LAB # 13

To Study and Understand the Working Principles of Hydro Electricity and Tidal Energy Generation

Objectives:

- To study and understand the working of hydroelectricity and tidal energy generation
- To understand how to calculate potential energy, power density and capacity factor of hydroelectricity and tidal energy systems
- To understand how to calculate the global energy yield per person of both resources

Related Theory:

Renewable energy is energy that is collected from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. To make the ***transition*** from non-renewable energy like fossil fuels to renewable energy, it is essential that we know what the ***potential*** is of these renewable sources. We will take a look at some renewable sources and the physics behind it to calculate the potential of these source.

Before we move on, let us go through the concepts of primary ***energy potential***, ***system's efficiencies,*** and ***energy yield***. The primary energy potential is known as the available energy from the primary source. We may also express this as the ***power potential*** if you take the available energy per unit time.

$$Primary\ Power\ Potential = P = \frac{E}{Time}$$

The primary energy has to be converted into useful energy. We will look into the fundamental conversion ***efficiency losses*** for each of the renewable energy systems. *The output power of a system is equal to product of the primary power potential and its system efficiencies*. Depending on the technology, the ***maximum output power*** might be called the installed, nominal or rated capacity of a system.

$$Installed/Rated/Nominal\ Capacity = Maximum\ Capacity$$

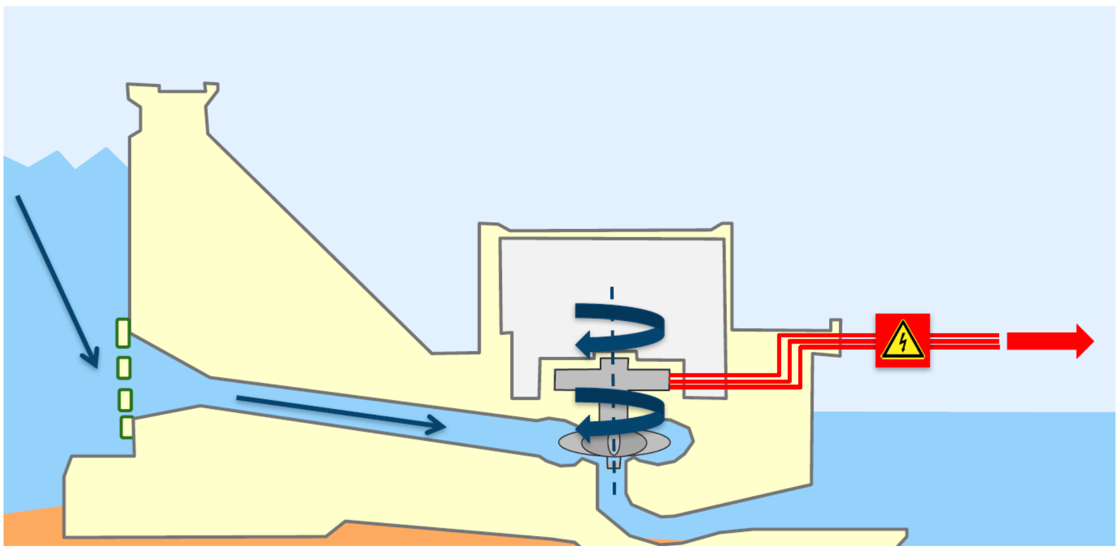
Throughout the year, the power output of a system changes. This could be caused by various reasons and it influences the yearly energy yield. How much the ***actual yield deviates*** from the nominal output is represented by the ***capacity factor***, which is equal to the energy yield divided by the nominal output multiplied by the time-interval. The capacity factor ***represents*** the practical ***losses*** of a renewable energy system.

$$Capacity\ Factor = \frac{E_{Yield}}{P_{nom.} * Time}$$

Hydroelectricity Energy:

A hydroelectricity dam is a system that ***converts*** the potential energy of water at a ***height difference*** into electricity. Hydro power plants are usually ***built*** next to a natural lake or water reservoir that collects the water incident on a large area.

Let's look in more detail to the hydropower generation. We start with the sun. ***Sunlight*** evaporates seawater, resulting in the formation of ***clouds***. The water vapour in clouds precipitates as rain or snow, that is then ***collected*** in a large ***reservoir***, through streams and rivers. Due to this precipitation the reservoir ***fills up*** to a certain ***height***. This ***water*** contains ***potential energy***. Once the water ***drops down*** the energy is converted to mechanical energy by a ***rotating turbine***. The turbine is connected to a huge ***electric generator*** to convert the mechanical energy into electrical energy. The generator is connected via ***transformers*** to the electricity grid to deliver electricity.



Let's take a look at the factors that determine the primary energy potential, efficiencies and the energy yield.

Hydropower uses the ***potential energy*** in the reservoir's water. *Potential energy is the energy that is released by dropping a certain mass from a certain height*. This is shown in the following equation. Where E_{pot} is the potential energy in Joule, 'm' is the mass of the water, 'g' is the gravitational constant of 9.8, and 'h' is the height difference between the source and the outflow of the dam. We can also express this as the ***potential power*** if instead of mass, the ***mass flow*** is used.

$$E_{pot} = m_w * g * h \qquad [\mathrm{J}] = [\mathrm{kg}] * [\mathrm{m\,s^{-2}}] * [\mathrm{m}]$$
$$P_{pot} = \dot{m}_w * g * h \qquad [\mathrm{W}] = [\mathrm{kg\,s^{-1}}] * [\mathrm{m\,s^{-2}}] * [\mathrm{m}]$$

The ***mass*** is strongly related to the amount of ***rainfall*** and ***total area*** from which the reservoir collects the water. This is referred to as the ***catchment area***. If we know the size of this area, we can estimate the ***total energy potential*** of a certain region or dam. The water mass, m_w, is related to the ***precipitation*** according to the below equation:

$$m_w = precip * \rho * A_{catch} \quad [\mathrm{kg}] = \frac{[\mathrm{m}^3]}{[\mathrm{m}^2]} * [\mathrm{kgm}^{-3}] * [\mathrm{m}^2]$$

where the ***precipitation*** is the ***amount of rainfall*** in cubic meters per square meter, $\boldsymbol{\rho}$ is the density in kilograms per cubic meter and ***A*** is the catchment area in square meters.

There are some ***factors*** that ***reduce*** the ***conversion efficiency*** of a hydropower plant. The ***losses*** in the hydropower system are mainly caused by ***three factors***. When the water flows from the inlet to the outlet, the potential energy is converted into kinetic energy. The water flow loses some of its ***kinetic energy*** due to ***friction*** at the edges of the ***pipe***. The ***second loss*** mechanisms occur, when the ***turbine converts*** the kinetic energy of the water to rotational, or mechanical energy. Finally, some losses occur in the ***generator and transformer***, where mechanical energy converted to electrical energy and when the electrical energy is converted to a higher voltage.

The final ***energy yield*** of a hydropower plant can be strongly ***influenced*** by the weather conditions, especially the amount of precipitation. This affects the available water flow and the height difference of the water and consequently the potential energy. This explains why seasonal fluctuations in the power output occur. Another factor is that the power plant, like many systems, has a certain ***down time*** for maintenance and repair.

Now, let us work through an ***example***. Let's say a certain region has about ***500 mm*** of ***rain*** per year and there is no meltwater from mountain snow or glaciers. Additionally, the ***height*** difference between the source and the outflow of the dam is ***100 m***. With this information we can calculate the ***energy potential***, in Joules as following:

$$Rain\ fall = 500\ mm\ , h = 100m$$

$$\therefore\ Where\ rain\ of\ 1000\ mm = 1m^3$$

$$Precipitation = 1m^3 * \frac{500}{1000} = 0.5m^3$$

$$\therefore\ Where\ density\ of\ water = \rho = 1000\ kgm^{-3}$$

$$Mass = m_w = 0.5m^3 * 1000\ kgm^{-3} * 1m^2 = 500\ kg$$

$$Energy\ Potential = E_{pot} = 500\ kg * 9.81\ ms^{-2} * 100m = 490\ kj$$

$$Energy = E_{pot} = \frac{490\ kj}{60 * 60} = 136\ Wh$$

If we divide by the total hours in a year, we obtain a ***power density*** of 0.016 Watts per square meter.

$$P_{pot} = \frac{136Wh}{8760h} = 0.016\ W$$

Note that this calculation is purely the potential energy. This does not consider the efficiencies of the system.

To learn more about the ***total energy yield*** we will take a closer look to next example: the ***Itaipu Dam*** on the border of Brazil and Paraguay. The Itaipu dam is the ***second*** largest hydropower plant on the planet. It has a total ***installed generation capacity*** of ***14GW***, and, in 2015, has reached a **energy yield** of ***89.5 TWh*** per year. Using these values, we can calculate the ***capacity factor***.

$$Capacity\ Factor = 89.5TWh * \frac{1}{8760h} * \frac{1}{14GW} = 0.73$$

So, on average, the Dam produces electricity at maximum capacity during ***73%*** of the time. Note this value is much higher than the ***average global capacity factor*** for hydropower of ***0.40***.

Hydroelectricity is the ***biggest*** contributor to renewable energy electricity with a global installed capacity of ***1211 GW***, producing approximately ***3975 TWh*** of electricity. If we take a population of ***7.5 billion people***, this results in an energy density of ***1.45 kWh*** per person per day.

Global Energy Yield= $3975\ [\mathrm{TWh\ year^{-1}}]$ Global Population= $7.5 * 10^9 [\mathrm{person}]$

$$E_{GlobalYield} = 3975\ [\mathrm{TWh\ year^{-1}}] * {}^{1}\!/_{7.5\ *\ 10^9}\ [\mathrm{person^{-1}}] * {}^{1}\!/_{365}\ [\mathrm{year\ day^{-1}}]$$

$$E_{GlobalYield} = 1.45\ [\mathrm{kWh\ person^{-1} day^{-1}}]$$

Tidal Energy:

Previously, we discussed the most common form of Hydropower. There are however ***more ways*** to ***harvest*** energy from water. ***Tidal energy*** is a special type of energy, where solar radiation is not the primary energy source.

The tides are caused by the ***gravitational pull*** of the ***moon*** and the ***sun***. At ***high tide***, the water has a greater height than at low tide. This ***height difference*** means that some potential energy is available. *Just as in a hydropower plant*, the potential energy is transformed into kinetic energy, which is then used to generate electricity. The main ***difference*** is that the water reservoir gets ***replenished*** with the ***tides***, instead of through rainfall. Alternatively, tidal energy can be harvested by ***placing turbines*** in a ***tidal flow*** in the ***sea***.

The ***primary energy potential*** is calculated in the same way as with hydropower. The potential energy is equal to the ***mass*** of the water multiplied by the ***gravitational constant***, multiplied by the ***height difference***.

$$E_{pot} = m_w * g * h \qquad [\mathrm{J}] = [\mathrm{kg}] * [\mathrm{m\ s^{-2}}] * [\mathrm{m}]$$

$$P_{pot} = \dot{m}_w * g * h \qquad [\mathrm{W}] = [\mathrm{kg\ s^{-1}}] * [\mathrm{m\ s^{-2}}] * [\mathrm{m}]$$

If we look at this equation more closely, we see that the ***mass*** depends on the ***height difference*** between low and high tide. Therefore, in total the potential energy depends quadratically on this height difference.

$$m_w = h * A_{reservoir} * \rho \qquad [\mathrm{kg}] = [\mathrm{m}] * [\mathrm{m}^2] * [\mathrm{kg\ m}^{-3}]$$

$$E_{pot} = A_{reservoir} * \rho * g \ * h^2$$
$$[\mathrm{J}] = [\mathrm{m}^2] * [\mathrm{kg\ m}^{-3}] * [\mathrm{m\ s}^{-2}] * [\mathrm{m}]^2$$

The ***main conversion losses*** are also the ***same*** as those of a ***hydropower plant***. As you may remember, these were caused by the ***friction, turbine, and electrical losses***.

The ***energy yield*** is determined by the ***tidal variations***, which depend on the ***position of the sun and the moon*** with respect to the ***Earth***. From these two, the influence of the moon is the greatest. This is because the moon is closer to the Earth.

The above picture shows the difference between ***Spring*** and ***Neap*** tides. The ***orange*** sphere represents the tide created by the ***sun***, and the blue sphere represents the tide created by the ***moon***. The ***highest*** tides are created during ***spring*** tides. This is because the moon and the sun are aligned with each other. About seven days later, during neap tide, the sun's pull is perpendicular with respect to that of the moon. This creates lower tides.

Let's run through a calculation example to assess the potential of tidal energy. Let's assume a ***height*** difference of ***10 meters*** between low tide and high tide, flowing through a ***column*** with a surface ***area*** of ***1 square meter***. The ***density*** of salt water is approximately ***1025 kg/m^3*** and the ***gravitational constant*** is equal to ***9.81*** meter per square second. With this data we can calculate the ***energy potential*** as following:

$$h = 10m \, , A_{column} = \ 1m^2 \, , \rho = 1025kgm^{-3} \, , g = 9.81ms^{-2}$$

$$E_{pot} \ = 1m^2 * 1025kgm^{-3} * 9.81ms^{-2} * (10m)^2 = 1MJ$$

$$E_{pot} \ = \frac{1MJ}{3600} = \frac{277.77Wh}{1000} = 0.27KWh$$

With this data we calculate the energy potential, which is approximately equal to 1 MJ, or 0.27 kWh per square meter per tide. Because this is for an area of 1 square meter, this is actually the potential energy density of this basin ***per square meter***.

So, what about the power density? As there are ***2 tides*** in a ***day***, we can say that the source gets replenished twice a day.

$$E_{pot.daily} = 0.27 \ KWh \ m^{-2} tide^{-1} * 2 \ tide \ day^{-1} = 0.55 \ KWh \ m^{-2} \ day^{-1}$$

If we divide this by the ***total hours*** in a ***day***, we find that the average ***potential power density*** as:

$$P_{ave} = \frac{0.55\ KWh\ m^{-2} day^{-1}}{24h\ day^{-1}}$$

$$P_{ave} = 22.7\ Wm^{-2}$$

Note that the system efficiencies have not yet been taken into account.

We will calculate the ***capacity factor***, but also, using this information, find out the system's efficiencies. To do this, we will take a look at the ***Rance tidal power station*** in ***France***. This tidal power station is one of the biggest tidal power stations in the world, with an ***installed capacity*** of ***240MW***. It produces on average approximately ***500 GWh*** per year. The ***height*** difference is ***8 meters*** and the ***area*** of the reservoir is ***22.5 square kilometers***.

$$Capacity\ Factor = 500GWh * \frac{1}{8760h} * \frac{1}{240MW} = 0.24$$

$$P_{ave.output} = 240MW * 0.24 * \frac{1}{22.5\ km^2} = 2.6\ Wm^{-2}$$

Doing this, we find an average power density of 2.6 W/m^2.

Before we can calculate the system's efficiency, we first have to calculate the ***primary energy potential of this station***. With a ***height difference*** of ***8 meters***, we obtain a potential energy of 0.63 MJ per area per tide.

$$E_{pot} = 1025\ Kgm^{-3} * 9.8ms^{-2} * (8m)^2 = 0.63\ MJ\ m^{-2} tide^{-1}$$

$$E_{pot.daily} = 0.63MJm^{-2} tide^{-1} * 2\ tide\ day^{-1} = 1.26\ MJ\ m^{-2} day^{-1}$$

$$E_{pot.daily} = 1.26\ MJ\ m^{-2} day^{-1} = 0.35KWh\ m^{-2} day^{-1}$$

This is a total of 0.35 kWh per square meter, which equates to an ***average power density*** of 14.6 W per square meter.

$$P_{ave.pot} = 0.35KWh\ m^{-2} day^{-1} * \frac{1\ day}{24h} = 14.6\ Wm^{-2}$$

We can now find the ***system's efficiency***, by dividing the average output density by the average primary power density. This is equal to 18 %.

$$\eta = \frac{P_{ave.output}}{P_{ave.pot}} = \frac{2.6\ Wm^{-2}}{14.6\ Wm^{-2}} = 18\%$$

Only a few tidal plants exist all over the world. They have a combined capacity of around ***500 MW***. This makes the contribution of tidal energy to the world electricity production negligible. According to our previously calculated capacity factor, this results in an annual yield of ***1.05 TWh*** per year.

Global Energy Yield= $1.05\ [\mathrm{TWh\ year^{-1}}]$ Global Population = $7.5 * 10^9 [\mathrm{person}]$

The global yield, per person per day, equals to a small value of 0.38 Wh.

$$E_{GlobalYield} = 1.05\ [\mathrm{TWh\ year^{-1}}] * {}^{1}/_{7.5\ *\ 10^9}\ [\mathrm{person^{-1}}] * {}^{1}/_{365}\ [\mathrm{year\ day^{-1}}]$$

$$E_{GlobalYield} = 0.38\ [\mathrm{Wh\ person^{-1} day^{-1}}]$$

Conclusion and Comments: