Week Three: it begins with HYDRO-POWER

The oldest "green power" taken advantage of by humans (even before they had become humans!) is direct solar power. The second oldest is bio-fuel power, until modern times all fires needed wood, or fuels extracted from animals (alive or dead). Hydro-power and wind power probably share the position of the third-oldest. We will begin Week Three with the hydro, which is appropriate, because there still much rain.... :-)

The old charming waterwheels shown at the figures below generated perhaps 1 or 2 kiloWatts of power, at most. Things has changed dramatically when people started using hydro-power for generating electricity. Today the record-keeper, the "Dam of Three gorges" hydro-power plant, generates over 20 GigaWatts of power, some 20 milion times more than an ancient waterwheel. The power of the largest American hydro-power plants are not as spectacular as that of the Chinese and Brazilian supermonsters – but they are by no means small. The largest American is, by the way (or by the FREEway, you may see it from I-86) on the Columbia River, not very far from us. Note that the famous Hoover Dam is not the largest American hydro-power plant as far as the power generated is concerned – contrary to what many people think, – it's perhaps "the best known", because of the height of the dam and the spectacular surroundings.

Hydro-power: used by humans since the ancient ages….

Modern installations:

Two world's largest hydropower plants:

Itaipu Dam, on the border between Brazil and Paraguay, until recently the largest (14,000 MW)

Itaipú Dam, Paraguay/Brazil. The world's largest hydroelectric facility.
Credit: Itaipu Binacional

The Dam of Three Gorges In China, currently the largest (22,500 MW)

(for comparison: average power consumption in Oregon: 5,300 MW; Entire USA : about 550,000 MW, or 550 GW, or 0.55 TW..

The largest US hydropower station, and another very large one:

Hoover Dam →
(power: 2080 MW; 4 TW-hour annually)

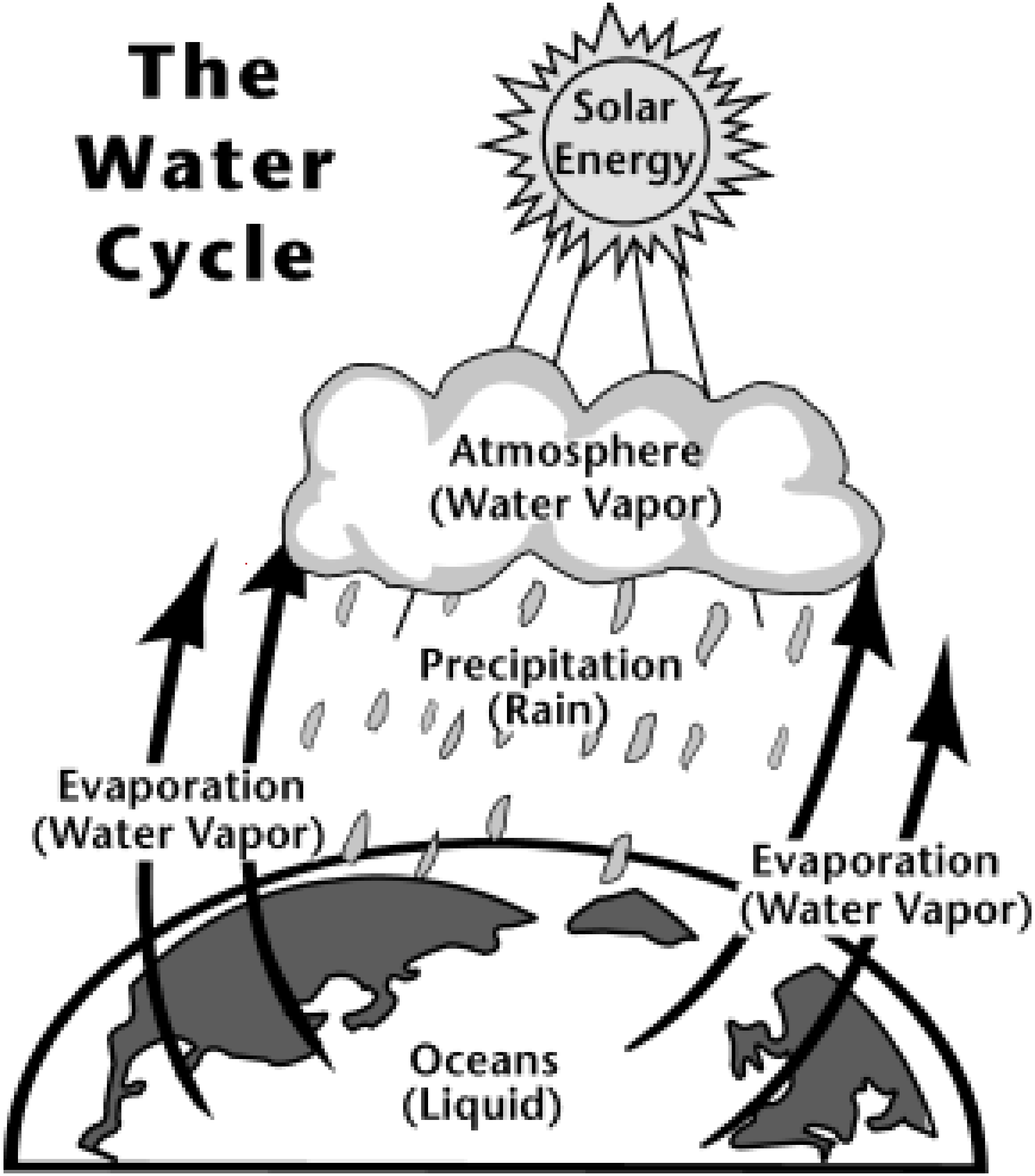
Grand Coule Dam (Columbia River):
(6800 MW; 22.6 TW-hour annually)

The “origin” of hydro-power

Please keep in mind that Hydro-power is nothing else than converted solar power. There are many good things spanning indirectly from the energy coming from Sun. Water from oceans, seas, lakes, rivers, and even from moist soil, when heated up by solar radiation, yields water vapor that rises up and forms clouds – the clouds then condensate and the water returns to the Earth surface in various forms of precipitation: as rain, snow, hail... The water that has returned to mountains and other high areas then begins its “trek” toward the oceans. On the way, it loses its potential energy. Harnessing hydro-power by us is nothing else than “capturing” this potential energy before it all dissipates.

Hydroelectric Energy actually is Solar Energy "somewhat transformed" by the lady shown below:

Mother Nature

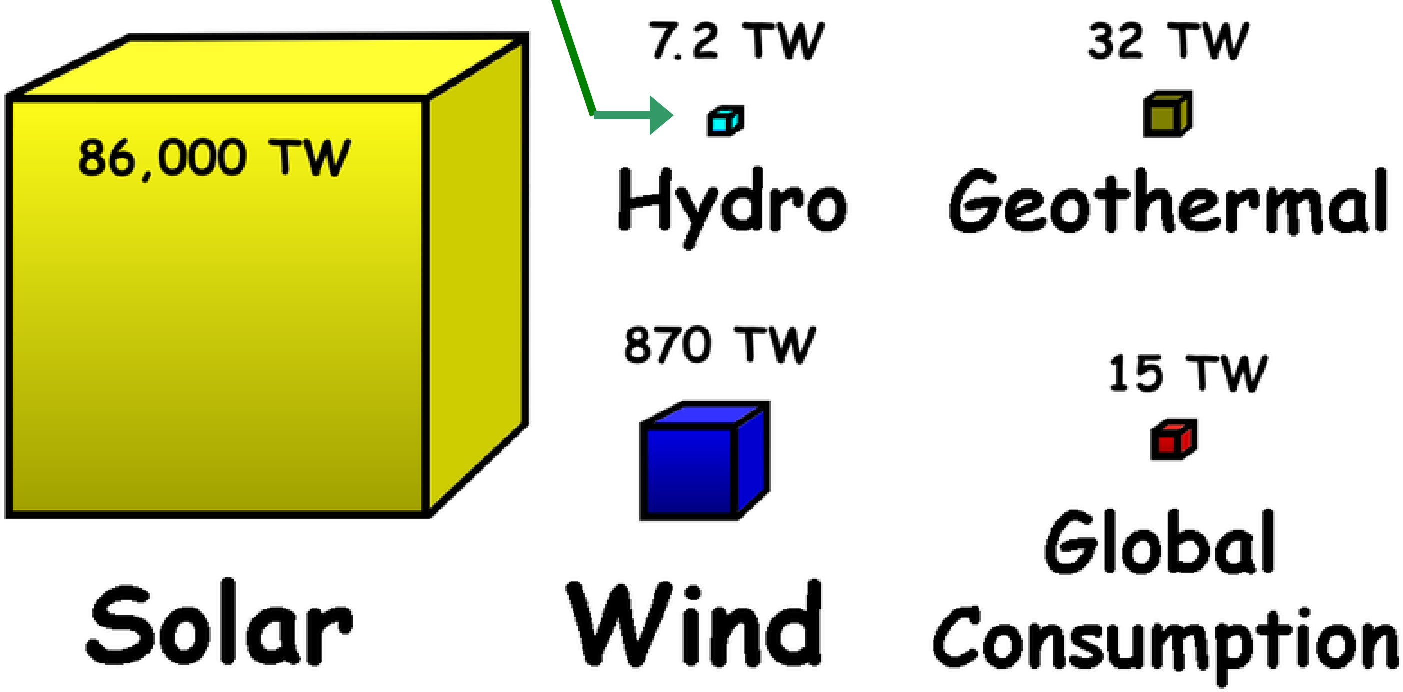


In the next figure, it is shown how much radiative power our planet receives from the Sun – and how much of it is converted to hydro-power that can be harnessed by us. It's almost one-half of the total global consumption of power. We still use only a fraction of those available resources – but even if we managed to harness them all, they would not satisfy all our needs. However, ot since there are still available resources not yet taken advantage of, it would be a wise thing to start using them. In contrast to fossi fuel resources, hydro-power resources <u>cannot be exhausted!</u>

Global hydropower resources:

Enough to satisfy almost 50% of the current global consumption.

But the power supplied by all existing installation is only 6% of the total global consumption.



On the next two pages, it is shown how the global population "apetite" for electric power is growing over time – and what is the contribution of different sectors of power industry to satisfying these needs.

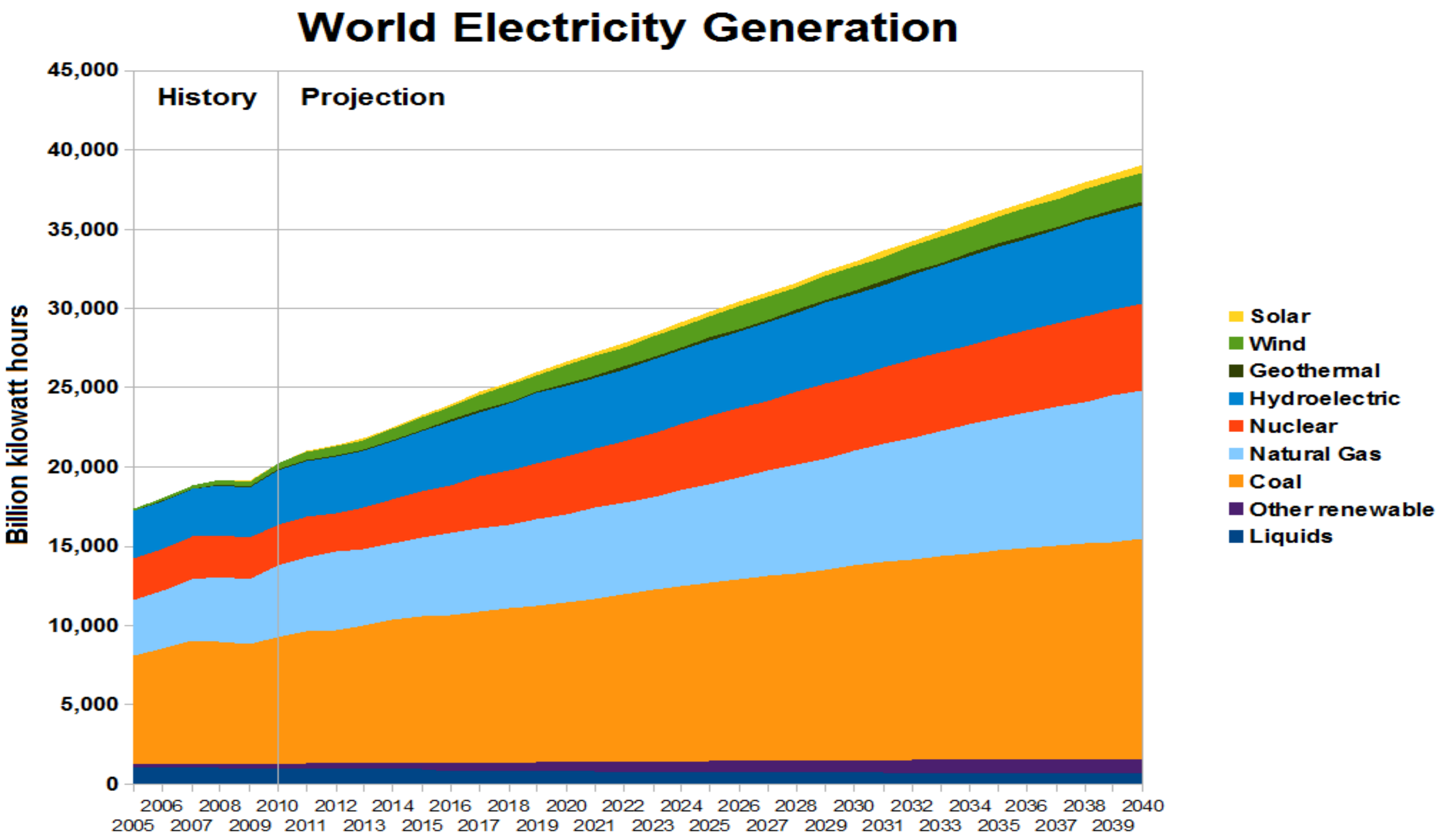
According to the World Energy Council, the current (2016) share of hydro-power in global power generation is 16.4%. As indicated by predictions, this figure is not expected to change significantly over the next 20-30 years.

On the graphs, it is also shown how much hydropower is generated by different countries. China generates most, but if one considers how big the populations in each country is and calculates the hydropower generation per one million population, then Brazil (current

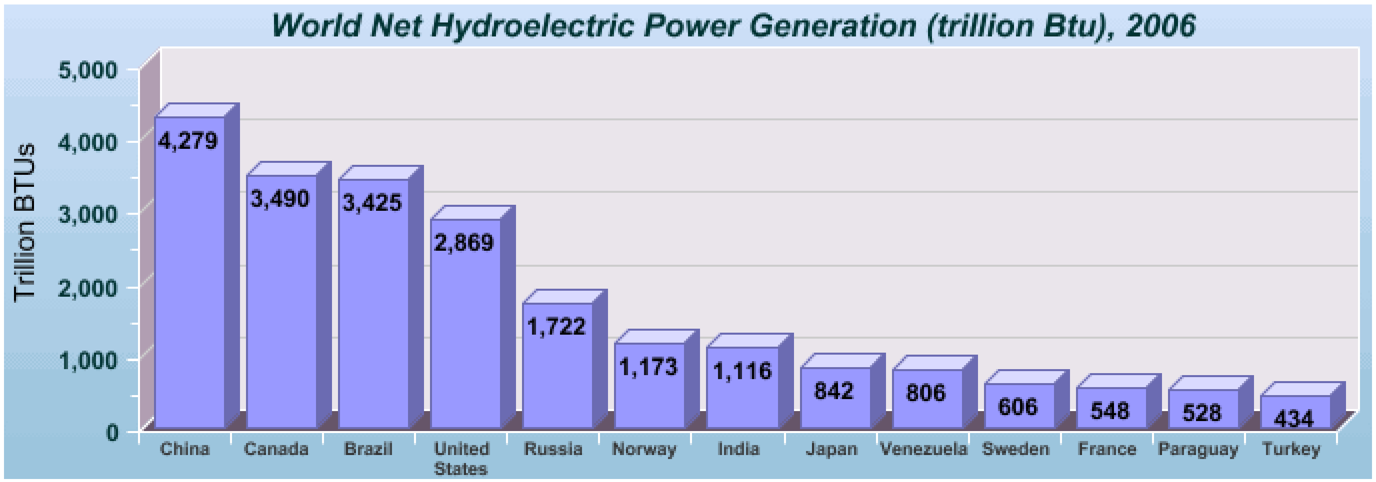
population slightly over 200 million) is the unquestionable winner, and the US is also ahead of China.

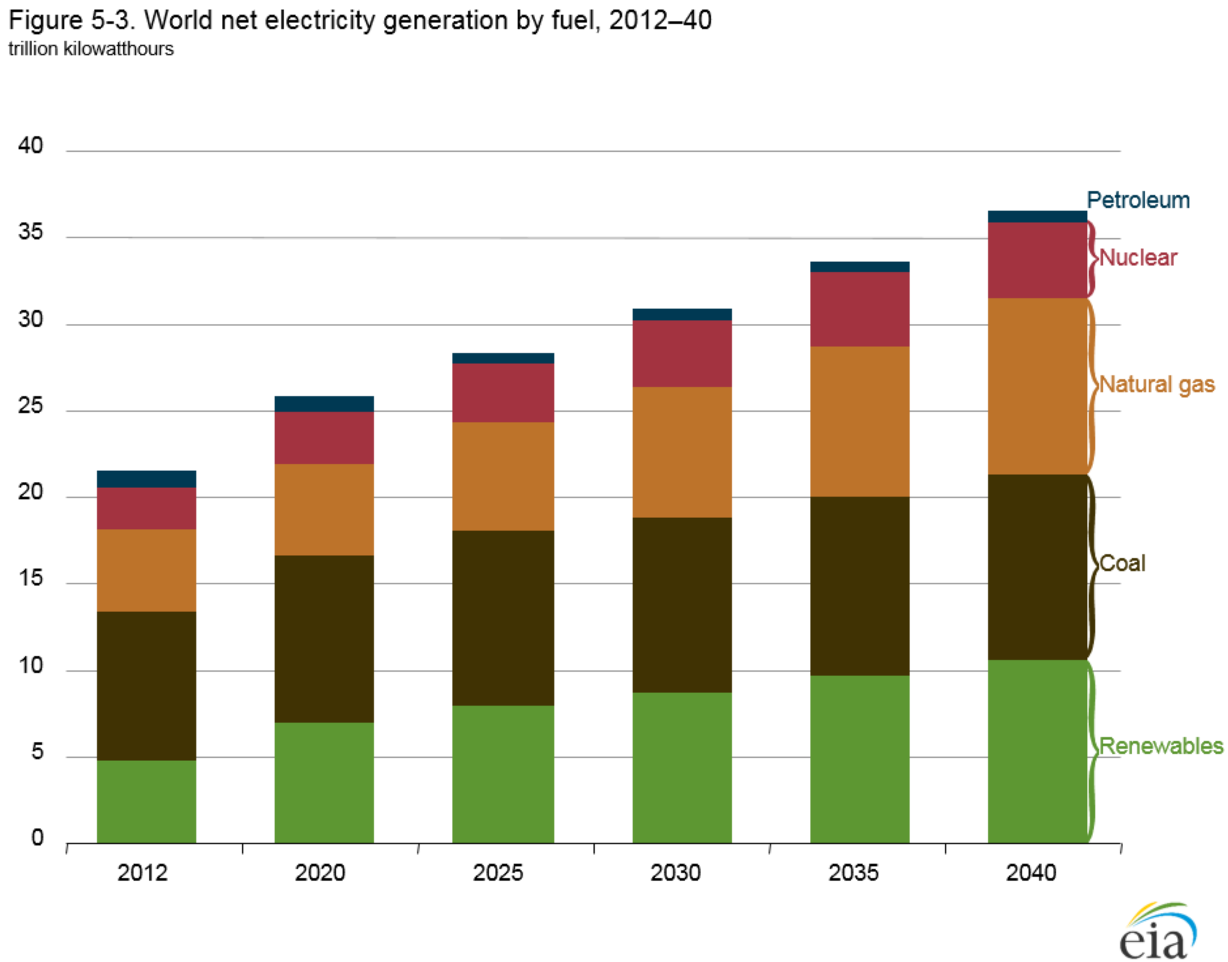
It is also remarkable that Brazil satisfies over 90% of its power needs from hydro. Norway, in which the hydro-sector satisfies 100% or even more of the country's needs (more than 100% – how is it possible? Yes, it is, Norway exports its surplus of electric power to other countries, primarily to Denmark through an undersea transmission line capable of transmitting up to 2 GW of power).

In the US, according to the US Energy Information Administration, the share of hydropower in the total usage is perhaps less impressible, it is about 6.5% of the total.



Hydropower production, by countries:



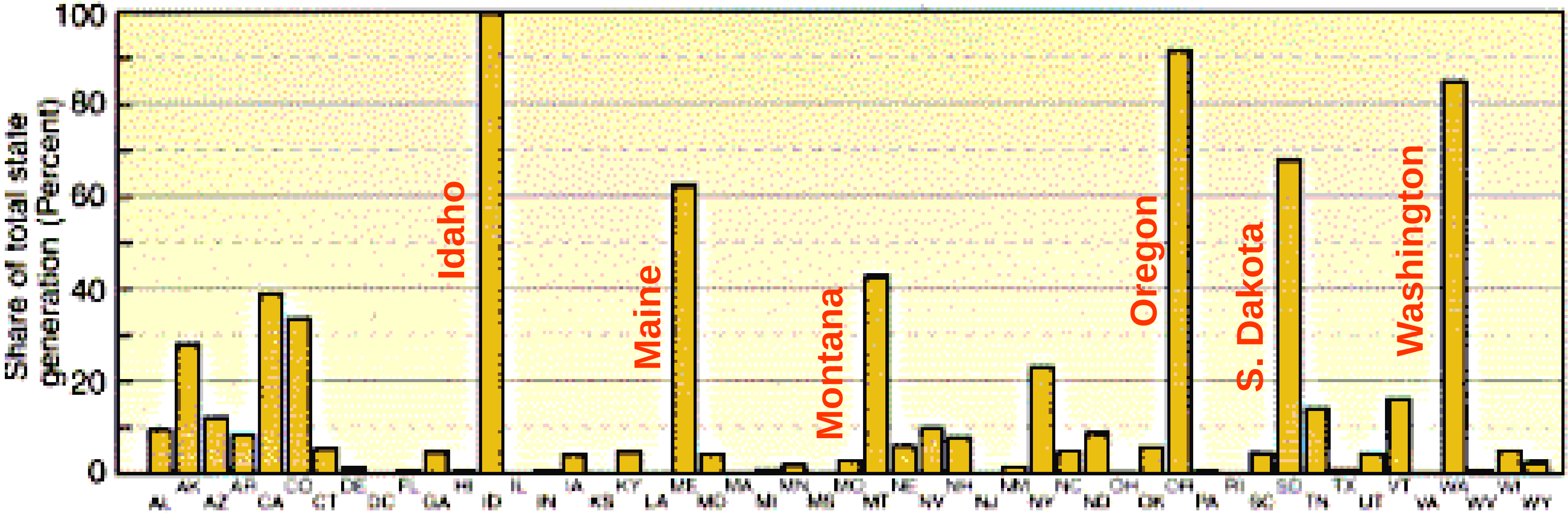


Global electricity generation, in units of trilion kWh.

However, in the US the share of hydropower in individual states is very the different. The graph in the page below is from the year 1995 and is no longer very accurate. Current data from individual states can be found in this Wikipedia article, or in this US Energy Information Administration Web site – in the latter, there is a map with all states and if you click on one, you get info not only about hydropower generation in it, but also a bounty of info about all other power sources in this state.

Electric Utility Hydroelectric Net Generation by State

(January - December 1995)



But how exactly is electric power generated at hydropower facilities?

There are two major techniques. One is by exploiting rivers in which the stream gradient is not very high, but high is the volume of water flow ing downriver. Along the river bed, th e flowing water gradually loses its potential energy. If there is a dam on the river giving rise to an artificial lake, however, then the potential energy of water flowing into the lake is "fixed" at a value corresponding to the altitude of the lake's surface. Now, if there is an opening in the dam at the lake's bottom, the water squirts out, its potential energy at the surface level is converted to kinetic energy.

The speed of the "jet" flowing out is given by the solution of the famous *tank draining problem*, formulated by Daniel Bernoulli nearly 300 years ago – and is:

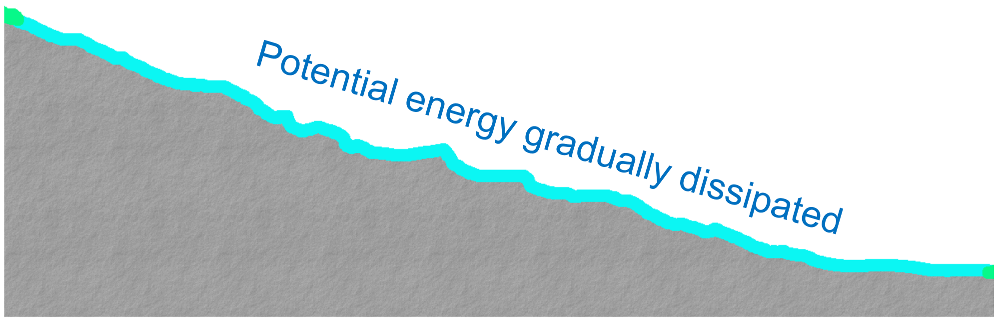
$$V_{\text{jet}} = \sqrt{g(H_{\text{surface}} - H_{\text{outlet}})}.$$

For details of the formula derivation, look, e.g., at this Web site.

The kinetic energy of the "water jet" is harnessed and converted to mechanical work (needed for turning the electricity generator). The most often used turbine type is the "Kaplan Turbine", looking very much like a giant propeller. Its efficiency is very high, it can "capture" over 90% of the kinetic energy of the outlet stream.

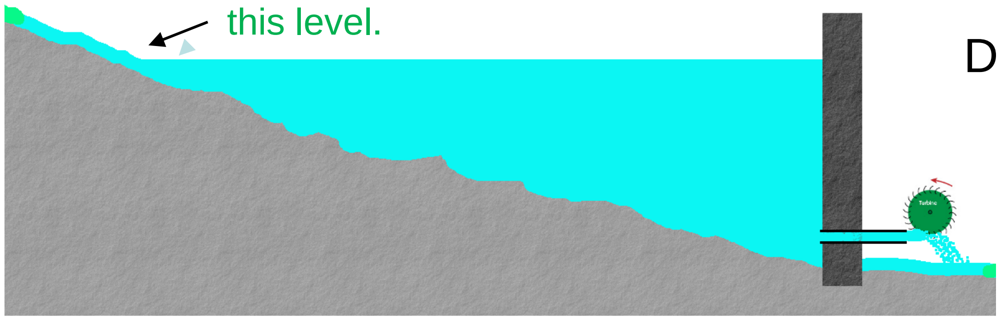
Ways of harnessing hydroelectric power: the most common – by building a dam on a river.

Normally, when flowing downriver, water gradually loses its poterntial energy:



However, if we make a dam....

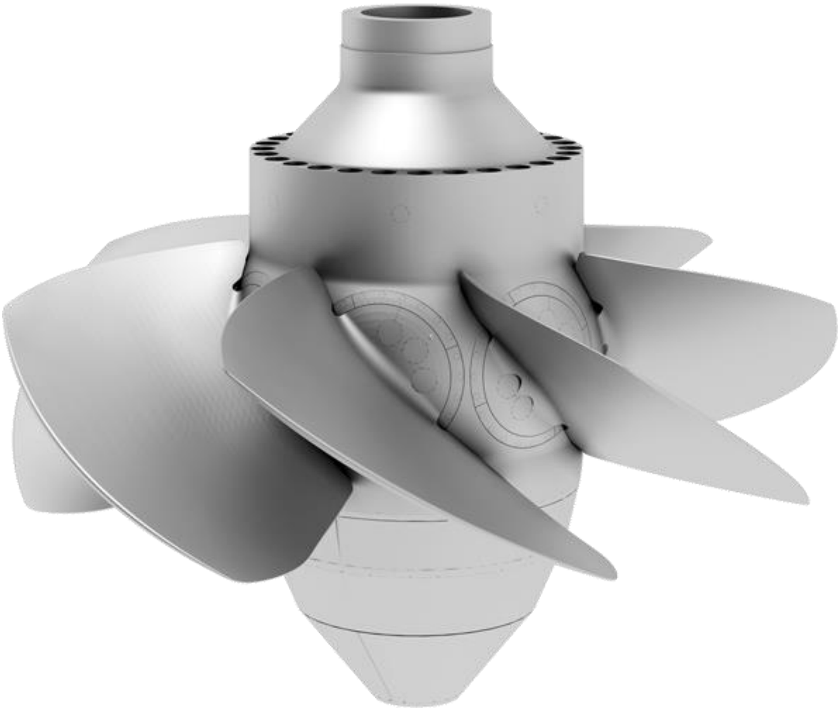
Now, the potential energy of flowing-in water is “fixed” at this level.



Due to energy conservation, at the outlet the potential energy of water at the surface is converted to kinetic energy, and this is passed to the turbine.

The Kaplan turbine:

The rotor alone:



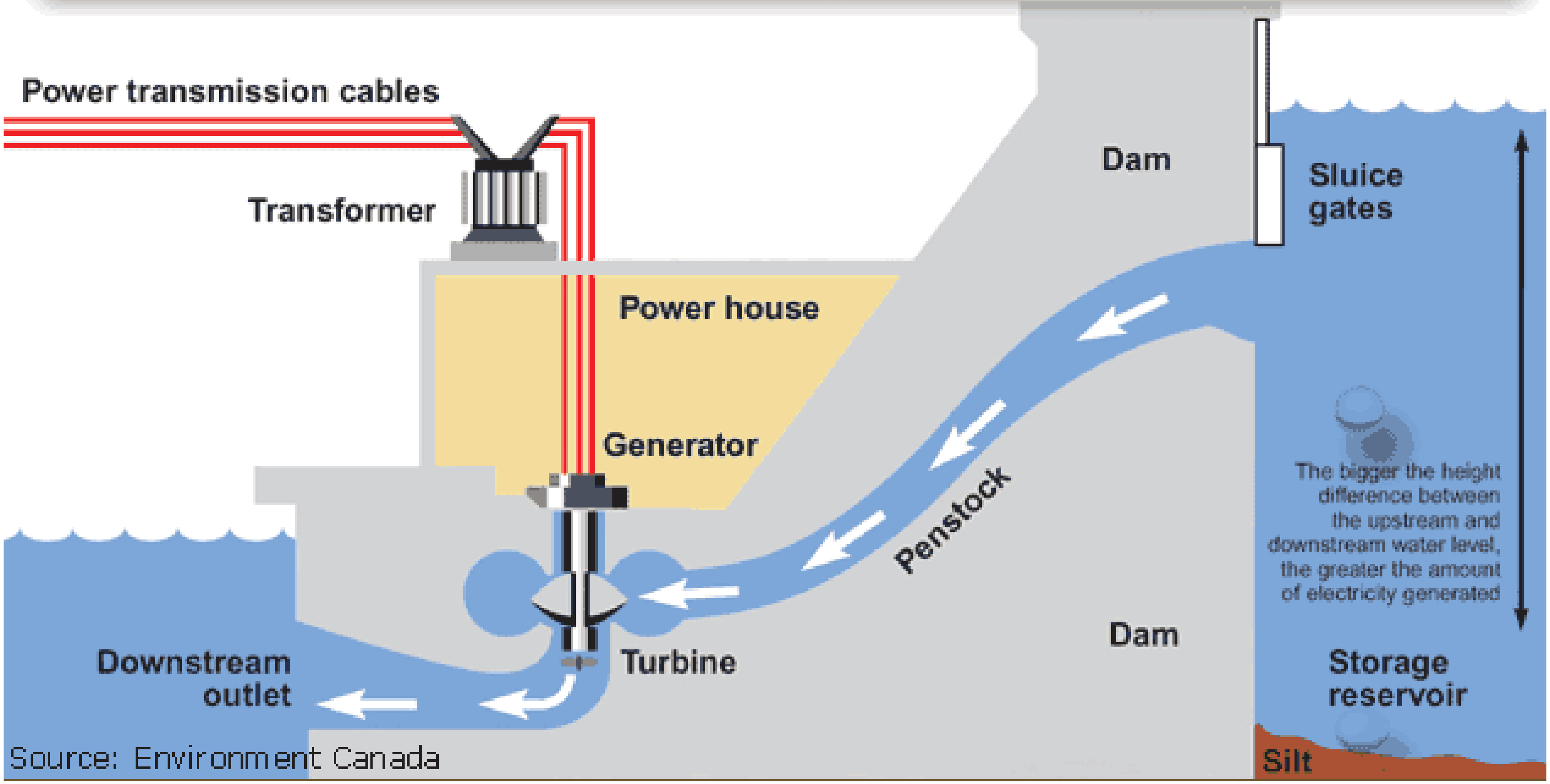
How the rotor is mounted in the outlet tube:

Below, there is a more accurate schenatic picture showing how things in a typical hydropower plant with Kaplan turbines are organized. The water outlet is not at the bottom of the lake, it's rather close to the water surface, and water flows down through a special tube, called "penstock". But no matter from where the water is taken, the kinetic energy of the flow reaching the turbine is the same. The Kaplan turbine is positioned vertically, not in a horizontal tube, as was shown above in the photograph – it's a more common arrangement, please take a look at this Web site, in which also the efficiency of the Kaplan turbine is discussed – it can convert over 90% of the kinetic energy of water flowing through it to mechanical work.

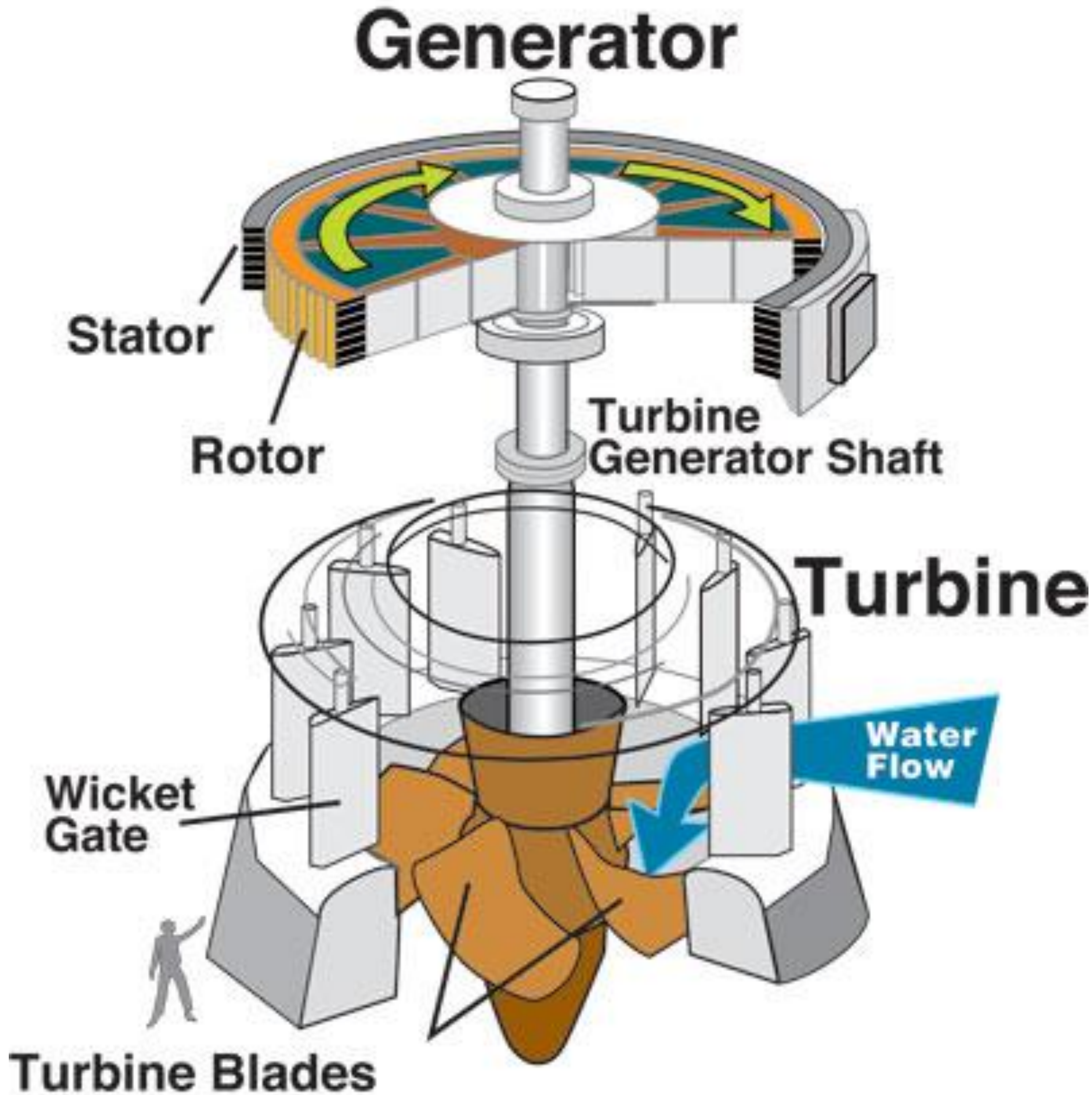
In the vertical turbine arrangement, the generator is positioned above the turbine. It's convenient, because now another Kaplan can be placed on the same axle above the generator. What for?! – well, if the generator acted instead as an electric motor, the other Kaplan would send water from the lower reservoir "uphill". Again, what for?! – well, such an option is important in the so-called *Pumped Storage Hydropower Plants*, about which we will be talking shortly.

A nice animated picture showing how things happen in a hydropower plant with a Kaplan turbine is shown in this Web site, set up by one of the federal government agencies.

Hydroelectric power generation



Source: Environment Canada


Generator
Stator
Rotor
Turbine
Generator Shaft
Turbine
Water
Flow
Wicket
Gate
Turbine Blades

Sometimes there is much less water in a stream than in a big river – but the stream flows at high altitude, and at some point cascades down a steep mountain side, or even forms a waterfall. It's a good situation for bulding a power plant of another type. Namely, the water is "sent downhill" through a pipeline. For each 10 meters (33 feet) of vertical drop the pressure in the pipe increases by one Atmosphere[1], and if the overall vertical fall is large, e.g., several hundred meters, then the pressure at the bottom of the pipeline becomes really high, and water squirts from the nozzle at the pipeline's end with a very high speed. The turbine type appropriate for converting the water's kinetic energy to

[1] An Atmosphere (symbol: atm) is a pressure unit that was widely used in the old days, but now is barely tolerated by the official SI system. But sometimes it is convenient to use it, because the pressure of 1 atm is approximately equal to the pressure of ambient air – so that if a pressure is expressed in the units of atm, one quickly gets the idea of what is being talked about.

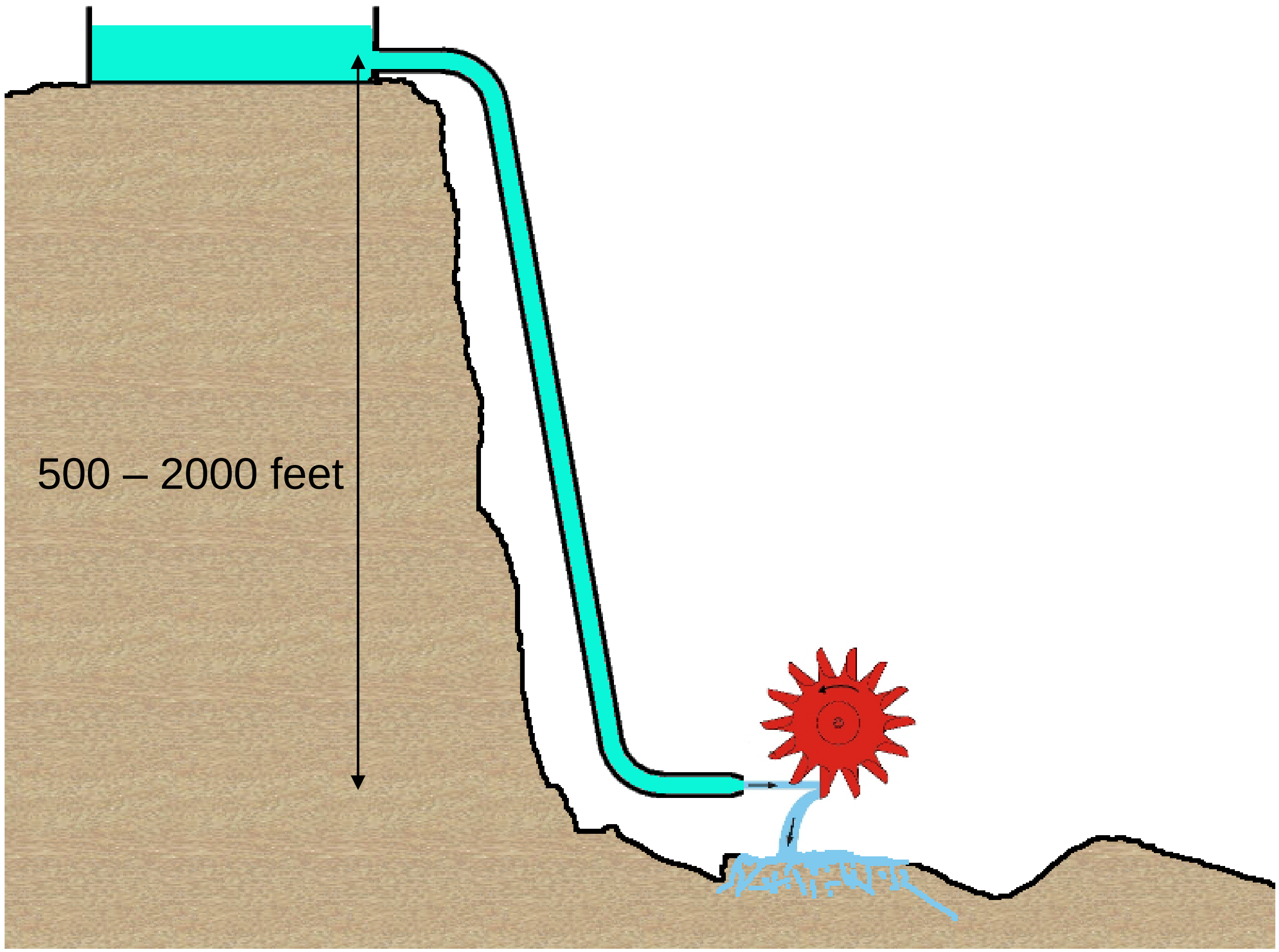
work in such a situation is the *Pelton Turbine.*

In the next page it is shown how a power plant with a Pelton turbine is organized, and on the page that follows is more about the Pelton Turbine itsels. T

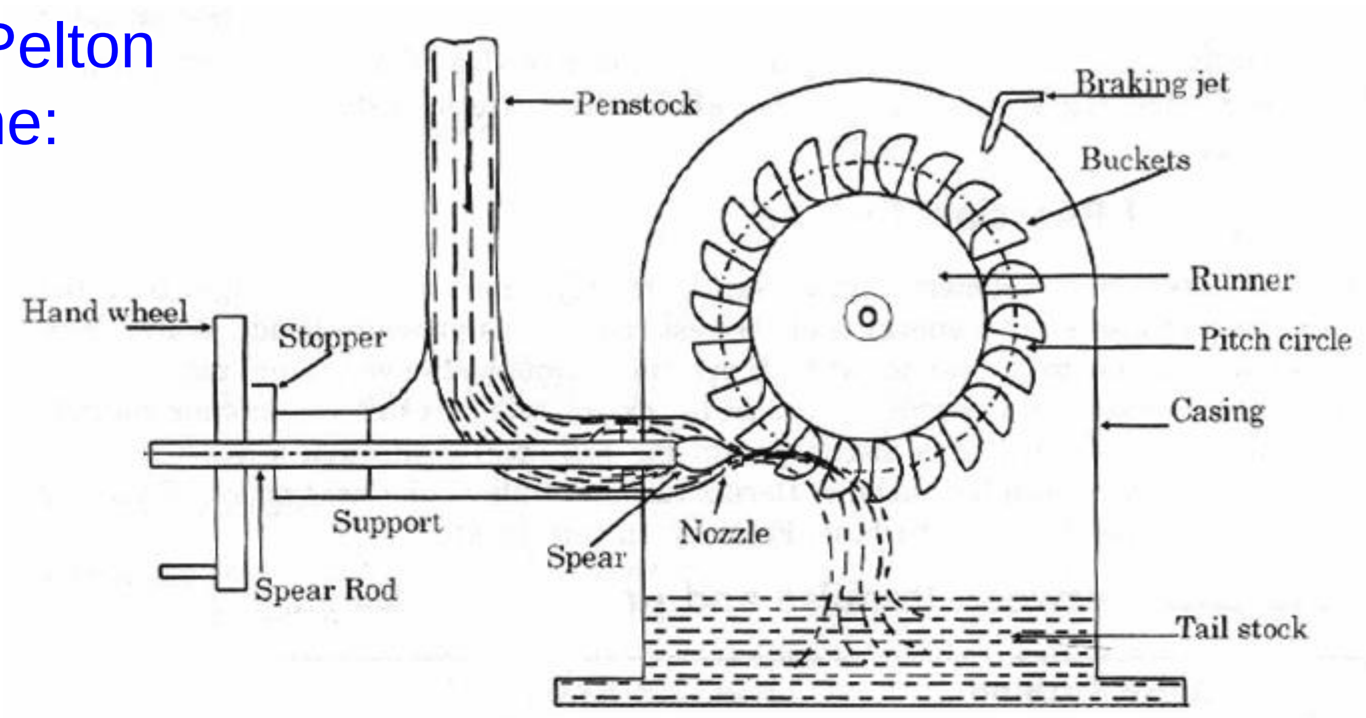
Then, on the next page is a photo of at real plant, which is perhaps the most famous of all the Pelton-type installations in the world. It's located in Rjukan, Norway, in a narrow valley. During World War II, when Norway got under Nazi occupation, the occupants started using the electric power generated in the plant for extracting the so-called "heavy water" from ordinary water. In heavy water, normal hydrogen is repalced by its heavier isotope, Deuterium. In ordinary water, there is roughly one Deuterium atom per 5500

atoms of normal hydrogen. The process of extracting D_2O from ordinary water, H_2O, consumed much electric power. However, D_2O was crucial for the Nazi efforts of building an atomic bomb. The Allies tried more than once to destroy the plant from the air, but, because of its location in a narrow valey – or, a canyon rather – it was impossible to hit it with bombs. Finally, the plant was twice sabotaged by a British commando teams who parachute-landed in nearby mountain area. This authentic story was used in 1965 for making a movie "The Heroes of Telemark" in which one of the commandos was played by a famous American actor, Kirk Douglas ("Telemark" is the name of a mountain area in Norway, where Rjukan is located).

A power plant with a Pelton turbine – particularly popular in Norway



The Pelton turbine:



Perhaps the most famous hydroelectric power plant in the world using the Pelton turbine technology: in Rjukan, Norway, located in a narrow canyon. Water is brought down from a high altitude by ten pipelines.

PUMPED STORAGE HYDROELECTRIC PLANTS

One great advantage of hydropower technology is that it makes it possible to build plants in which large amount of energy can be stored and used later ”on demand”. Such complexes are called ”pumped storage plants. In the area of energy storage, they are definitely the record-keepers. Energy can be stored in other ways, in electric batteries, or thermally – in huge reservoirs of molten salts – or as compressed air, (we will be talking about all such methods later in the cour). However, the largest existing hydroelectric storage complex (in the US, in Bath County, Virginia) can store about 50 times more energy than the largest presently existing system using another technology.

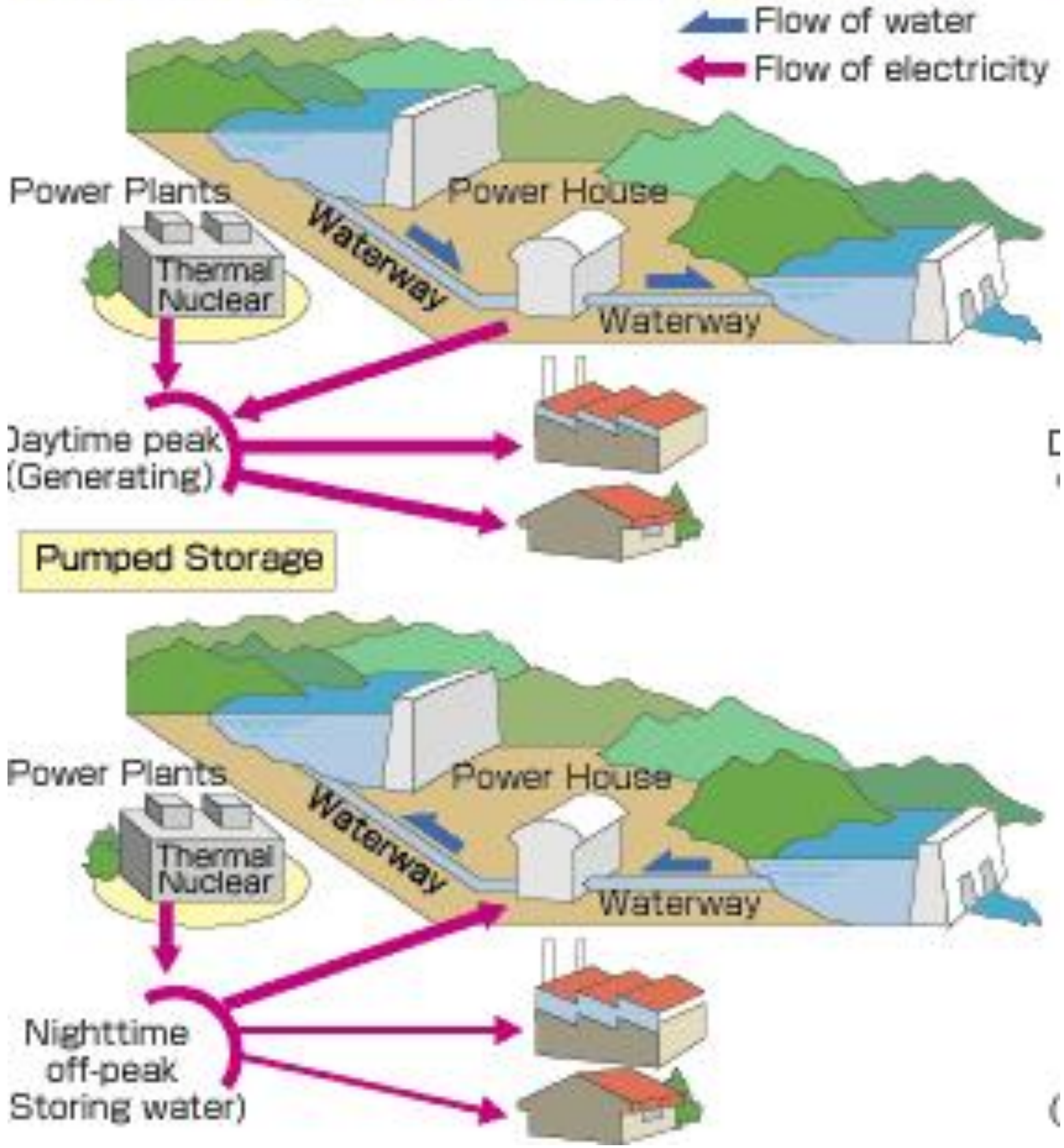
The idea of hydropower storage is very simple – one needs two reservoirs, called the "lower" and the "upper". When there is surplus of electric power (e.g., in the night hours), water is pumped from the lower pool to the upper. Then, when the utility system uses maximum power (e.g., during the "peek hours", the water from the upper pool is sent to turbines – this part of the operation is exactly the same as in an "ordinary" power plant.

There are some problems with this technology – if the complex is expected to store a large amount of energy, then the upper pool should be able to contain a huge amount of water, and it should be located considerably higher than the lower pool. The thing is that there are not too many places in the world that offer favorable conditions: first, there must be a mountain with a flat top and enough space in the summit region to enable building a sizable “upper pool”. Second, there must be a long steep slope, at the bottom of which the “lower pool” has to be installed. Third, there must be plenty of water available in the area. From the quiz about the Bath County storage complex, you will certainly conclude that finding other locations good for building complexes of similar magnitude may be a difficult task – and in many geographic areas, just a hopeless task!

The first picture below shows schematically the two modes of operation of a storage plant – the upper graph shows the “generation mode”, in which water is sent

down to turbines, and the lower graph displays the situation in the "storage mode". The graphs are self-explanatory, I believe.

Pumped Storage Hydroelectric Power Plants



In the next picture, there is a "cross section view" of the installation in an existing hydroelectric storage facility. There are several ways such an installation can be built. One possible variant is to make the pumping unit and the ectricity generating unit completely separate. Yet, a smarter solution is to use the generator as an electric motor. It should be noted that electric power generators usually can work "the other way", as motors. When the "input" to a generator is work, it converts it to "output" electric energy; but if the "input" is electric current you send to the generator, the "output" is mechanical work.

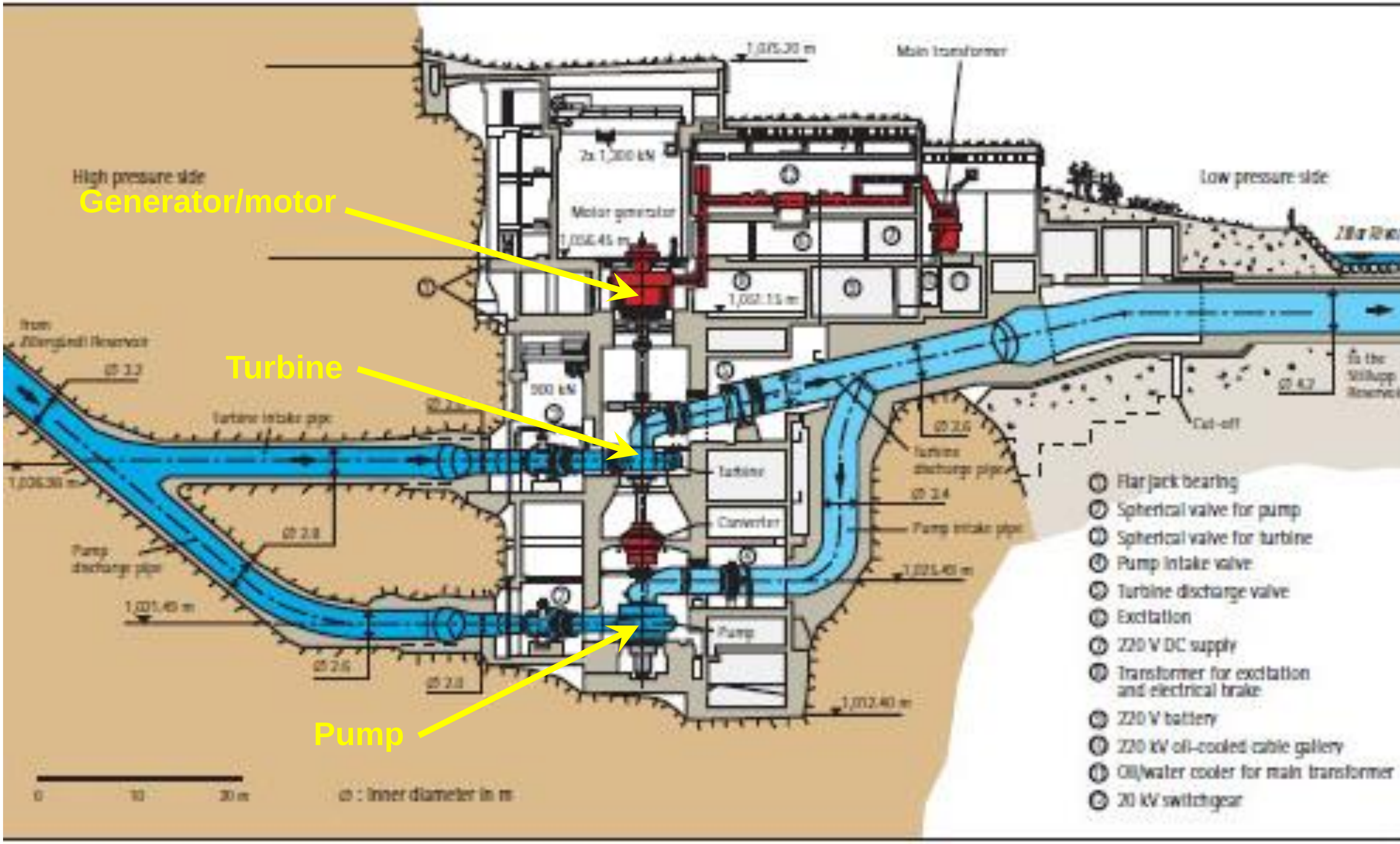
Accordingly, quite often in existing installations one generator/motor services both the turbine and the pump,

as is shown in the graph – and special valves enable the operators to sent the water coming from above to the turbine, or to switch to the other mode, in which water from the lower pool first flows to the the pump due to its suction action, and from there it is "pushed up" by the same pump all the way to the upper pool.

Yet another ingenious simplification of the system is to use the so-called "Francis Turbine" which is a "double-action device" – i.e., can operate both ways, as a turbine extracting power from the flowing water, or as a pump sending water in the opposite direction. Essentially, all pumped storage installations built in the recent past use the Francis turbine/pump technology.

There is a nice animation on Youtube showing the op-

eration of a pumped storage system accompanied by an interesting comment. If you would like to find a more "in-depth" description of the Francis turbine technology, this article is certainly worth reading – also, because of the excellent graphic material, beautiful photographs and highly instructive technical drawings.



Cross-sectional view of Häusling Power House

QUIZ 3

In the famous Bath County pumped storage system , the upper pool is located 385 meters above the lower pool (average vertical distance, because the difference between highest and the lowest water level in the upper pool is over 30 meters). The capacity of the upper pool is 14 million cubic meters. The maximum water flow to the turbines during the the generation period is 852 m^3 per second. With such a flow, the new turbines recently installed generate 3001 MW of power. Based on the above data, find: (a) the efficiency of the generating system, (b) how long the plant can generate maximum power, and (c) what is the total energy stored, when the upper pool is completely filled.

A graph showing a typical daily activity of a pumped-storage plant: Pumping (mostly, during night hours), and Power Generation – the power generated may sharply go up and down, depending on how much "backup" the nation's power system needs at a given moment.