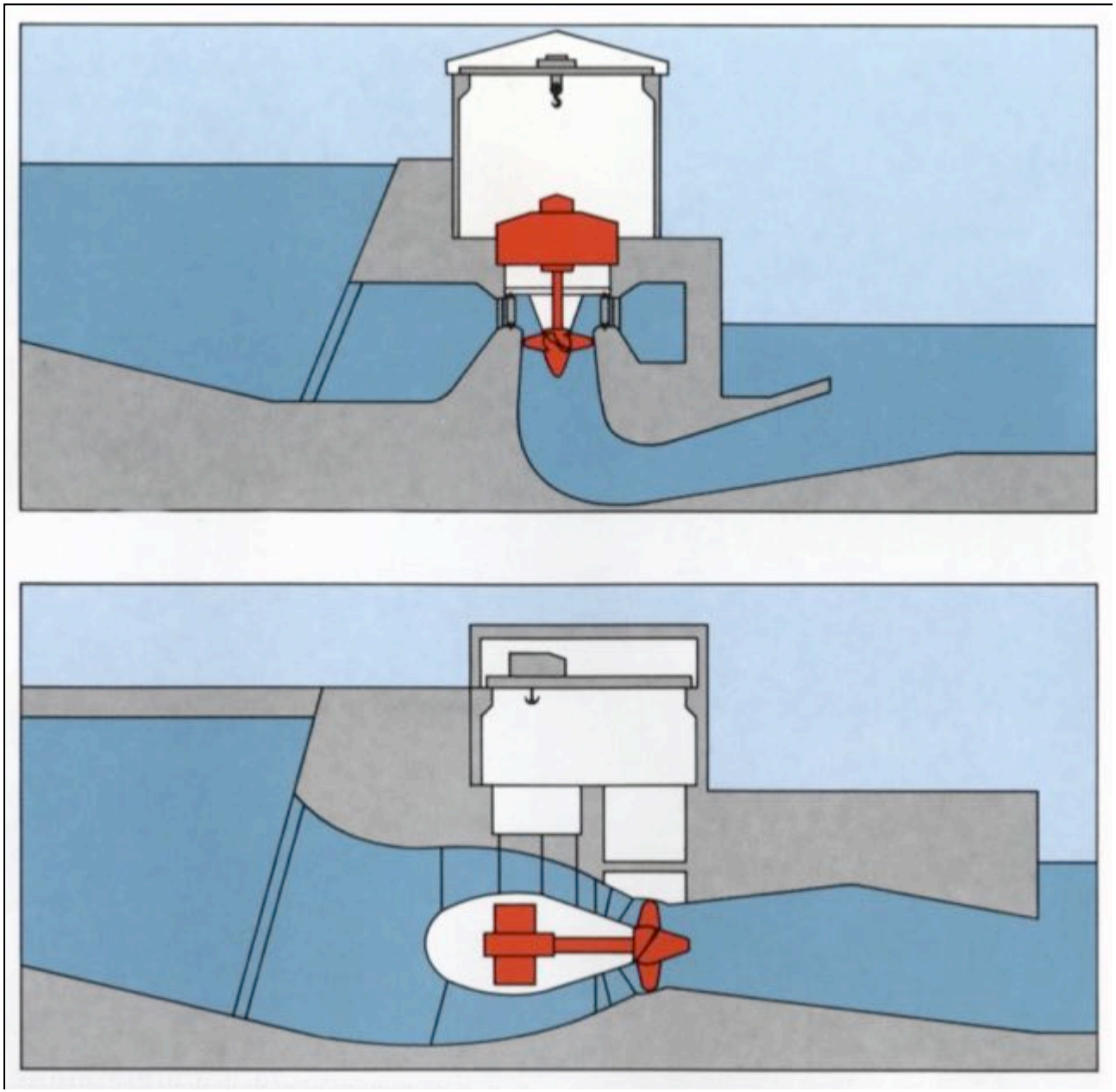
Storage lake	Canton	Volume [Mio. m³]	Area [km²]	max.depth [m]
Lac des Dix	Wallis	401	3.65	227
Lac d'Émosson	Wallis	227	3.27	161
Lac de la Gruyère	Freiburg	220	9.28	75
Lac de Mauvoisin	Wallis	211	2.08	180
Lago di Lei	Italien, Graubünden	197	4.1	133
Lago di Livigno	Italien, Graubünden	165	4.71	119
Wägitalersee	Schwyz	150	4.18	65
Lago di Luzzone	Tessin	108	1.27	181
Lago di Vogorno	Tessin	105	1.68	204
Grimselsee	Bern	103	2.72	100
Zervreilasee	Graubünden	101	1.61	140
Mattmarksee	Wallis	101	1.76	93
Sihlsee	Schwyz	97	10.72	23
Limmerensee	Glarus	93	1.36	122
Lac de Moiry	Wallis	78	1.4	120
Göscheneralpsee	Uri	76	1.32	106
Albignasee	Graubünden	71	1.26	108
Lai da Sontga Maria	Graubünden	67	1.77	86
Schiffenensee	Freiburg	66	4.25	38
Lago del Sambuco	Tessin	63	1.11	124
Oberaarsee	Bern	61	1.46	90
Lai da Marmorera	Graubünden	60	1.41	65
Klöntalersee	Glarus	56	3.29	49
Lago Ritóm	Tessin	54	1.49	69
Lac de l'Hongrin	Waadt	53	1.6	105
Lac de Tseuzier	Wallis	51	0.85	140
Lai da Nalps	Graubünden	45	0.91	122
Lai da Curnera	Graubünden	41	0.81	136
Lac de Salanfe	Wallis	40	1.85	48
Gigerwaldsee	St. Gallen	36	0.71	135
Total		3197	77.88	

Ref.: Rafael M. Almeida, Rafael Schmitt, Steven M. Grodsky, Alexander S. Flecker, Carla P. Gomes, Lu Zhao, Haohui Liu, Nathan Barros, Rafael Kelman & Peter B. McIntyre , "Floating solar power: evaluate trade-offs", Nature Vol 606 9 June 2022 , pp. 246-249

9.6. RIVER HYDROPOWER PLANT



9.6.1. TURBINE HOUSING OF RIVER HYDROPOWER PLANT



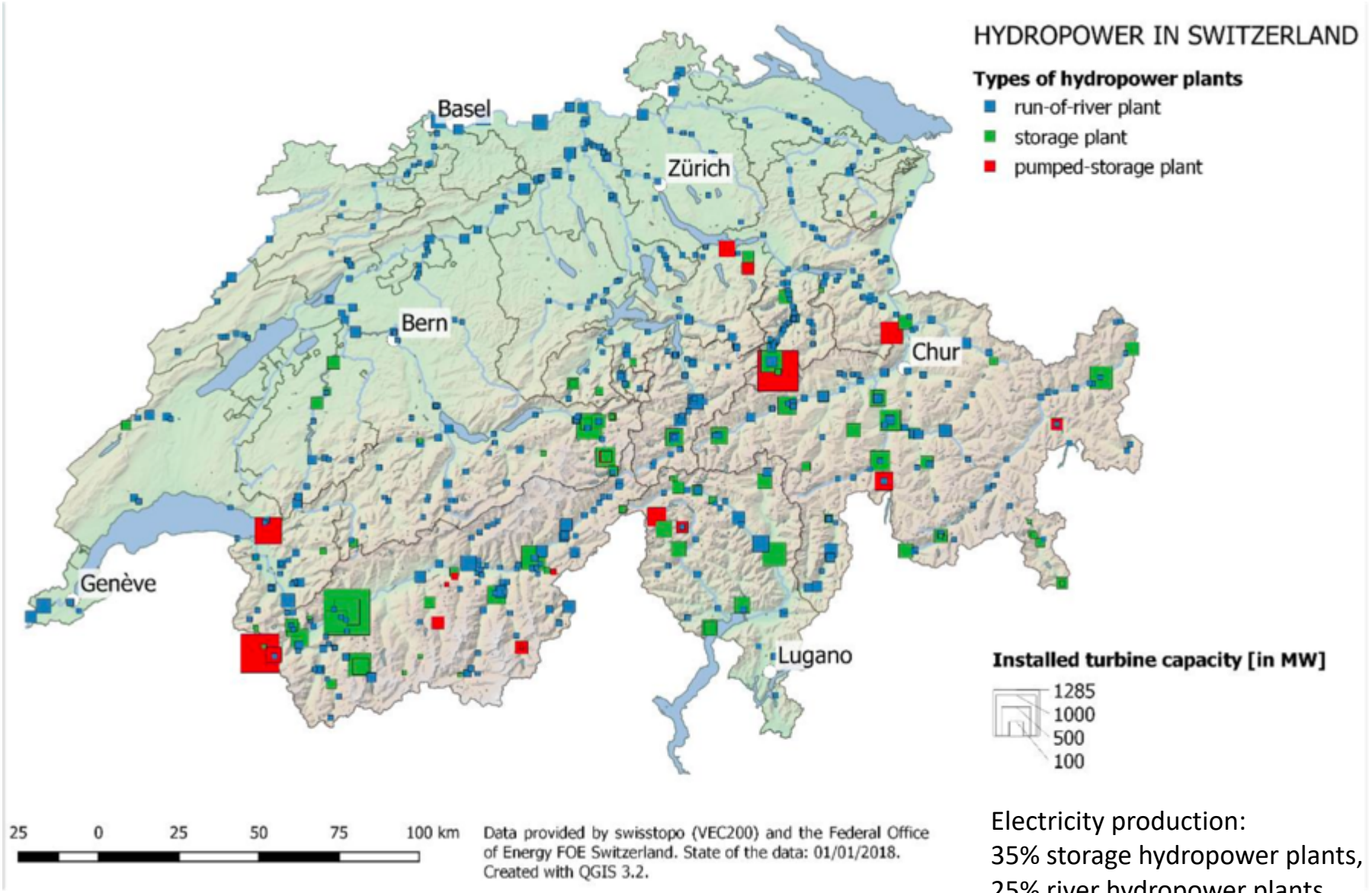
9.6.2. EFFICIENCY OF RIVER HYDROPOWER

Sl. No.	Particulars	Design	Operating		
01	Unit load (MW)	100	100	75	50
	Component efficiencies				
	Units	%	%	%	%
02	Water conductor efficiency	94.36	97.36	96.50	96.54
03	Hydraulic efficiency of turbine	94.64	93.23	90.64	75.18
04	Volumetric efficiency of turbine	99.99	99.94	99.93	99.91
05	Mechanical efficiency	99.40	99.40	99.40	99.40
06	Generator efficiency	98.67	98.35	98.13	96.54
07	Auxiliary efficiency	99.50	99.75	99.64	99.16
	Auxiliary power				
08	Auxiliary power (% of gross generation)	0.50	0.253	0.422	0.836
	Overall system performance				
09	Gross overall efficiency (%)	87.59	86.74	85.32	69.65
10	Net overall efficiency (%)	87.15	88.52	85.01	69.06
11	Specific water consumption ($m^3/s/MW$)	0.452	0.435	0.480	0.624

Table 1 gives the component efficiencies of the hydro power plant at 50 %, 75 % and 100 % load. The drop in operating efficiency per unit drop in load is deduced from the performance data as 0.052 %/MW between 75–100 MW while it is 0.224%/MW between 50–75 MW. Below 50 MW it is around 0.497 %/MW.

Ref.: Siddhartha Bhatt M and Jothibasu S, "Optimization of Annual Energy Generation in run of the River of Hydro Power Plants", The Journal of CPRI, Vol. 8, No. 4, December 2012, pp. 317–328

9.7. HYDROPOWER PLANTS IN SWITZERLAND



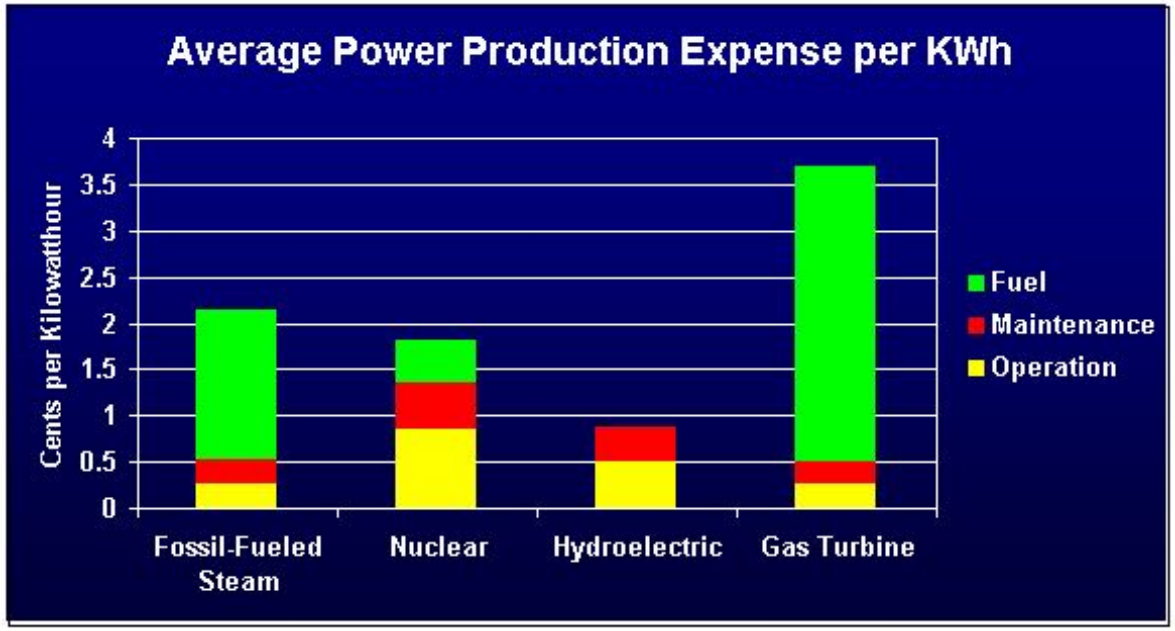
Electricity production:
35% storage hydropower plants,
25% river hydropower plants,
36% nuclear power plants
4% oil fired power plants

9.7.1. COST OF HYDROPOWER ELECTRICITY

Grande Dixence SA
Gravity dam h = 285m, l = 700m, V = 6 Mm^3
Reservoir V = 400 Mm^3
Catchment area 46 km^2, Surface = 3.65 km^2
Commission date 1965
Inst. Power = 2.069 GW
Annual Generation = 2300 GWh
Storage capacity = 1962 GWh

Production = 2103 GWh (2021)
Total cost = 156.2 Mio. CHF
Operational cost 20%
Energy and grid cost 16%
Deductions 25%
Financial cost 16%
Taxes 26%

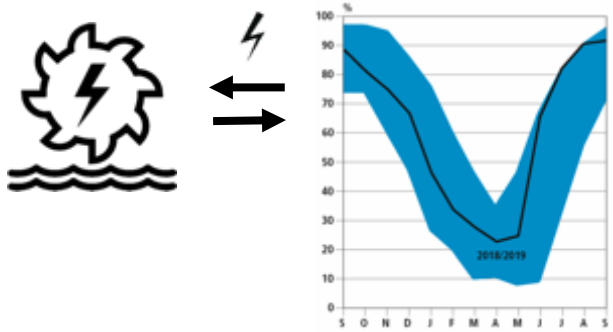
resulting Electricity production cost = 7.43 Rp./kWh

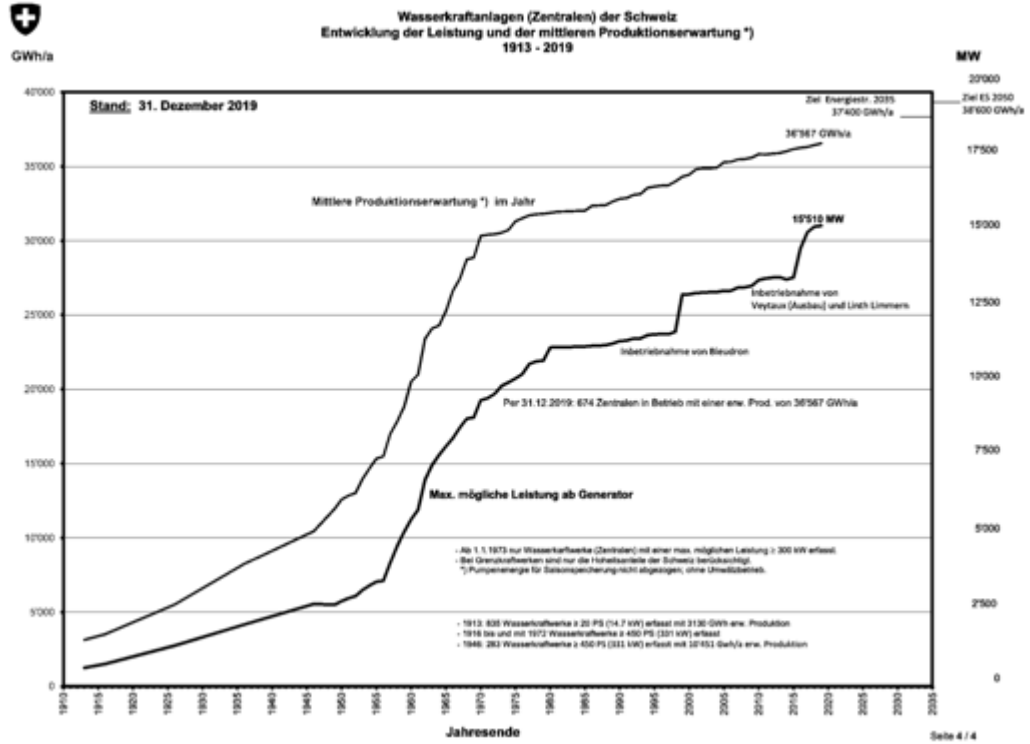


Ref.: Grande Dixence SA, annual report (2021)

Ref.: http://www.wvic.com/content/facts_about_hydropower.cfm

9.7.2. SWISS INSTALLED HYDROPOWER

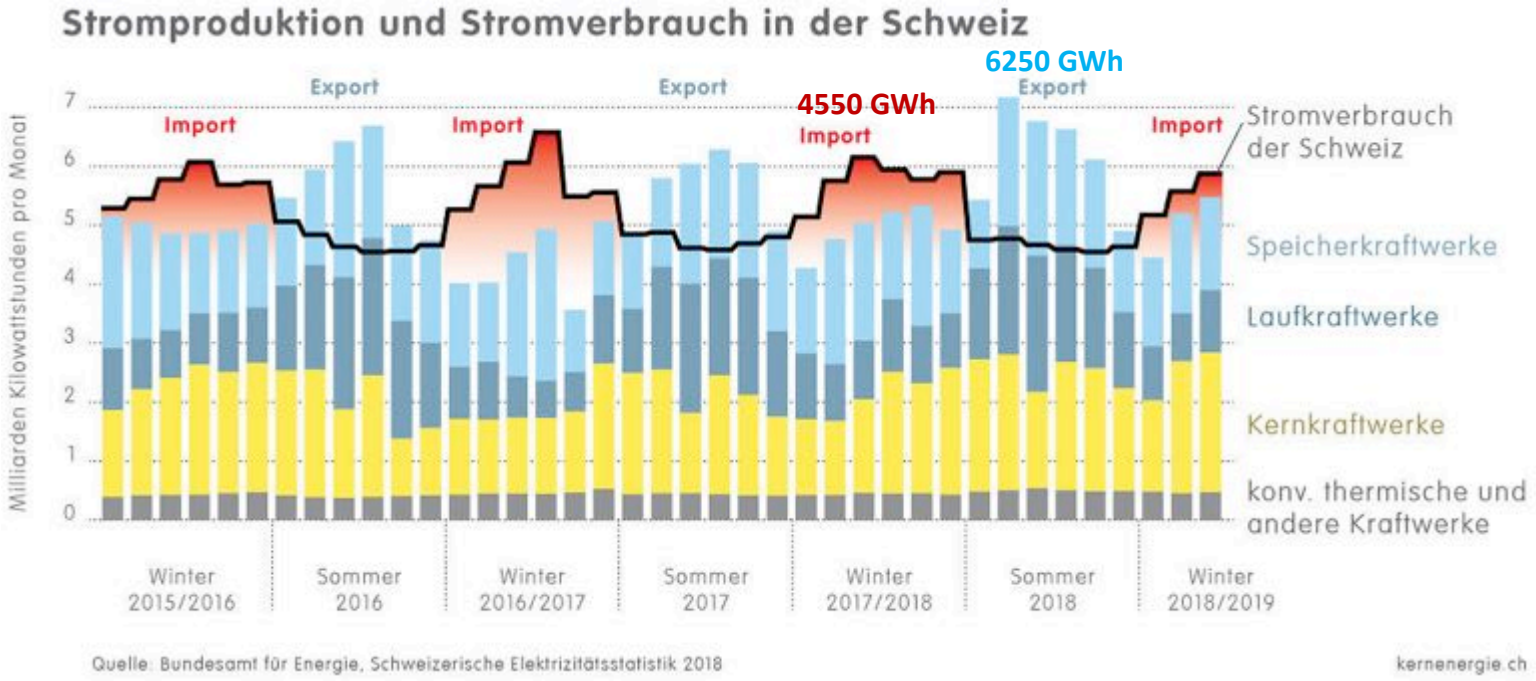


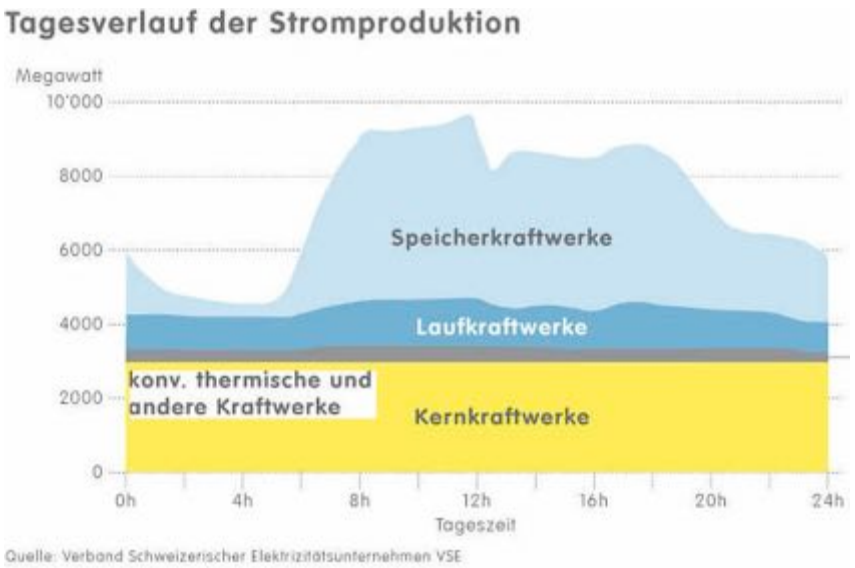


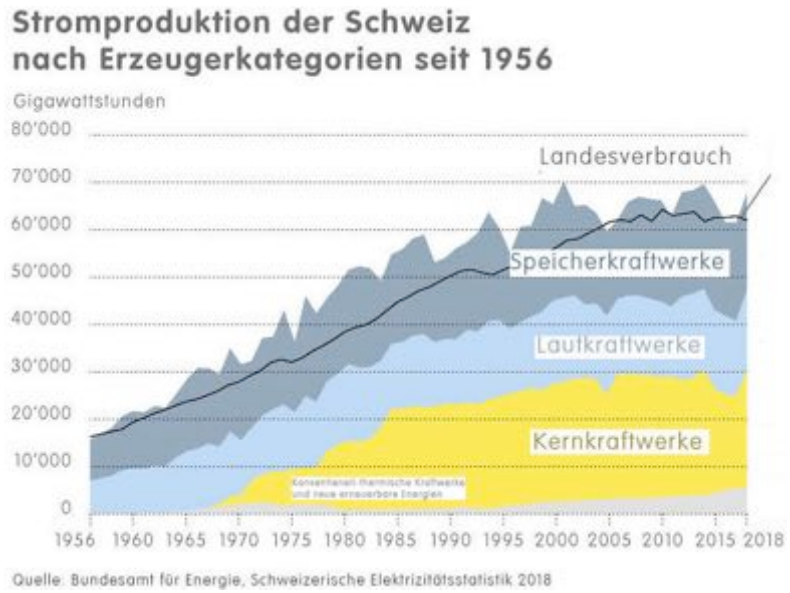
Type	Cost [Cts./kWh]
River	5.63
Storage lake	6.89
Pumped storage	8.23
Total	6.74

Powerstation	Storage capacity [GWh]	Power [MW]	Cost [MCHF]
Grande Dixence	1’962	1’260	1’700
Grimsel	560	1’380	660
Linthal	275	1’439	2’100
Emosson/Nant de Drance	18	900	1’800
TOTAL	8800	8000	8’260

9.7.3. ELECTRICITY PRODUCTION IN SWITZERLAND



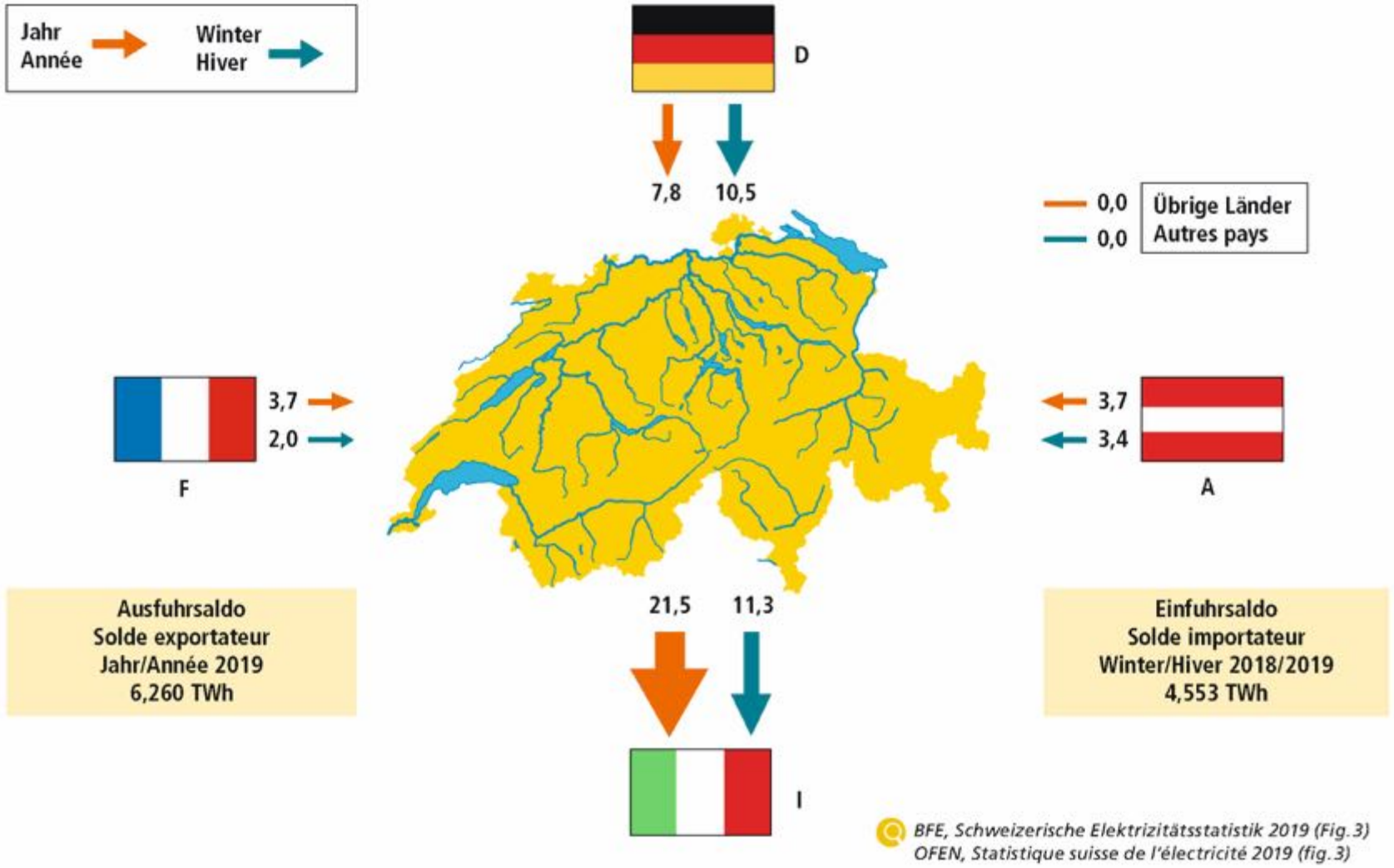




9.7.4. SWISS ELECTRICITY TRADING

Fig. 3 Einfuhr-/Ausfuhr-Saldo 2019 (in TWh), physikalische Werte
Solde importateur/exportateur 2019 (en TWh), valeurs physiques

Electricity total: 58 TWh/year



BFE, Schweizerische Elektrizitätsstatistik 2019 (Fig. 3)
OFEN, Statistique suisse de l'électricité 2019 (fig. 3)

9.8. GLOBAL HYDROPOWER PLANTS

Power Plant	Country	Year	Power [GW]	Power [TWh·a^{-1}]
Yang Tse	P.R. China	2003	18.1	159
Itaipu	Brasil	1983	12.5	110
Guri	Venezuela	1986	10.2	90
Grand Coulee	USA	1942	6.5	57
Sajan	Russia	1978	6.4	56
Krasnojarsk	Russia	1967	5.9	52
La Grand 2	Canada	1979	5.2	46
Churchill F	Canada	1971	5.1	45
Bratsk	Russia	1961	4.4	39
Ust Urimsk	Russia	1977	4.2	37
Tucurui	Brasil	1984	3.9 (7.2*)	34 (63*)
Cabora Bassa	Mozambic	1977	2.4 (7.2*)	21 (63*)
Eisernes Tor	Serbia	1970	2.0 (2.6*)	18 (23*)

9.8.1. PHOTOS OF HYDROPOWER PLANTS

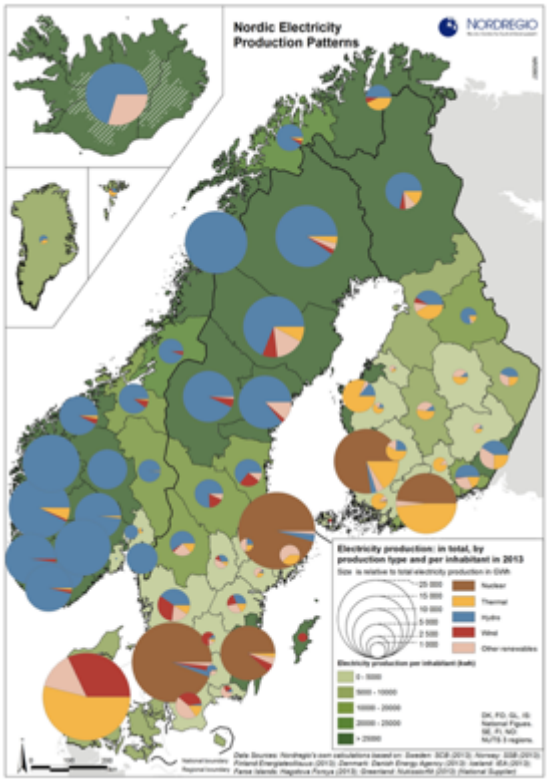
Three Gorges Hydroelectric Power Plant,
Water Resource: Yangtze River

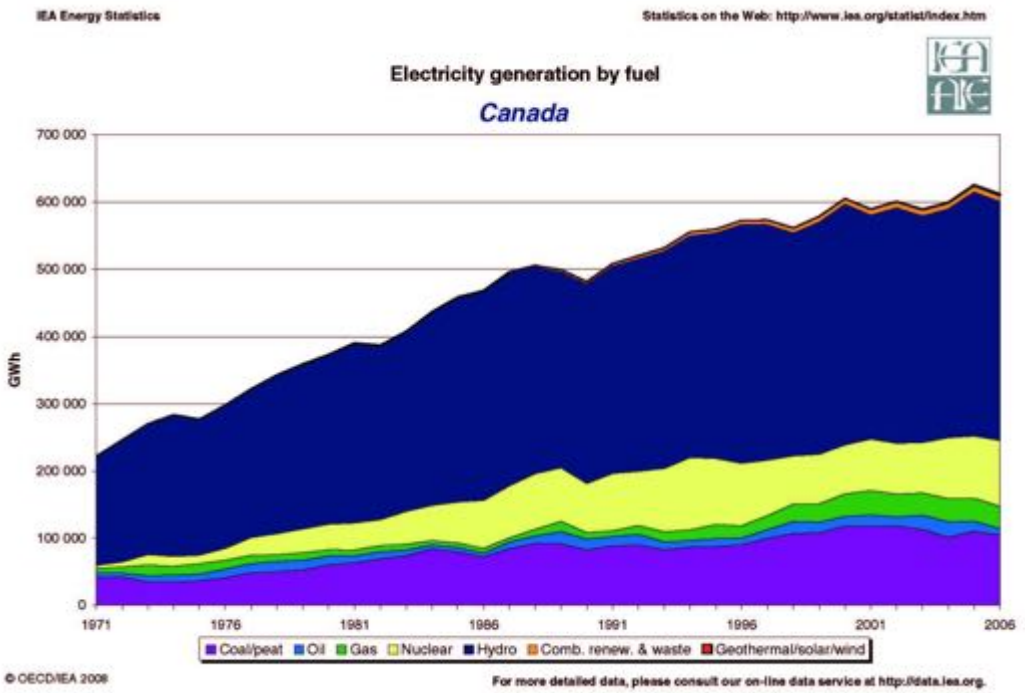
Itaipu Hydroelectric Power Plant,
Water Resource: Parana River

Guri Hydroelectric Power Plant,
Water Resource: Caroni River

Tucurui Hydroelectric Power Plant,
Water Resource: Tocantins River

9.8.2. HYDROPOWER IN NORWAY AND CANADA

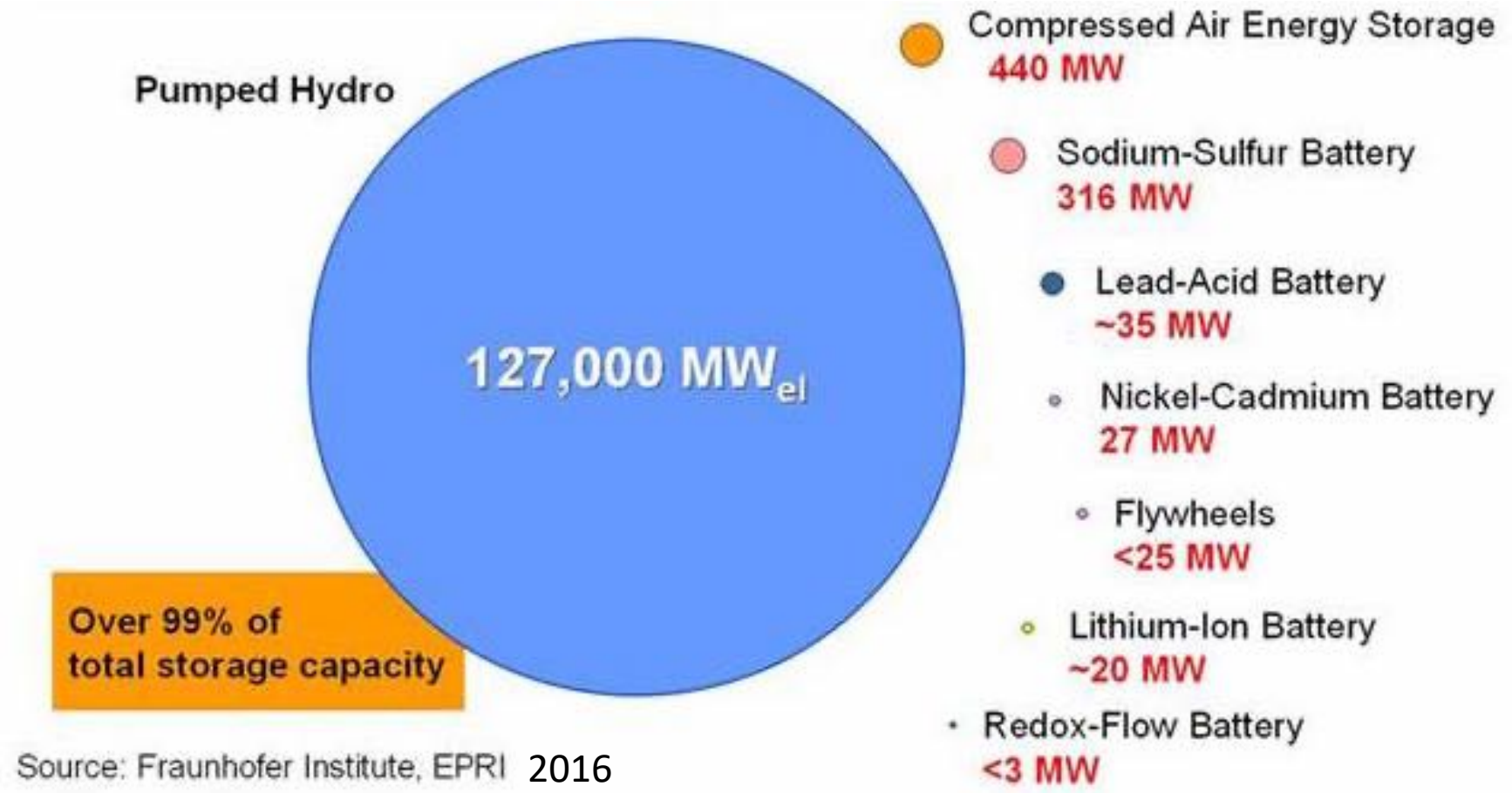




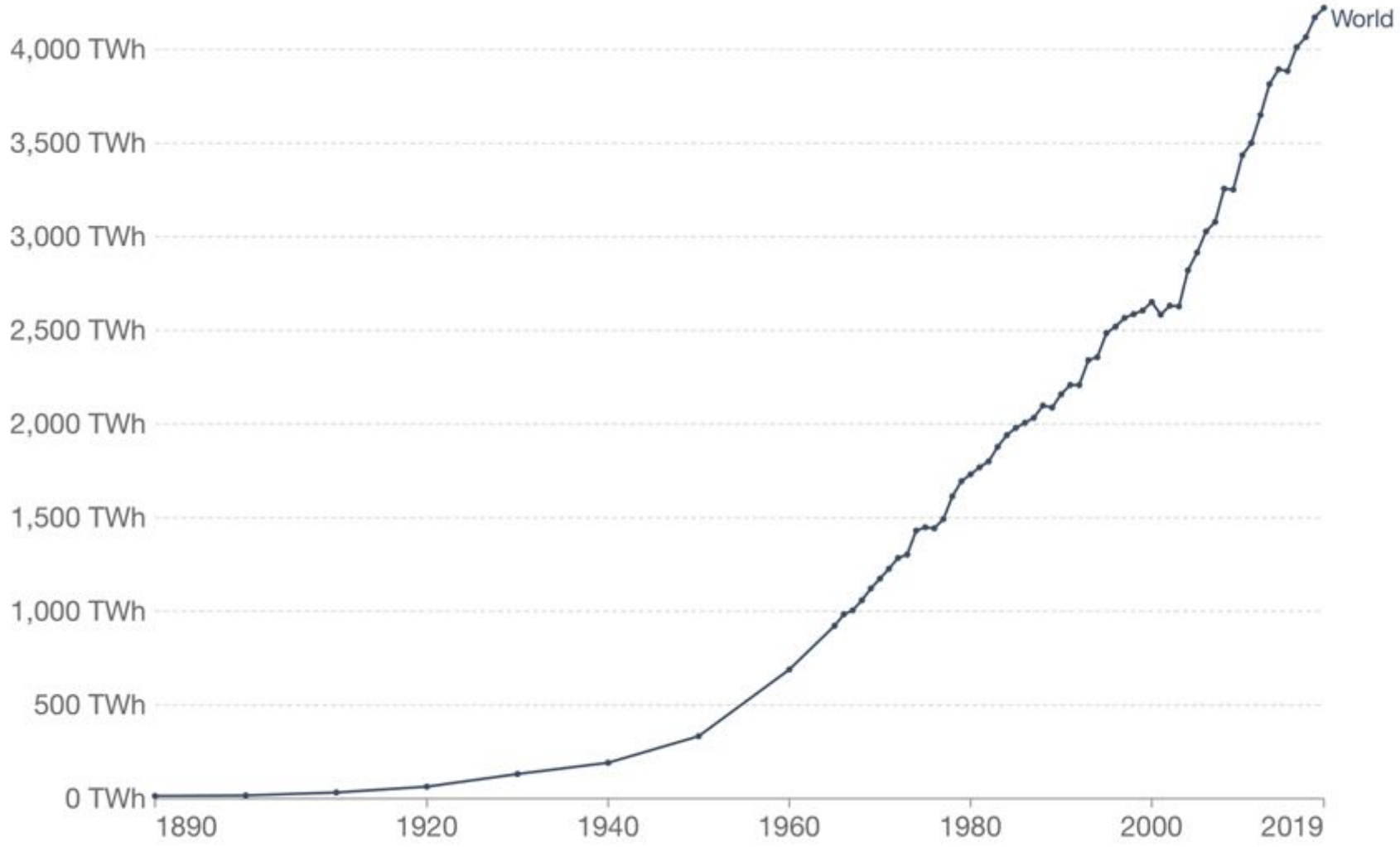
At the beginning of 2021, there were 1681 hydropower plants in Norway, with a combined installed capacity of 33 TW. In a normal year, the Norwegian hydropower plants produce 136.4 TWh, which is 90 % of Norways total electricity production.

In 2018, Canada produced 647.7 TWh of electricity. More than half of the electricity in Canada (61%) is generated from hydro sources. The remainder is produced from a variety of sources, including natural gas, nuclear, wind, coal, biomass, solar, and petroleum.

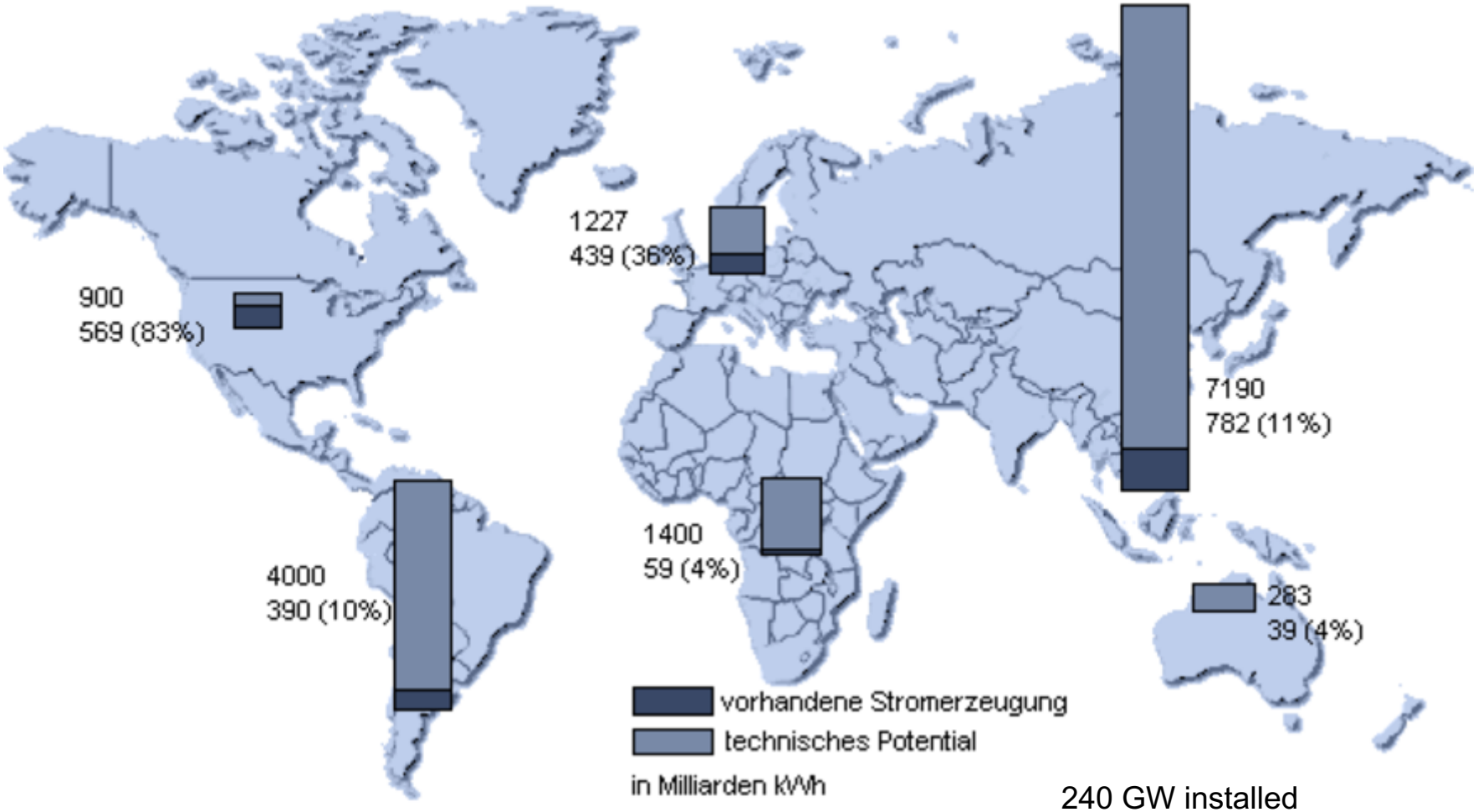
9.8.3. WORLDWIDE INSTALLED STORAGE POWER FOR ELECTRICITY



9.8.4. ANNUAL GLOBAL HYDROPOWER PRODUCTION



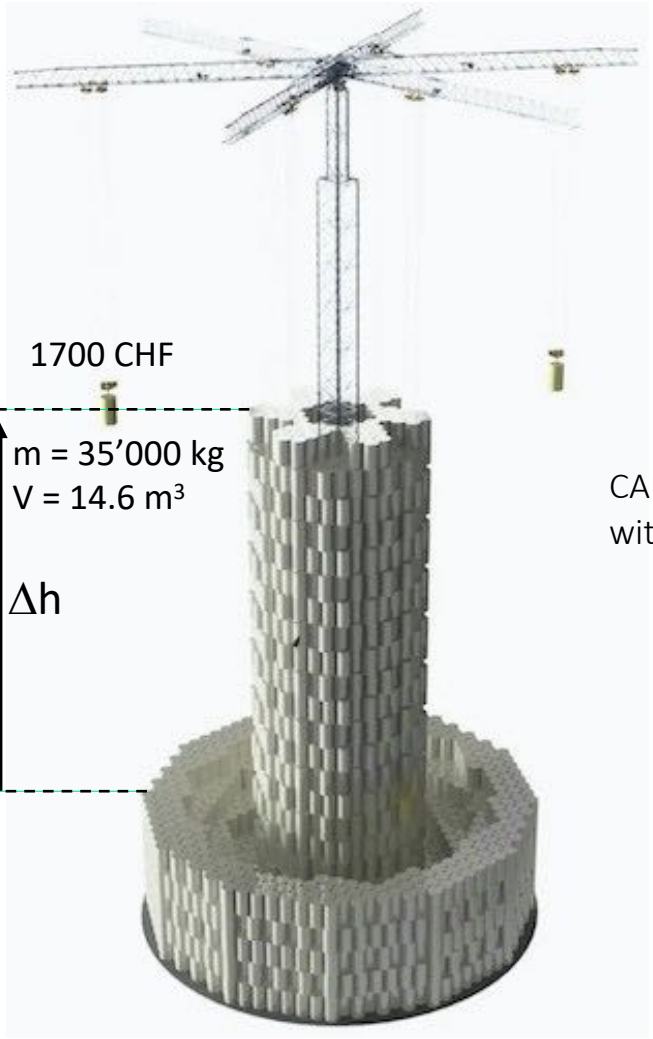
9.8.5. INSTALLED AND PLANNED HYDROPOWER STATIONS (2000)



240 GW installed
1500 GW technical potential

9.9. ENERGY STORAGE TOWER

Energy Vault's Commercial Demonstration Unit energy storage tower in Castione, Switzerland.
Photo: Energy Vault



CAPEX: 0.5 CHF/kWh
without crane

η = 80%

$E_{pot} = m \cdot g \cdot h$

$W = \eta \cdot m \cdot g \cdot h$

Energy density

$W/V = 0.8 \cdot g \cdot 2400 kg/m^3 \cdot 0.5 \cdot h_{max} = 0.26 kWh/m^3$

$W/m = 0.8 \cdot g \cdot 0.5 \cdot h_{max} = 0.1 kWh/kg$, $h_{max} = 100m$

Concrete production 72.5 kg CO_2/ t concrete

EXERCISE

1) How many times does the water exchange in the atmosphere per year?

2) Estimate the precipitation in Switzerland per year and the energy potentially in the water.

3) Why is the efficiency of water turbines limited to approx. 90%?

4) Calculate the power of hydro power plant with h = 500 m, and dV/dt = 220 m^3/s.

5) Calculate the power of river hydro power plant with h = 10 m, and dV/dt = 500 m^3/s.