Adam Jerzy Rajewski
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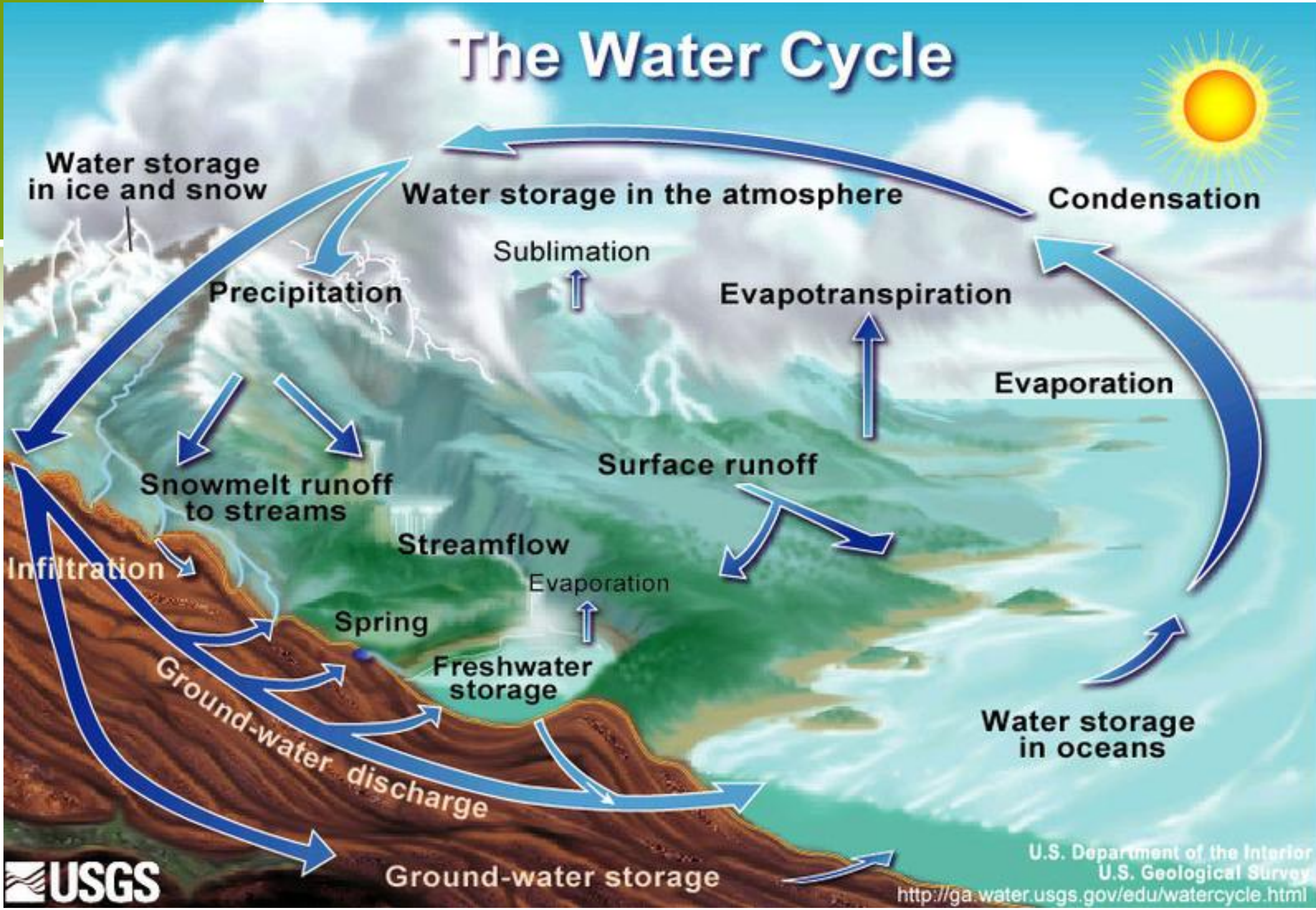
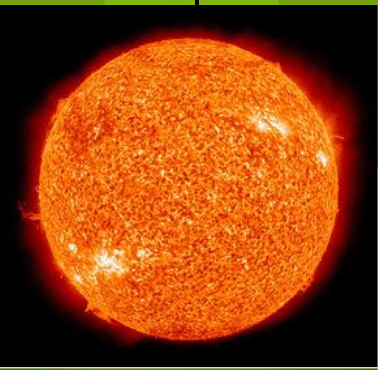
ITC

Hydroelectricity

THEORY


The Water Cycle
Water storage in ice and snow
Water storage in the atmosphere
Condensation
Sublimation
Precipitation
Evapotranspiration
Evaporation
Surface runoff
Snowmelt runoff to streams
Streamflow
Infiltration
Evaporation
Spring
Freshwater storage
Ground-water discharge
Water storage in oceans
USGS
Ground-water storage
U.S. Department of the Interior
U.S. Geological Survey
http://ga.water.usgs.gov/edu/watercycle.html

Energy conversion chain




Solar energy

↓

Internal energy of vapour

↓

Potential energy of water → Energy storage

↓

Kinetic energy of flowing water → Practical applications

Early applications

Hydraulic power Early uses

Irrigation systems

- Ancient Mesopotamia and Egypt
- Ancient China

Hydraulic clocks

Water wheels

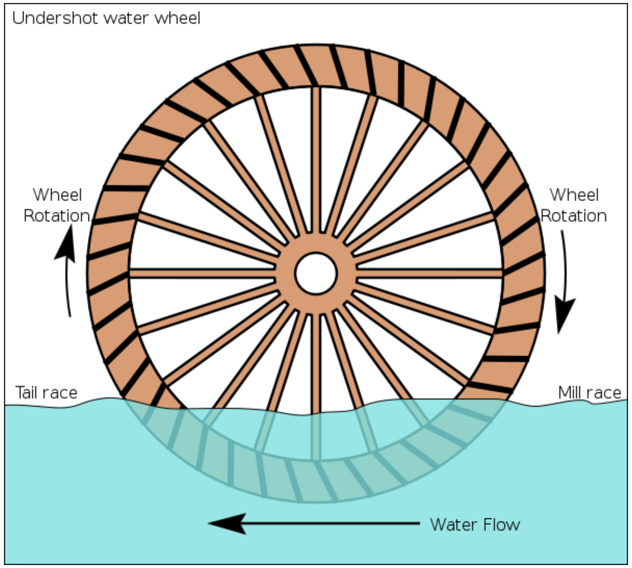
- Devices for converting hydraulic energy into mechanical energy of wheel's shaft
- Invented in ancient Greece
- Applications: water lifting, watermills, sawmills…

Types of water wheels

- Horizontal wheel
- Undershot wheel
- Breastshot wheel
- Overshot wheel
- Backshot wheel

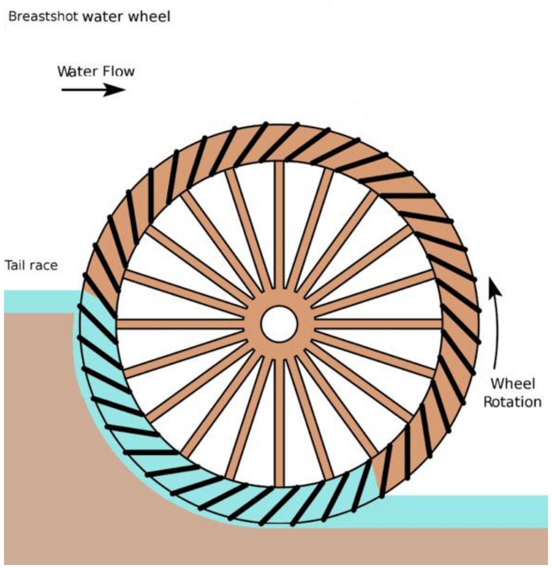
Undershot water wheel (stream wheel)

- The oldest solution
- Lowest efficiency (ca 20%)
- No hydraulic head needed (no benefits if there is)
- Easy to build – does not require changes in river flow
- Requires sufficient flow.



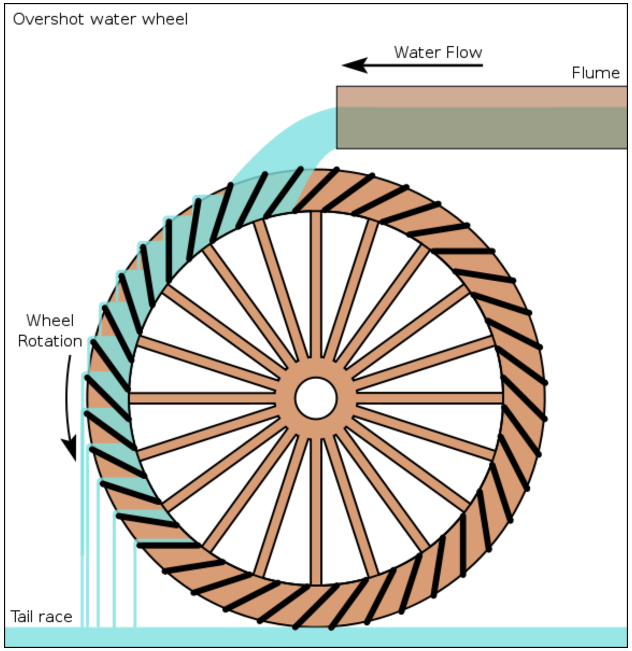
Breastshot water wheel

- Solution common in the US (industrial revolution)
- Average efficiency
- Buckets instead of simple paddles
- Preferred type for steady high-volume flows.



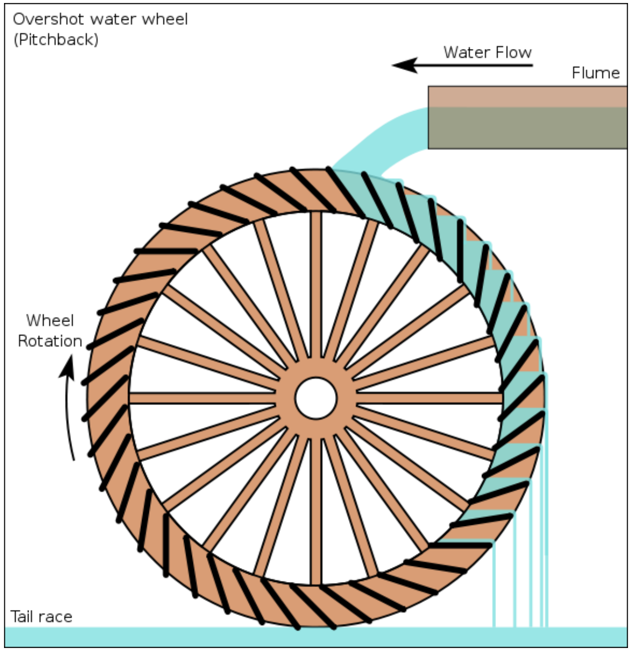
Overshot water wheel

- High efficiency (>60%)
- Benefits from available hydraulic head
- Requires water spilling (dam)
- Buckets instead of simple paddles



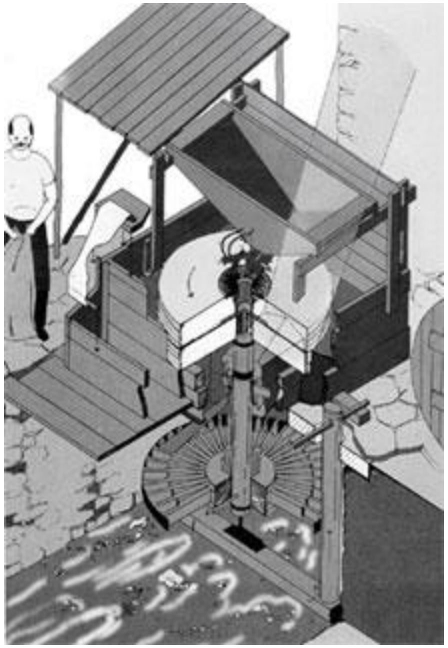
Backshot water wheel (Pitchback wheel)

- Combination of overshot and breastshot features
- Can operate at variable level of tail race (seasonal streams)



Horizontal water wheel

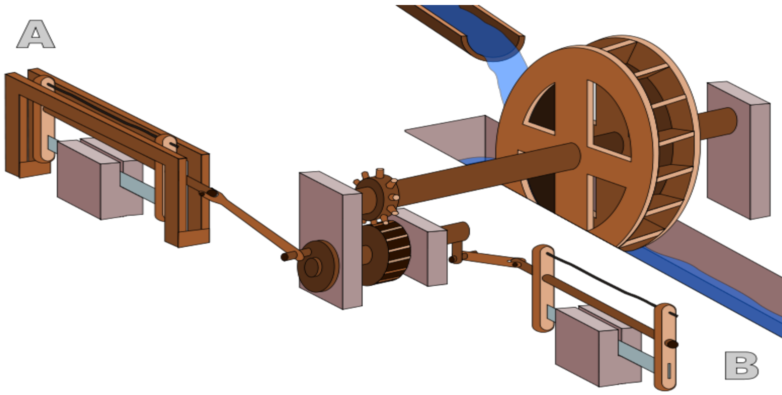
- Jet of water directed to the paddles
- Usually working machinery is installed on the same axis
- Popular in Scotland and southern Europe



Greek horizontal water wheel,
Pic. by Scottish Industrial Heritage Society

Hierapolis sawmill

- Roman-built mill in Hierapolis, Asia Minor, Second half, 3rd Century
- Breastshot water wheel
- The earliest known machine with a crank and a connecting rod:
  Torque –> Reciprocating movement



Modern applications –
– hydroelectricity

Is hydropower a renewable energy source?

Theoretically…

- Yes, if we consider solar energy to be renewable
- but…

Practically

- large hydro is usually considered separate category from „renewables”, because:
  - technology is well proven and needs no incentives,
  - environmental impact can be huge.
- Only small hydroelectric plants are considered „unconventional” and often only these are counted as RES.

Hydroelectric plants classification

Large

- Up to 22,000 MW of output
- Currently three plants over 10 GW in operation

Small

- Scandinavia, Switzerland: < 2 MW
- Poland: < 5 MW
- Most EU states: < 10 MW
- USA: < 15 MW
- Canada: < 50 MW

Micro

- Plants below 100 kW

Pico

- Generators below 5 kW

Hydroelectric plants classification

Conventional

- Dammed water
- Water accumulated in artificial reservoir

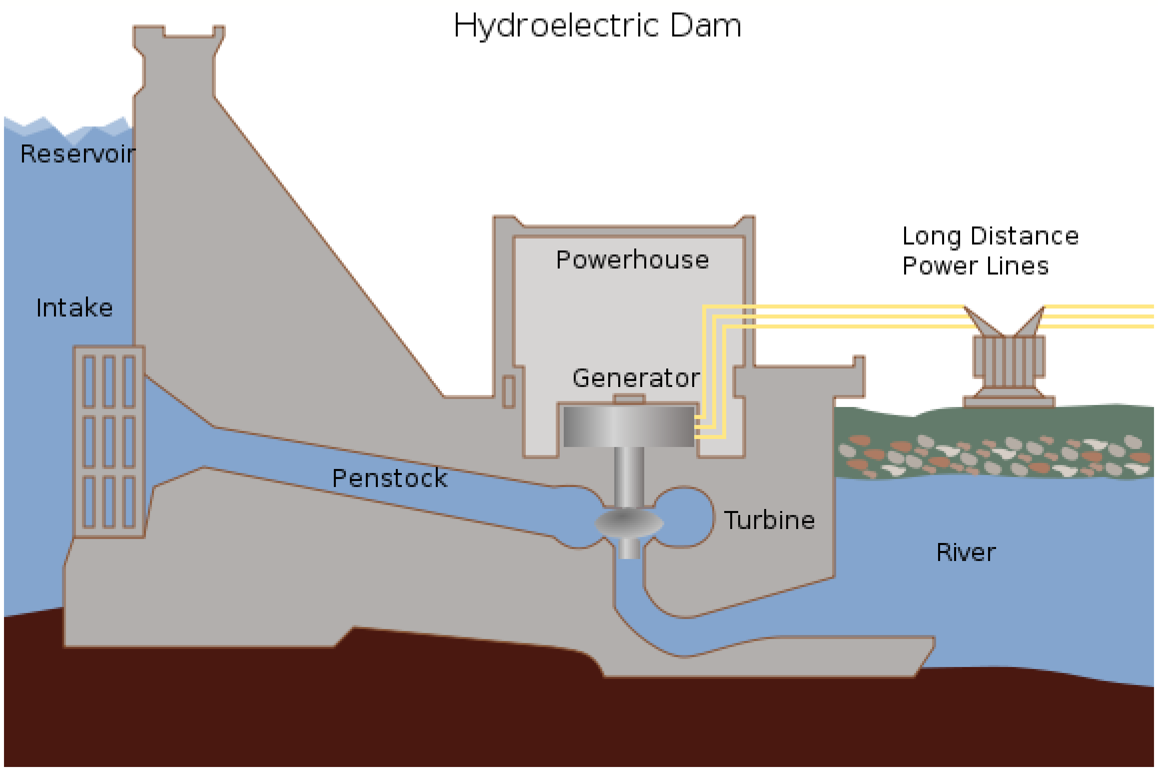
Run-of-the-river

- Dammed water (or in small scale – not necessarily)
- No reservoir

Pumped storage

- Not a power generation facility as such
- Storage for excessive electricity

Conventional dammed hydroelectric station



Run-of-the-river plant

TECHNOLOGY

Hydroelectric plant Technology – turbines

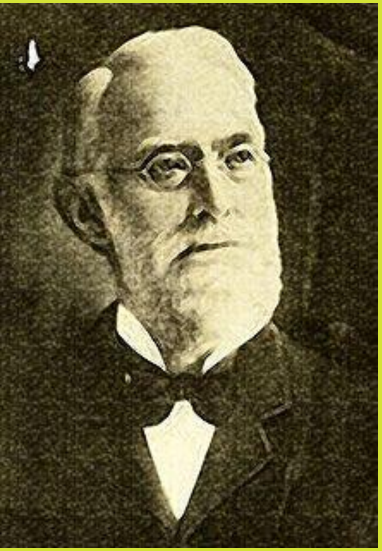
Impulse type

- Pelton turbine
- Turgo turbine
- Cross-flow turbine

Reactive type

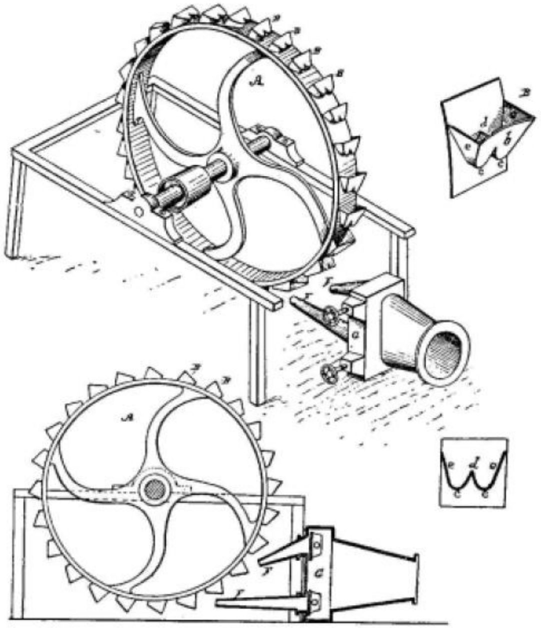
- Francis turbine
- Kaplan turbine
- Freeflow turbines (Tyson, Gorlov)

Pelton turbine



Lester Allan Pelton
(1829-1908)

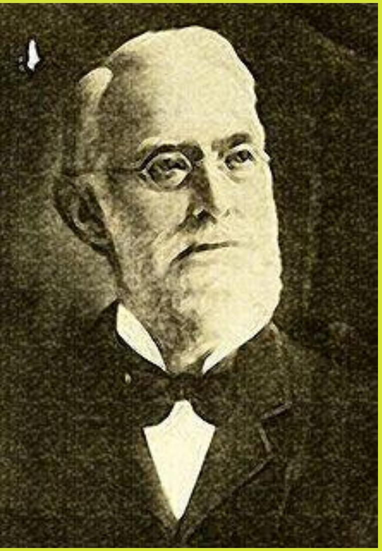
- Impulse water turbine
- Invented in 1870s
- Preferred for high head and low flows



Original figure from Pelton's patent application
Via Wikipedia

← Pelton turbine rotor, Walchenseekraftwerk, Germany

Pelton turbine



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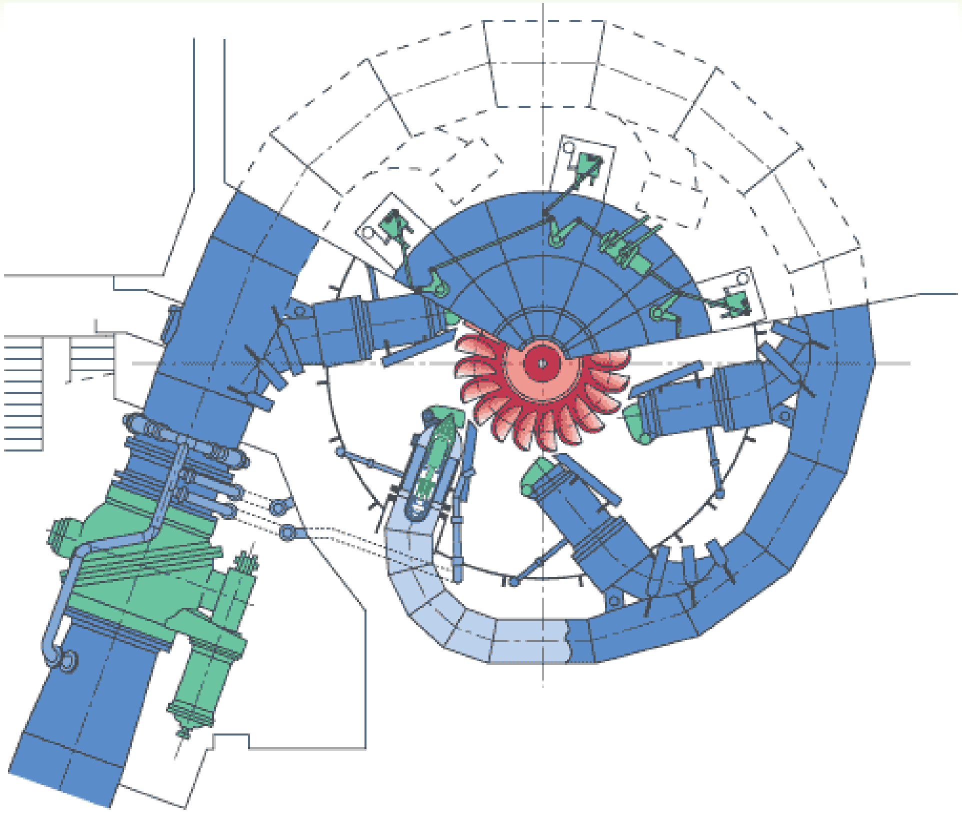
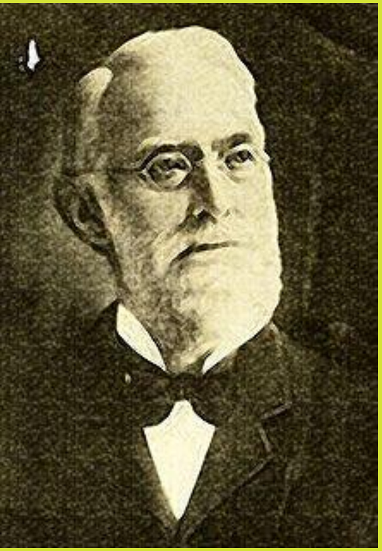


Pelton turbine



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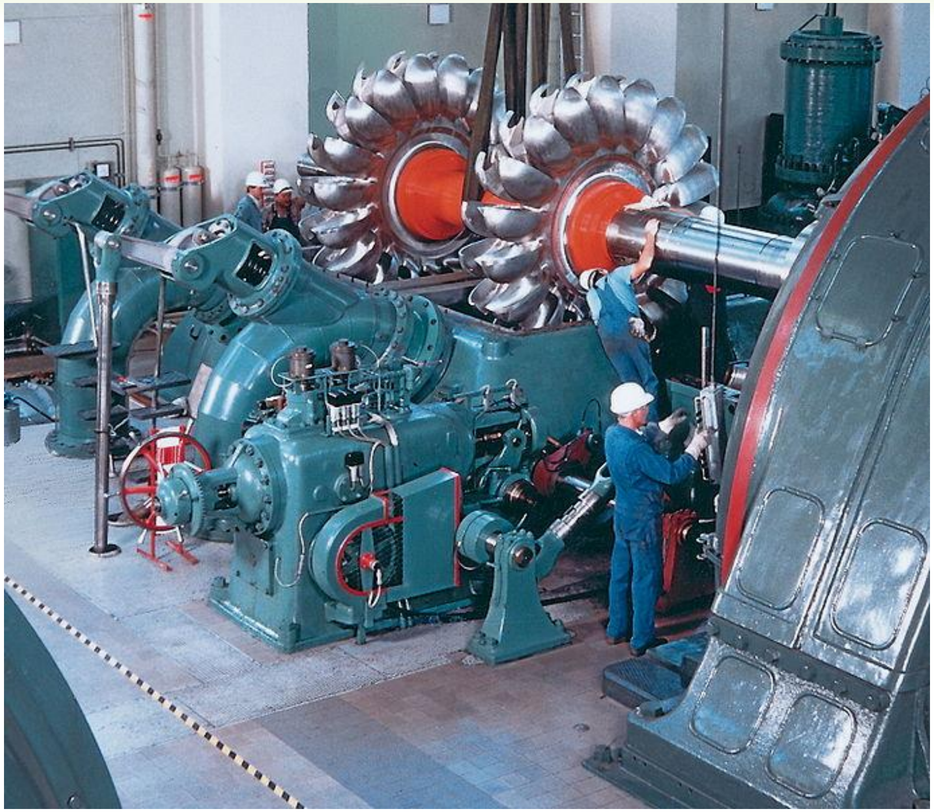
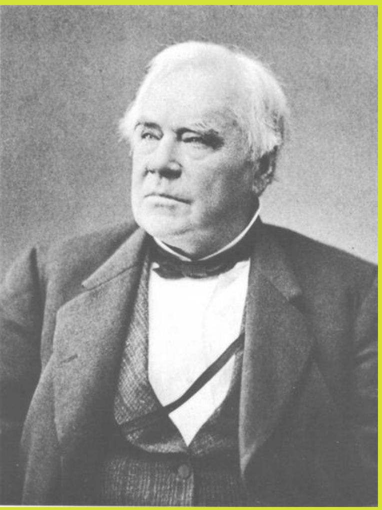


Pelton turbine rotors, Walchenseekraftwerk, Germany

Francis turbine

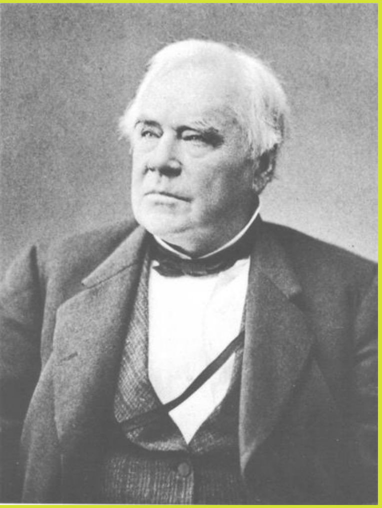


James B. Francis
(1815-1892)

- Inward flow reaction water turbine
- Invented in 1840s
- Most widely used water turbine type
- Wide range of head and flows, but not useful for lowest head values
- All really large-scale applications.

Francis turbine runner for the Three Gorges Dam

Francis turbine



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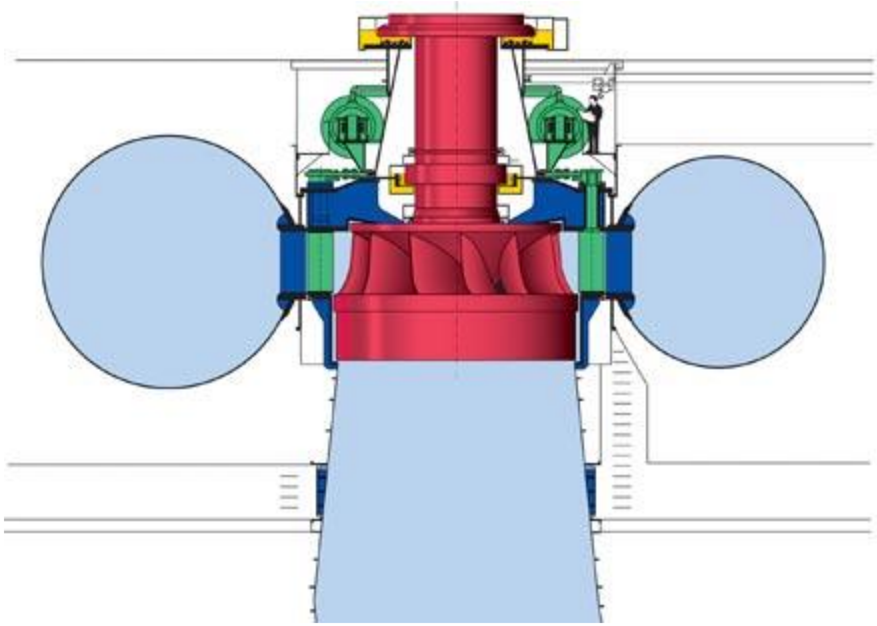
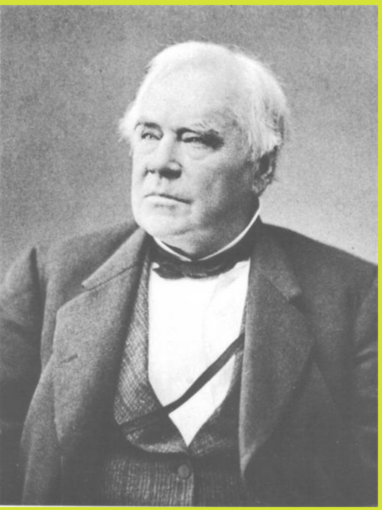
(1815-1892)



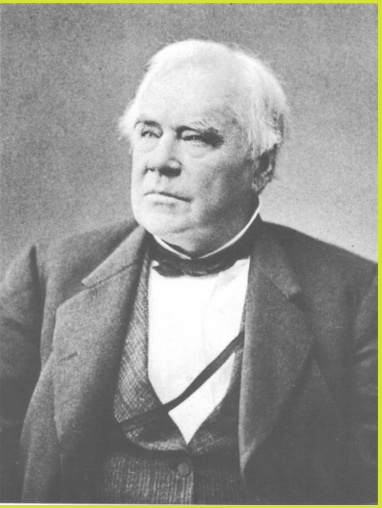
Francis turbine



James B. Francis
(1815-1892)

Guide vanes in closed (left) and fully-open (down) position

Francis turbine



James B. Francis
(1815-1892)

Kaplan turbine

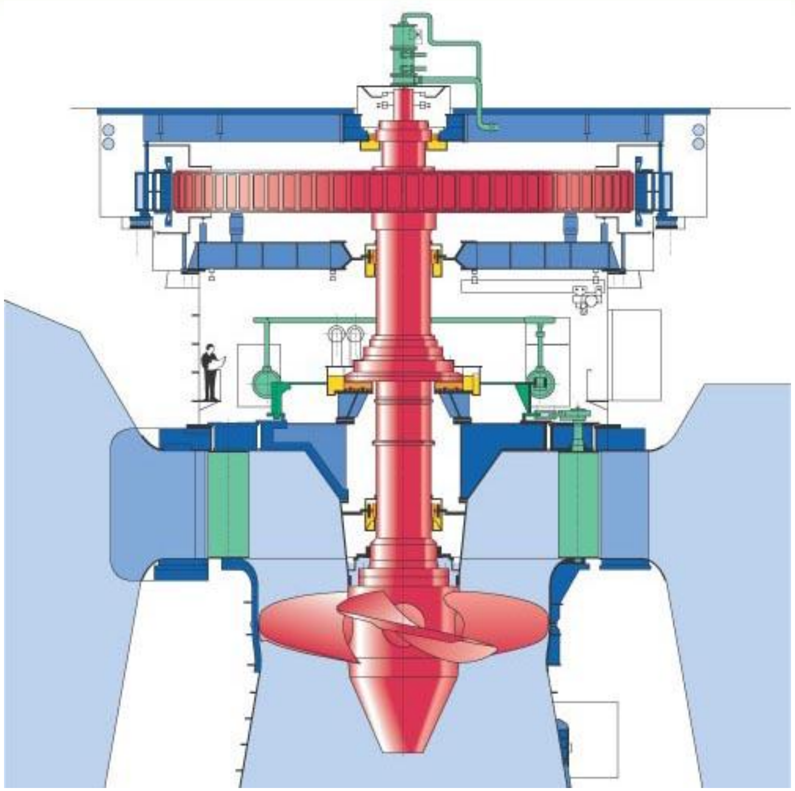
Viktor Kaplan
(1876-1934)

- Propeller-type reaction water turbine
- Evolution of the Francis turbine concept
- Invented in 1913
- Automatically adjusted blades
- Low-head, high-flow applications

Bonneville Dam – Kaplan turbine after 61 years of service

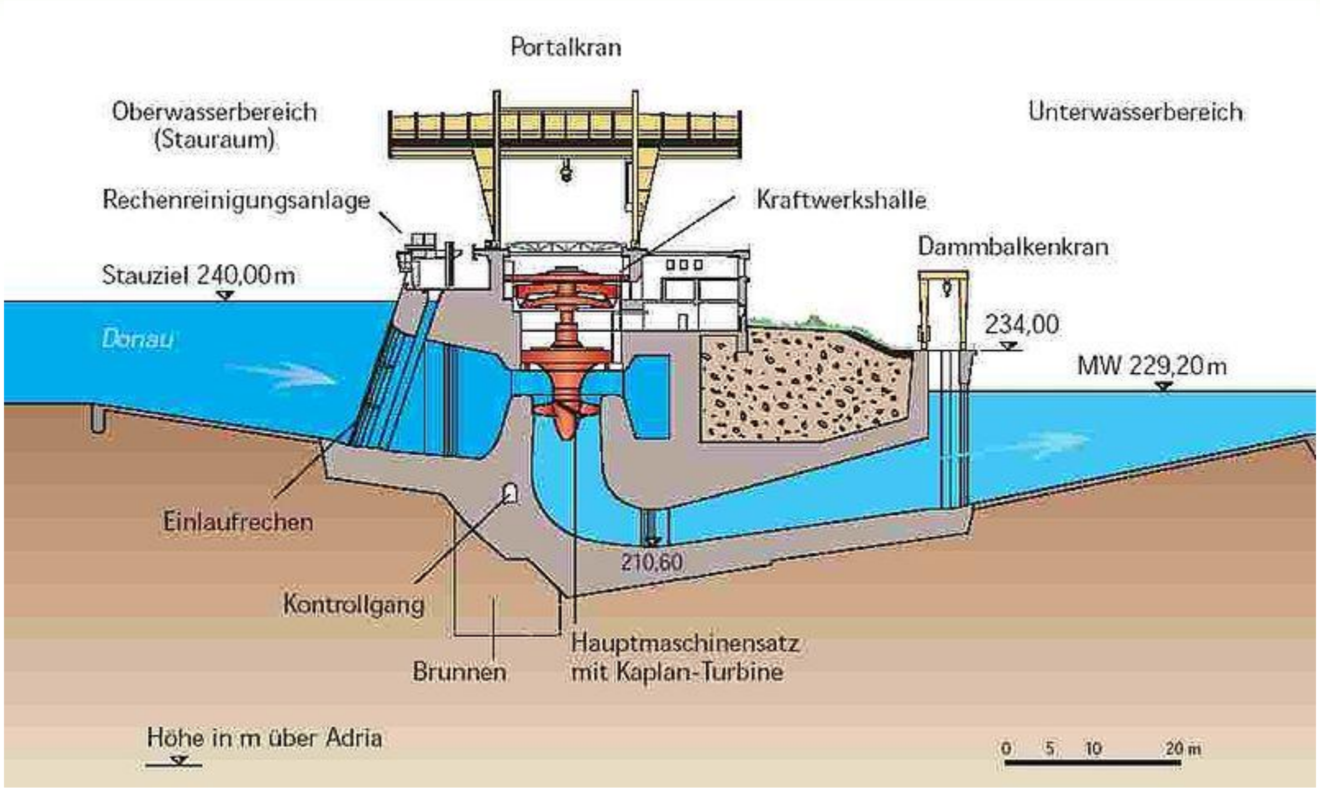
Kaplan turbine

Viktor Kaplan
(1876-1934)



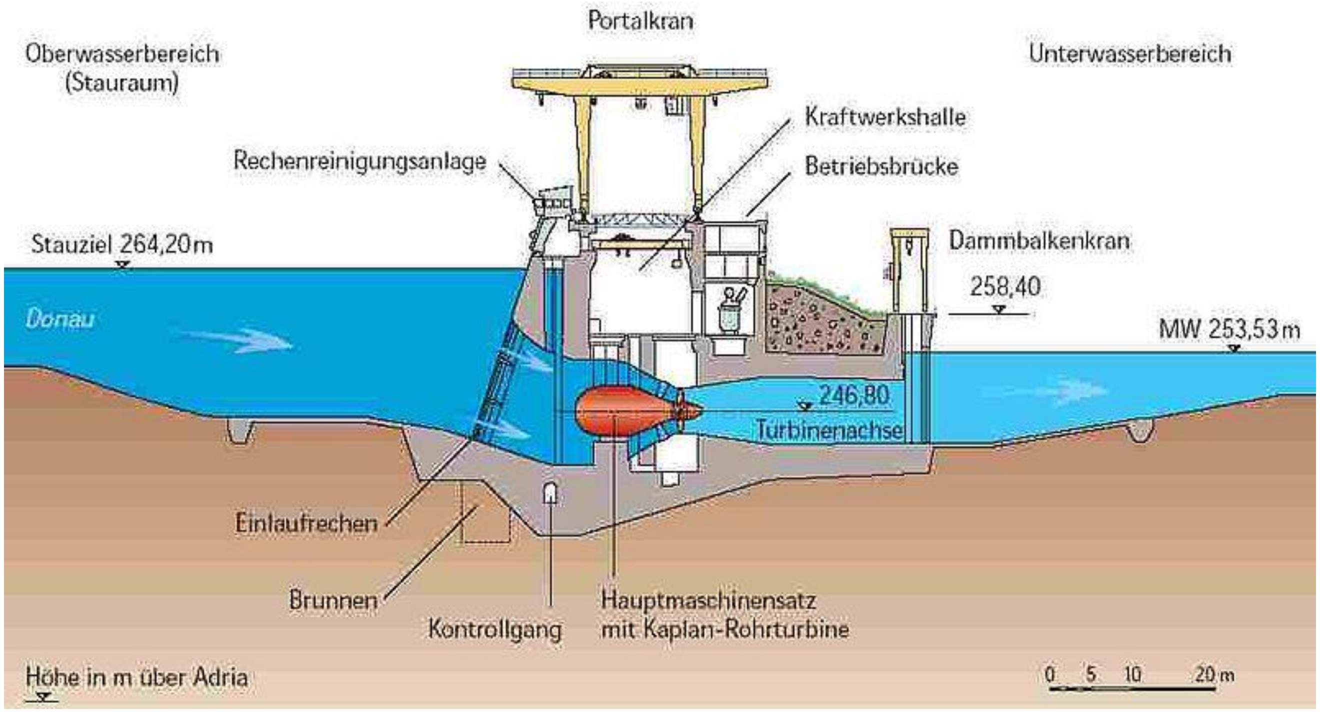
Vertical Kaplan turbine

Viktor Kaplan
(1876-1934)



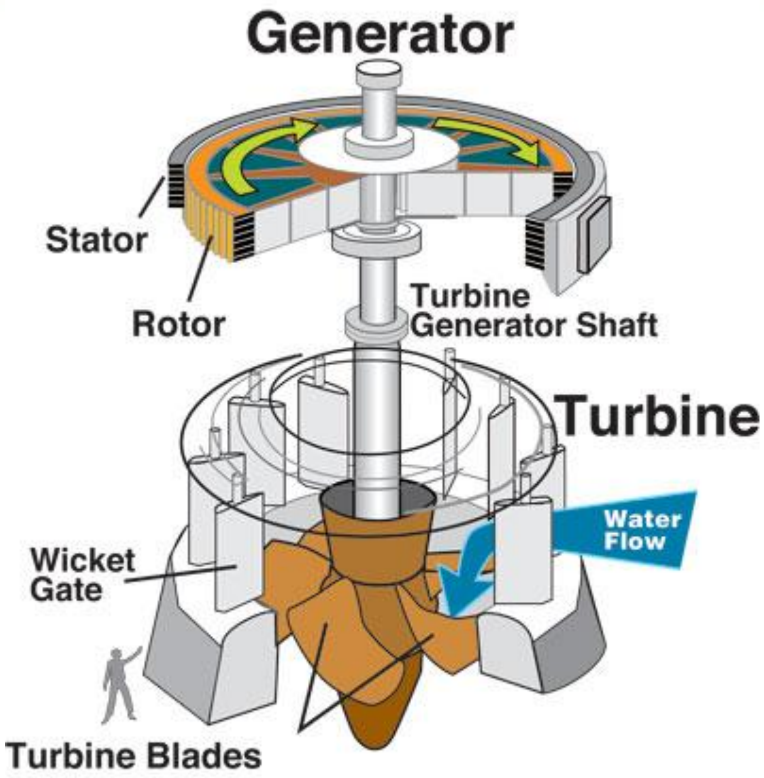
Horizontal Kaplan turbine

Viktor Kaplan
(1876-1934)



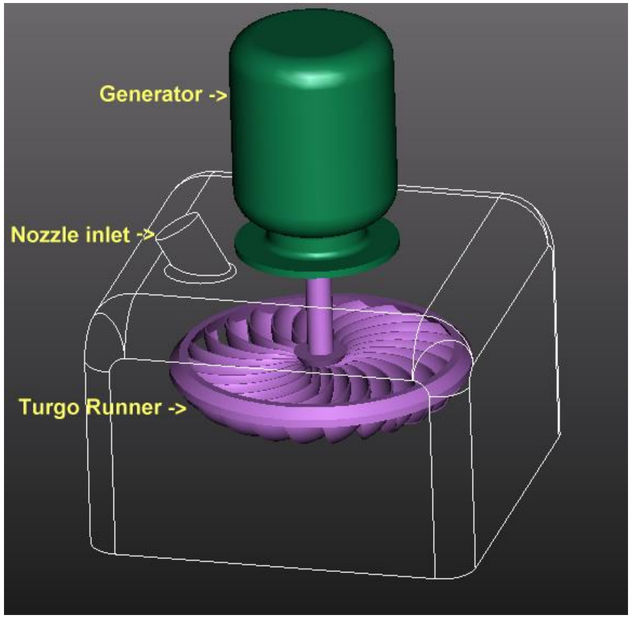
Vertical Kaplan turbine

Viktor Kaplan
(1876-1934)



Turgo turbine

- Impulse water turbine
- Invented in 1919
- Efficiencies below 90%
- Low-flow medium-head applications



Cross-flow turbine (Banki-Michell, Ossberger)

- Impulse water turbine
- Patented in 1903 (Michell) and 1933 (Ossberger)
- Lower efficienies than Kaplan, Francis or Pelton
- Low cost
- Good flexibility (good partial-load performance)
- Small-scale applications

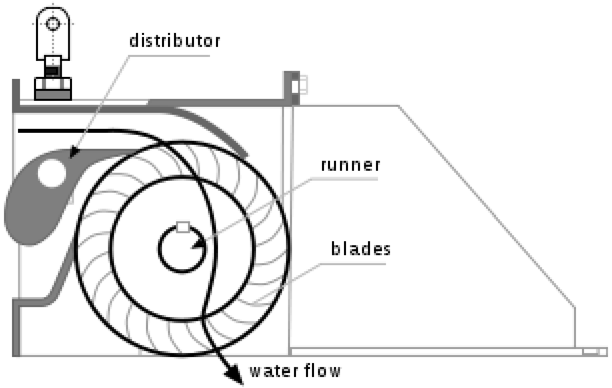


figure 6.7

Cross-flow turbine (Banki-Michell, Ossberger)

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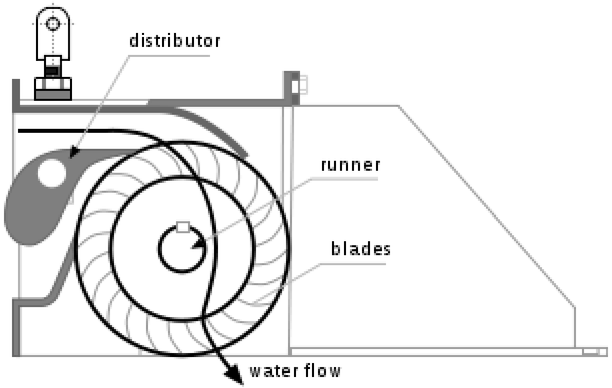
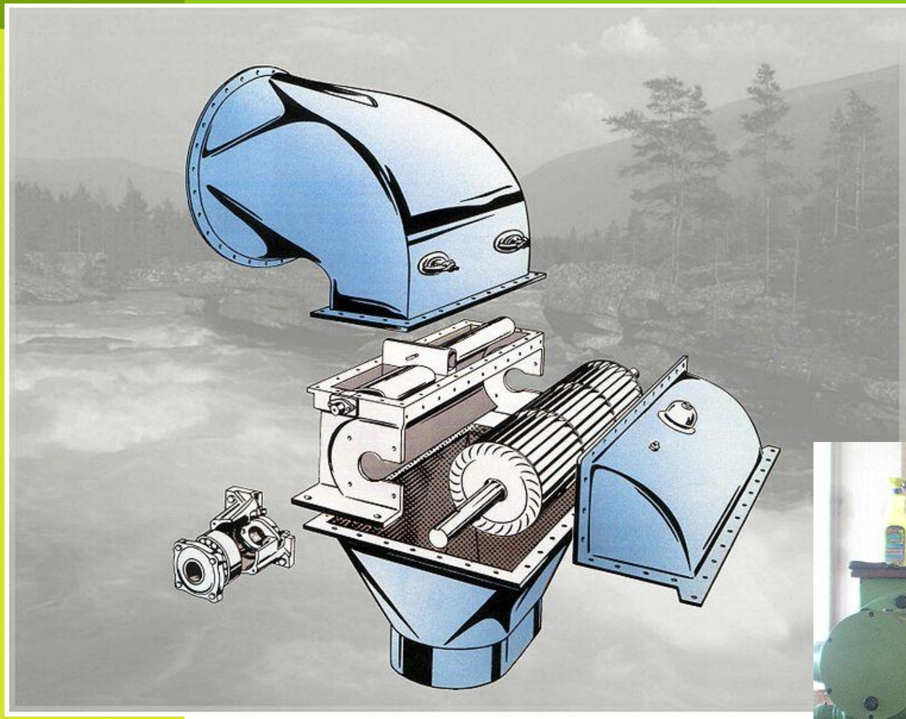
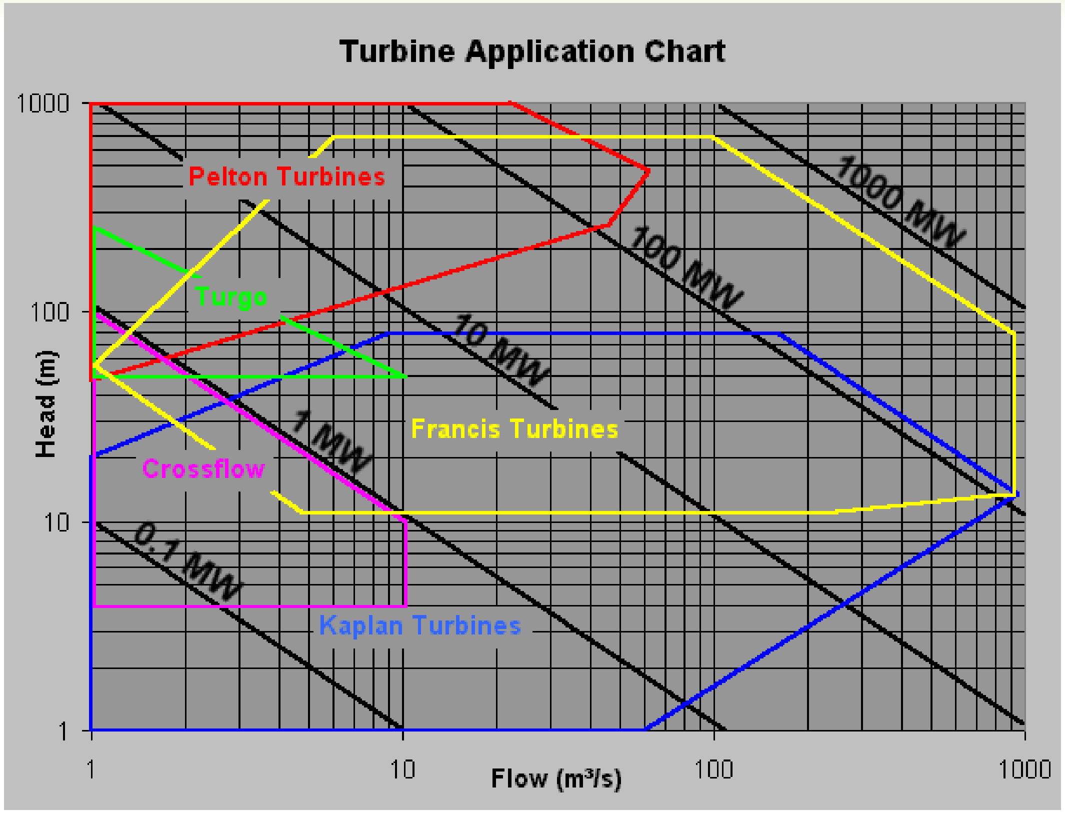


figure 6.7

Ossberger turbine



What type of turbine?



Available power

$$P = Q \cdot \rho \cdot g \cdot h \cdot \eta$$

P – Power (W)

Q – Flow (m^3/s)

ρ – Water density (kg/m^3)

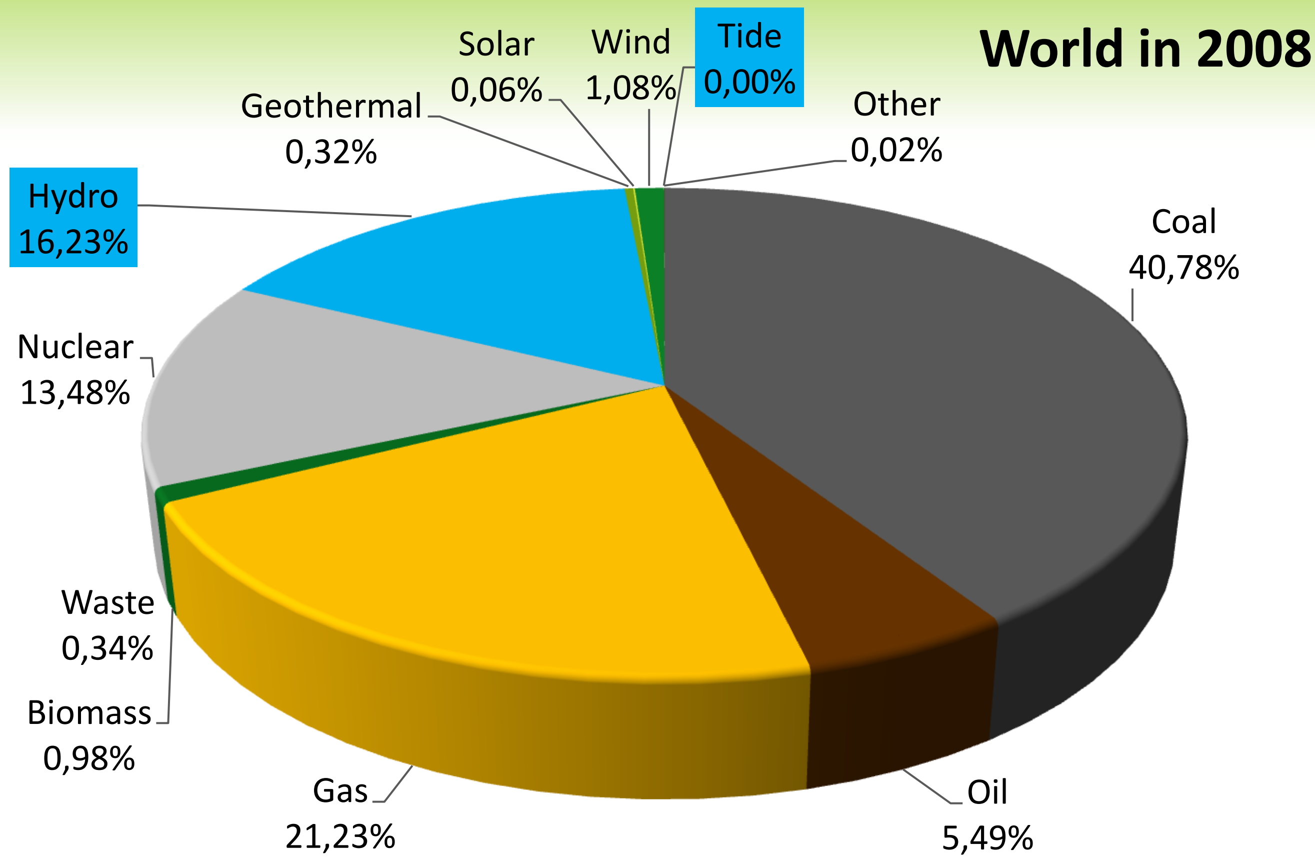
g – gravitational acceleration (m/s^2)

h – hydraulic head (m)

η – turbine efficiency

Applications

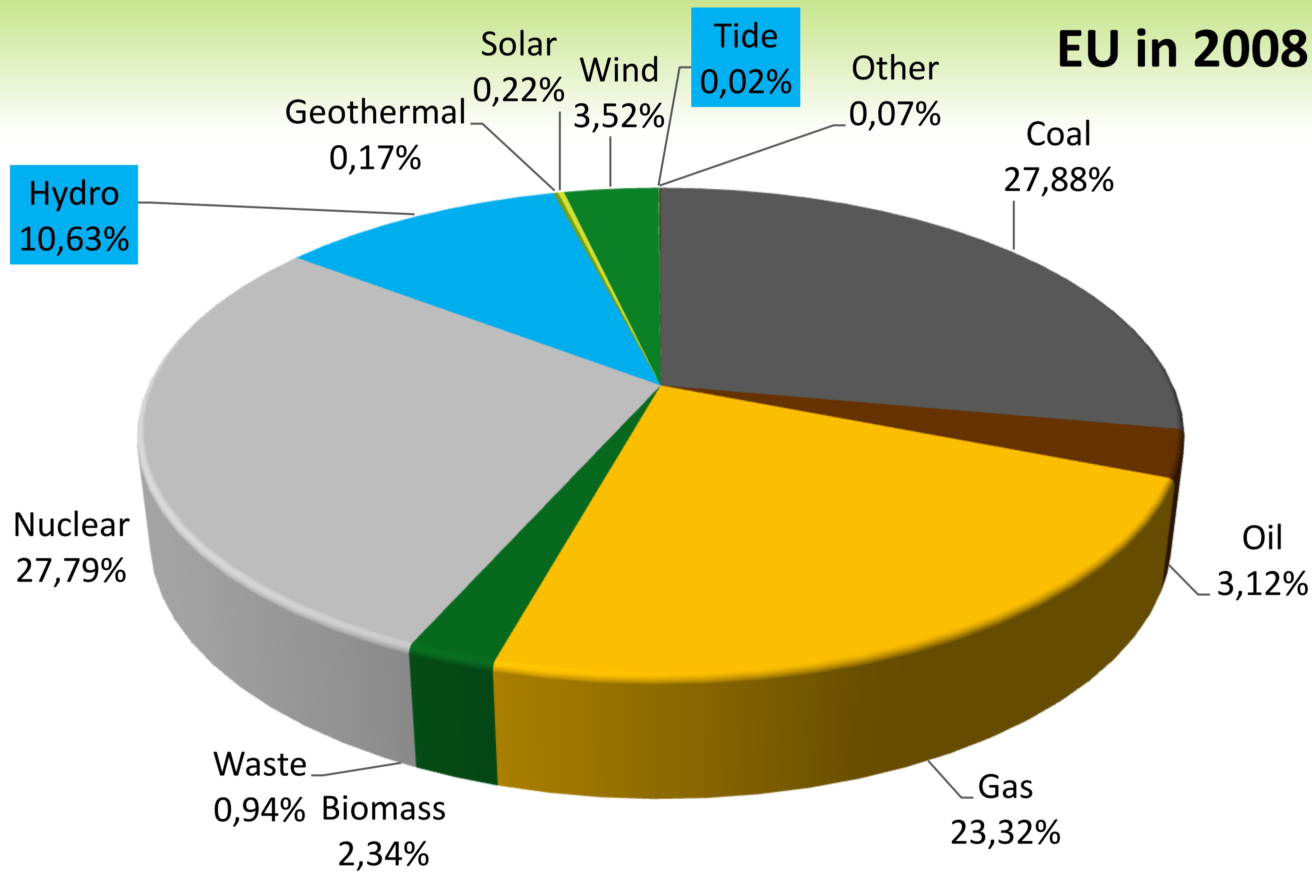
Electricity generation



Data by:

Classic hydroelectric plants: 3,287,554 GWh (including pumped storage!)
Tidal power plants: 546 GWh
Total global generation in 2008: 20,260,838 GWh.

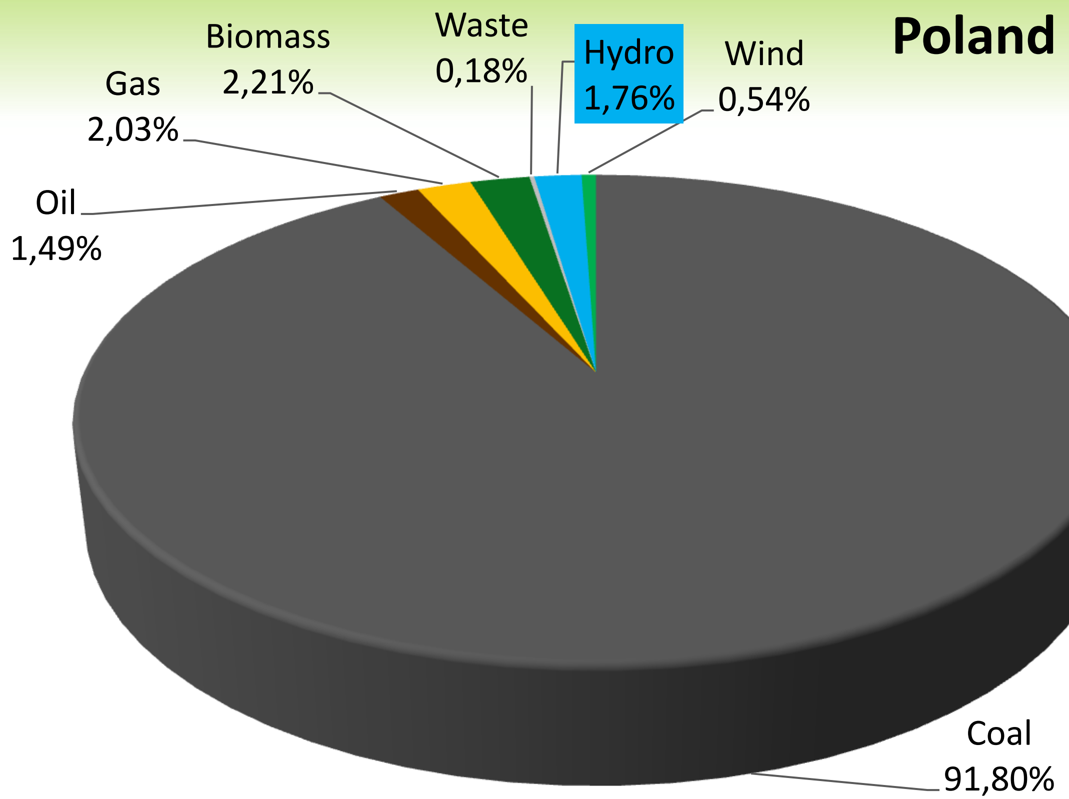
Electricity generation



Data by:

Classic hydroelectric plants: 358,672 GWh (including pumped storage!)
Tidal power plants: 513 GWh
Total EU generation in 2008: 3,373,072 GWh.

Electricity generation



Data by:

Classic hydroelectric plants: 2747 GWh (including pumped storage!)
Tidal power plants: NONE
Total generation in 2008: 156,177 GWh.

TOP 10 HYDROPOWER (2009)

Country	Annual generation (TWh)	Installed capacity (GW)	Capacity factor	% of total capacity
China	652.0	196.790	0.37	22.25
Canada	369.5	88.974	0.59	61.12
Brazil	363.8	69.080	0.56	85.56
USA	250.6	79.511	0.42	5.74
Russia	167.0	45.000	0.42	17.64
Norway	140.5	27.528	0.49	98.25
India	115.6	33.600	0.43	15.80
Venezuela	85.96	14.622	0.67	69.20
Japan	69.2	27.229	0.37	7.21
Sweden	65.5	16.209	0.46	44.34
…				
Poland	3.0	2.2	0.15	6.22

Largest hydroelectric plants in the world

Classic plants (with reservoir)

- Three Gorges Dam, Yangtze River, PRC –22,500 MW
- Itaipu Dam, Paraná River, Brazil-Paraguay – 14,000 MW
- Guri Dam, Caroni River, Venezuela – 10,235 MW

Run-of-the-river plants

- Jinping II, Yalong River, PRC – 4,800 MW
- Chief Joseph Dam, Columbia River, WA, USA – 2,620 MW
- John Day Dam, Columbia River, OR-WA, USA – 2,485 MW

Pumped storage

- Kannagawa, Japan – 940 MW (2012, 2,820 MW planned for 2020)
- Bath County Pumped Storage Station, VA, USA – 2,772 MW
- Guangdong, PRC, 2400 MW

Three Gorges Dam

Gravity dam on Yangtze River

- Length 2335 m
- Height 185 m

Reservoir

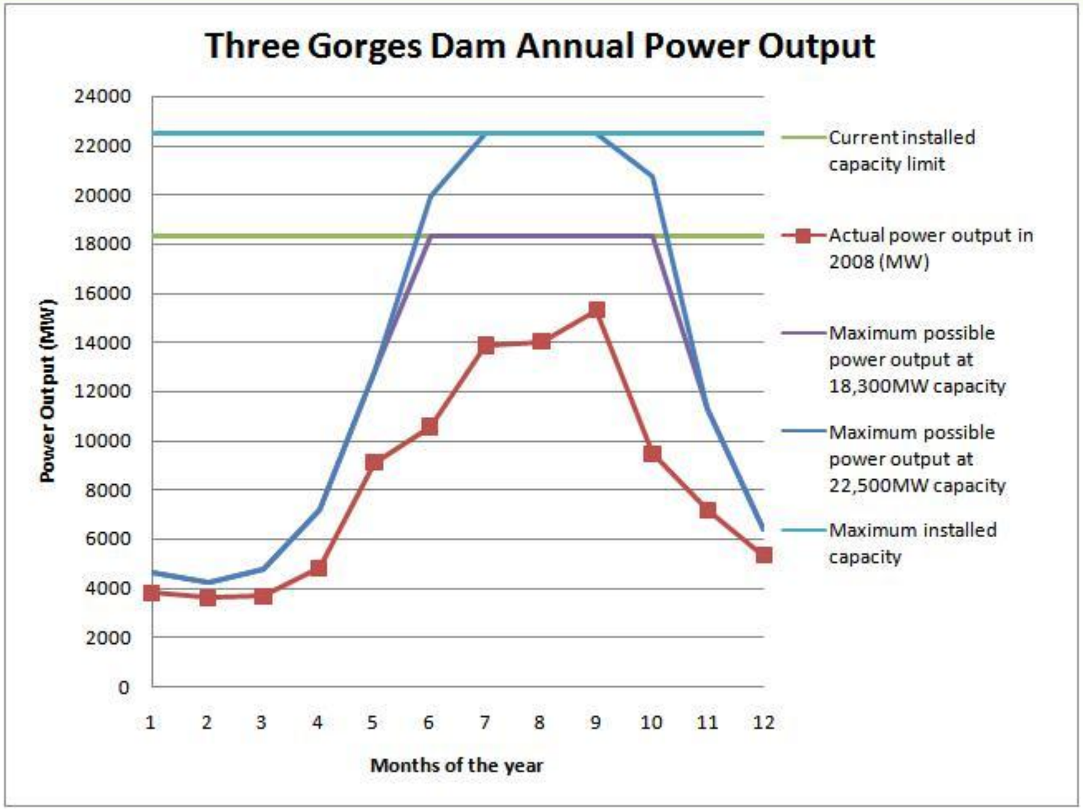
- Maximum water level 175 m ASL
- Surface 1045 km^2
- Capacity 39.3 km^3

Power plant

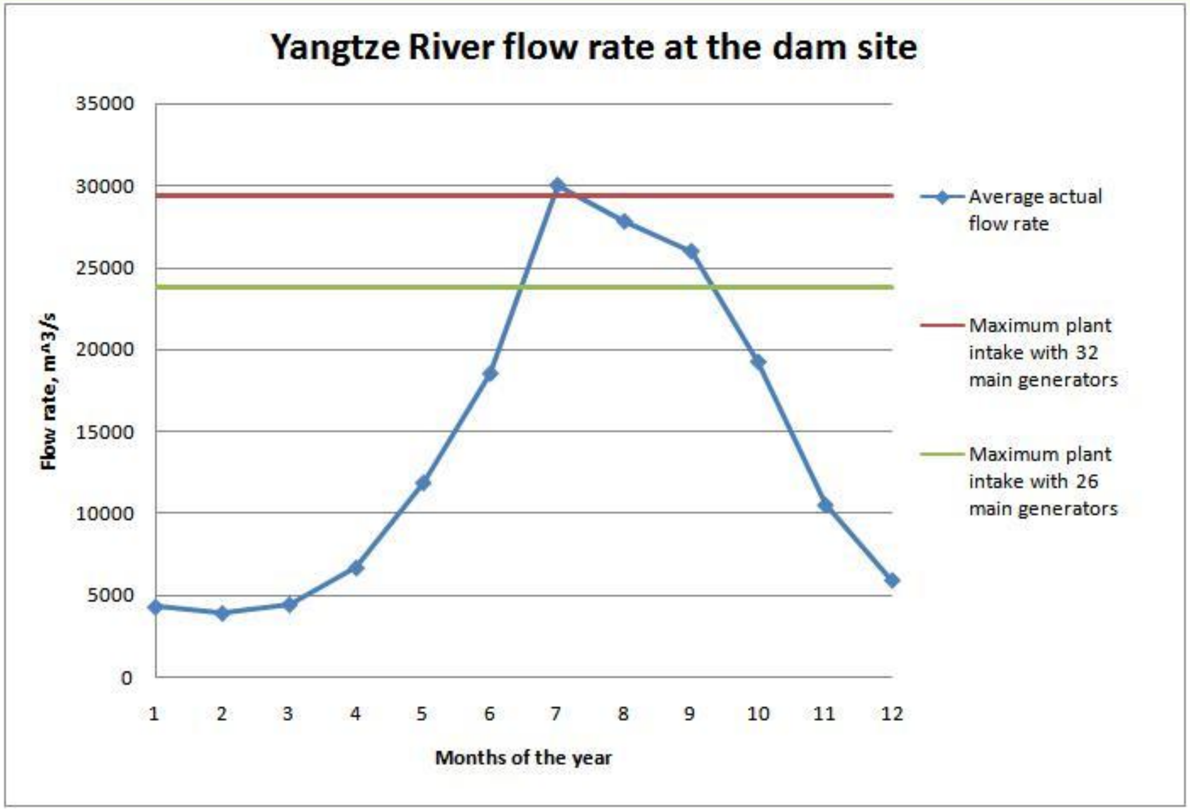
- Three locations: both ends of the dam and underground to the south
- 30 × 700 MW Francis turbine by VGS and Alstom
  Rotor diameter 9.7 m (VGS) / 10.4 m (Alstom), speed 75 rpm
  Efficiency 94% (average), 96.5% (maximum)
- 2 × 50 MW own consumption Francis turbines
- Design head 80.6 m, flow rate 600…950 m^3/s

Three Gorges Dam

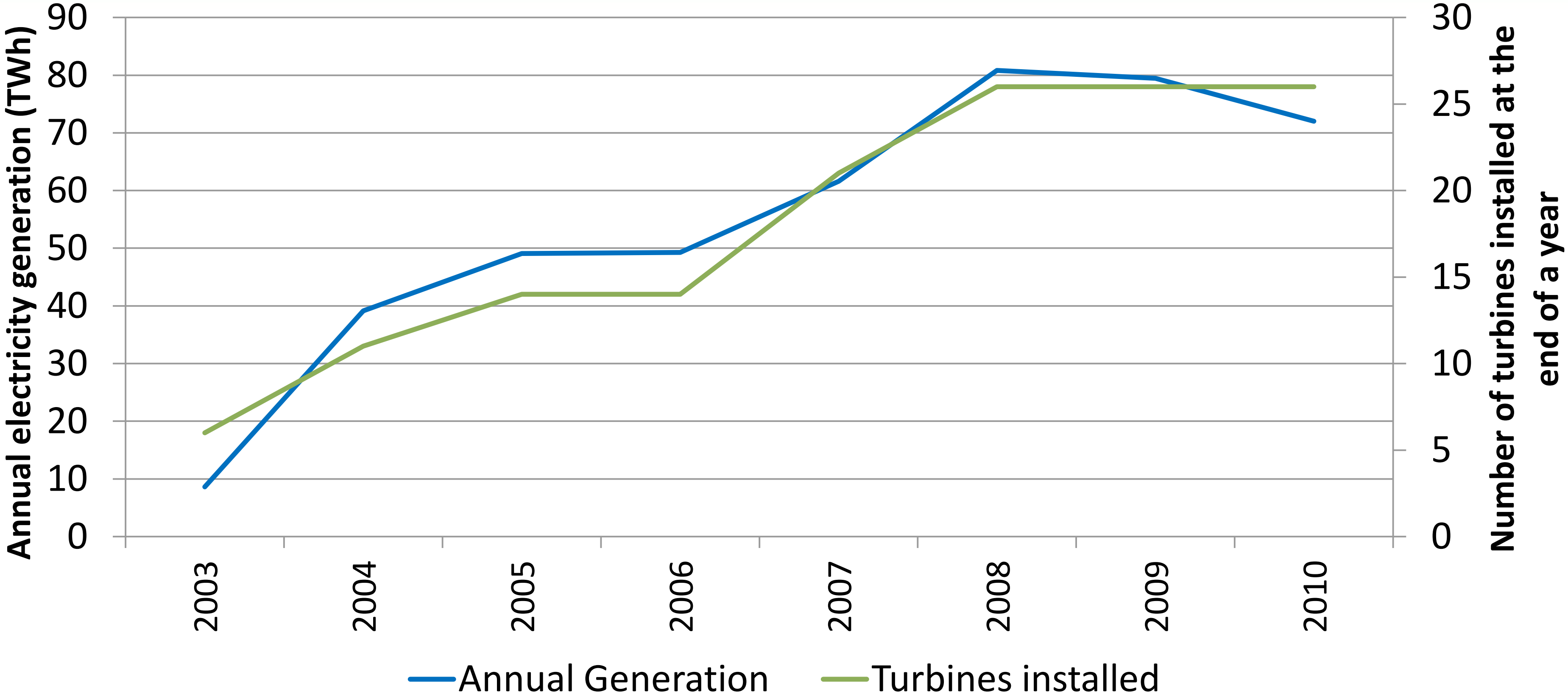
Three Gorges Dam



Three Gorges Dam



Three Gorges Dam



Itaipu Dam

Gravity dam on Paraná River

- Length 7235 m
- Height 196 m

Reservoir

- Capacity 29 km^3
- Head 118 m

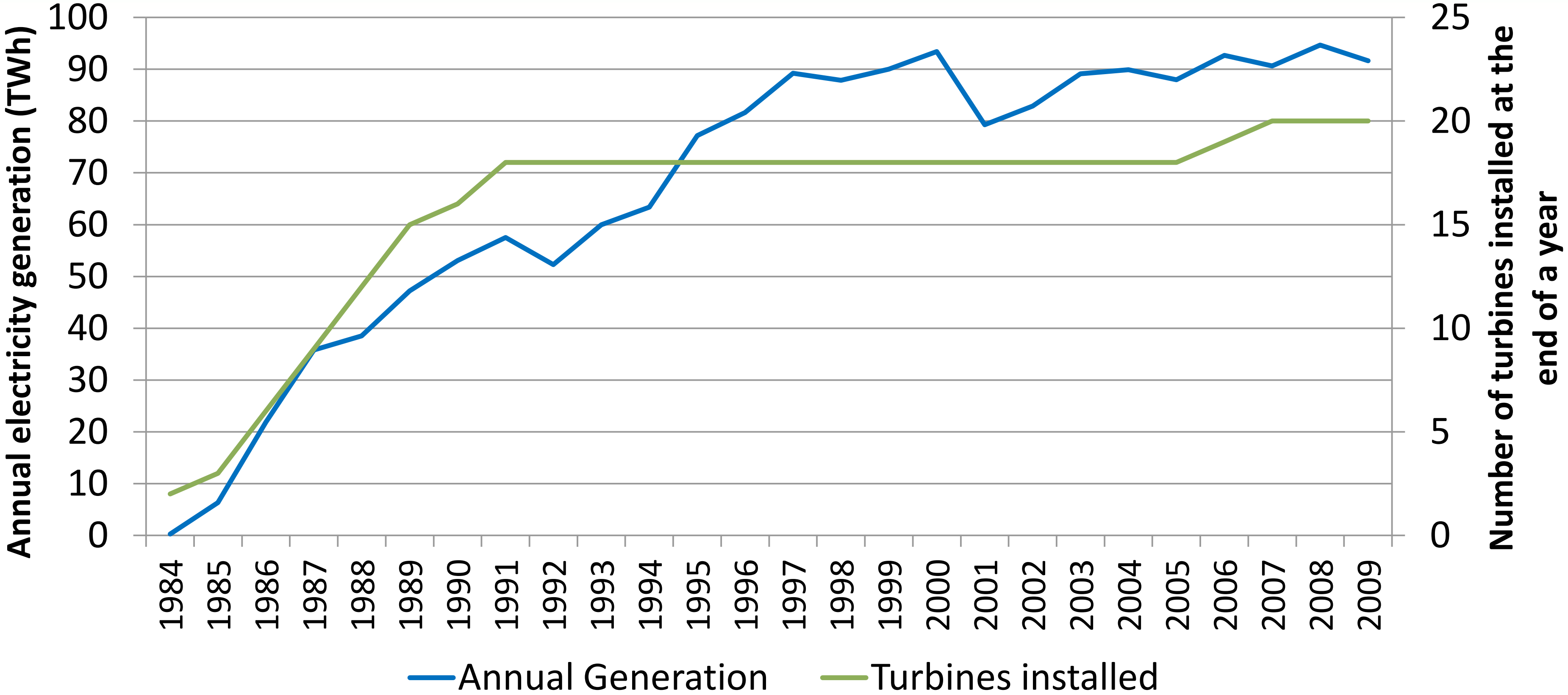
Power plant

- 20 × 700 MW turbines (10 for Brazil, 10 for Paraguay)
  Actual power can reach 750 MW
- Nominal flow for each turbine is 700 m^3/s
- Commissioned in 1984, full power in 2007
- Annual power generation ca 90 TWh (capacity factor ca 75%)

Itaipu Dam

Itaipu Dam

Itaipu Dam


100
90
80
70
60
50
40
30
20
10
0
Annual electricity generation (TWh)
25
20
15
10
5
0
Number of turbines installed at the end of a year
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Annual Generation
Turbines installed

Cleuson-Dixence complex Switzerland

Grande Dixence Gravity Dam

- Length 5.3 km
- Height 285 m – the highest gravity dam in the world

Reservoir – Lax de Dix (Lake Dix)

- Capacity 0.4 km^3

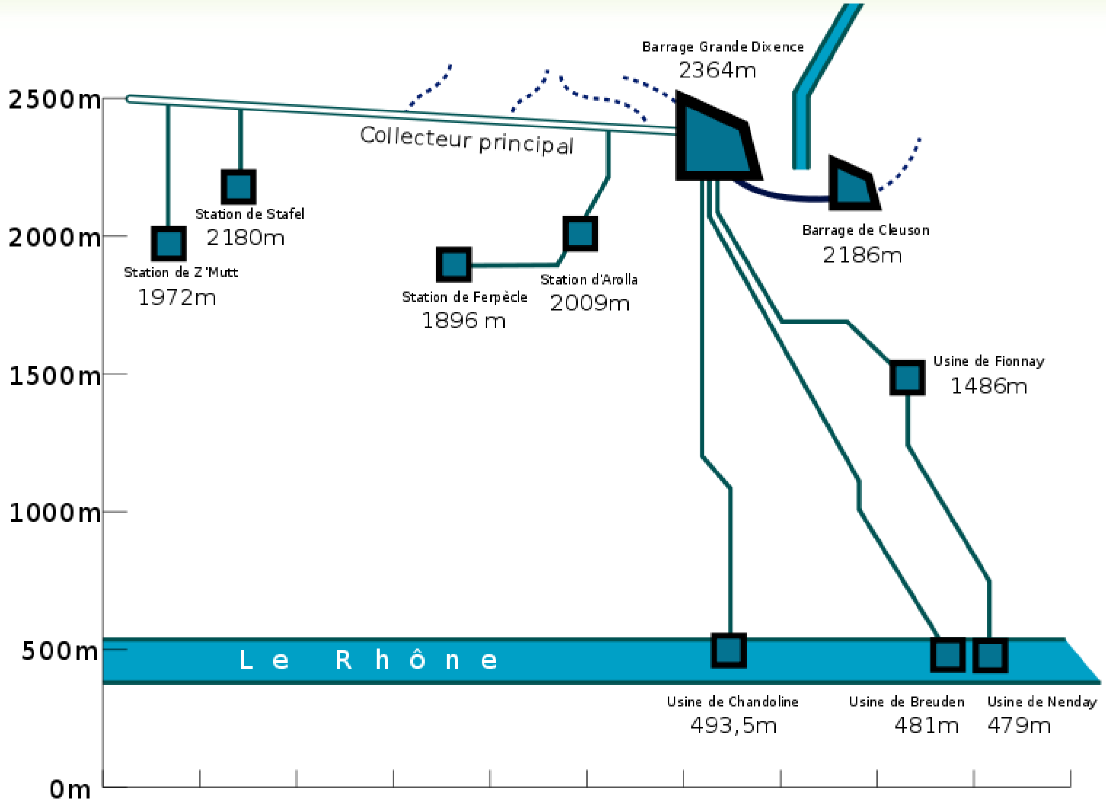
Power plants

- Chandoline, 120 MW (5 Pelton turbines)
- Fionnay, 290 MW (6 × double Pelton wheel)
  Head 874 m, max flow 45 m^3/s
- Nendaz, 390 MW (6 × double Pelton wheel)
  Head 1008 m, max flow 45 m^3/s
- Bieudron, 1269 MW (3 × Pelton)
  Head 1869 m, max flow 45 m^3/s, efficiency 92.37%

Pumping stations

- Z'mutt, Stafel, Ferpècle, Arolla – pumping water from glaciers into the Lax de Dix

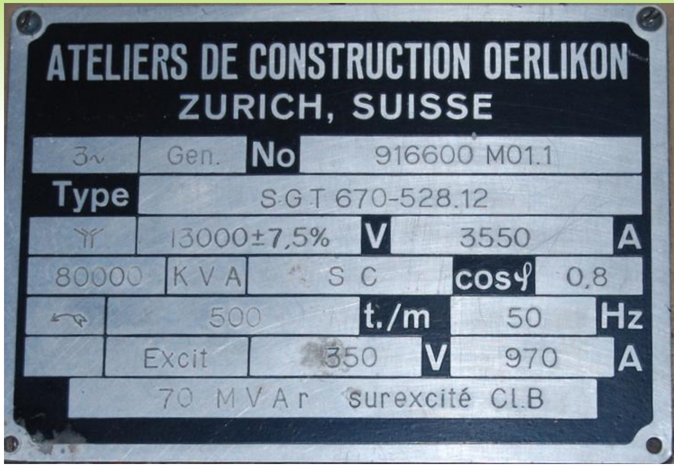
Cleuson-Dixence complex Switzerland



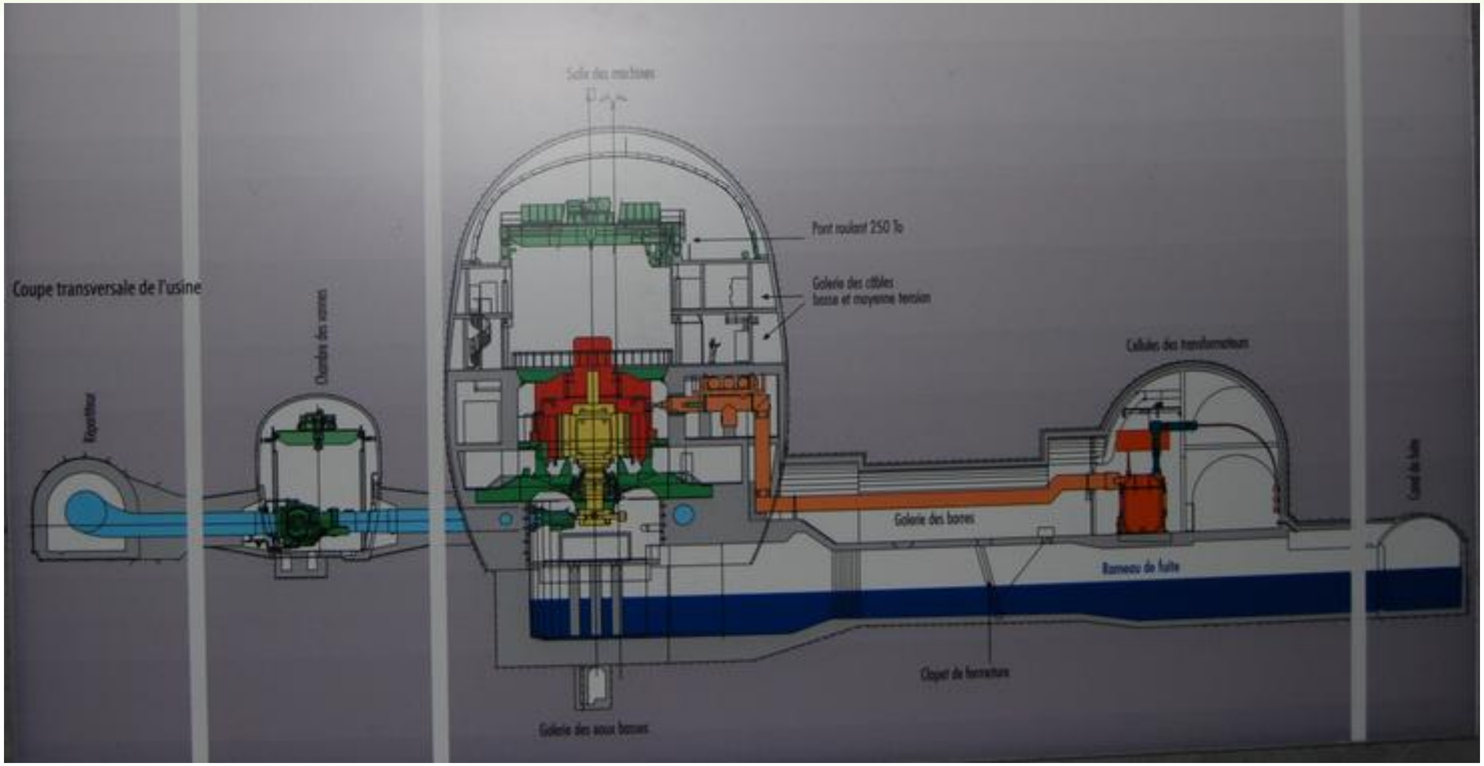
Grande Dixence Dam

Usine de Nendaz

Usine de Nendaz



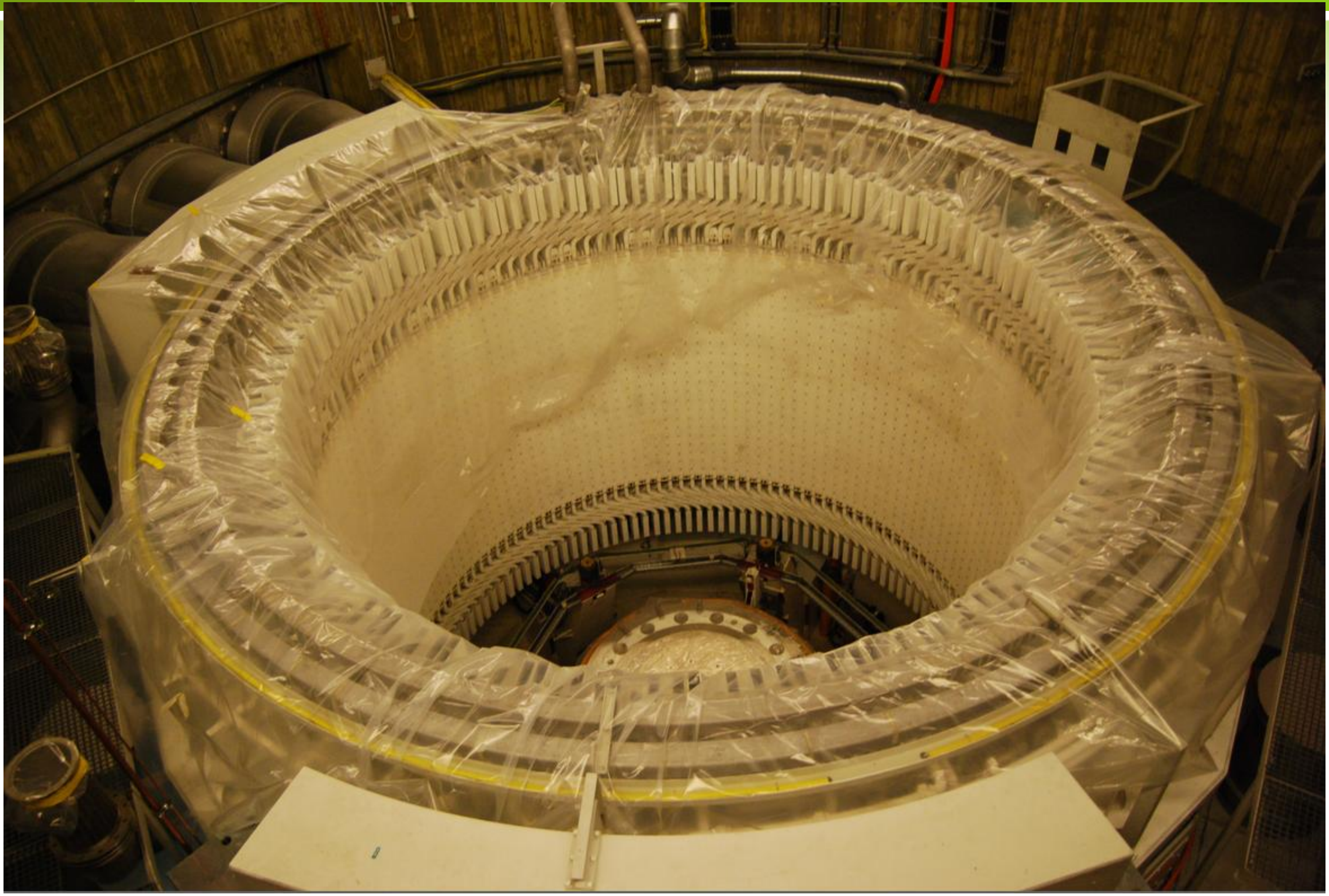
Usine de Bieudron



Usine de Bieudron

Usine de Bieudron

Usine de Bieudron



Hydroelectricity in Poland (09.2012)

Flow-type plants

- > 50 MW: 1 plant, Włocławek, 160.2 MW
- 10-50 MW: 5 plants, 129.6 MW
- 5-10 MW: 6 plants, 48.2 MW
- 1-5 MW: 61 plants, 138.7 MW
- 0.3-1 MW: 90 plants, 54.6 MW
- < 0.3 MW: 599 plants, 44.1 MW

Pumped storage / Flow

- Dychów, 91.3 MW
- Niedzica, 92.75 MW
- Solina, 198.6 MW

Pumped storage

- Żarnowiec, 716 MW
- Porąbka-Żar, 500 MW
- Żydowo, 156 MW

Elektrownia Wodna Żarnowiec

Upper reservoir - Czymanowo

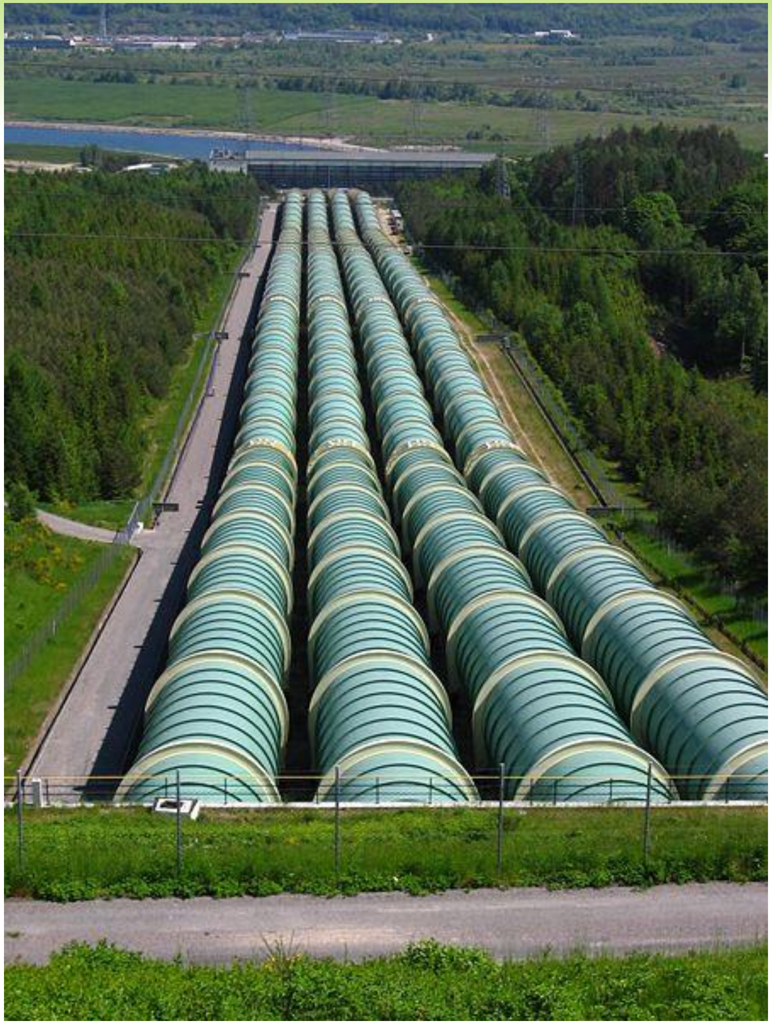
- Area 122 ha
- Capacity 13 million m^3

Lower reservoir – Żarnowiec Lake

Power plant

- 4 reversible turbine-pump Francis units
- Pumping power 4 × 200 MW
- Power generation capacity 4 × 179 MW
- Controlled remotely from KDM in Warsaw
- Commissioned in 1983, planned to cooperate with NPP

Elektrownia Wodna Żarnowiec



Elektrownia Wodna we Włocławku

Dam on Vistula River

- Head 8.8 m

Reservoir – Włocławek Lake

- Length 58 km, average width 1.2 km
- Capacity 408 million m^3

Power plant

- 6 Kaplan Turbines, 160.2 MW
- Nominal flow 2190 m^3/s, head 8.80 m
- Average generation 739 GWh/a
- Commissioned in 1970

Elektrownia Wodna we Włocławku

Lower Vistula Cascade as originally planned

ZEW Solina Myczkowce

Two dams on San river

- Solina Dam – gravity dam, upstream
  Length, 664.8 m, height 81.8 m
- Myczkowce Dam – earth dam, downstream
  Length 386.0 m, height 17.5 m
  Flow stabilization

Two reservoirs

- Solińskie Lake
- Myczkowskie Lake

Two power stations

- EW Solina – 198.6 MW, 4 × Francis turbines
  May operate as pumped storage (2 turbines reversible)
- EW Myczkowce - 8.3 MW, 2 × Kaplan turbine –
  – flow of the river plant

ZEW Solina Myczkowce

Solina Dam

Hydroelectricity vs Environment

Hydroelectricity

Clean…

- Hydroelectric power generation does not create any harmful gas releases

…but not necessarily environment-friendly

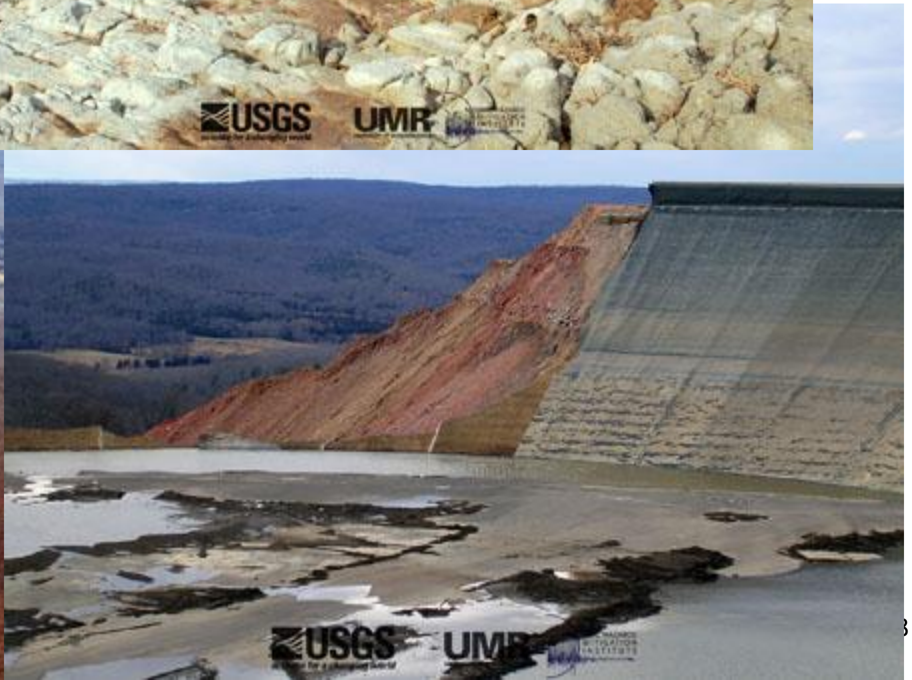
- Dam construction
- Reservoir creation – land flooding
- Change of conditions in water ecosystems
- Threat of dam breech

Fish ladder John Day Dam, USA

TAUM SAUK HYDROELECTRIC PS

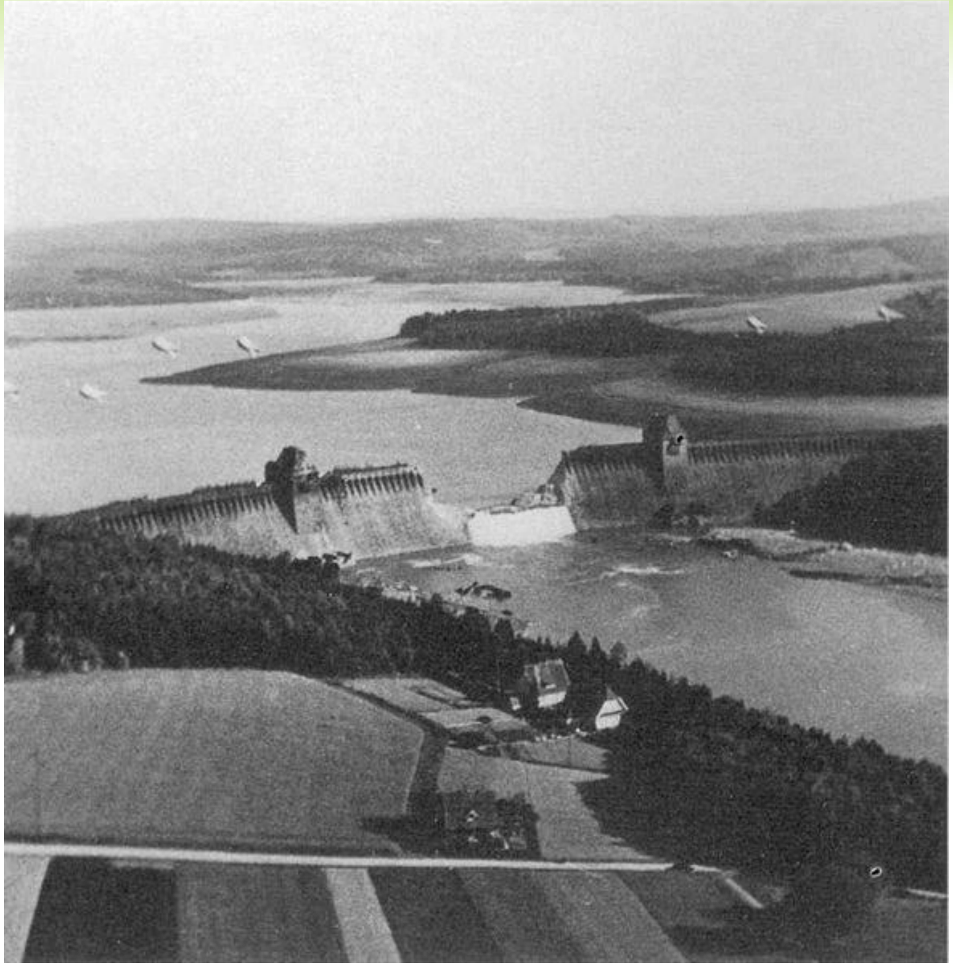
- 2 × 250 MW pumped storage station in Missouri
- Artificial upper reservoir without any natural water inflow
- On 14 December 2005 a software error resulted with overfilling the upper reservoir
- Walls had been already weakened by constant leakages
- Wall failure – breech in NW part

Taum Sauk Hydroelectric PS



Möhne Dam breeched by RAF, 16/17 May 1943

Intentional action
1579 fatalities



Sayano-Shushenskaya GES 17 August 2009

- Dam on the Yenisey River
- 10 × 640 MW

Sayano-Shushenskaya GES 17 August 2009

- Turbine „blows up"
- Power plant is flooded
- Local blackout
- Gates closing needs manual operation
- 75 fatalities

Sayano-Shushenskaya GES 17 August 2009

Marine energy

Sources of marine energy

- Tides
- Currents
- Waves
- Salinity gradients
- Temperature difference

Sources of marine energy Theoretical potential

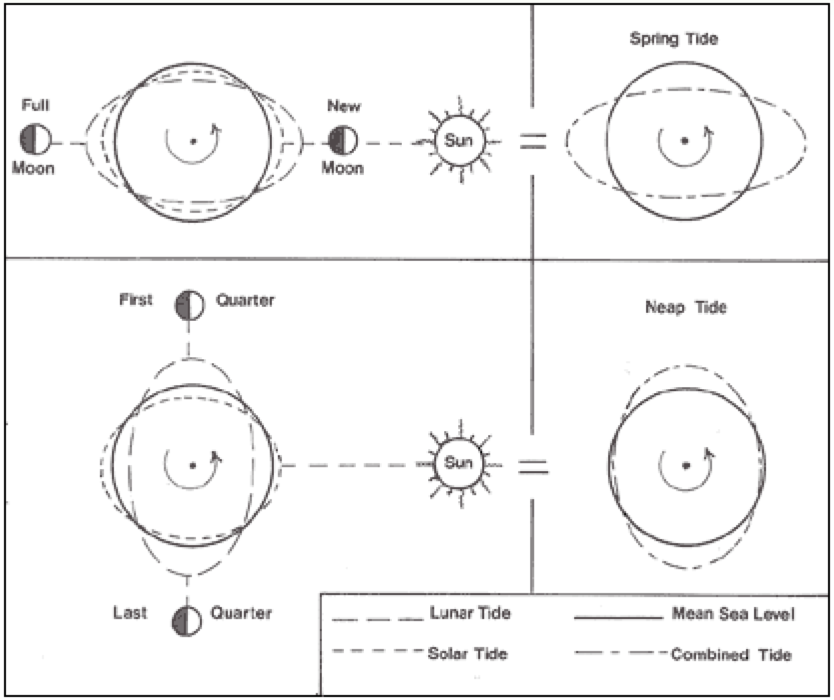
Type	Capacity (GW)	Annual generation (TWh)
Wave power	1,000-9,000	8,000-80,000
Marine current power	5,000	50,000
Ocean thermal energy	1,000	10,000
Tidal power	90	800
Osmotic power	20	2,000

Data by:

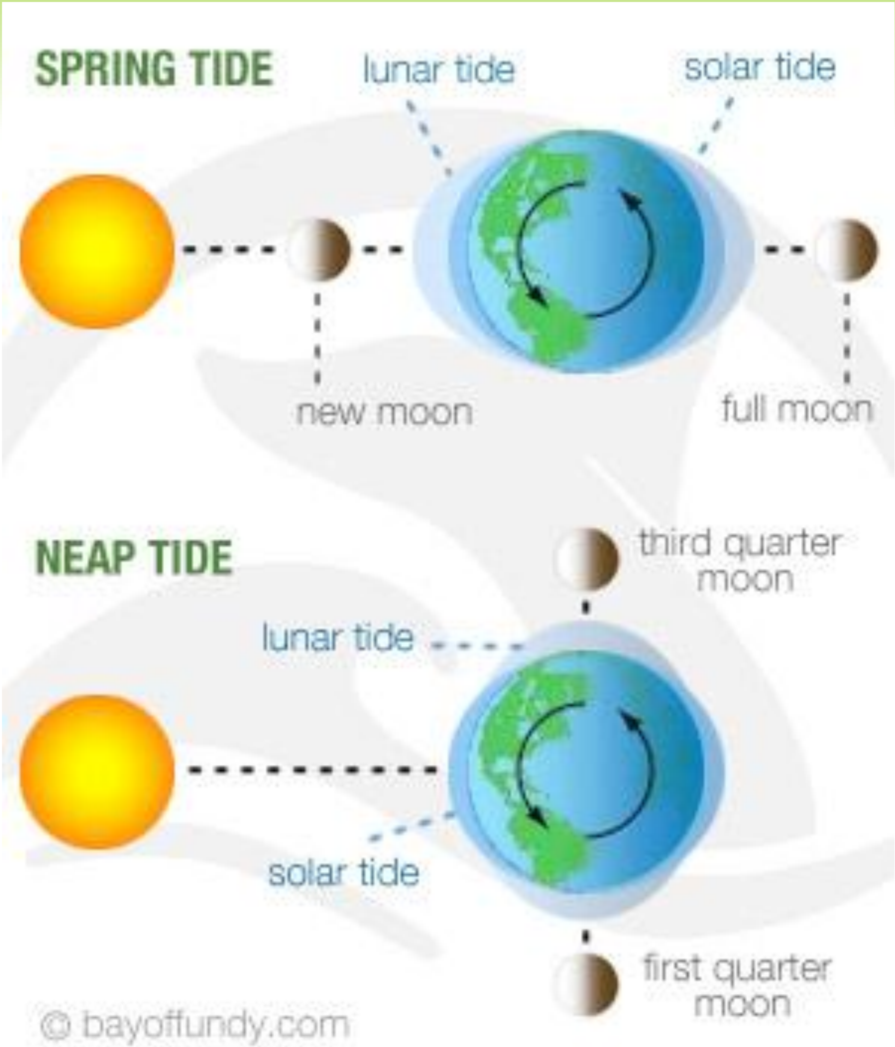
iea International Energy Agency

Tides

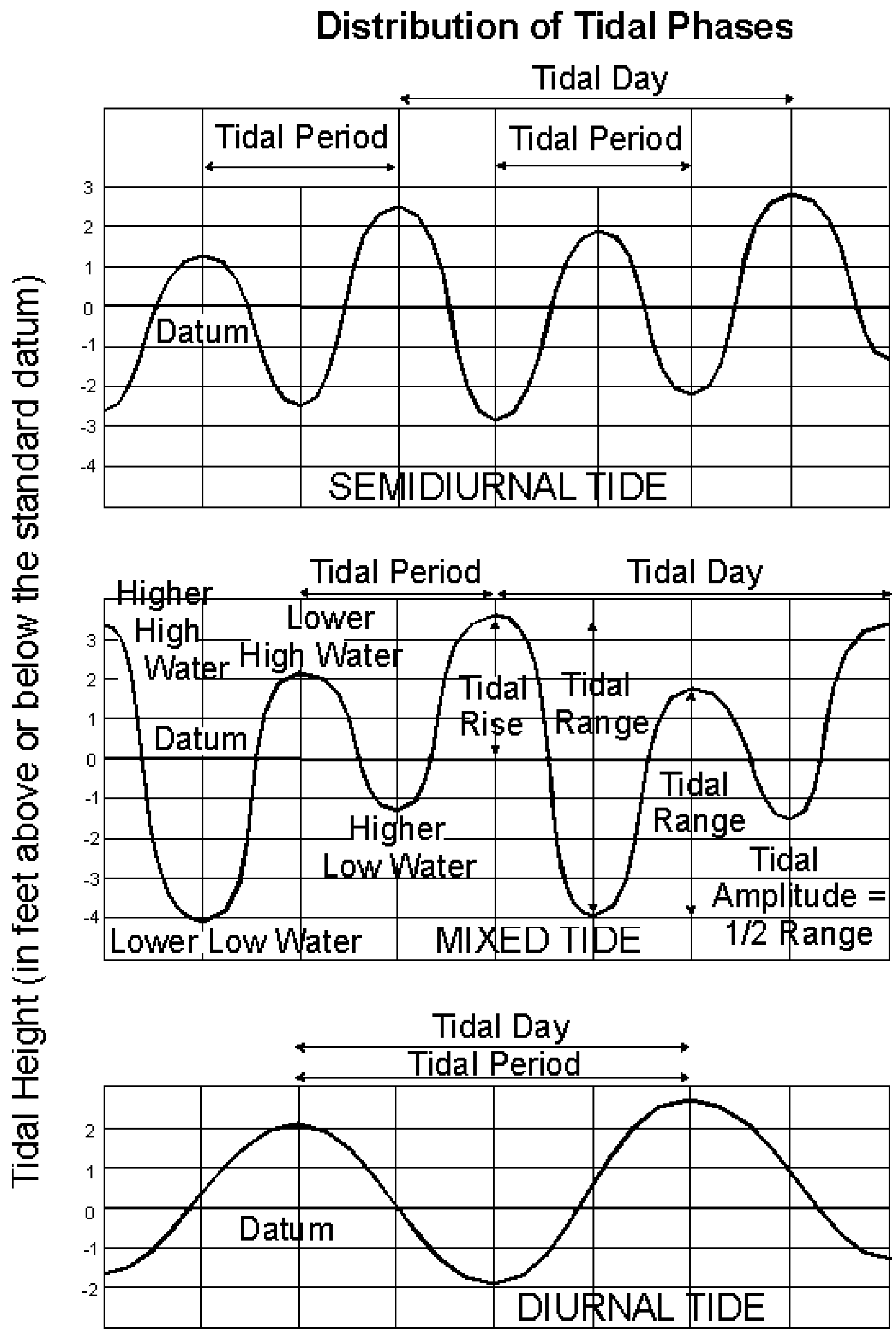
Tides
Spring tide vs Neap tide



Tides
Spring tide vs Neap tide

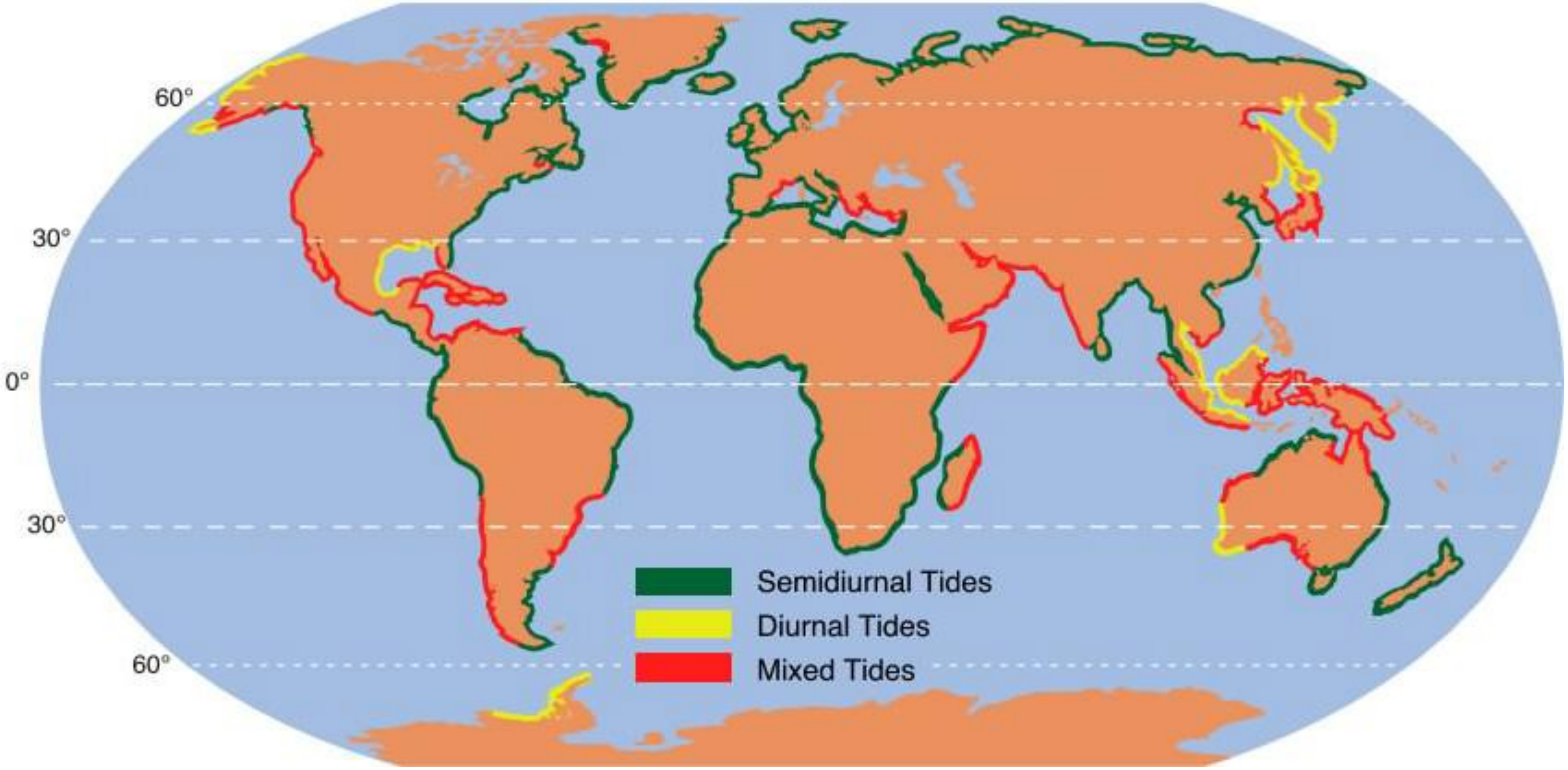


TIDES



Distribution of Tidal Phases
Tidal Height (in feet above or below the standard datum)
Tidal Day
Tidal Period
Tidal Period
Datum
SEMIDIURNAL TIDE
Tidal Period
Tidal Day
Higher High Water
Lower High Water
Tidal Rise
Tidal Range
Datum
Tidal Range
Higher Low Water
Tidal Amplitude = 1/2 Range
Lower Low Water
MIXED TIDE
Tidal Day
Tidal Period
Datum
DIURNAL TIDE

TIDES



Early use – Tidal mills

Tidal power generation

Tidal stream generation

- Direct use of moving water

Tidal barrages

- Barrages across bays or river mouths

Dynamic Tidal Power (DTP)

- T-shaped dam, using tide movement parallel to the coastline

Tidal barrages

- Water kinetic energy
- ↓ Water potential energy
- ↓ Mechanical energy
- ↓ Electricity

Tidal barrages

Dam

- Constructed across a mouth of a river or bay

Sluice gates

- Allow filling the reservoir or emptying it without power generation

Turbines

Tidal barrage Operation

Ebb generation

- The reservoir is filled through sluice gates during flood tide until high tide
- Power generation during ebb tide thanks to accumulated hydraulic head

Flood generation

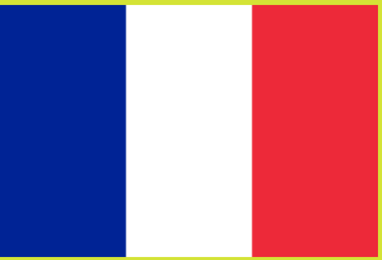
- The basin is filled through turbines during flood tide
- Less efficient:
  - Smaller reservoir volume at high head
  - River inflow decreases the head

Pumped storage

Dual-basin operation

- Two reservoirs, one filled at flood tide, the other emptied at ebb tide
- Complicated and terribly expensive to build
- Flexible – can almost continuously maintain hydraulic head

Usine marémotrice de la Rance



The first tidal power station in the world

- Construction started in 1963
- Commissioned in 1967
- Cost FRF 620M
- Owner - EdF

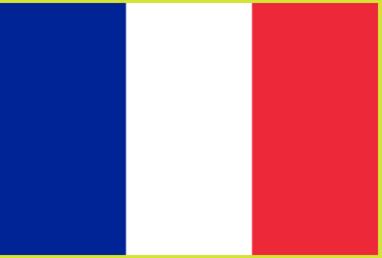
Location

- Rance River estuary, Brittany, France
- Average tidal range 8 m

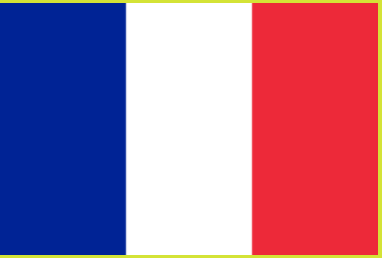
Technology

- 750 m long barrage (332.5 m of that – power plant)
- Tidal basin of 22.5 km²
- Installed capacity: 240 MW_{el} (24 × 10 MW_{el})
- Annual generation: 600 GWh
- Capacity factor: 0.28

Usine marémotrice de la Rance



Usine marémotrice de la Rance



Kislogubskaya PES

Tidal power station in a fjord

- Commissioned in 1968
- In 1994 put out of service due to financial reasons
- In 2000s converted into experimental facility for new turbines

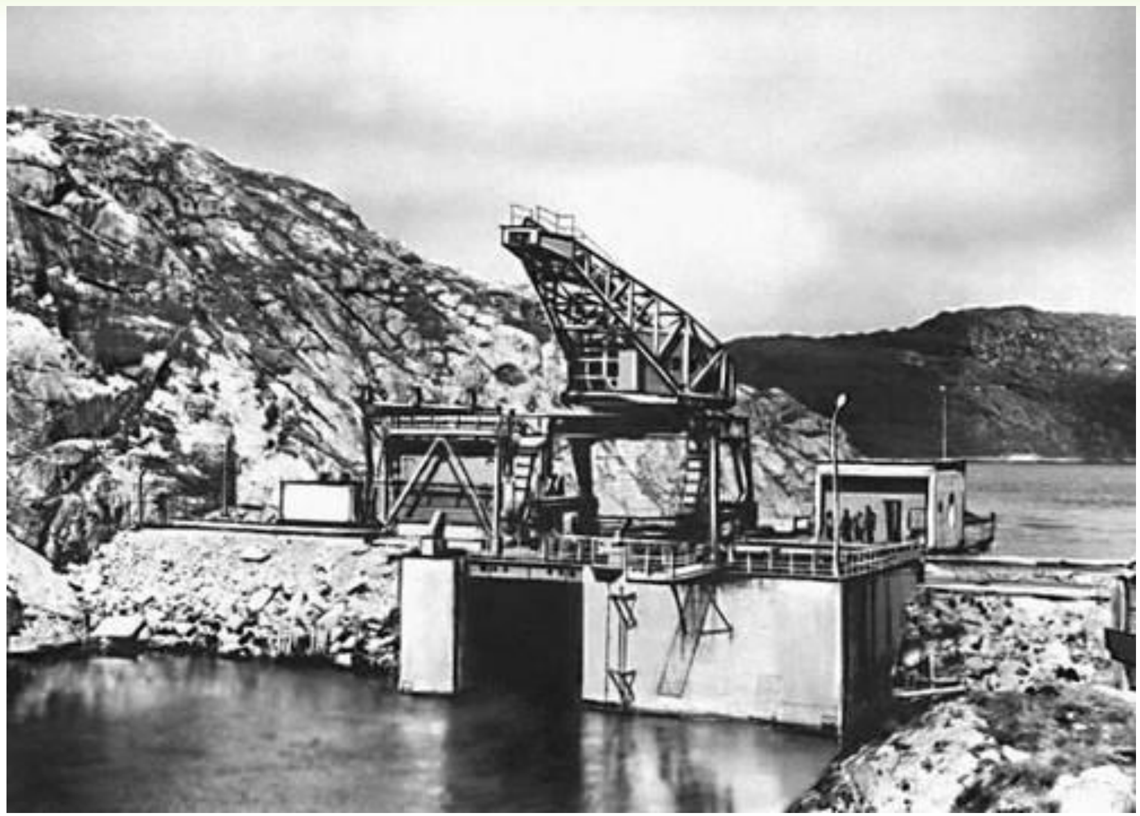
Location

- Kislaya Guba fjord, Kola Peninsula, Barents Sea, Russia

Technology

- Barrage across Kislaya Guba fjord
- Two planned turbines:
  - 1 × 400 kW, French-made, installed in 1996, removed after 1994
  - Another Soviet-built, never installed
- Generation 1968-1994: 8,018 MWh (capacity factor ca 9%)
- 1 × 200 kW turbine installed in 2004, delivered by FGUP “PU Sevmash”
- 1 × 1500 kW turbine installed in 2006, delivered by PGUP “PU Sevmash”

Kislogubskaya PES



Annapolis Royal Generating Station

Project info

- Commissioned in 1984
- Owned by Nova Scotia Power

Location

- Annapolis River, near Annapolis Basin, sub-basin of Bay of Fundy

Technology

- Barrage across the river, 225 long
- Installed capacity 20 MW_{el} (1 Kaplan turbine)
- Annual electricity generation ca 50 GWh
- Capacity factor 29%

Annapolis Royal Generating Station

Sihwa Lake Tidal Power Station

Project info

- Commissioned in 2011
- Installed on a seawall built in 1994

Location

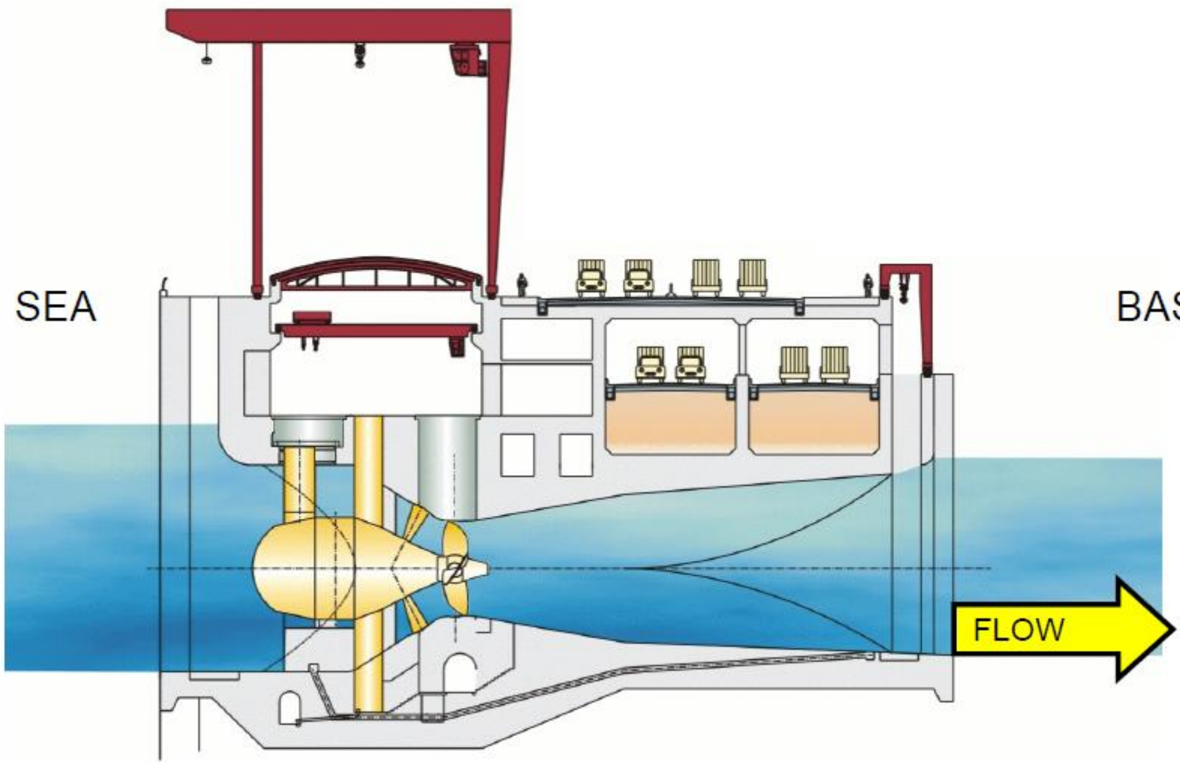
- Sihwa Lake, Gyeonggi Province, Republic of Korea

Technology

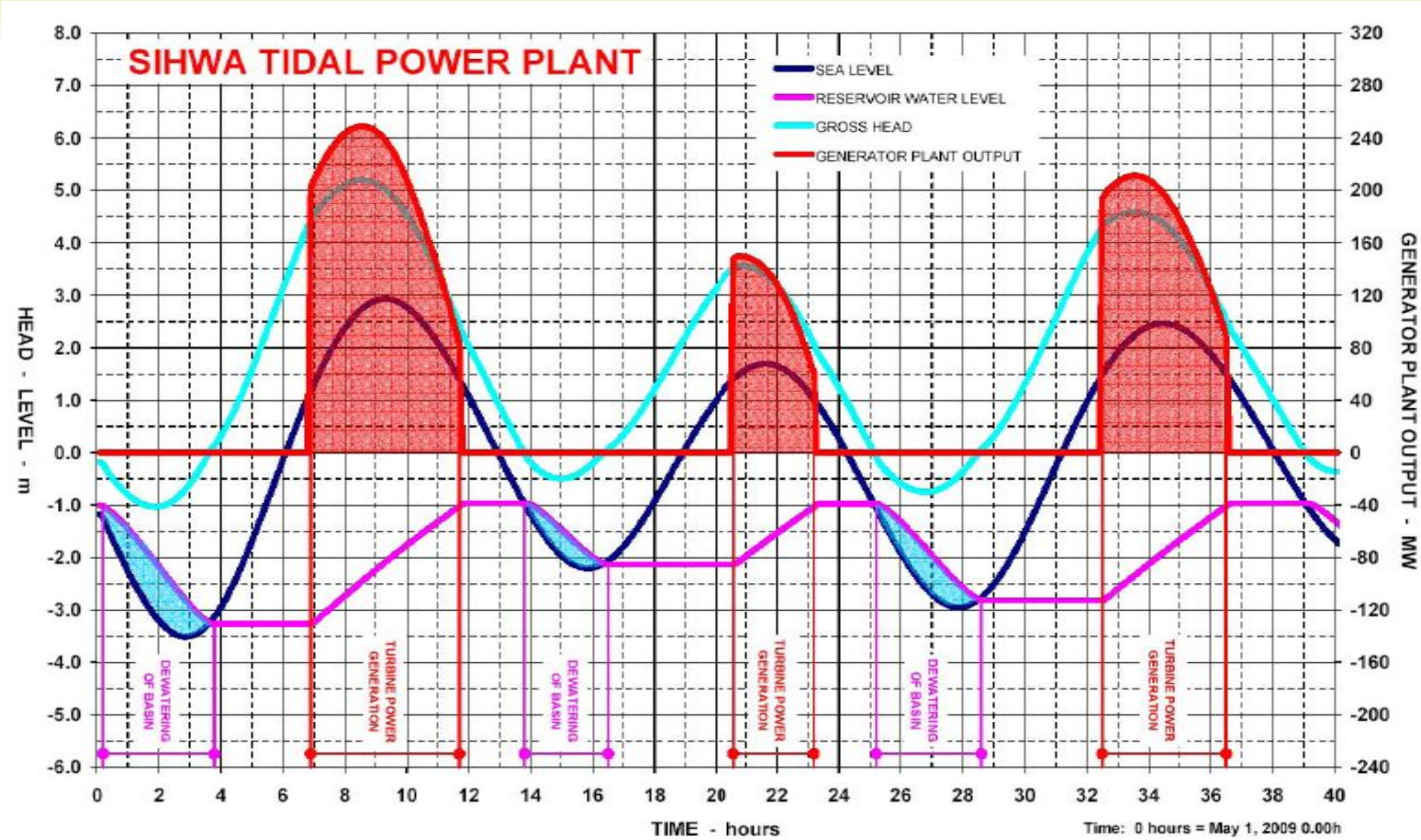
- 12.7 km long barrage
- Working basin area: 56 km^2
- Installed capacity: 254 MW_{el} (10 × 25.4 MW_{el} Kaplan turbine)
- Flood tide operation
- Average tide range
- Planned generation 550 GWh/a (capacity factor 25%)

Sihwa Lake Tidal Power Station

Sihwa Lake Tidal Power Station



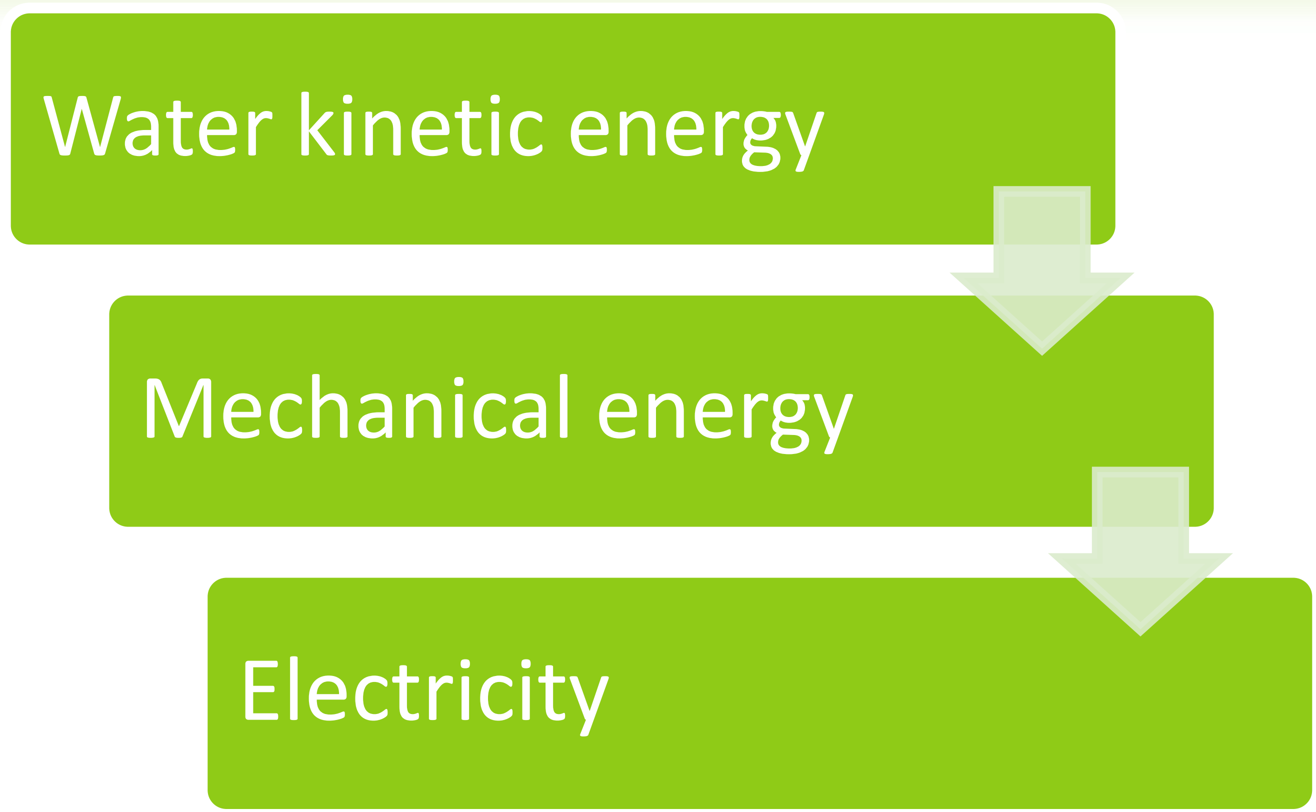
Sihwa Lake Tidal Power Station



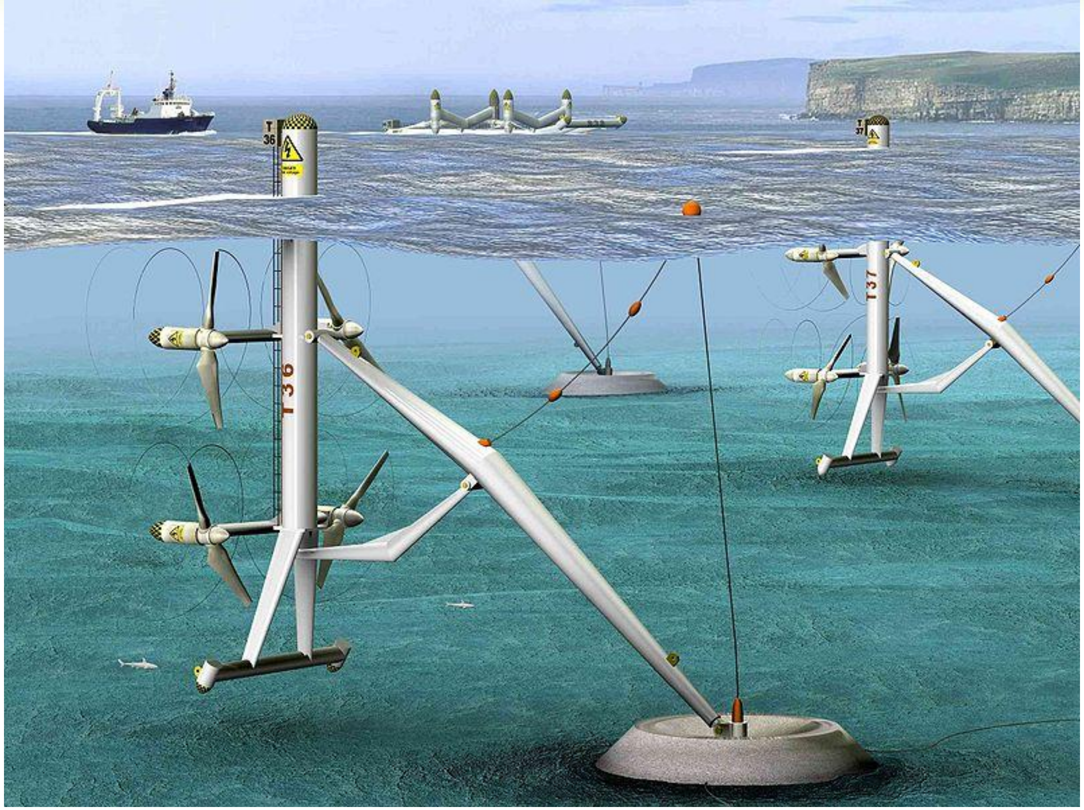
Sihwa Lake Tidal Power Station

Sihwa Lake Tidal Power Station

Tidal stream generation



Tidal stream generation



Tidal stream generation

Axial turbines

- Simple
- Shrouded (Venturi effect)

Crossflow turbines

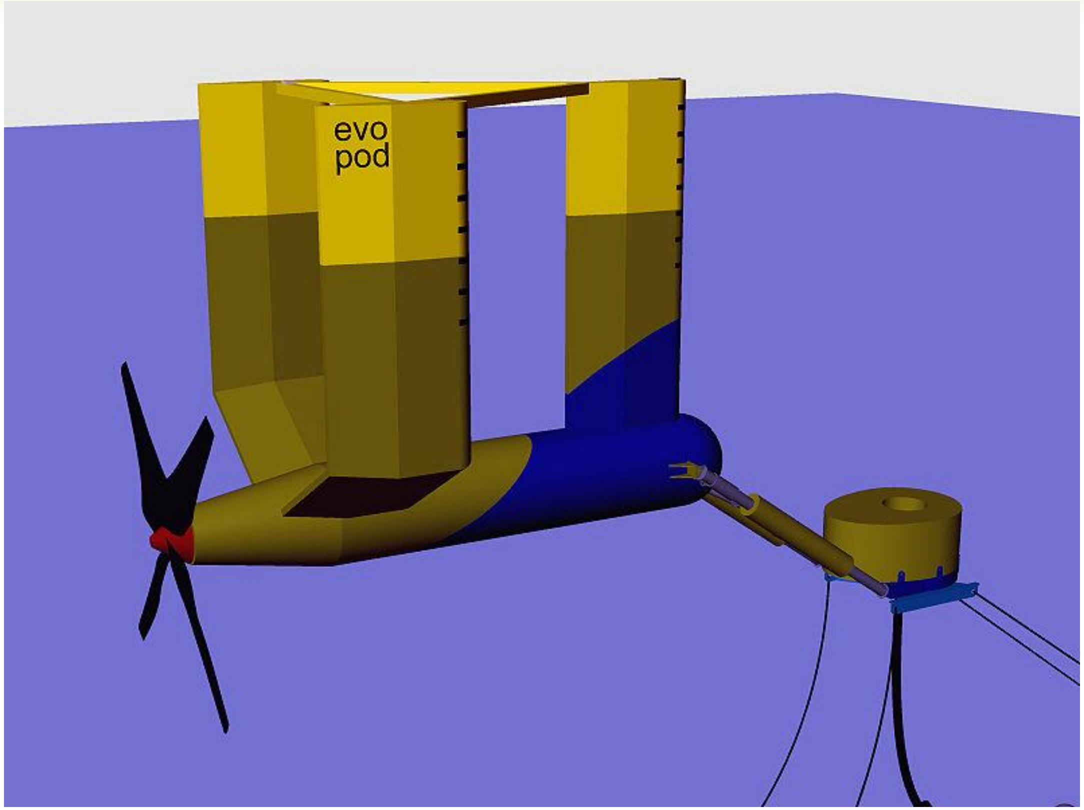
- Vertical axis
- Horizontal axis

Oscillating devices

Simple axial turbine

Shrouded axial turbine

EvoPod
Floating axial turbine



EvoPod
Floating axial turbine

Kvalsund

Project info

- Demonstration plant for Hammerfest Strom

Site

- Kvalsund, Finnmark, Norway
- Depth – 50 m

Technology

- 1 × HS300 300 kW Hammerfest Strom turbine

Strangford Lough

Project info

- Demonstration plant for the SeaGen solution
- Commissioned in 2008

Site

- Strangford Narrows, Northern Ireland, UK

Technology

- 1 × SeaGen, 1.2 MW unit supplied by Marine Current Turbines Ltd
- Operates for 18-20 hours per day

Strangford Lough

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Strangford Lough

Strangford Lough

Sound of Islay project

Project info

- Future project by Scottish Power Renewables
- Scheduled for completion in 2013 (?)

Site

- Sound of Islay, Scotland

Technology

- 10 × Hammerfest Strom HS1000 turbines, 10 × 1 MW_{el}

Dynamic tidal power

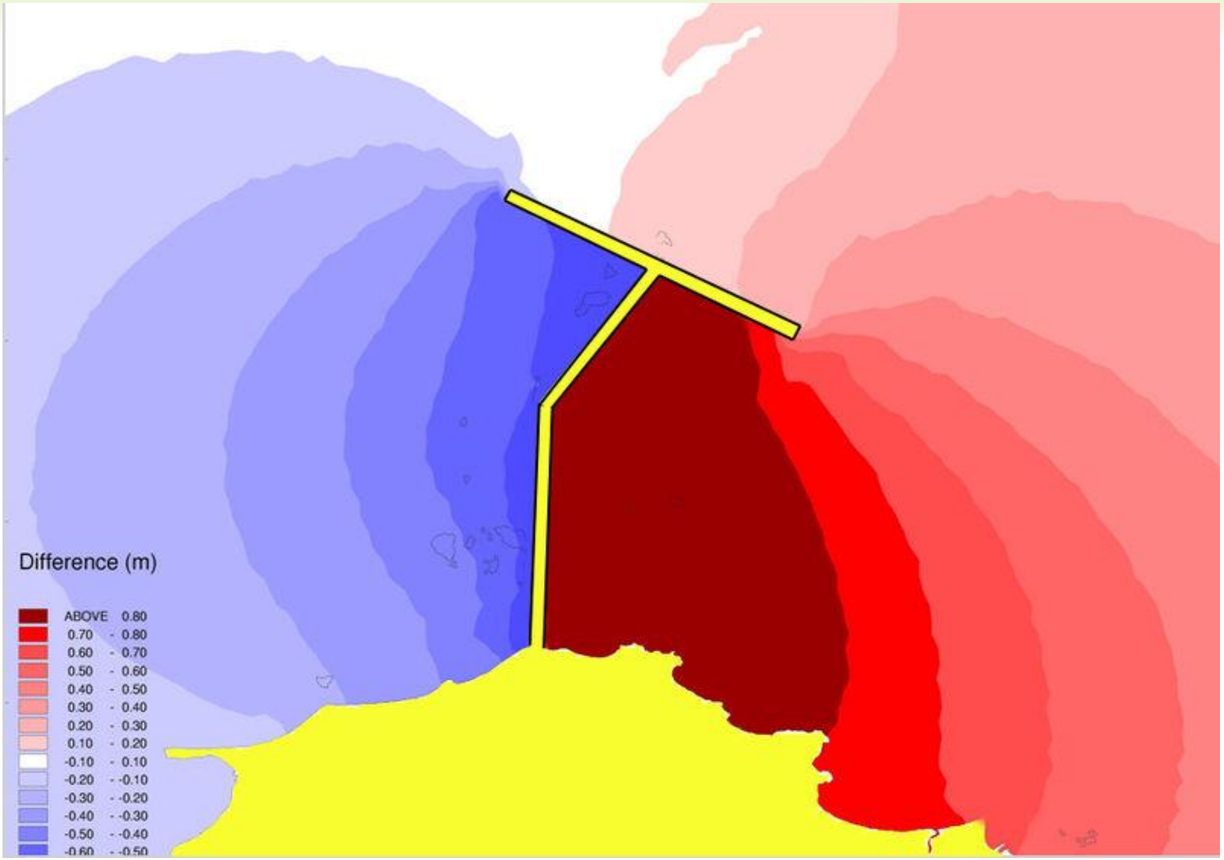
Technology

- Huge T-shaped dams perpendicular to the coastline (30-60 km)
- Using tide progress along the coastline (both directions)
- Up to 8 GW of single plant's capacity, capacity factor 30%
- Capacity proportional to the square of the dam's length

Implementation

- 1997 – patent by Dutch engineers,Kees Hulsbergen and Rob Steijn
- No projects yet – even a pilot plant needs to be huge

Dynamic tidal power

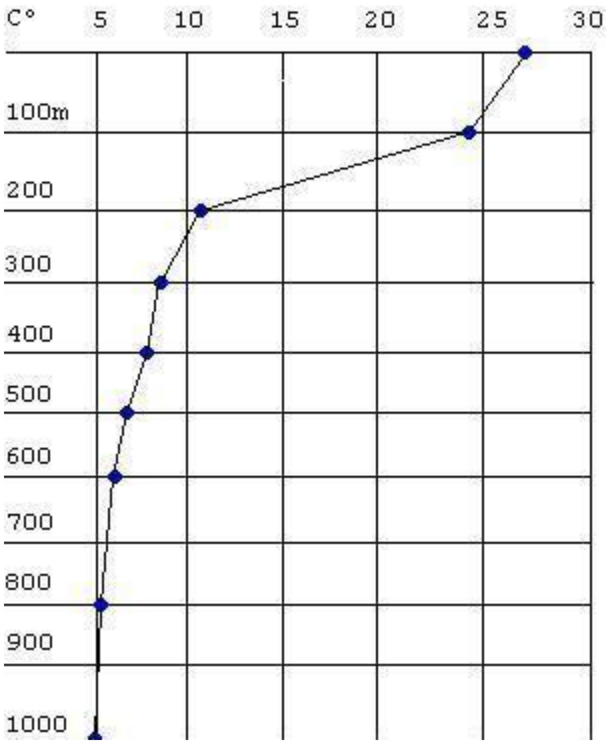


Ocean Thermal Energy Conversion (OTEC)

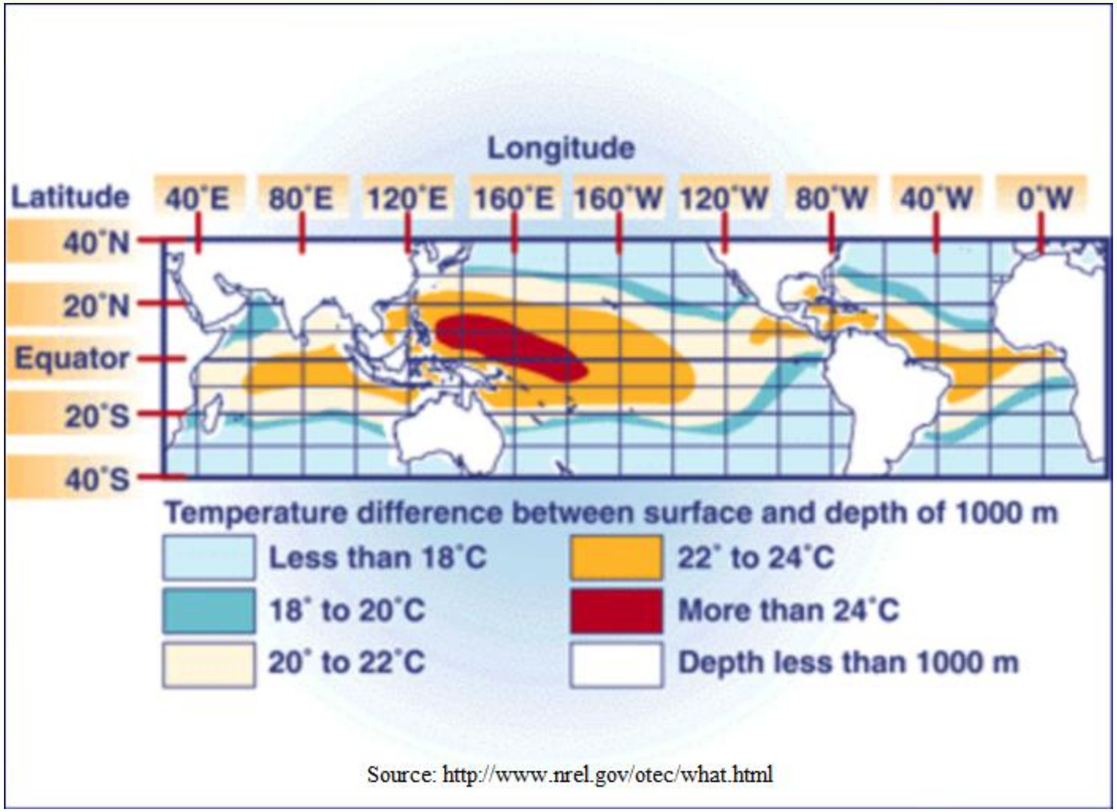
Thermal power plants

- Temperature difference between surface water and deep sea water
- Some 20 K difference needed
- Heat source – surface water
- Heat sink – cold water pumped up from large depth

Seawater temperature



OTEC


Longitude
Latitude
40°E
80°E
120°E
160°E
160°W
120°W
80°W
40°W
0°W
40°N
20°N
Equator
20°S
40°S
Temperature difference between surface and depth of 1000 m
Less than 18°C
18° to 20°C
20° to 22°C
22° to 24°C
More than 24°C
Depth less than 1000 m
Source: http://www.nrel.gov/otec/what.html

OTEC TECHNOLOGIES

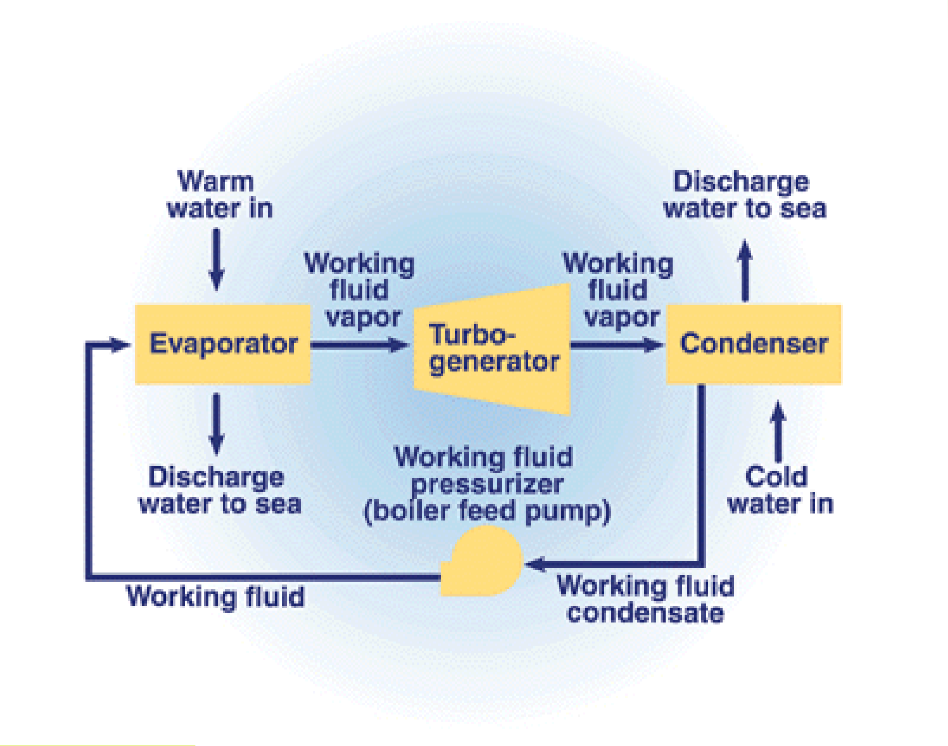
System types

- Closed cycle
- Open cycle
- Hybrid

Location

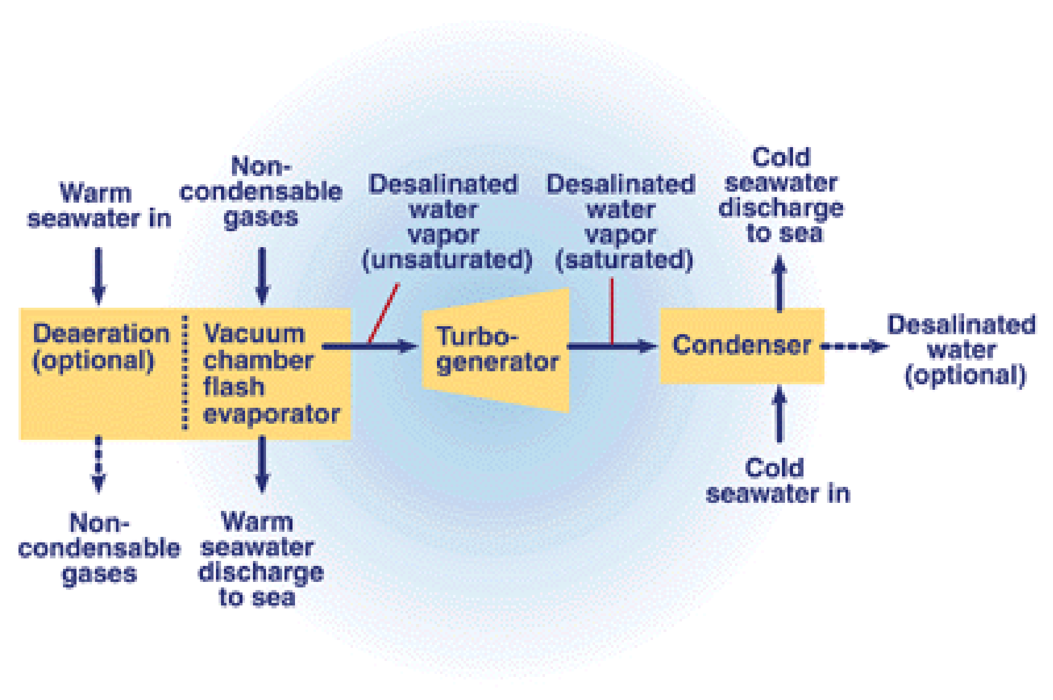
- Land-based (coastal)
- Shelf-mounted
- Floating

Closed Cycle OTEC



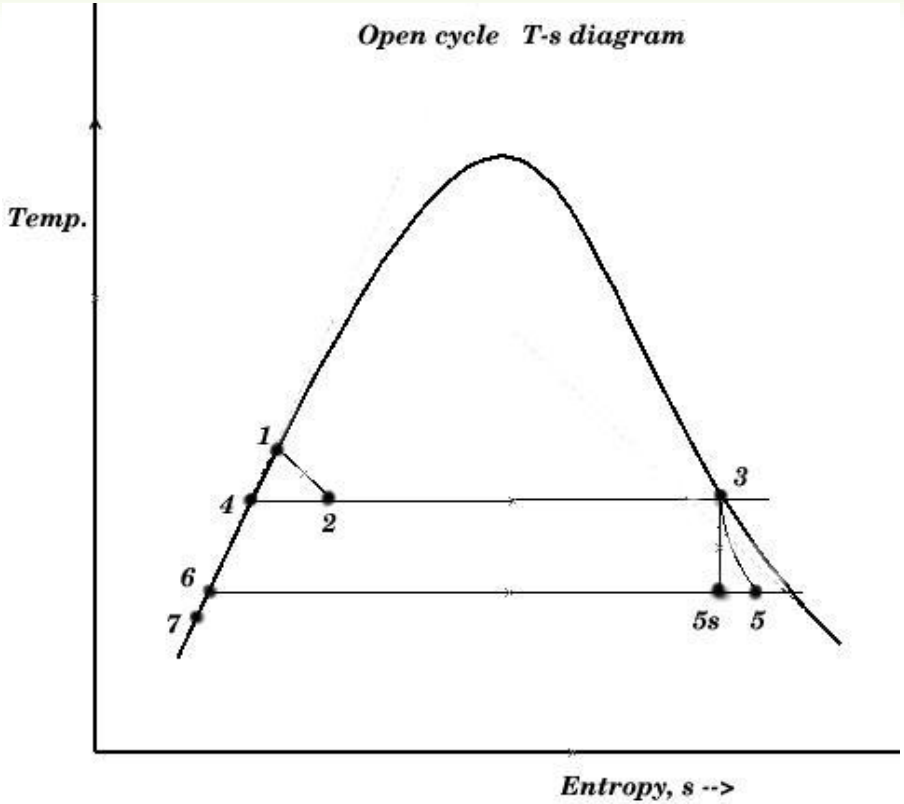
- Special working fluid required (ammonia, refrigerants)
- Low-temperature Rankine cycle (ORC)

Open Cycle OTEC

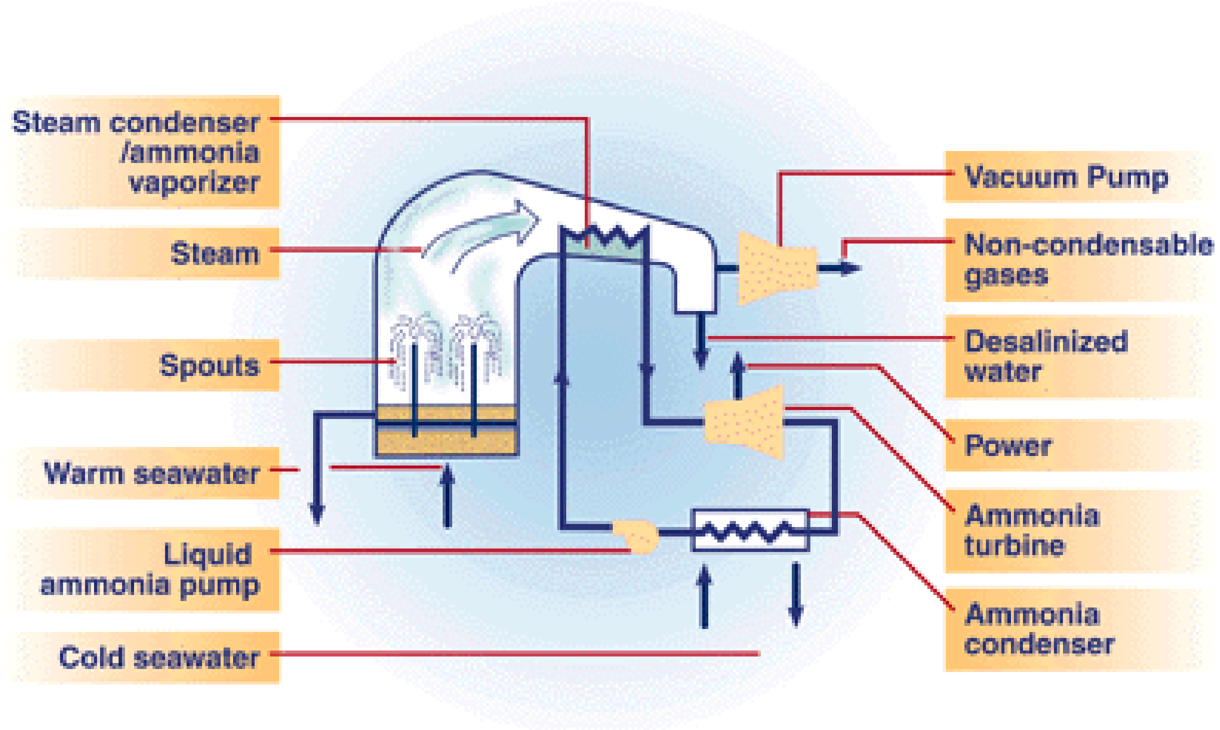


- Flash evaporation
- Live steam pressure ca 1.2 kPa (a)
- Potential supply of desalinated water

Open Cycle OTEC



Hybrid OTEC



Steam condenser /ammonia vaporizer
Steam
Spouts
Warm seawater
Liquid ammonia pump
Cold seawater
Vacuum Pump
Non-condensable gases
Desalinized water
Power
Ammonia turbine
Ammonia condenser

OTEC Experimental Facility Keahole Point, Hawaii, USA

View of OTEC facility at Keahole Pointe on the Kona coast of Hawaii. US Gov. - Department of Energy

OTEC Experimental Facility Keahole Point, Hawaii, USA

Plant history

- Operated 1992-1998

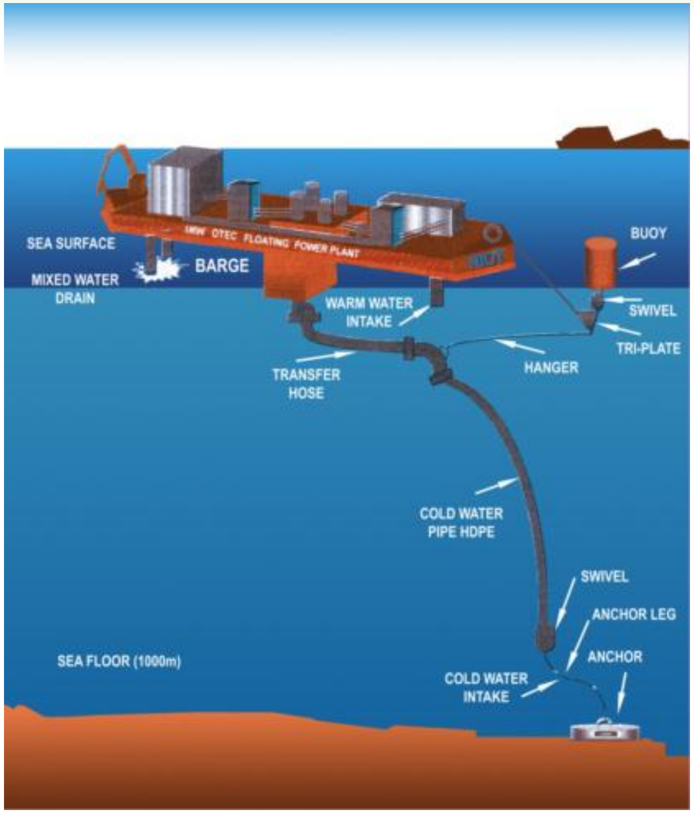
Process parameters

- Water temperature 26/6°C

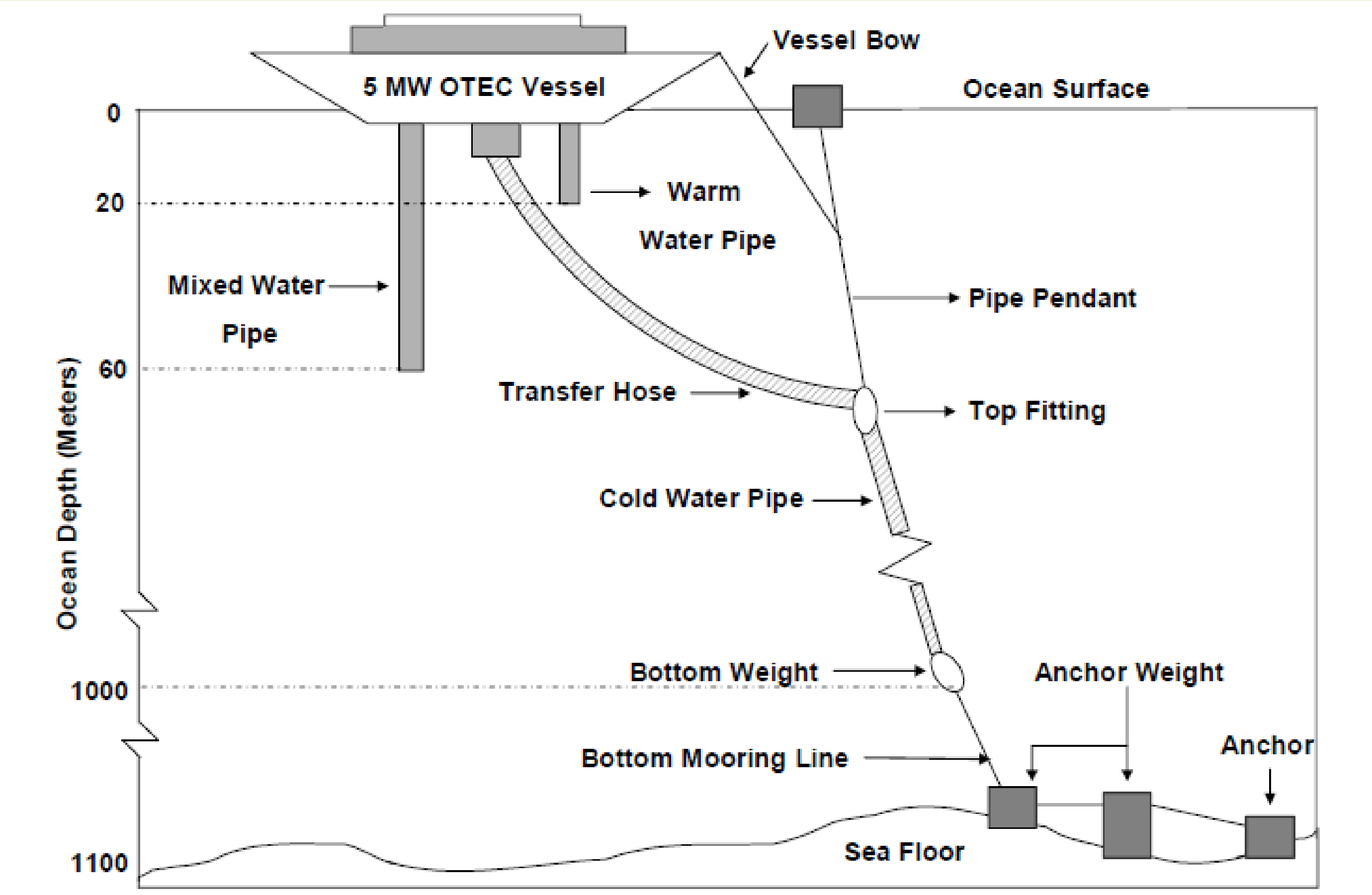
Technical parameters

- Installed capacity 210 kW_e
- 1800 rpm turbine, 10 ft diameter
- Fresh water production, 7000 US Gal/day

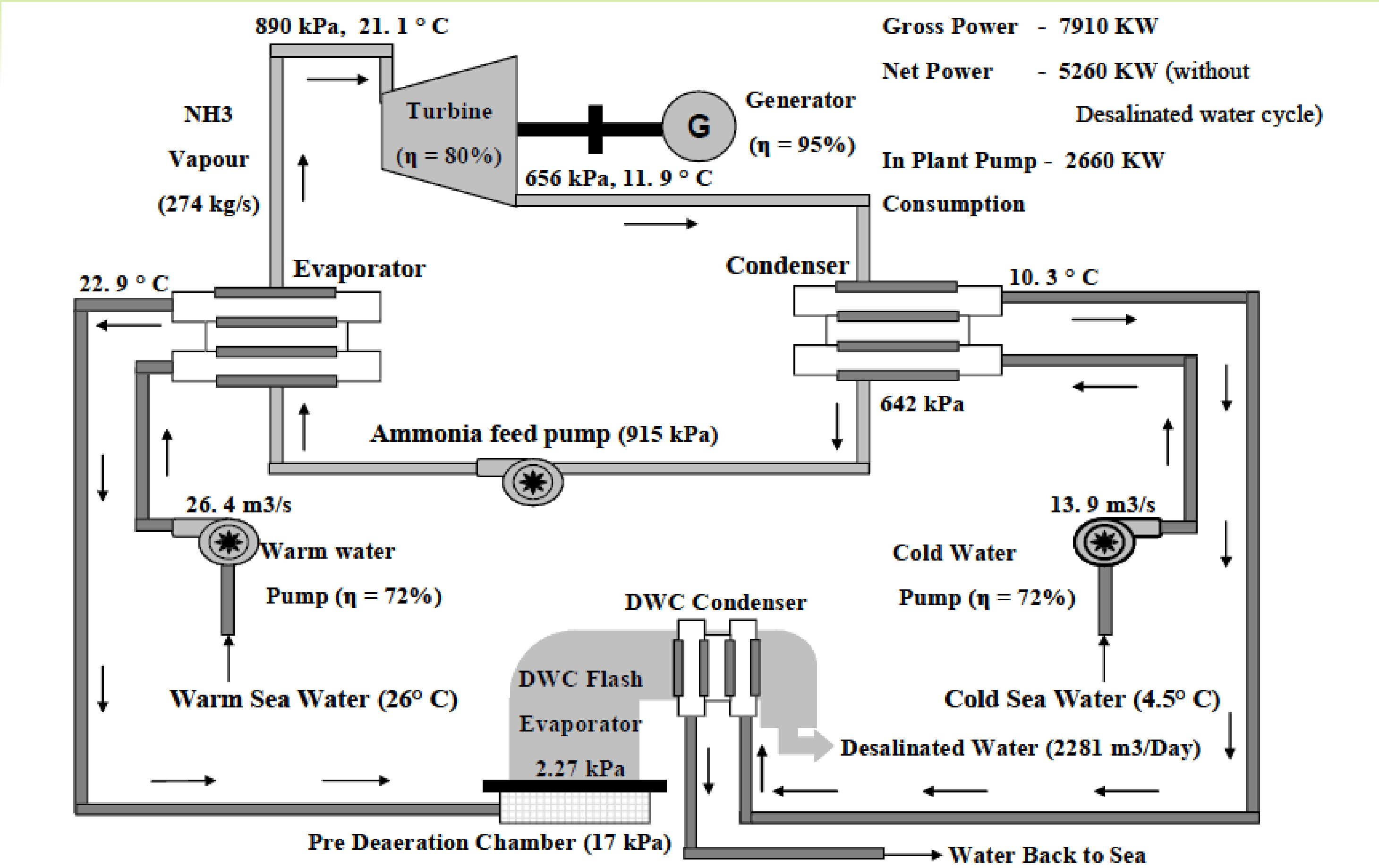
1 MW floating OTEC Tamil Nandu, India, 2000



OTEC
Indian development



OTEC
Indian development



Wave power

- Shore-based over-topping technology
- Off-shore over-topping technology
- Oscillating water column
- Off-shore pitching devices
- Off-shore point absorbers
- Submerged direct generation

Pelamis Wave Energy Converter

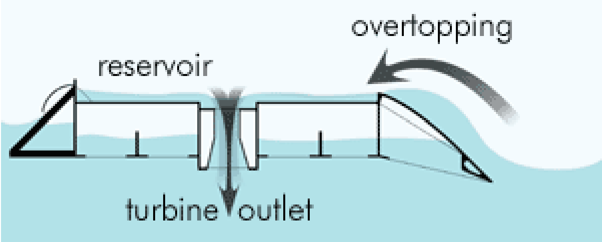
- Developed by Pelamis Wave Power company of Scotland
- Semi-submerged cylindrical sections connected by hinges
- Wave-induced motion is resisted by hydraulic cylinders which pump high pressure oil through hydraulic motors

Internal view of a Pelamis Power Conversion Module.

Aguçadoura Wave Farm

- Pilot plant for Pelamis technology
- Installed capacity 2.25 MW (3 × 750 kW)
- Two months of testing in 2008
- Uninstalled due to bearing problems, then tests suspended due to ownership problems

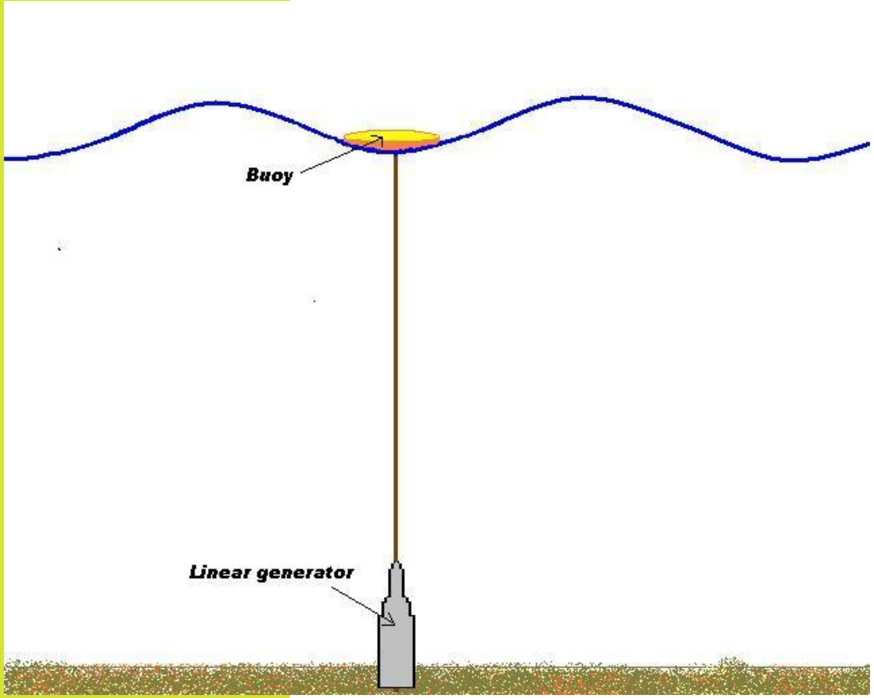
Wave Dragon



- Offshore overtopping concept
- Floating reservoir “collecting” waves
- Vertical Kaplan turbines produce electricity
- Tested in small scale in Denmark
- Full scale variant to be deployed at the North Sea, 7 MW around 2012

Wave Dragon

Lysekil Project



- Developed at Uppsala University, Sweden
- Project started in 2002
- Tested 2 km offshore since 2006
- 3 10 kW units installed by now

Osmotic power generation

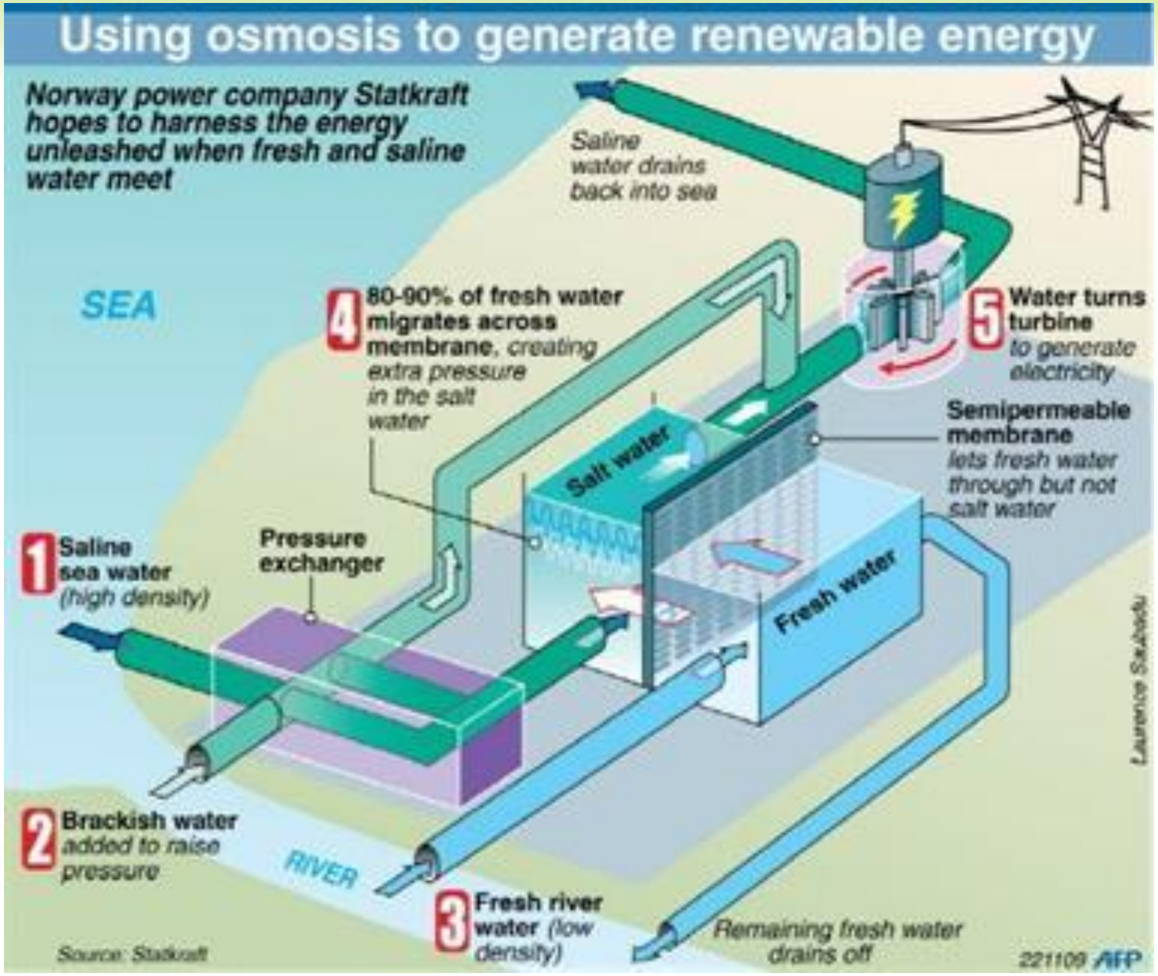
Operating principle

- Salt water and fresh water pumped to a tank, separated with a membrane
- Fresh water penetrating the membrane, creating additional pressure on the “salty” side
- Created pressure used to drive a hydro turbine

Development

- Pilot plant commissioned in 2009 by Statkraft
- Power output 4 kW
- Flow through membrane 10 dm^3/s, pressure 10 bar

Osmotic power generation



Thank you!