Energy and Environment

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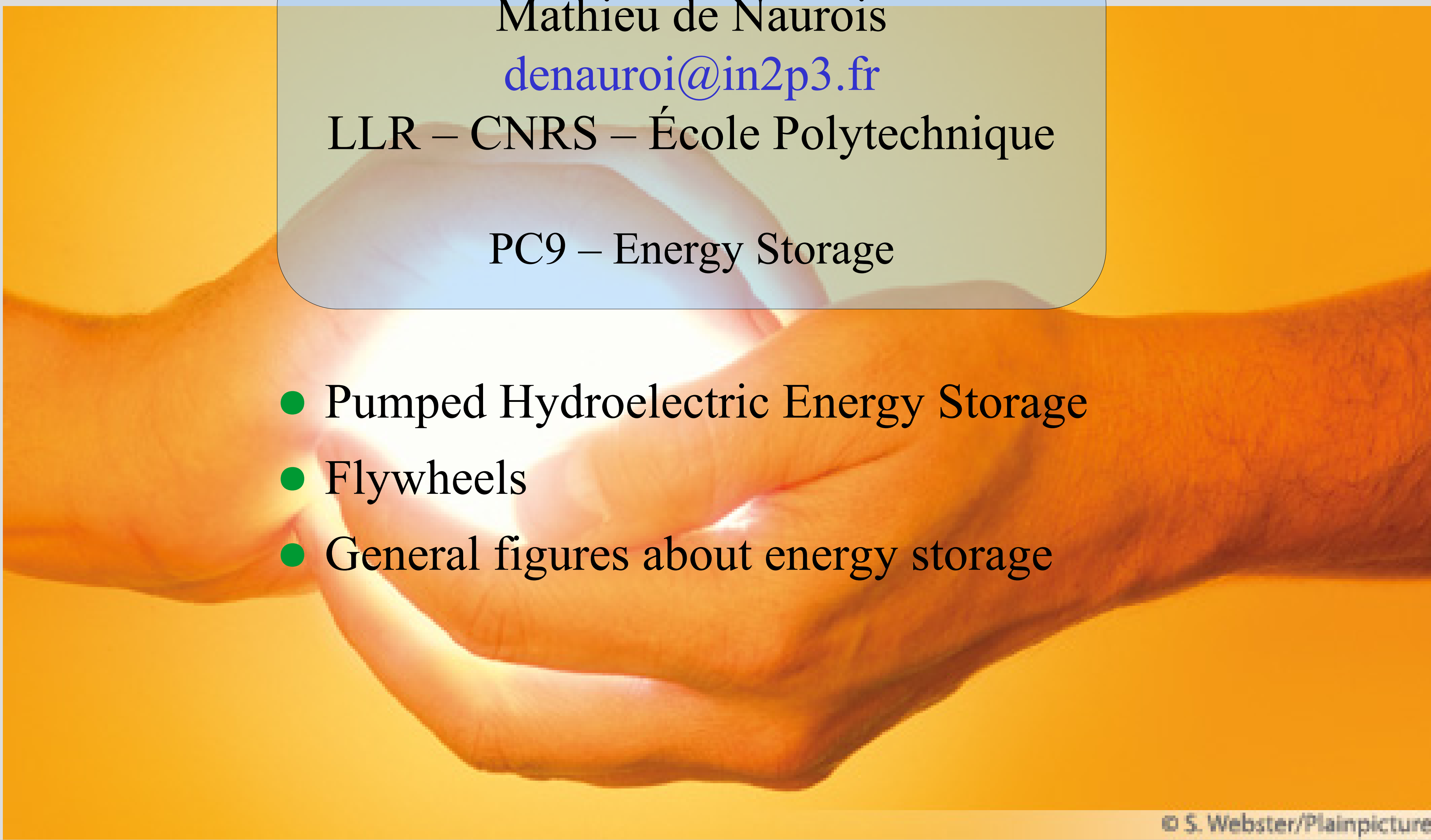
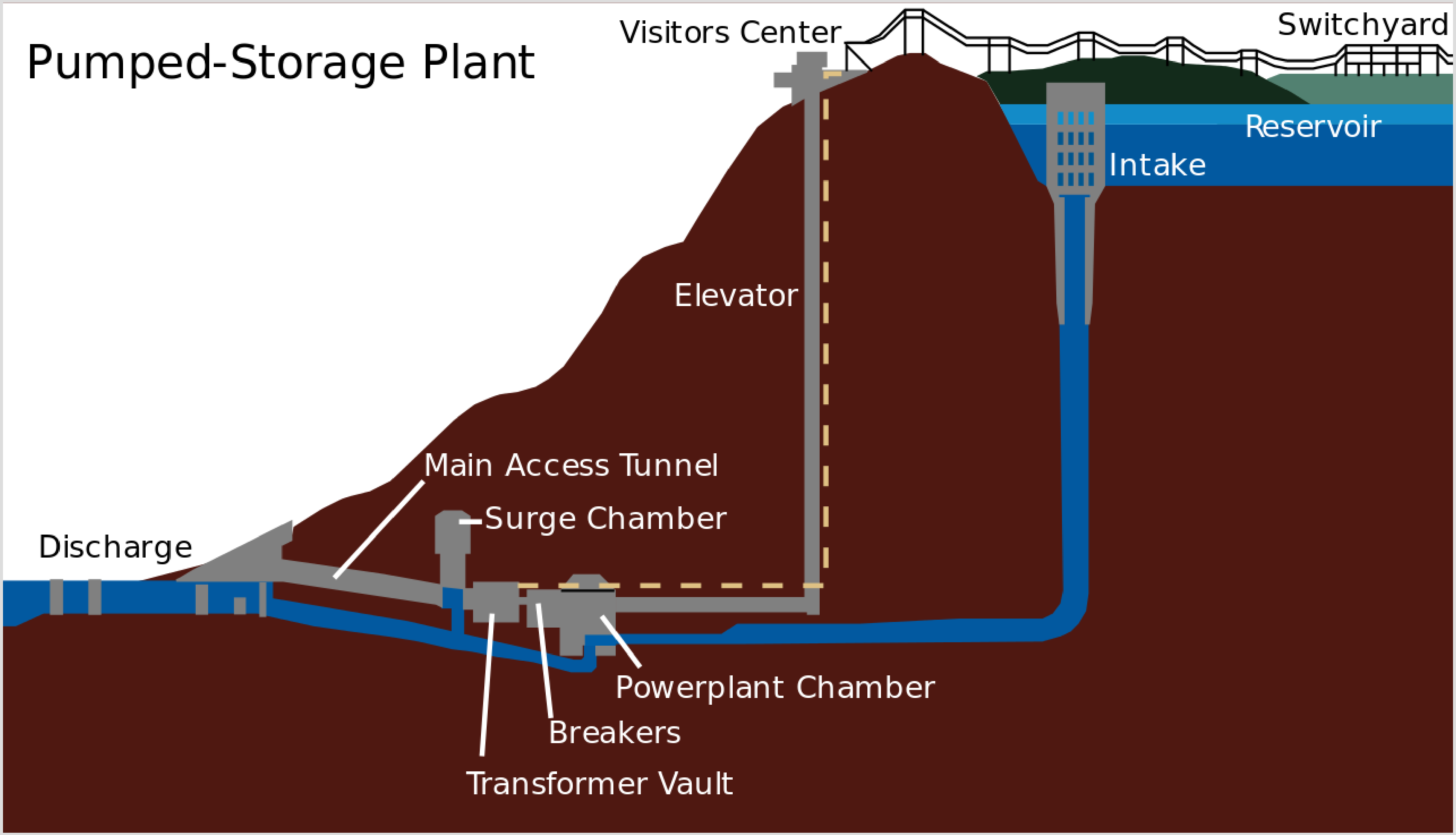
PC9 – Energy Storage

- Pumped Hydroelectric Energy Storage
- Flywheels
- General figures about energy storage

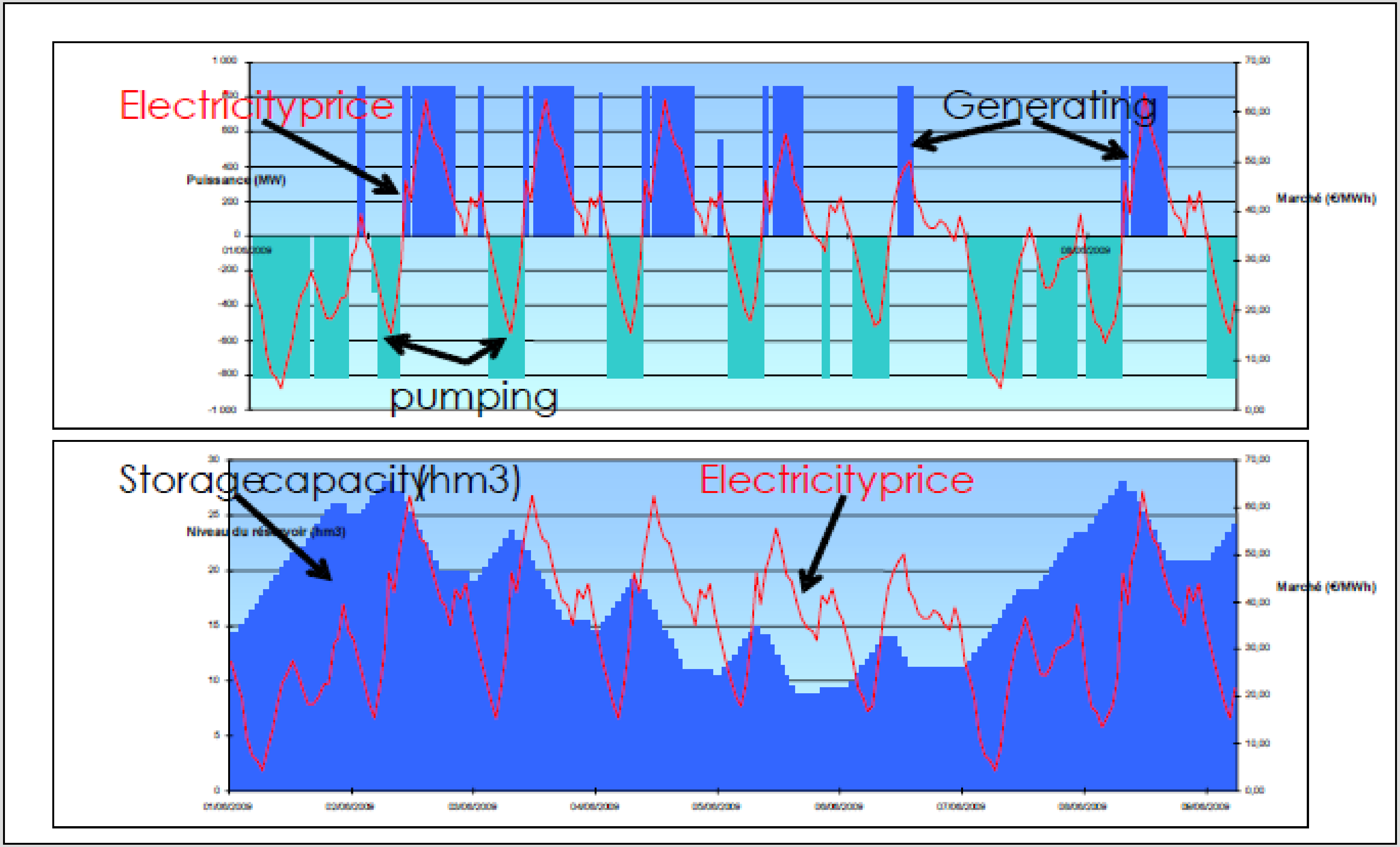


Pumped Hydroelectric Energy Storage – PHES



Typical Operation Mode

- Day/Night variation of demand → Price variation



Pumping Stations Capacities Worldwide

Country	# PHES P > 1000MW in operation	# PHES P > 1000MW in construction (2016)	Remarkable Installations
China	13 – 17900 MW	6 – 8200 MW	Huizhou 2450 MW Guangzhou 2400 MW Tianhuangping 1800 MW
United States	10 – 14300 MW	*	Bath Country 3000 MW Ludington 1870 MW
Japan	7 – 9300 MW	2 – 4400 MW	Kannagawa 2820 MW Okutataragi 1930 MW

Pumping Stations In Europe

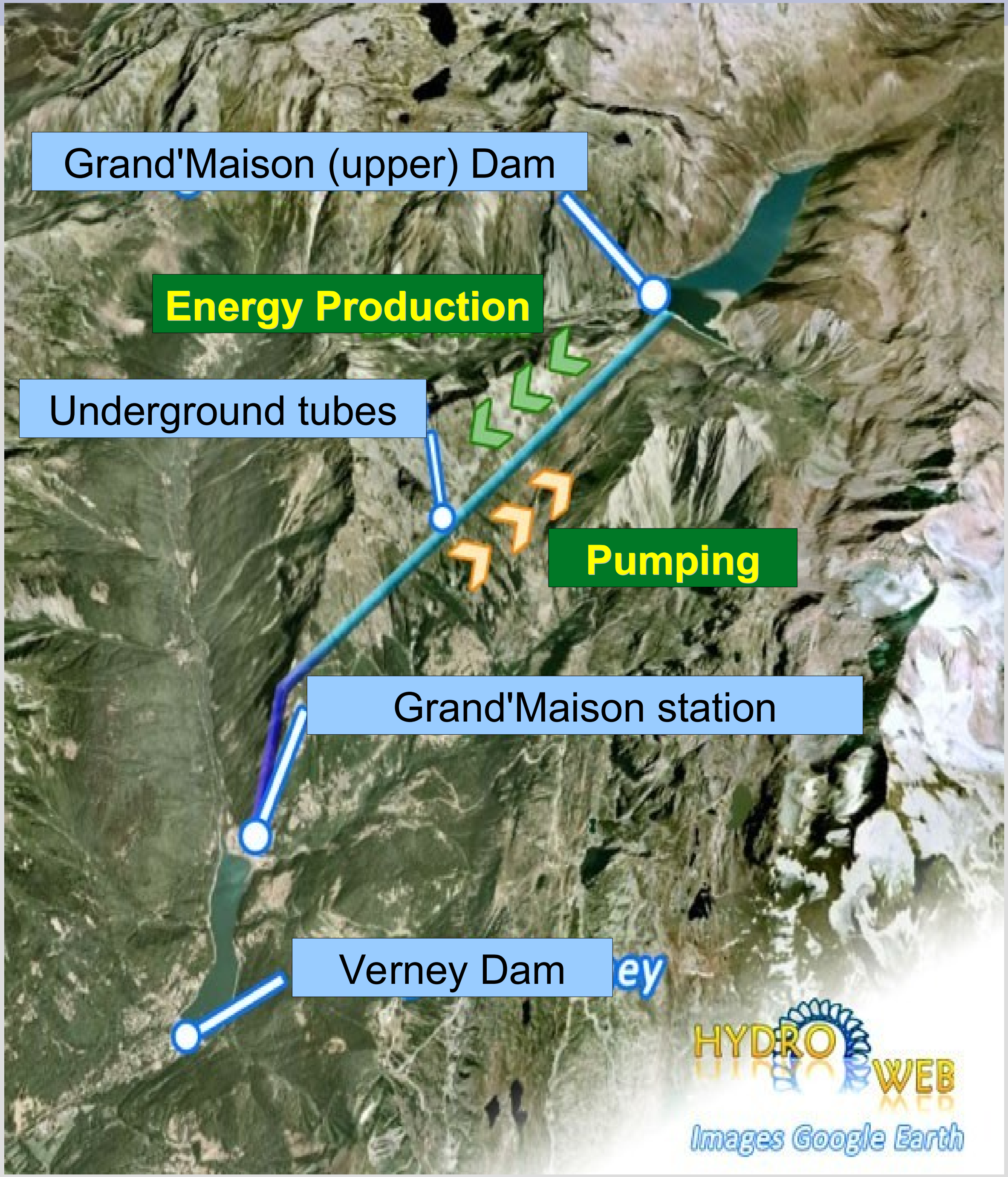
Country	Installed Capacity	Under Construction	Main installations
Germany	2580 MW	1300 MW	Goldisthal 1060 MW Markensbach 1050 MW
Austria	1480 MW	570 MW	Malta-Reisseck 1030 MW
Spain	1600 MW	850 MW	Cortes-LaMuela 910 MW
Portugal	2260 MW	950 MW	Alqueva 520 MW
Italy	4330 MW	*	Roncovalgrande 1060 MW Entracque 1320 MW Edolo 1000 MW
Swizterland	3190 MW	1900 MW	Lintz-Limmern 1000 MW Nant de Drance 930 MW
France	4200 MW	*	Grand Maison 1790 MW Montezic 910 MW Super Bissorte 730 MW
United-Kingdom	2490 MW	*	Dinorewig 1730 MW

https://www.encyclopedie-energie.org/les-stations-de-pompage-step/

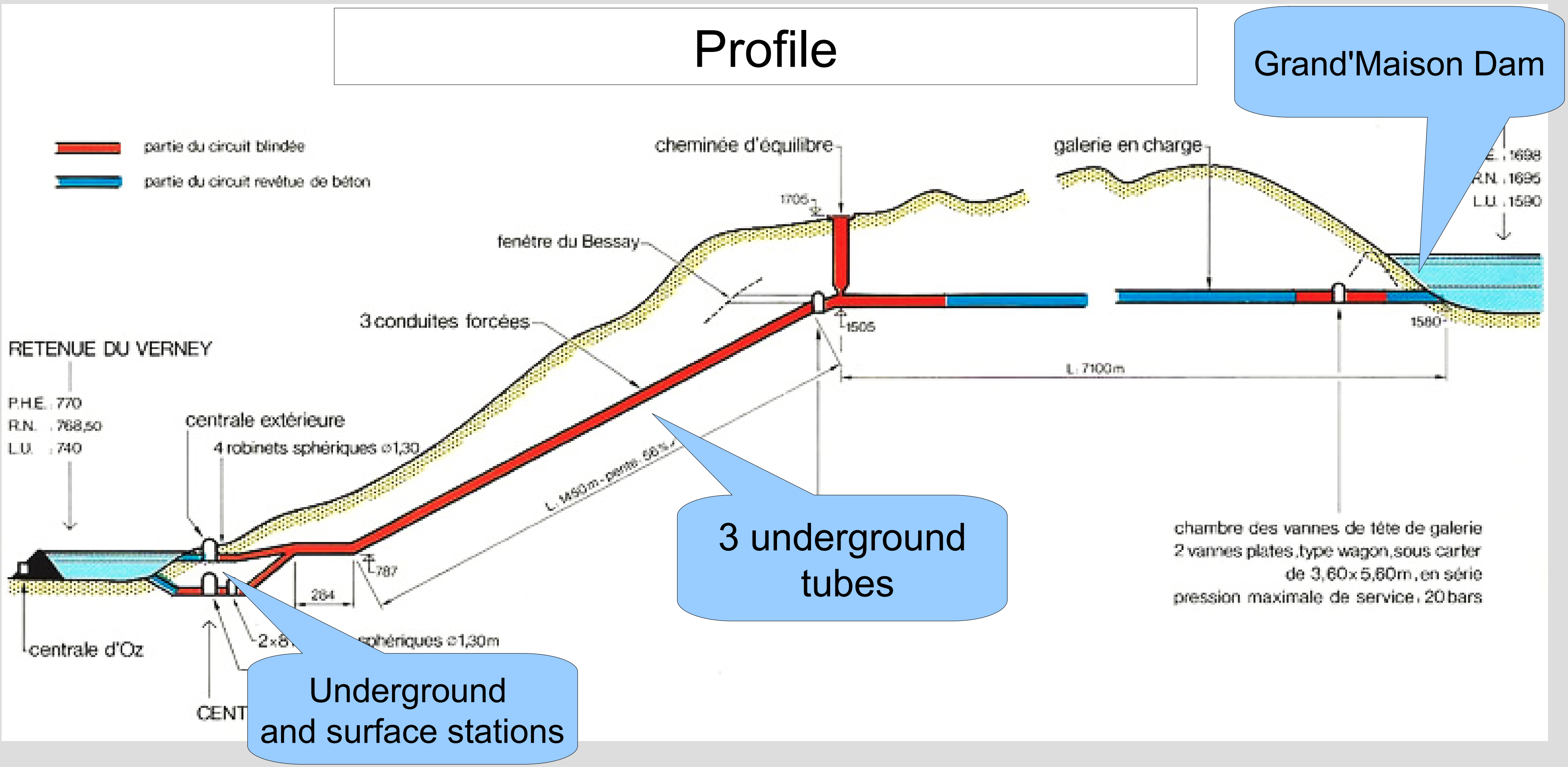
Transfer Pumping Stations in France

- Transfer Pumping Stations in France :
  - Grand Maison (1997), 1070 MW
  - La Coche (1976), 285 MW
  - Le Cheylas (1979), 485 MW
  - Montézic (1983), 920 MW
  - Rance (1966), 240 MW hybrid pumped water-tidal plant
  - Revin (1976), 800 MW
  - Super Bissorte (1978), 720 MW

Pumped Storage Pumping Stations – Grand'Maison



Transfer Pumping Stations – Grand'Maison



Grand'Maison

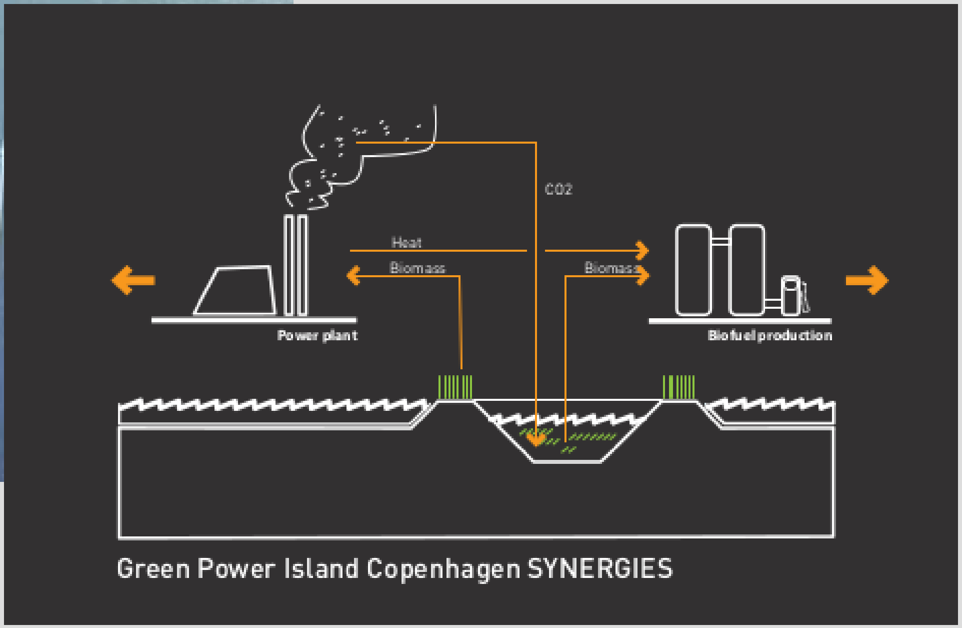
- Upper reservoir

- Lower reservoir

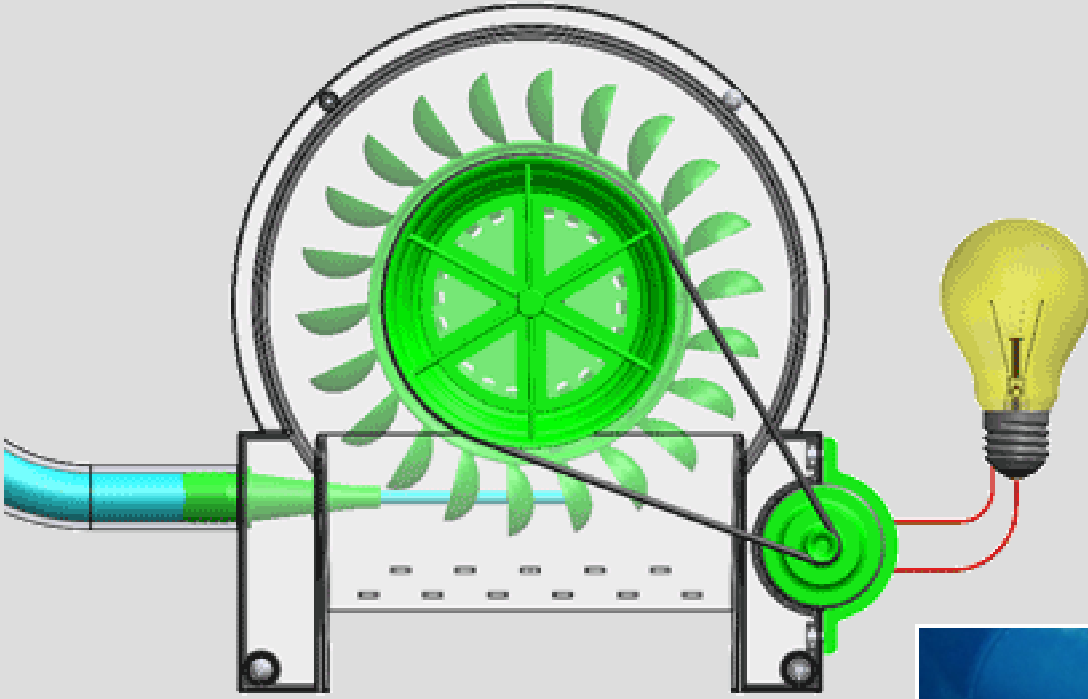
Transfer Pumping Stations on shore

- Okinawa station in Japan

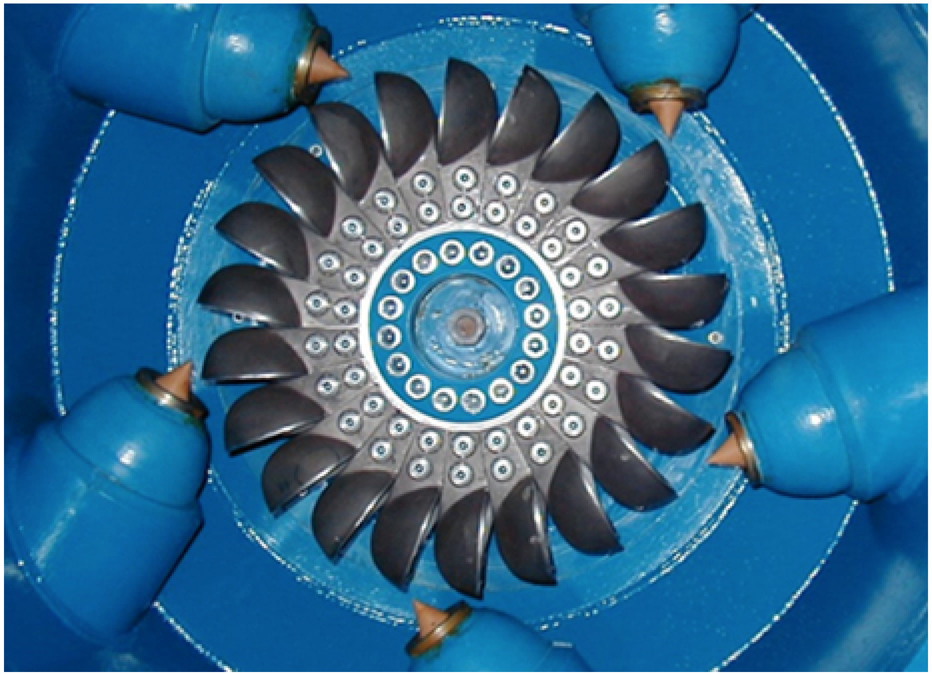
Artificial Atoll Concept - GreenPower Island



Pelton Turbine

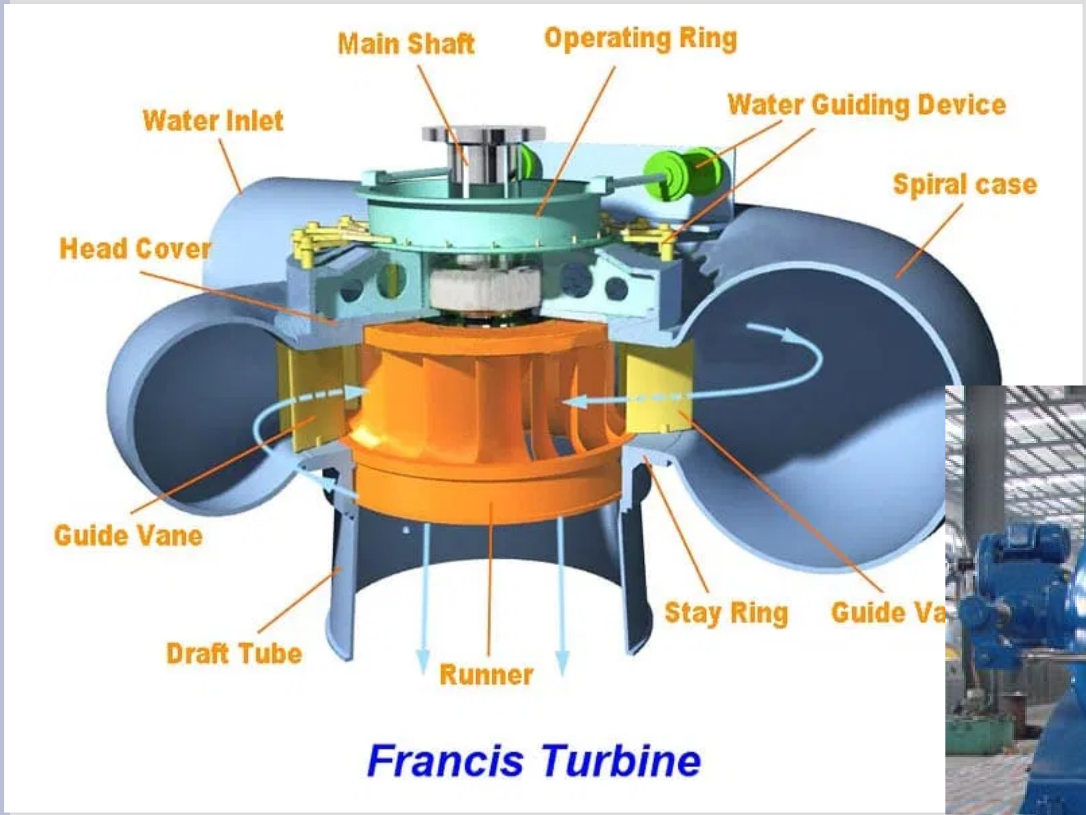


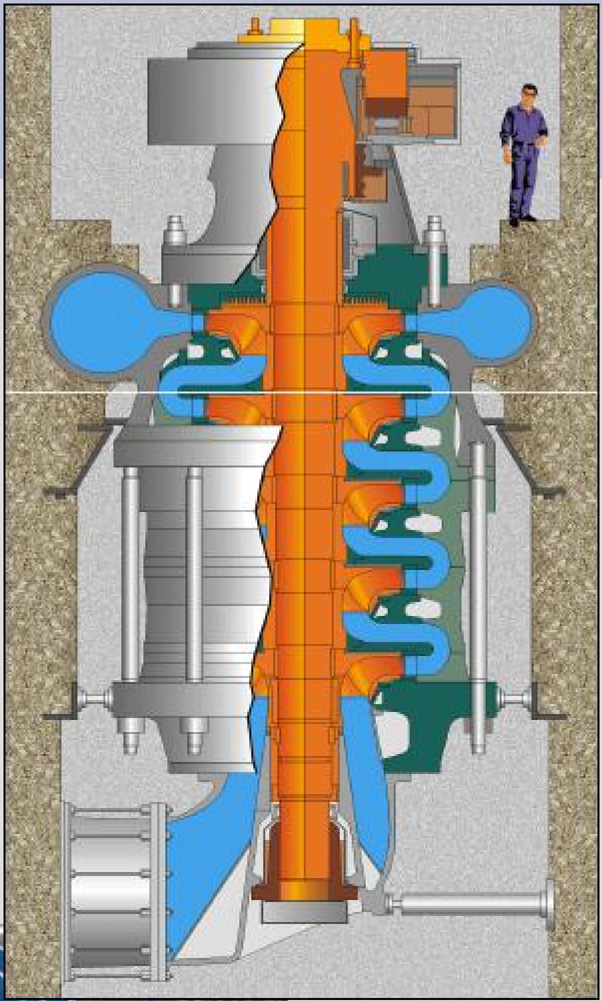
- Adapted for large height
- Yield ~ 90%
- Used only in turbining



Francis Turbine

- Reversible (can act as a pump)
- Yield 80 to 95%
- Used in multi-staged pumps

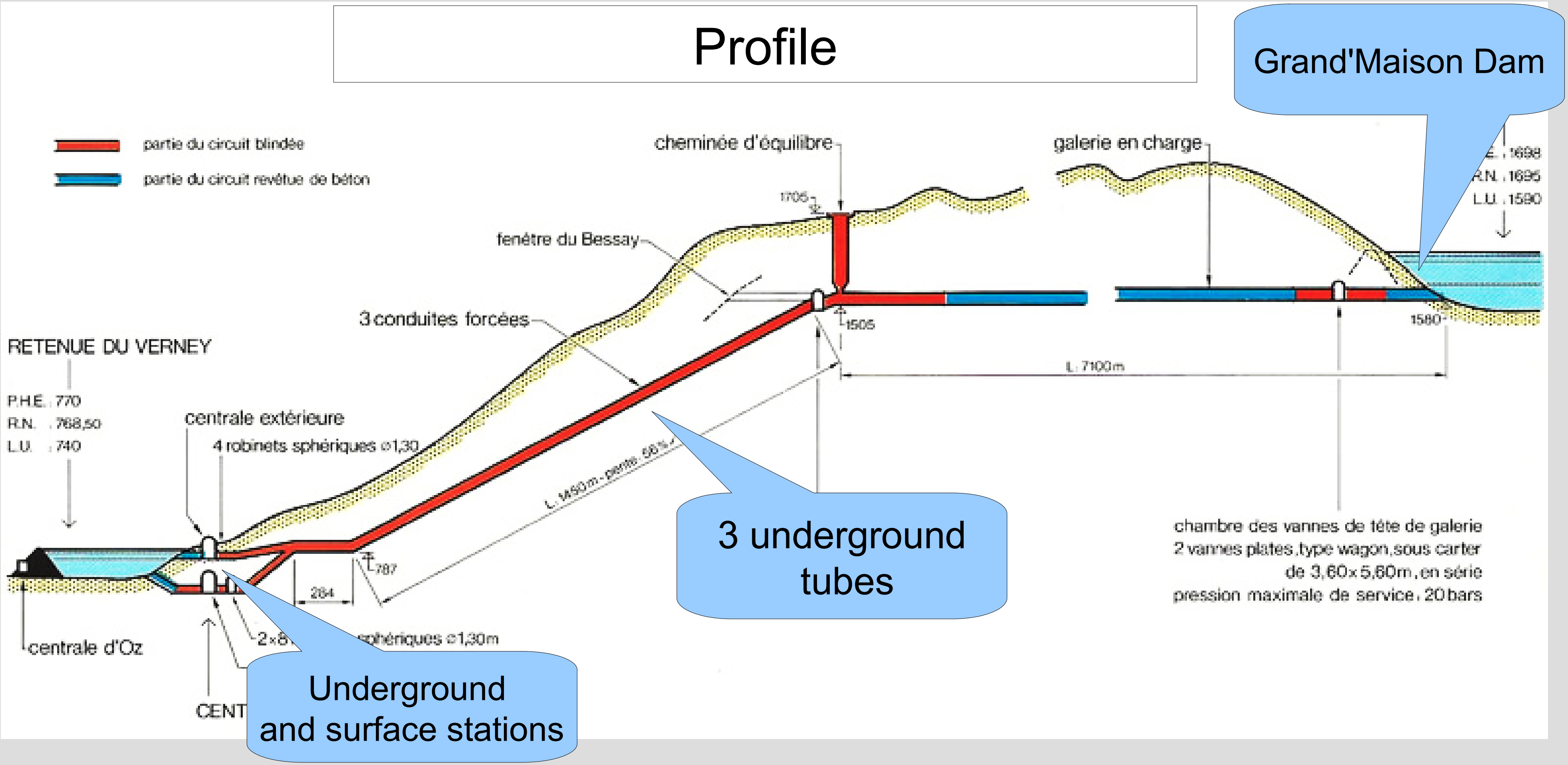




Francis Turbine of 3 George Dam

- Largest in the world (10 m ⌀), 800 MW/turbine

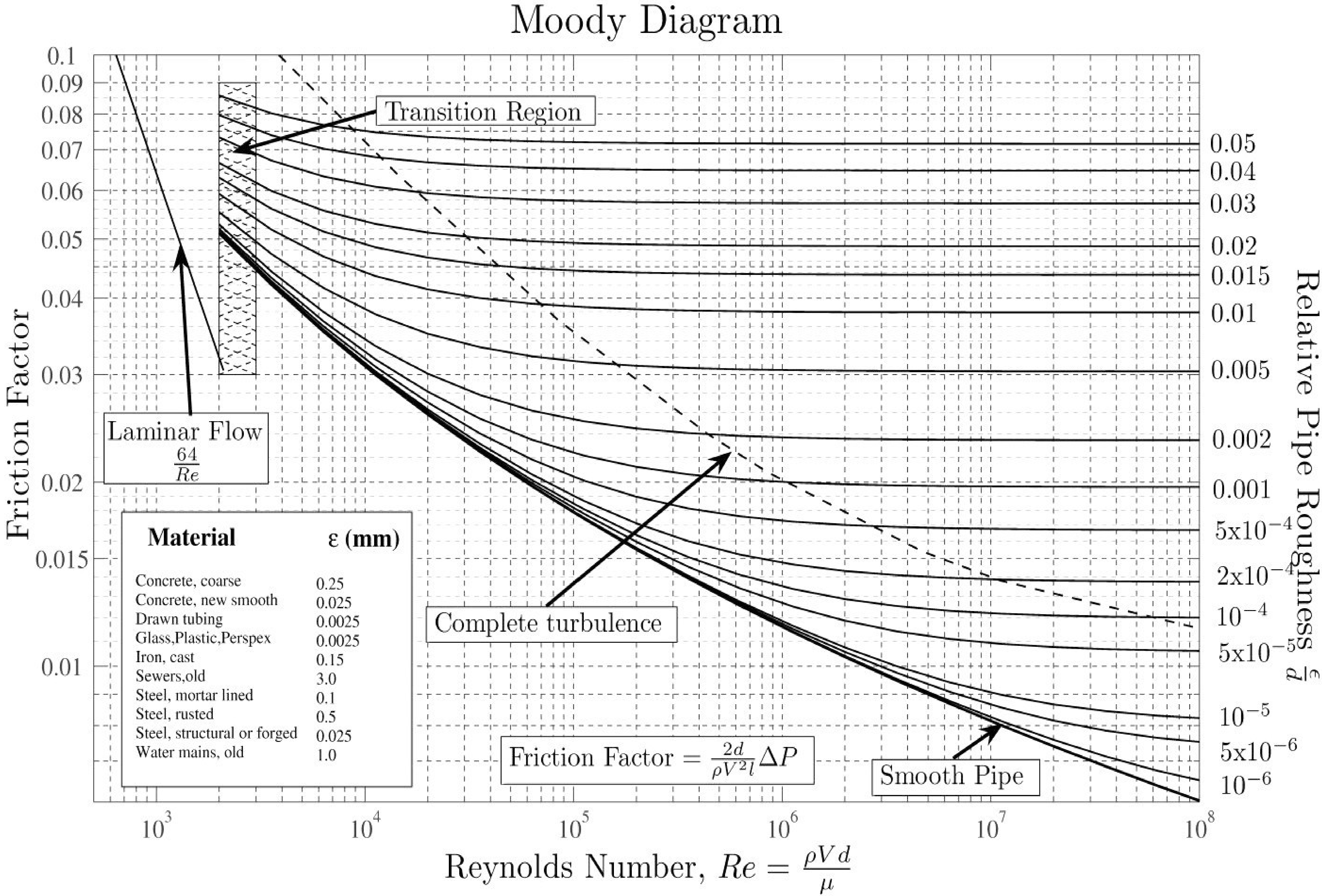
Transfer Pumping Stations – Grand'Maison



Overall Yield

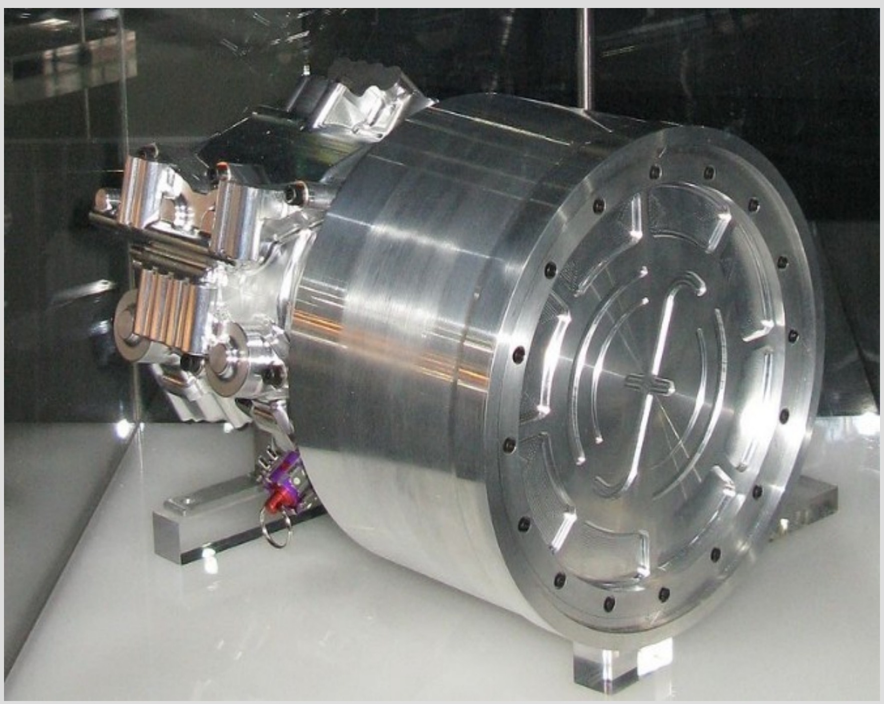
Pumping Mode Yield (%)	Equipment	Turbine Mode Yield (%)
92,5	Reversible Turbine/Pump	91,5
98,0	Alternator/Motor	98,5
99,0	Transformer	99,0
89,7	Net Yield	89,2

- Overall yield for a complete cycle ~ 80%
- Some power (~2%) used by auxiliary equipment


Moody Diagram
Friction Factor
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.015
0.01
Transition Region
Laminar Flow
64/Re
Complete turbulence
Friction Factor = 2d/(ρV²l) ΔP
Smooth Pipe
Relative Pipe Roughness ε/d
0.05
0.04
0.03
0.02
0.015
0.01
0.005
0.002
0.001
5x10⁻⁴
2x10⁻⁴
10⁻⁴
5x10⁻⁵
10⁻⁵
5x10⁻⁶
10⁻⁶
Material
ε (mm)
Concrete, coarse 0.25
Concrete, new smooth 0.025
Drawn tubing 0.0025
Glass,Plastic,Perspex 0.0025
Iron, cast 0.15
Sewers,old 3.0
Steel, mortar lined 0.1
Steel, rusted 0.5
Steel, structural or forged 0.025
Water mains, old 1.0
10³
10⁴
10⁵
10⁶
10⁷
10⁸
Reynolds Number, Re = ρVd/μ

Flywheels

- Short-term energy storage, mechanical system regulation (smooths the operation regime)
- Used recently in formula 1: additional power (80 hp) during 6 seconds, enough for overtaking



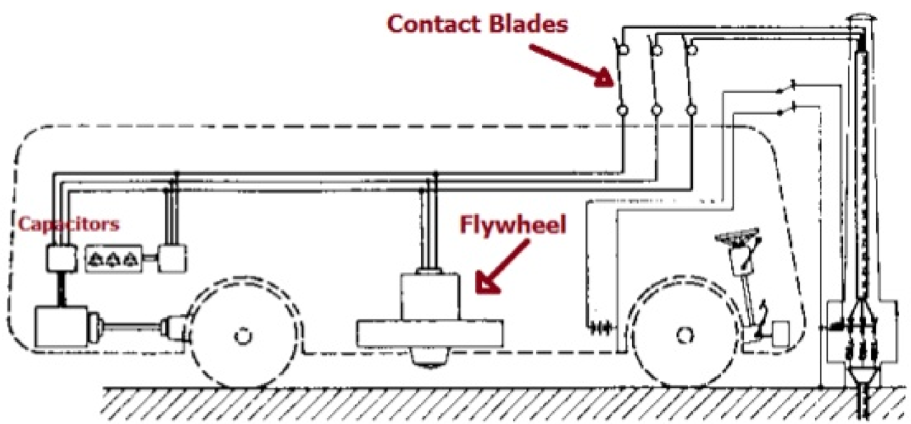
Volant d'inertie de Formule 1

Gyrobus

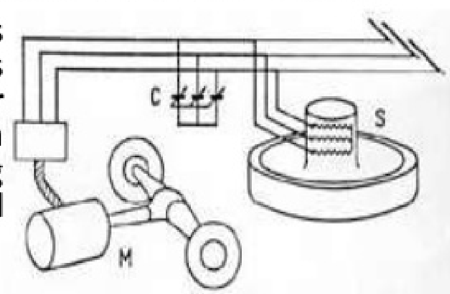
- Recharge above bus stop using a pole
  - Quiet and clean operation
  - Two times more expensive than a regular bus, but cheaper to operate

Gyrobus

- 1500 kg flywheel



To obtain tractive power, capacitors would excite the flywheel's charging motor **(Electric motor generator)** so that it became a generator, in this way transforming the energy stored in the flywheel back into electricity.



Charging

- 3 phase fast charging slot

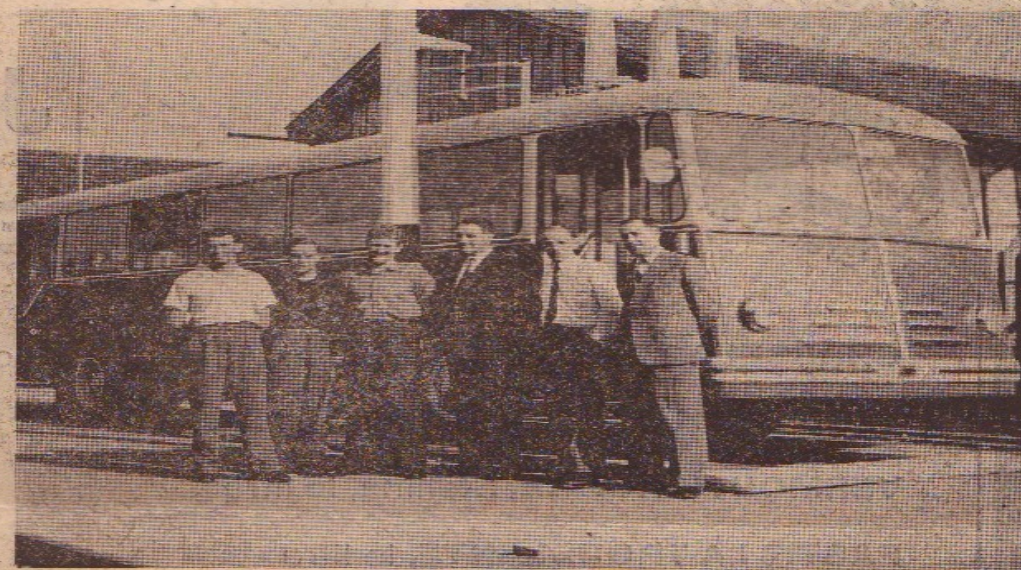
Flywheel

- Needed flywheel for a bus (150 kW)

Material	Max Speed (m/s)	Max Speed (km/h)	Energy per kilo (kJ)	Mass (kg)
Concrete	65,9	237,4	2,2	21620,0
Aluminium	471,4	1697,1	111,1	423,0
standard steel	478,5	1722,8	114,5	410,5
Titanium	536,9	1932,8	144,1	326,1
Fiberglass	1143,5	4116,8	653,8	71,9
carbon fiber	1567,5	5643,1	1228,6	38,3
Kevlar	1585,5	5707,9	1256,9	37,4
Carbon Nanotubes	6802,1	24487,4	23134,0	2,0

Gyrobus

- 7 years of operation
  - 712 000 km for two buses



La sortie du premier gyrobus des ateliers d'Oerlikon avec la délégation communale d'Yverdon au premier plan. (arc)

La gloire éphémère des gyrobus

Le 1er octobre 1953, le premier véhicule de transport public mû par un électrogyro entrait en service à Yverdon. Il s'agissait d'une première mondiale qui faisait la une de tous les journaux.
Le gyrobus alliait les avantages du trolleybus à ceux de l'autobus, à savoir: absence de ligne de contact ; roues entraînées par un moteur électrique, donc sans bruit et sans gaz d'échappement ; mobilité.

Ces véhicules, témoins de l'esprit d'initiative qui animait les organes dirigeants de l'époque, n'ont malheureusement pas rencontré le succès escompté. Les ennuis techniques étaient nombreux, notamment la sustentation du gyro, le nombre de voyageurs était limité, et en 1955 déjà, soit deux ans après leur mise en service l'on envisageait leur remplacement par un service de bus qui a été réalisé en 1960.

Malgré ce contretemps, le réseau n'a cessé de se développer. A l'ori-

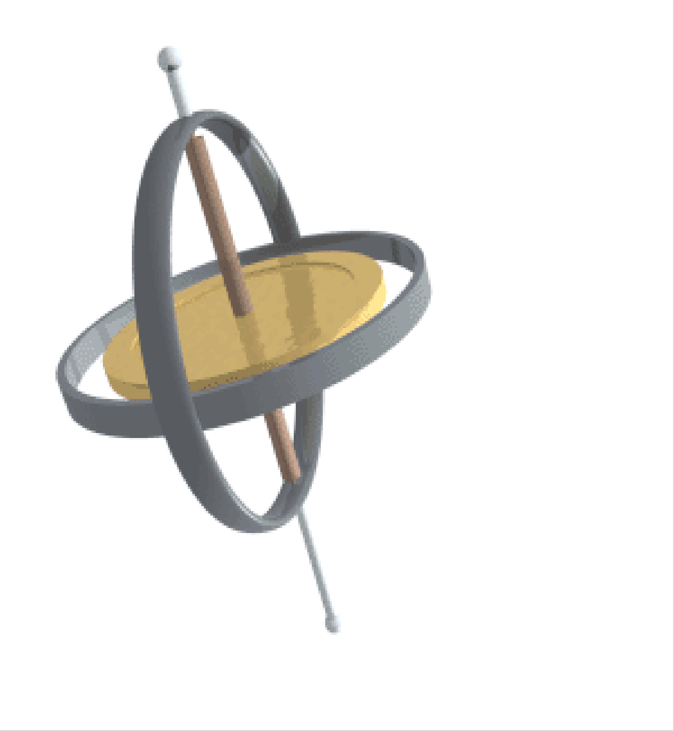
La SA a toujours été déficitaire, à l'instar de tous les transports publics urbains.

La Société fêtera en cette fin de semaine le 25e anniversaire de sa constitution, qui correspond avec la mise en circulation des premiers gyrobus. L'évènement sera marqué par les manifestations suivantes :

L'usage des Transports publics d'Yverdon-Grandson sera gratuit durant un week-end, soit le samedi 18 et le dimanche 19 novembre.

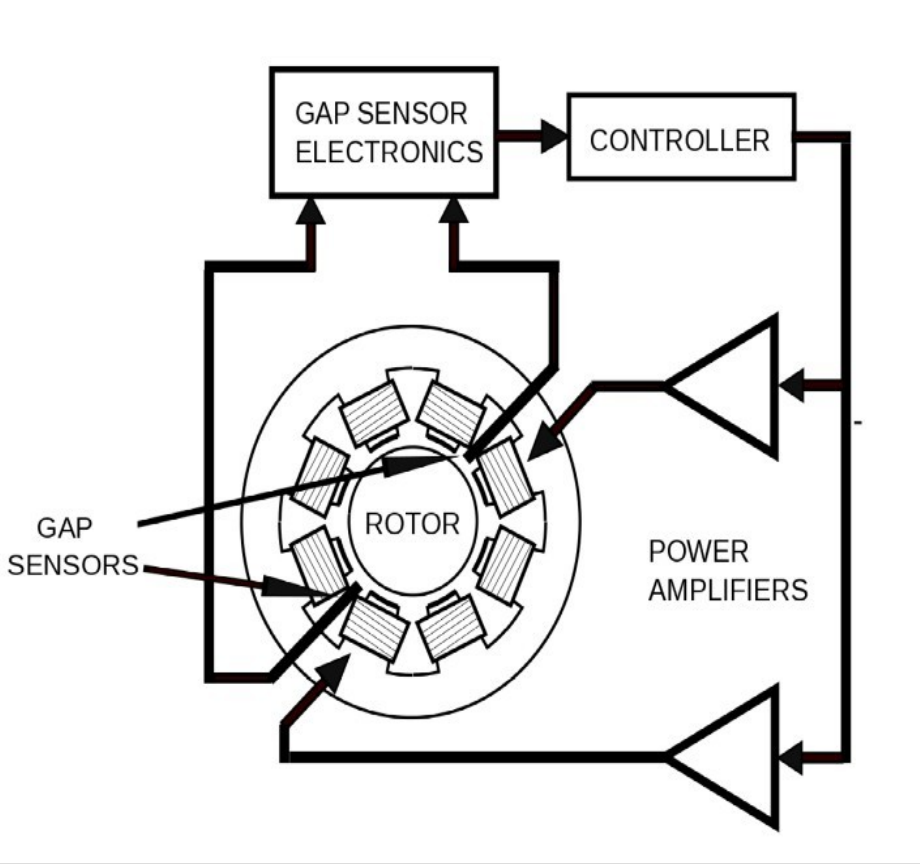
Balancing problem

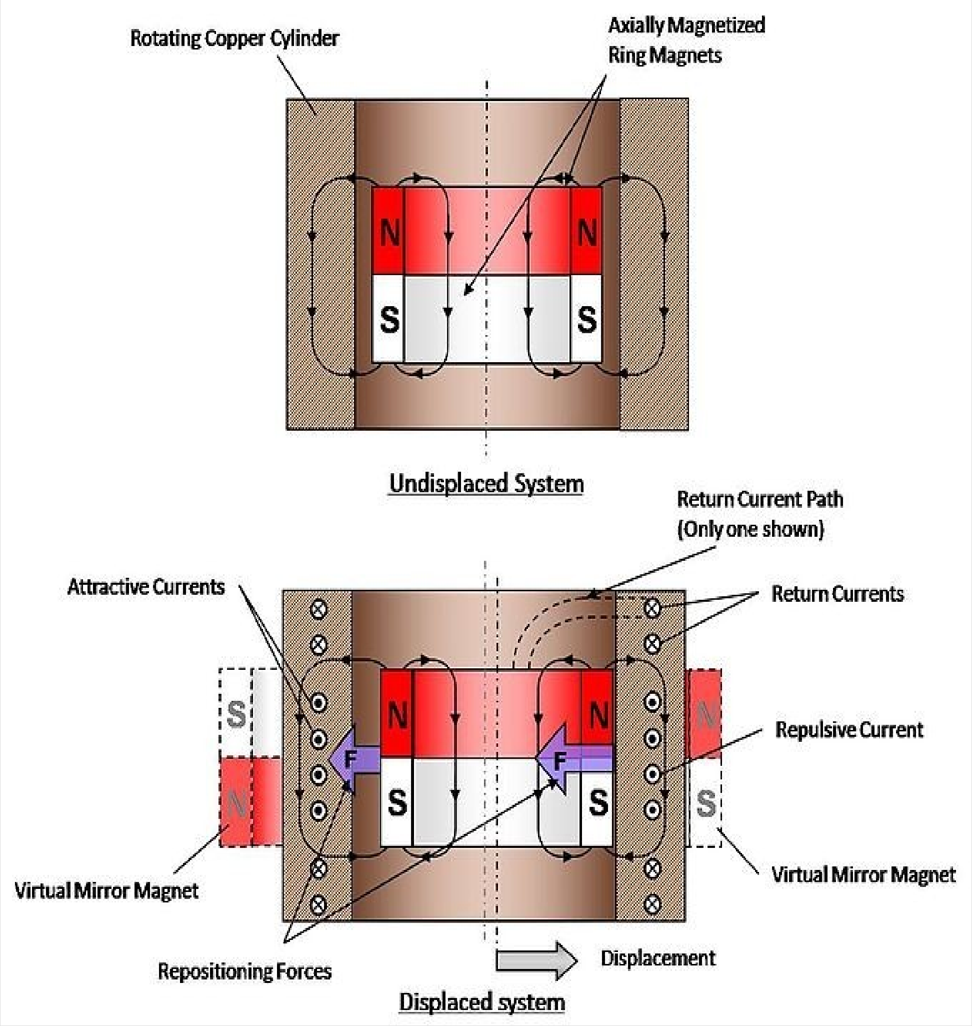
- Secondary effect of the disk
  - Gyroscopic effect on the axis (problematic in turns and uphill)
  - Can be solved by mounting two counter discs, but technologically difficult.



Magnetic bearings

- Based on the principle of magnetic levitation without contact
  - active mechanisms (with feedback)
  - passive mechanisms under development (based on induction)

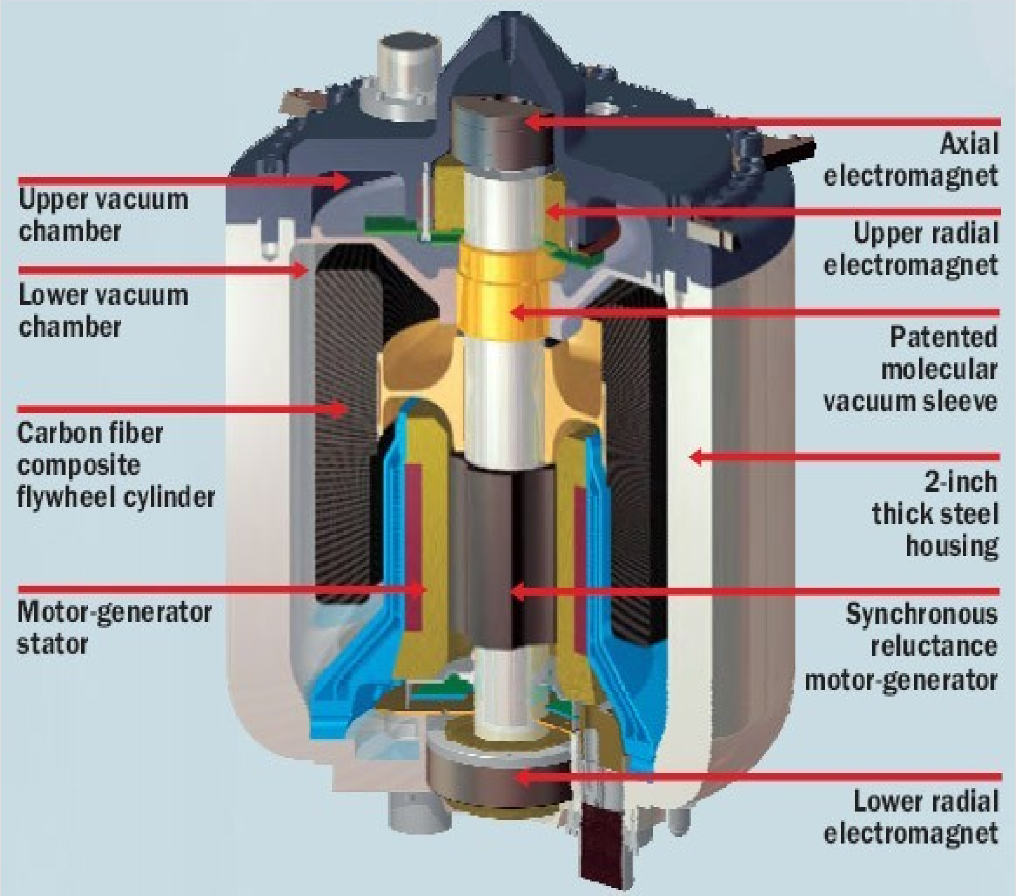




Other usages : UPS (Stabilized Power Supply)

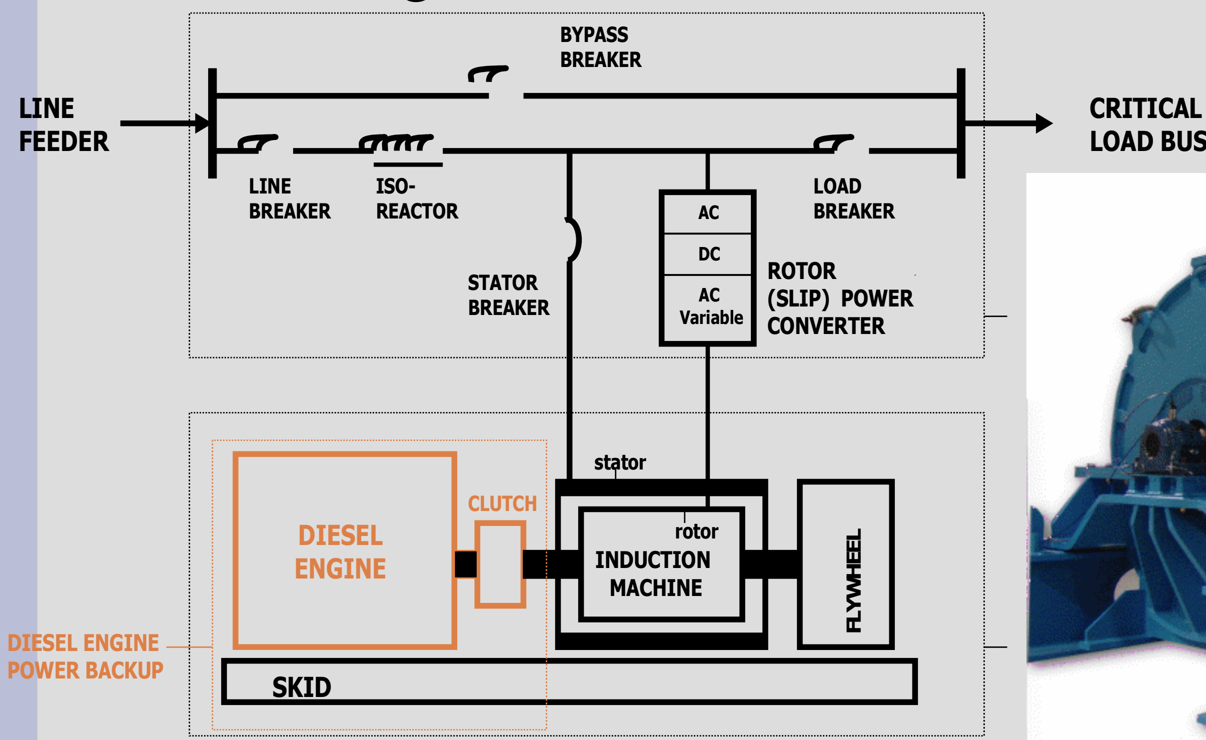
- 12 seconds of operation at 200 kW → Allows starting an auxiliary system type generator
  - Less maintenance, less polluting than batteries
  - No temperature sensitivity
  - Longer life (20 years)

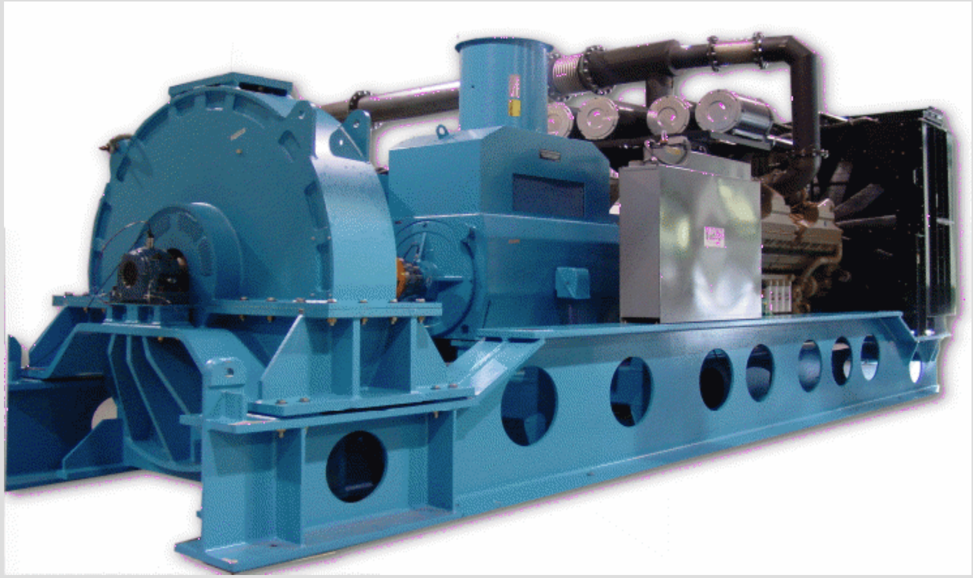
Pentadyne GTX



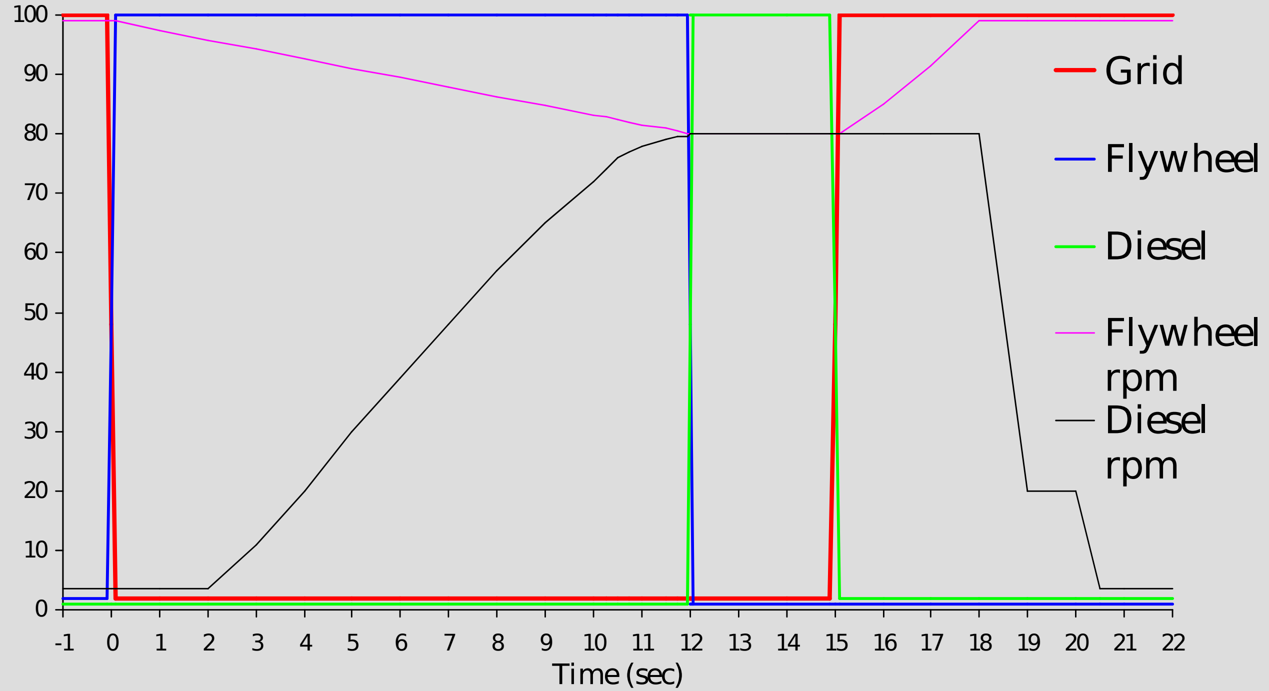
Power Systems

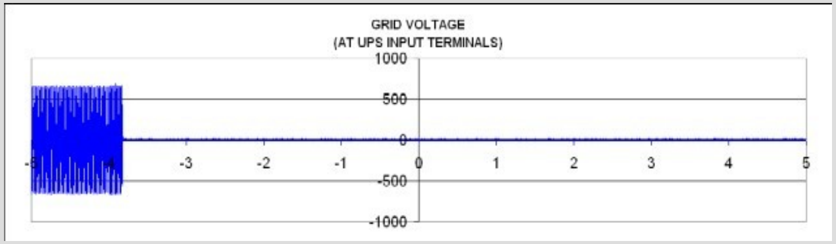
- Flywheel coupled to a diesel engine
  - 1.7 MW machine
  - The steering wheel can compensate for 12 seconds, relayed by Diesel engine
  - Operates a full frequency filtering, smooth over voltage and under voltage

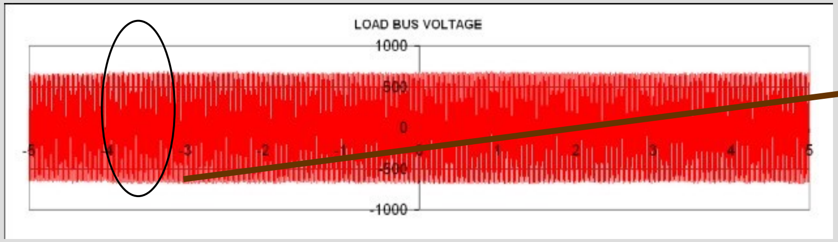


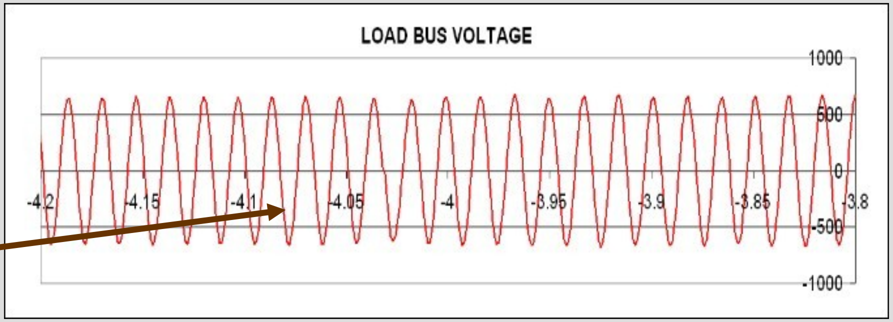


Operations


Grid
Flywheel
Diesel
Flywheel rpm
Diesel rpm
Time (sec)

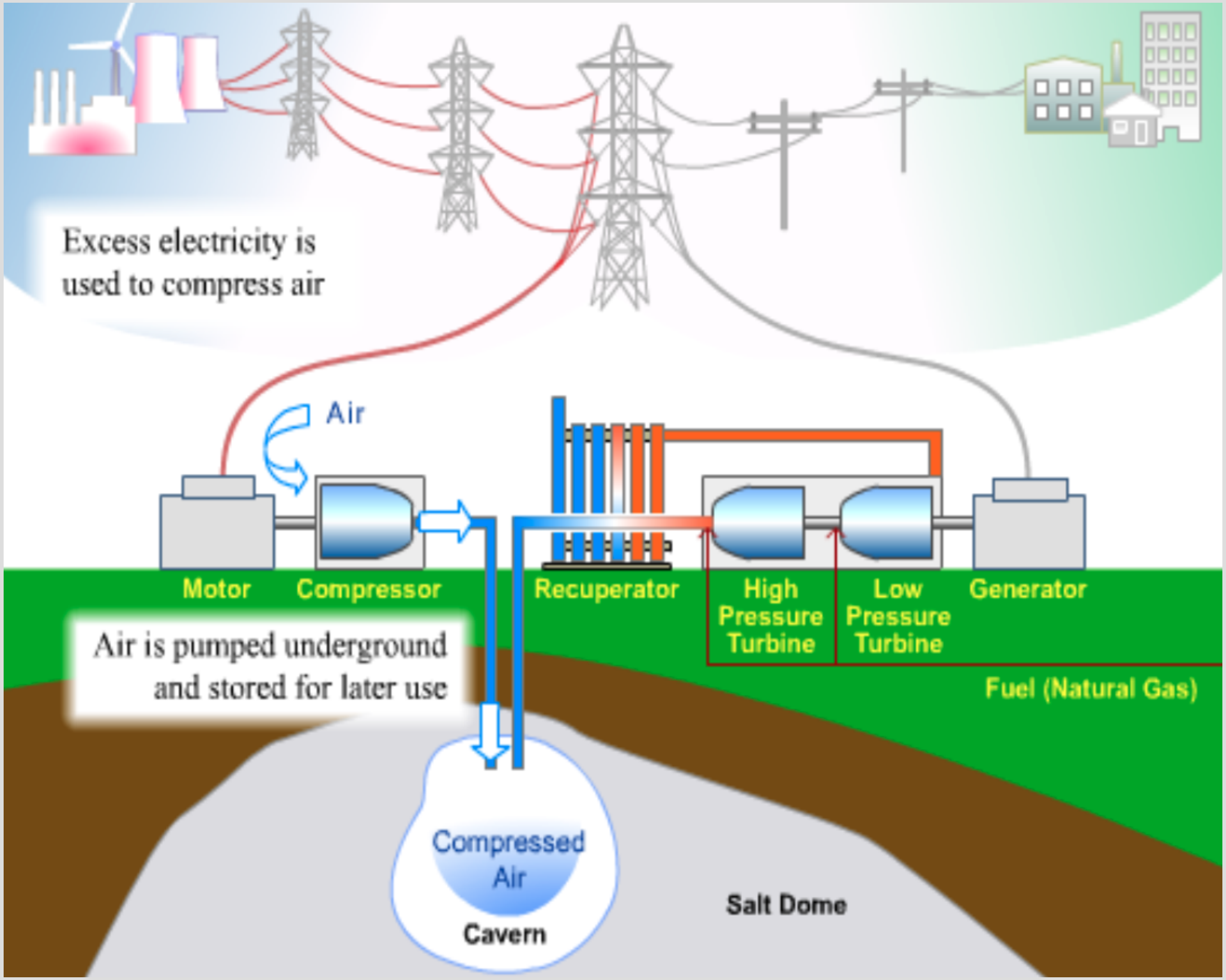

GRID VOLTAGE
(AT UPS INPUT TERMINALS)


LOAD BUS VOLTAGE


LOAD BUS VOLTAGE

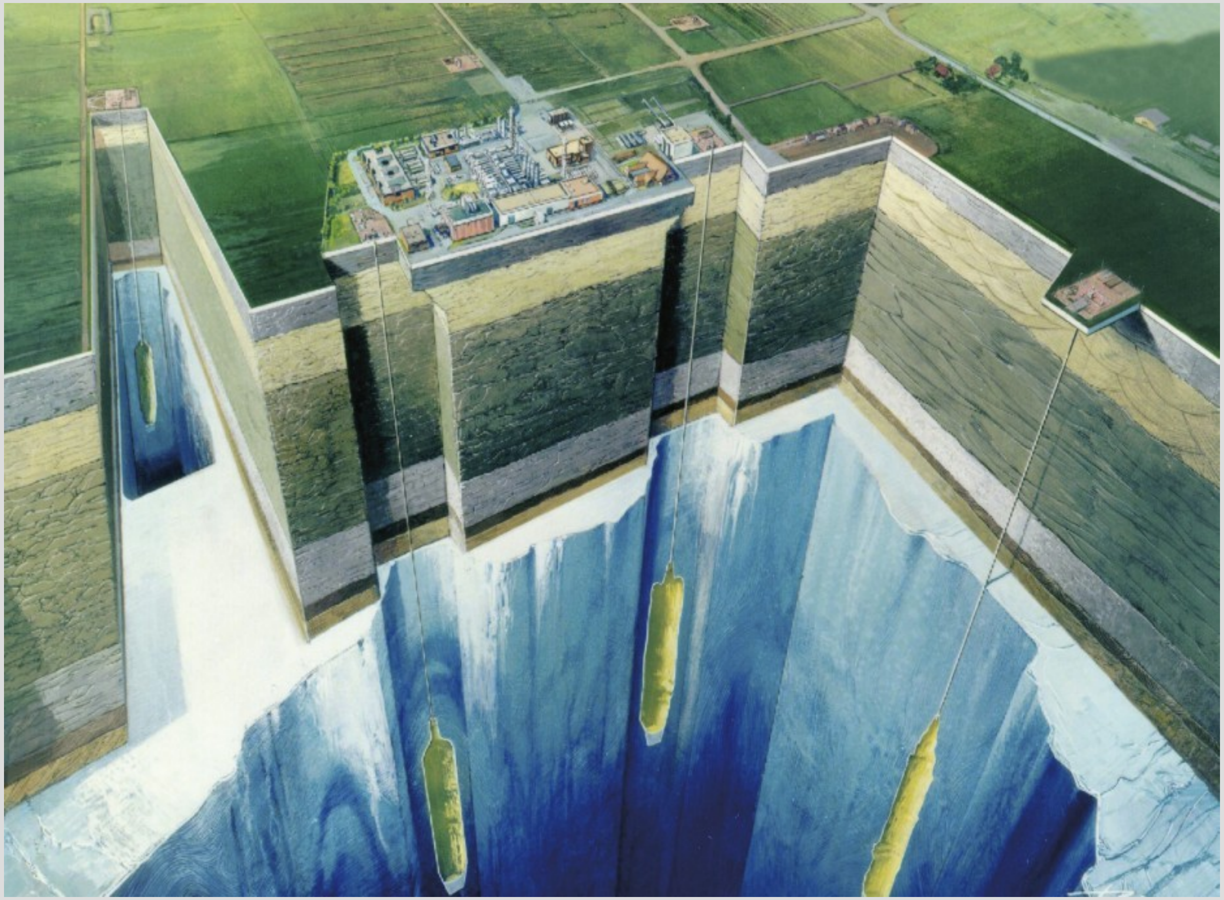
Compressed Air Storage

- Diabatic storage: compression heat is lost
- Adiabatic storage: heat recovery through a heat exchanger



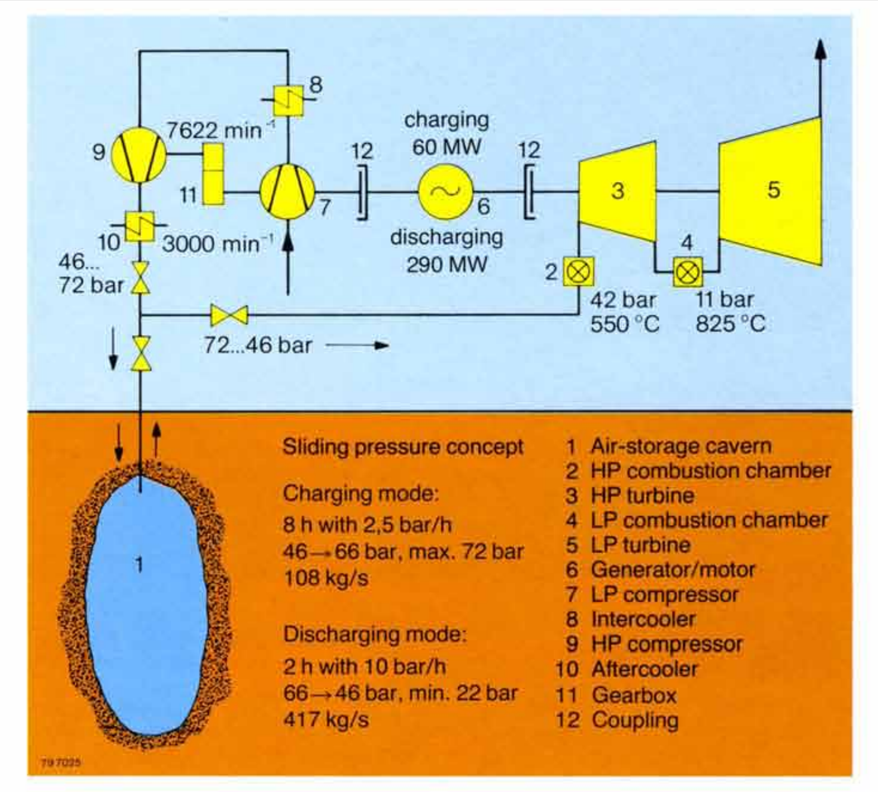
Compressed Air Storage – Digging caverns

- Digging using water in salt domes:
  - Resistance to high pressure (200 bar) and frequent changes of pressure
  - Virtually impermeable
  - But environmental energy cost of digging



Huntorf station

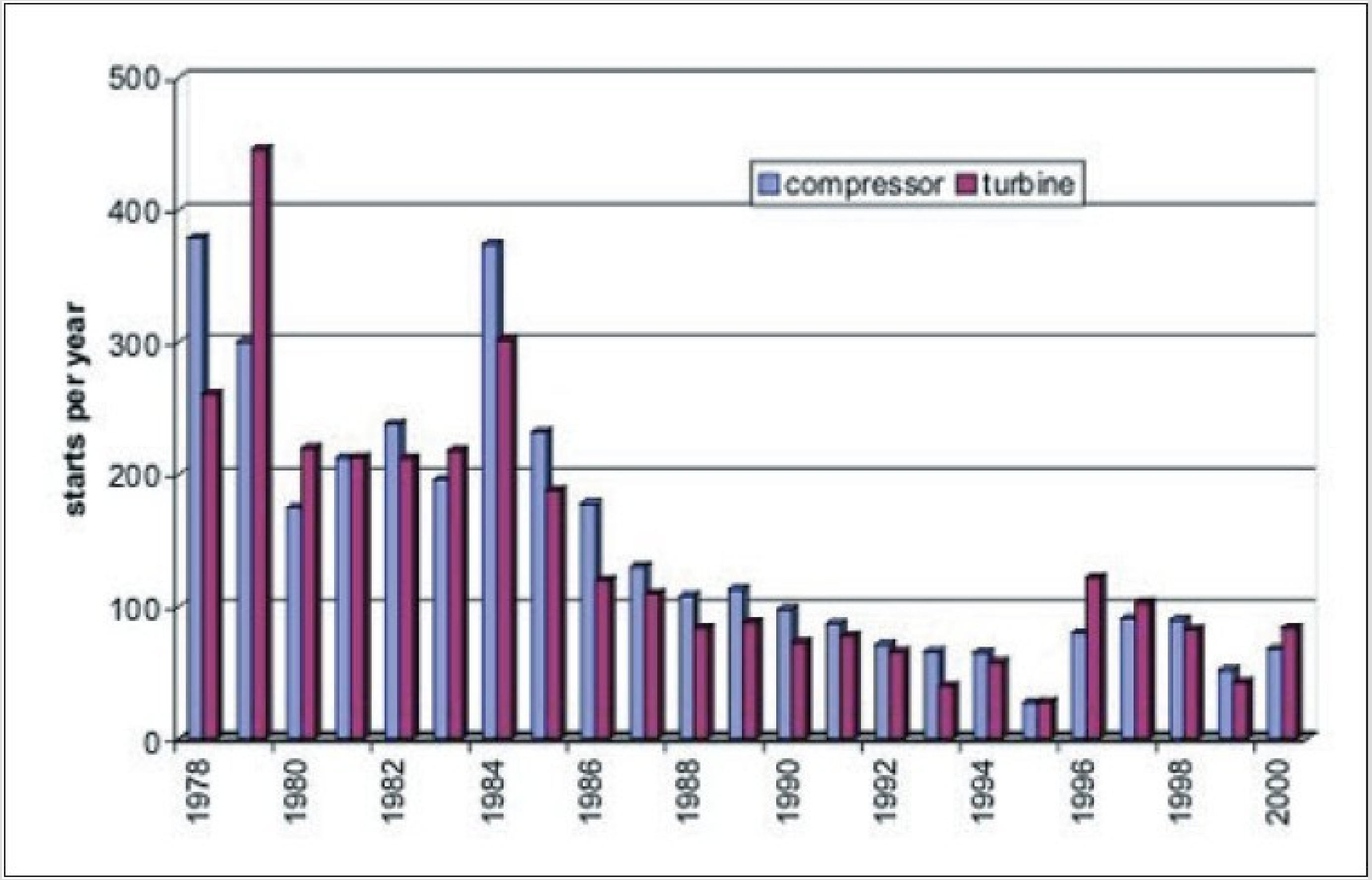
- Installed in 1978, Northern Germany
  - Two caverns of compressed air → 300 000 m³



Gas Turbine	
Rating	290 MW
Speed	3000 min^{-1}
Air consumption	417 kg/s
Inlet conditions HP Turbine	42 bar/550 °C (823 K)
Inlet conditions LP Turbine	11 bar/825 °C (1098 K)
Specific heat rate	5800 kJ/kWh
Fuel	Natural gas
Generator/Motor	
Apparent power	341 MVA
Frequency	50 Hz
Voltage	21 kV
Speed	3000 min^{-1}
Cooling	Hydrogen/Water
Compressors	
Number of compressors	2
Total driving power	60 MW
Construction of LP compressor	axial
Speed	3000 min^{-1}
Construction of HP compressor	centrifugal
Speed	7622 min^{-1}
Intake conditions	10 °C/1.013 bar
Air flow	108 kg/s
Conditions after compressor	46 to max. 72 bar/50 °C
Number of intercoolers	3
Number of aftercoolers	1
Air Storage	
Type of storage	Sliding pressure
Volume	2 x 150 000 m^3
Pressure range	20 bar
Pressure gradient during discharge	10 bar/h

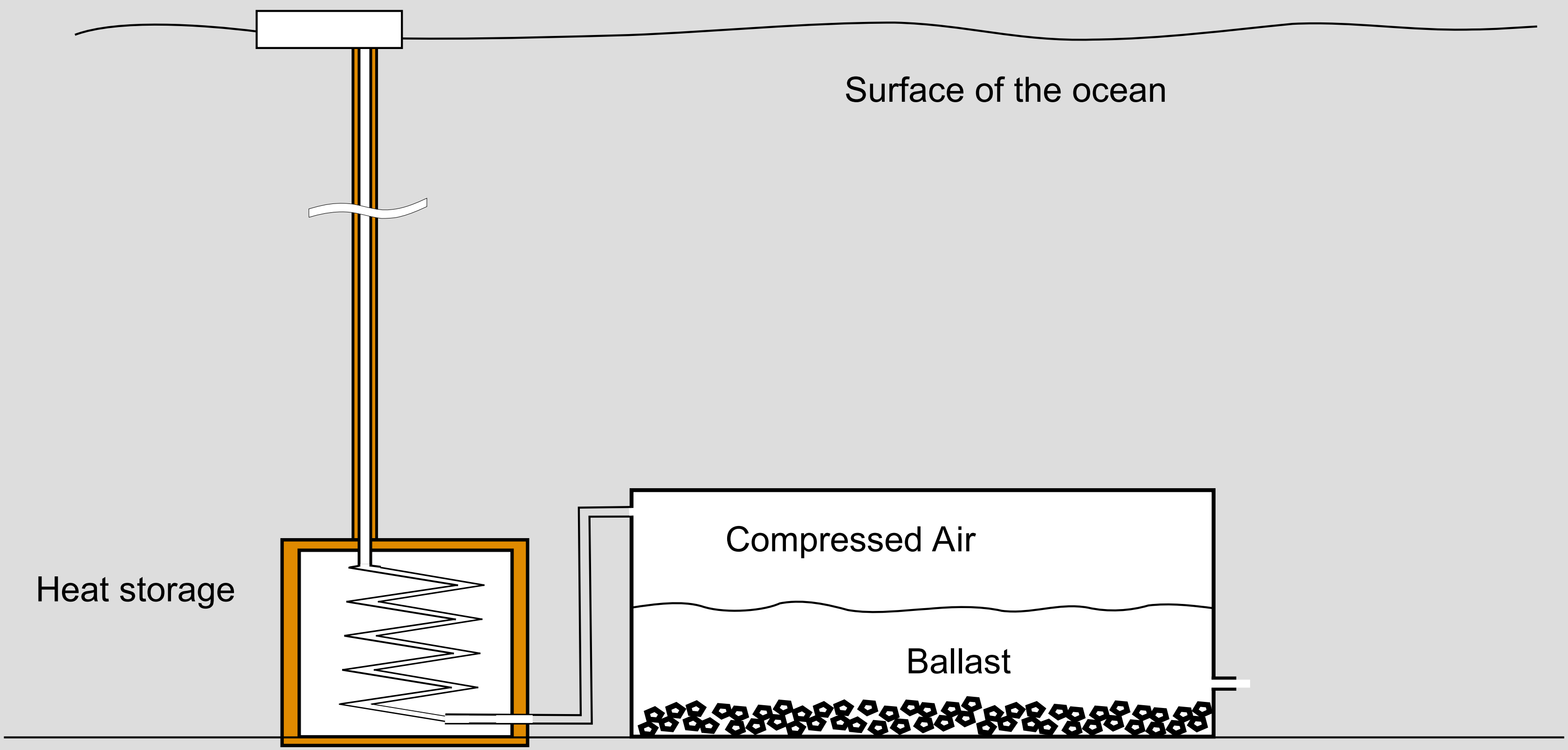
Operation

- Number of cycles per year (20 years of operation)
- Actual Yield ~ 40%
- Stopped in 2001 following the rupture of a steel tubing (corrosion)



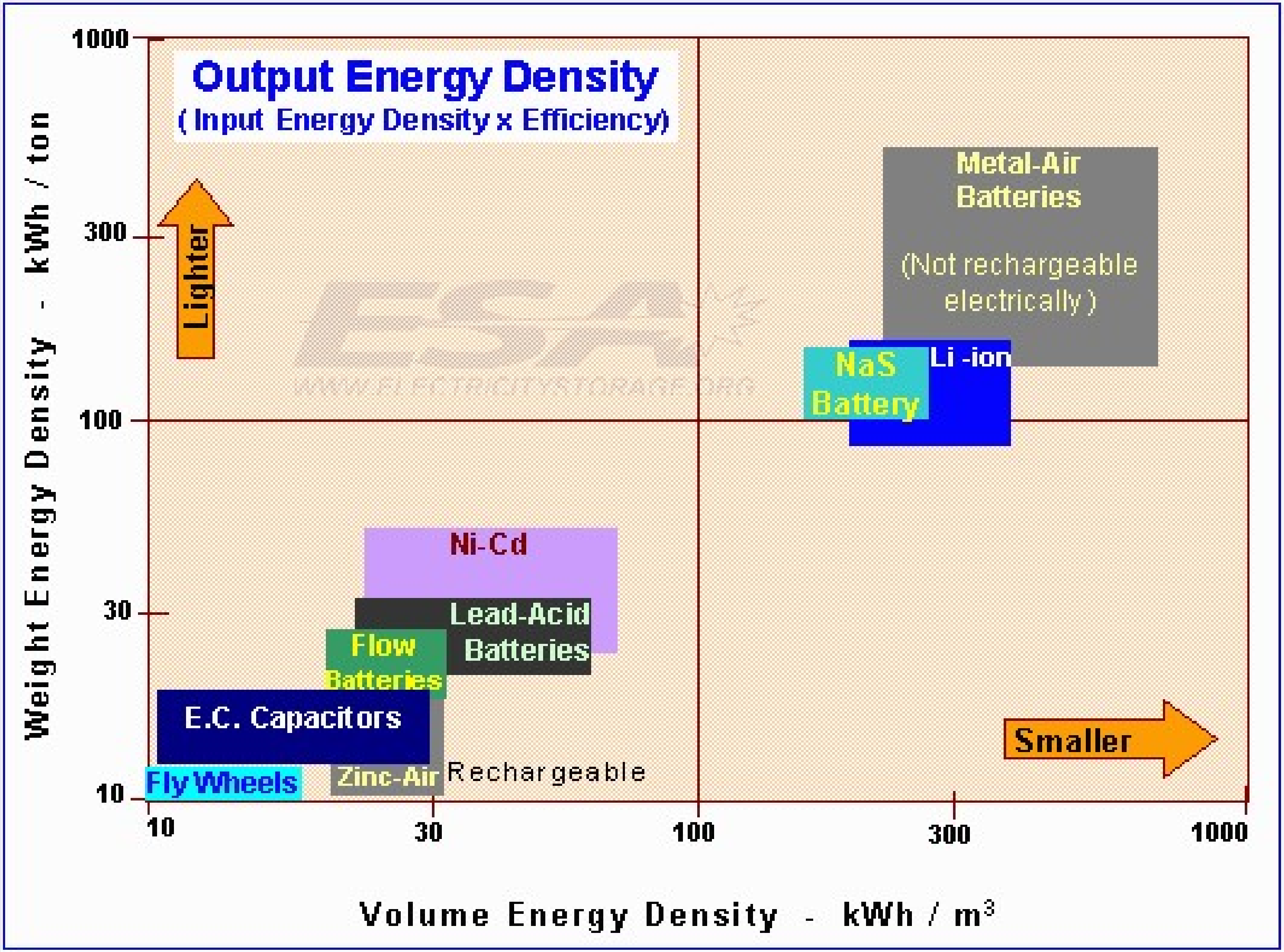
Submarine version

- Easier design

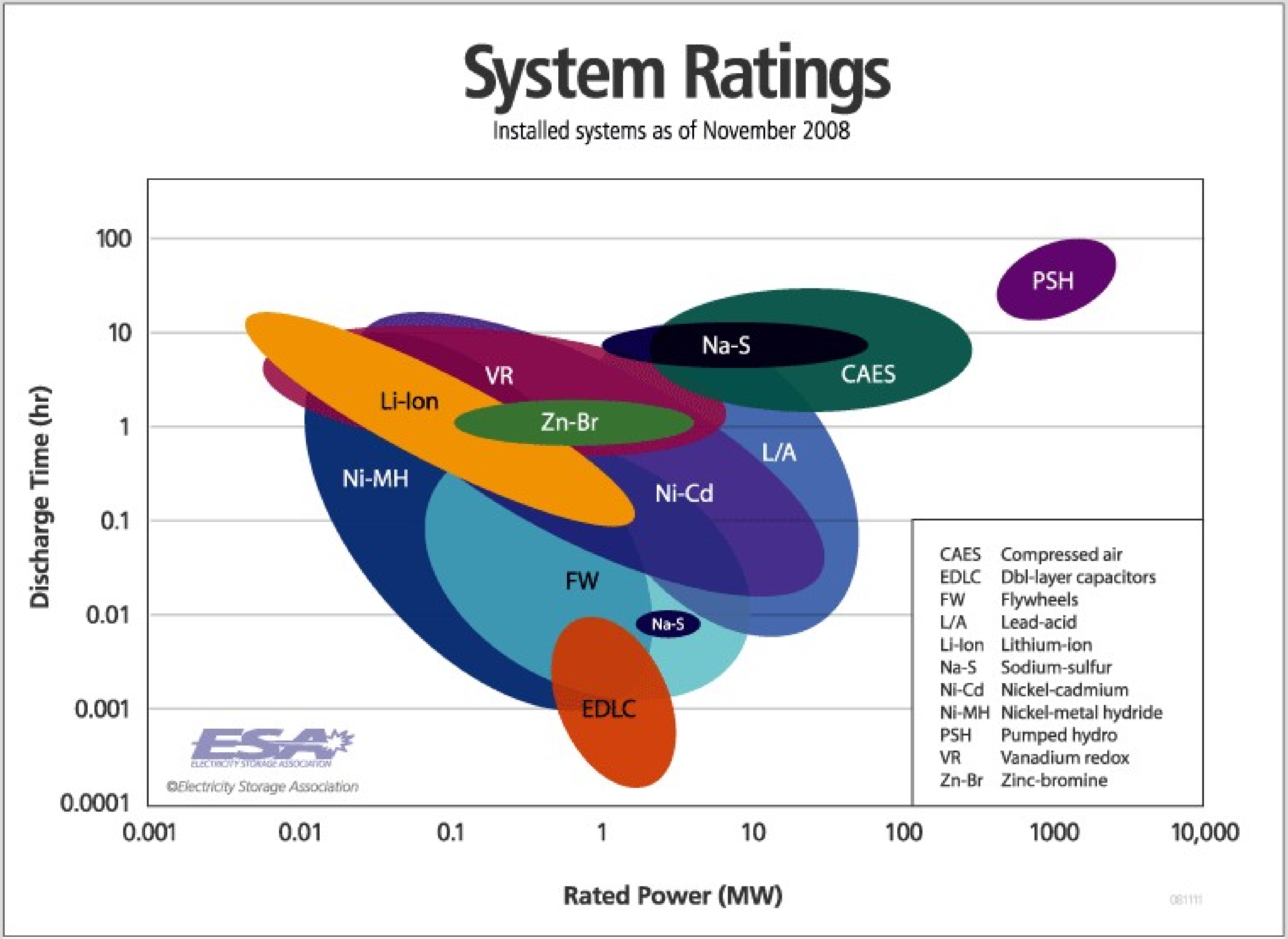


Some Comparison Elements

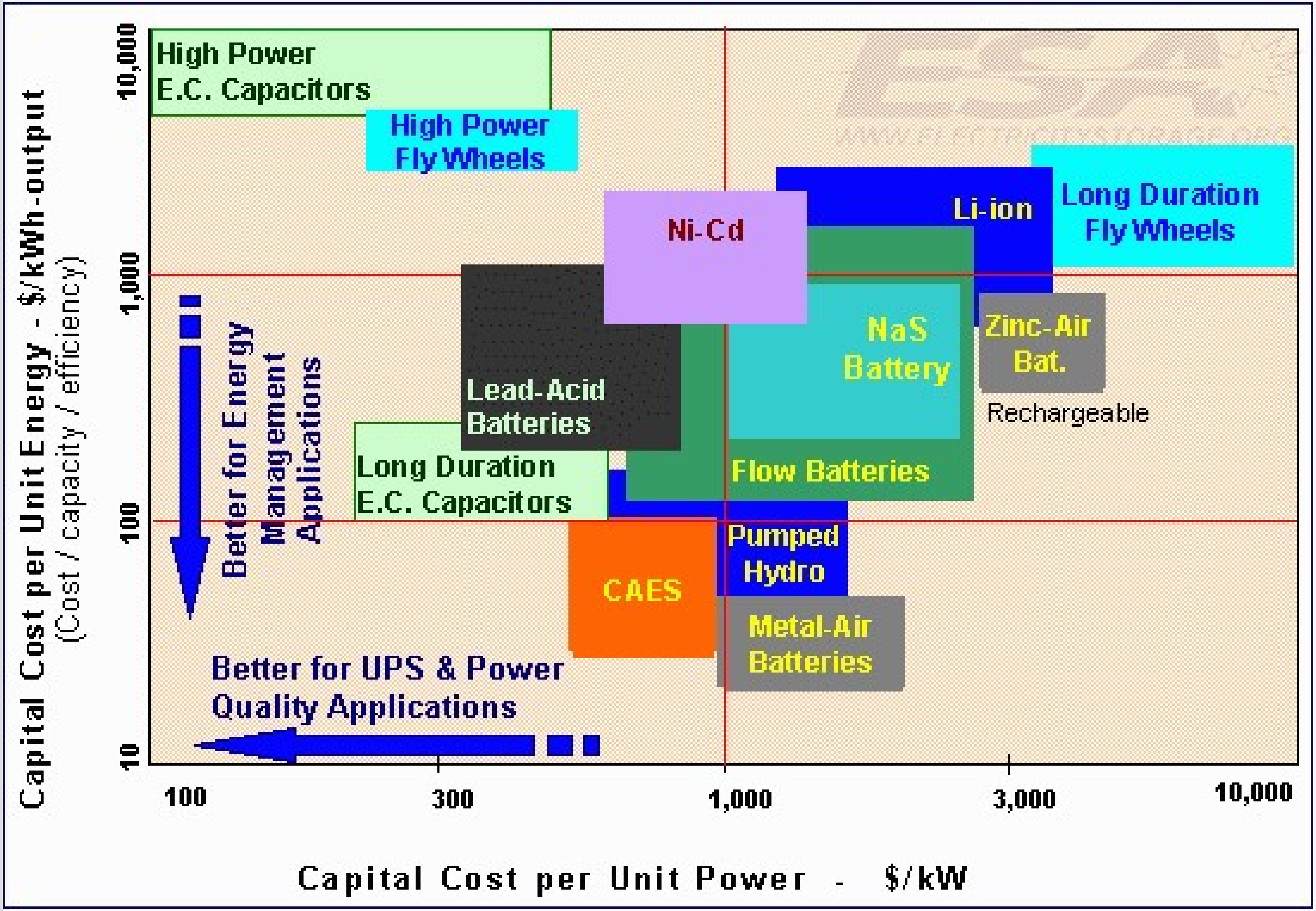
Energy Density



Discharge Time

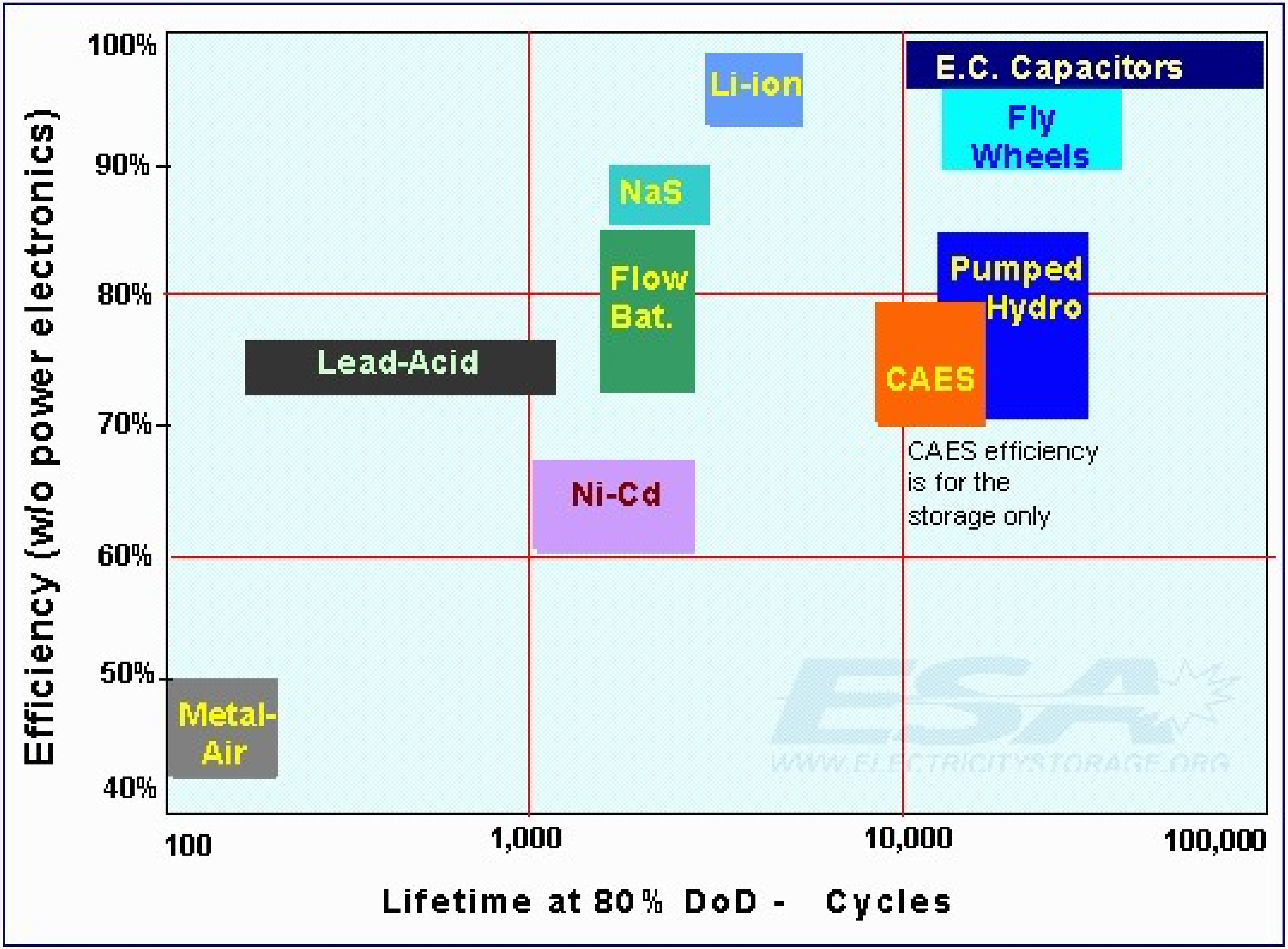


Investment



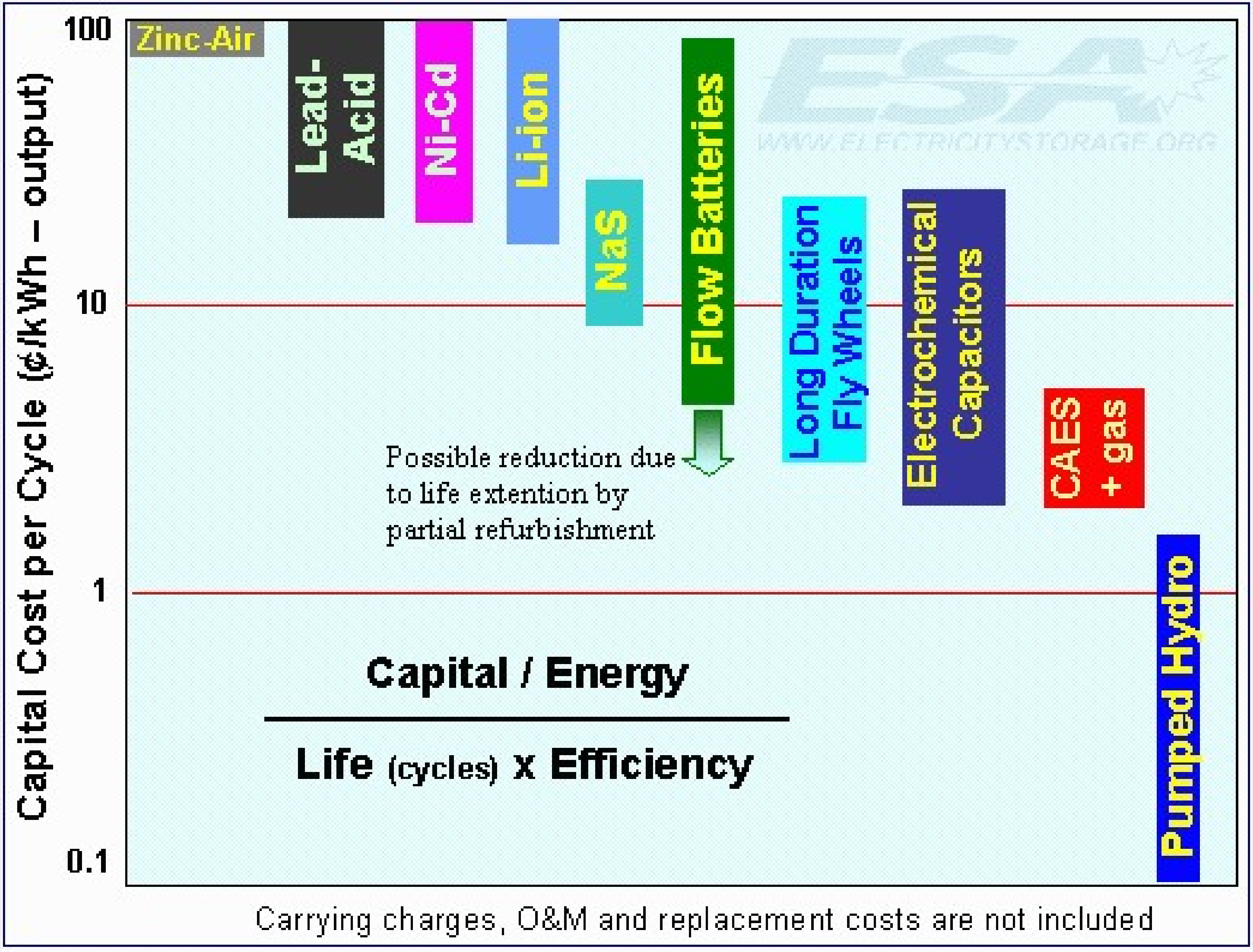
High Power
E.C. Capacitors
High Power
Fly Wheels
Ni-Cd
Li-ion
Long Duration
Fly Wheels
Lead-Acid
Batteries
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Long Duration
E.C. Capacitors
Flow Batteries
Pumped
Hydro
CAES
Metal-Air
Batteries
Better for Energy
Management
Applications
Better for UPS & Power
Quality Applications
Capital Cost per Unit Energy - $/kWh-output
(Cost / capacity / efficiency)
10,000
1,000
100
10
100
300
1,000
3,000
10,000
Capital Cost per Unit Power - $/kW

Lifetime

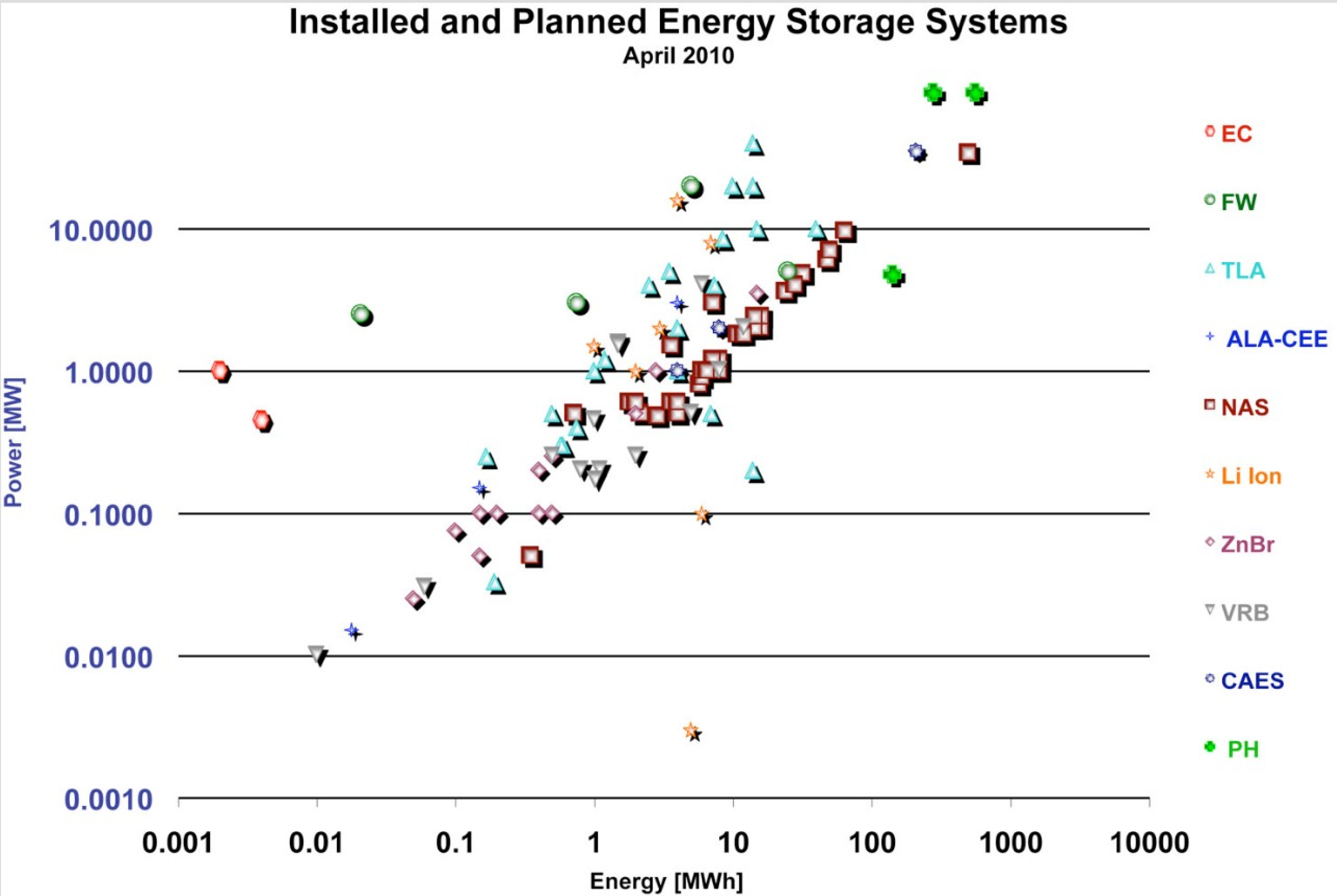


100%
90%
80%
70%
60%
50%
40%
Efficiency (w/o power electronics)
Li-ion
E.C. Capacitors
Fly Wheels
NaS
Flow Bat.
Pumped Hydro
Lead-Acid
CAES
CAES efficiency is for the storage only
Ni-Cd
Metal-Air
100
1,000
10,000
100,000
Lifetime at 80% DoD - Cycles

Cost per cycle



Installations



Overall comparison

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

http://www.electricitystorage.org