REET 2020

Energy Conversion

3 – Hydro Energy

Hydro Energy

Hydro energy refers to energy that is derived from the motion of water.

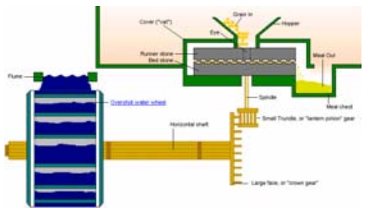
Hydro energy originates in many different forms:

- **Potential Energy from water stored at a higher elevation in a dam,**
- **Kinetic Energy from the natural flow of water in rivers or ocean currents,**
- **Tidal Energy from the tides caused by the gravitational attraction of the moon and the sun, and**
- **Wave Energy from waves induced by the wind.**

Hydro Energy

Historically, hydro energy has been utilized for a variety of applications:

Gristmills

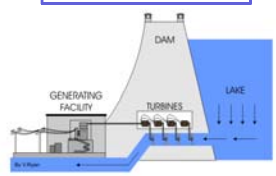


https://licmillstones.wordpress.com/what-are-millstones-anyway/

500,000+ waterwheel-driven gristmills are still in use around the world today.

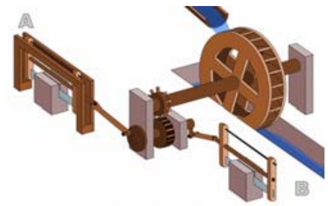
https://informa-press.it/tour-mulino-bianco-lungomare/

Electric Power Plants



http://mechanicalgalaxy.blogspot.com/search/label/mechanical%20animations

Sawmills

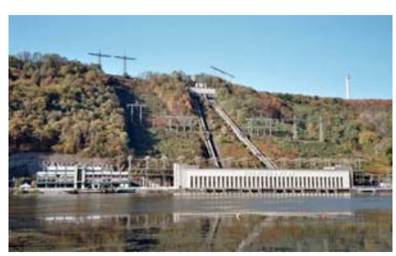


https://commons.wikimedia.org/wiki/File:R%C3%B6mische_S%C3%A4gem%C3%BChle.svg

Hydro-Electric Energy

<u>Hydro-electric energy</u> is a term that is usually reserved for energy that is derived from hydroelectric dams, diversion facilities, or pumped-storage facilities.

Chief Joseph Dam in Washington



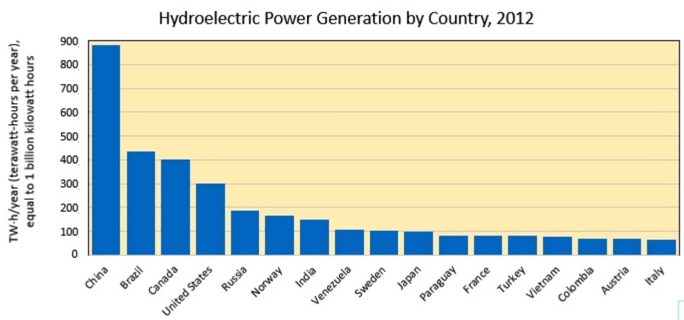
Koepchenwerk Power Station in Germany

https://kids.kiddle.co/Hydropower

Hydro-Electric Energy

Hydropower represents about 17% of the world's total electricity production.

China is the largest producer of hydroelectricity, followed by Brazil, Canada, and the United States.



https://water.usgs.gov/edu/wuhy.html

US Hydro-Electric Energy

Hydro-electric energy provides about 7% of the electricity generated in the US and about half of the electricity from all renewable sources.

Over 70% of Washington State's electricity comes from hydropower, and 11 states get more than 10%of their electricity from hydropower.

Hydropower costs less than most energy sources. States that get the majority of their electricity from hydropower, like Idaho, Washington, and Oregon, have energy bills that are lower than the rest of the country.

https://www.energy.gov/articles/top-10-things-you-didnt-know-about-hydropower

Hydro-Electric Facility Types

<u>Impoundment Facility</u> – uses a dam to store river water in a reservoir, the potential energy from which is used to drive an electric generator.

<u>Diversion Facility</u> – sometimes called run-of-river facility, channels a portion of a river's water through a canal or penstock, converting both the potential and kinetic energy of the water into electricity.

<u>Pumped Storage Facility</u> – excess electricity is stored as potential energy by pumping water uphill to a reservoir at a higher elevation. The water can then be released when needed to convert the potential energy back into electricity.

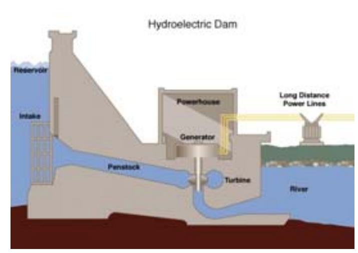
https://www.energy.gov/eere/water/types-hydropower-plants

Impoundment Facilities

<u>Impoundment facilities</u> utilize dams to obstruct or stop the flow of river water in order to form a reservoir or a lake.

A portion of the water is allowed to flow through a large pipe called a penstock, gaining velocity as it travels down hill.

The force from the moving water is used to spin a turbine that, in-turn, rotates an electric generator.



https://kids.kiddle.co/Hydropower

Potential Energy Due to Gravitation

The potential energy contained in water that is stored at a higher elevation is:

$$W = m \cdot g \cdot H \ \text{Joules}$$

where: $g = 9.8 \ {}^{\text{m}}\!/_{\text{s}^2}$ **is the acceleration due to gravity,**
m **is the mass of the water in kilograms, and**
H **is the height of the water in meters.**

Note that for estimation purposes, the acceleration due to gravity is often rounded to:

$$g \approx 10 \ \frac{\text{meters}}{\text{second}^2}$$

Introduction to Renewable Energy, Vaughn Nelson

Potential Energy Due to Gravitation

The mass of water can be defined in terms of the water's density and volume:

$$m = \rho \cdot V \ \text{kg}$$

where: $\rho = 1000 \ {}^{\text{kg}}\!/_{\text{m}^3}$ **is the density of water, and**
V **is the volume of the water in meters^3.**

Thus, the potential energy contained in water that is stored at a higher elevation is:

$$W = m \cdot g \cdot H \approx 10{,}000 \cdot V \cdot H \ \text{Joules}$$

The difference in height between the water source and the water's outflow is called the head.

Introduction to Renewable Energy, Vaughn Nelson

Hydro-Electric Power

Since power is the rate of energy conversion, the theoretical electric power that can be produced from a dam is:

$$P = \frac{W}{t} \approx \frac{10{,}000 \cdot V \cdot H}{t} = 10{,}000 \cdot Q \cdot H \quad \text{Watts}$$

where: Q **is the flow rate of the water in meters^3/second, and**
H **is the head in meters.**

Note that, if the efficiency (η) of the turbine is taken into account (typically 80-95%), then:

$$P \approx 10{,}000 \cdot \eta \cdot Q \cdot H \quad \text{Watts}$$

http://www.alternative-energy-tutorials.com/hydro-energy/small-scale-hydro-power.html

Hydro-Electric Facility Classification

The Department of Energy classifies hydro-electric facilities in terms of their size or capacity:

- **Large Hydropower: facilities having a capacity >30MW**
  - **usually feeds a large electric grid**
- **Small Hydropower: facilities having a capacity from 100kW to 10MW**
  - **often feeds an electric grid, but may also serve an industrial plant or a small community**
- **Micro Hydropower: facilities having a capacity <100kW**
  - **may feed an electric grid or serve an isolated home/community**

Pico-sized facilities, typically <5kW, may be used to supply remote loads that only require a small amount of electricity.

https://www.energy.gov/eere/water/types-hydropower-plants

Hoover Dam

Hoover Dam generates an average of about 4 billion kWh of hydroelectric power each year.

The plant has a nameplate capacity of about 2,080MW, including the two station-service units, which are rated at 2.4MW each.

There are 17 main turbines in the Hoover power plant that operate with an average head of around 160 meters.

https://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html

Hoover Dam

The Hoover Dam releases roughly 7.5 million acre-feet of water for electric energy production annually.

$$1\,\text{acre}\cdot\text{foot} = 1233.5\,\text{meters}^3$$

Assuming a 90% turbine efficiency:

$$\begin{aligned} W &\approx 10{,}000\cdot\eta\cdot V\cdot H \\ &= 10{,}000\cdot(0.9)\cdot(7.5x10^6\,\text{acre}\cdot\text{feet})\cdot(1233.5\,\tfrac{\text{meters}^3}{\text{acre}\cdot\text{feet}})\cdot 160\,\text{meters} \\ &= 13322\text{x}10^{12}\ \text{joules}\cdot(2.7\overline{7}x10^{-7}\,\tfrac{\text{kWh}}{\text{joule}}) \\ &= 3.7x10^9\ \text{kWh annually} \end{aligned}$$

https://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html

Largest Hydro-Electric Facilities

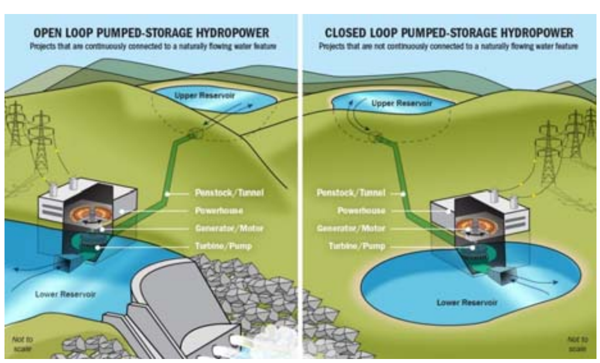
Rank	Name	Country	River	Years of completion	Installed capacity (MW)	Annual production (TW-hour)[6]	Area flooded (km²)
1	Three Gorges Dam	China	Yangtze	2008/2012	22,500	98.8[7]	1,084
2	Itaipu Dam	Brazil Paraguay	Paraná	1984/1991, 2003[8]	14,000	103.1 [1]	1,350
3	Xiluodu	China	Jinsha	2014[9]	13,860[10]	55.2	
4	Guri	Venezuela	Caroní	1978, 1986	10,235	53.41	4,250
5	Tucuruí	Brazil	Tocantins	1984, 2007	8,370	41.43	3,014
6	Grand Coulee	United States	Columbia	1942/1950, 1973, 1975/1980	6,809	20[12]	324
7	Xiangjiaba	China	Jinsha	2014[13]	6,448	30.7	95.6
8	Longtan Dam	China	Hongshui	2007/2009	6,426	18.7[14]	
9	Sayano–Shushenskaya	Russia	Yenisei	1985/1989, 2010/2014[15]	6,400	26.8	621
10	Krasnoyarsk	Russia	Yenisei	1967/1972	6,000	15	2,000

Three Gorges Dam

https://en.wikipedia.org/wiki/List_of_largest_hydroelectric_power_stations

Pumped Storage Facilities

Pumped storage facilities can be characterized as open loop, where there is an ongoing hydrologic connection to a natural body of water, or closed loop, where the reservoirs are not connected to an outside body of water.



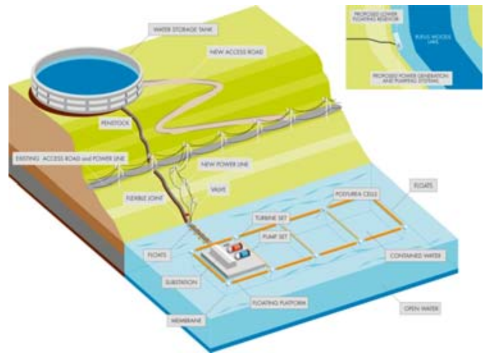
Pumped-storage currently accounts for 95% of all utility-scale energy storage in the United States.

https://www.energy.gov/eere/water/pumped-storage-hydropower

Pumped Storage Facility Research

Shell Energy's Hydro Battery – DOE Funding: $945,000

The DOE funded up to $9.8 million to develop innovative technologies for pumped-storage hydropower and non-powered dams, including a research project to investigate the feasibility of building a closed-loop, modular 5MW, PSH (pumped-storage hydropower) facility.



https://www.energy.gov/eere/water/pumped-storage-hydropower

Tidal Energy

Tidal energy facilities make use of the daily rise and fall of ocean water due to tides.

Tides are due to the gravitational attraction of the moon and the sun at the surface of the Earth.

The largest tidal ranges in the world are the Bay of Fundy (11.7 m), Ungava Bay (9.75 m), Bristol Channel (9.6 m), and the Turnagain Arm of Cook Inlet, Alaska (9.2 m).

The potential world tidal current energy is about 2,200 TWh/yr.

https://kids.kiddle.co/Tidal_energy

Tidal Energy

There are two types of tidal energy systems:

- **<u>kinetic energy systems</u> that extract energy from the moving water of rivers, tides and open ocean currents**
- **<u>potential energy systems</u> that rely on the difference in height (or head) between high and low tides.**

Tidal power sources are highly predictable, and if conditions permit construction of reservoirs, can also be dispatchable to generate power during high demand periods.

https://kids.kiddle.co/Tidal_energy

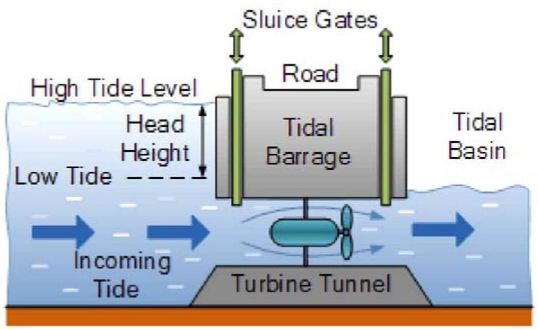
Tidal Potential Energy Systems

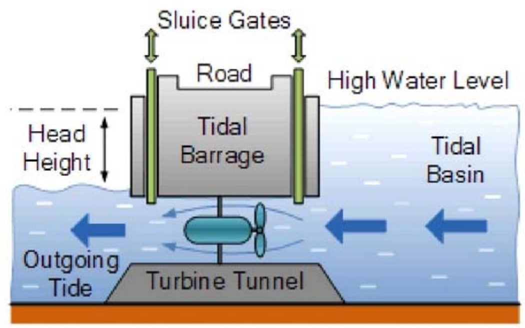
La Rance Tidal Power Plant, France – 240MW

https://www.nationalgeographic.org/encyclopedia/tidal-energy/

Tidal Potential Energy Systems

Potential energy systems often utilize barrages that capture the tidal energy by forcing the water that flows into and out of a basin to pass through a turbine that is used to drive an electric generator.

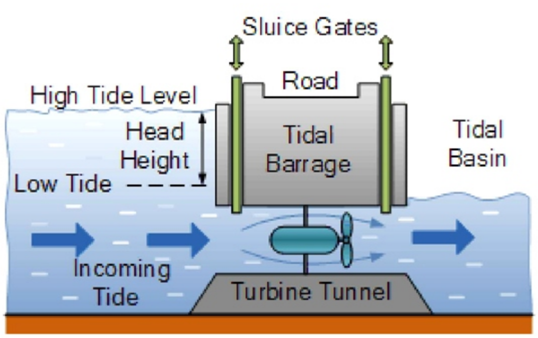




https://gambarsurat.com/ppt-energy-resources-coal-tidal-powerpoint-presentation.html

Tidal Potential Energy Systems

When the basin water is at low-tide level, the gates are closed, preventing water from flowing into the basin.



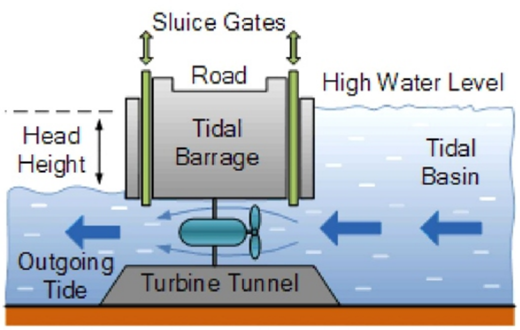
Once the tide reaches full height, the gates are opened.

Gravity provides the force necessary to push the ocean water through the turbine and into the basin, in-turn converting the potential energy into electricity.

https://gambarsurat.com/ppt-energy-resources-coal-tidal-powerpoint-presentation.html

Tidal Potential Energy Systems

Similarly, when the basin water is at high-tide level, the gates are closed, preventing water from flowing out of the basin.



Once the tide fully recedes, the gates are re-opened.

Gravity provides the force necessary to push the basin water back through the turbine and into the ocean, again converting potential energy into electricity.

https://gambarsurat.com/ppt-energy-resources-coal-tidal-powerpoint-presentation.html

Potential Energy System Example

Given a barrage with a 200m *x* 250m basin, if the difference in water level between low and high tide is 6 meters, determine the amount of potential energy that can be converted to electricity.

▼▼▼

Assuming a 6 meter height difference between low and high tide, the maximum volume of water that can either flow into or out of the basin is:

$$V = A \cdot H = 200\text{m} \cdot 250\text{m} \cdot 6\text{m} = 300{,}000 \text{ meters}^3$$

Potential Energy System Example

Given a barrage with a 200m *x* 250m basin, if the difference in water level between low and high tide is 6 meters, determine the amount of potential energy that can be converted to electricity.

Potential energy stored in water based on head level is:

$$W = m \cdot g \cdot H \approx 10{,}000 \cdot V \cdot H \text{ Joules}$$

But, as water either enters or exits the basin, its water level will change, causing the initial 6 meter differential (head) to decrease.

Assuming a linear flow rate, the average level differential will be 3 meters.

Potential Energy System Example

Given a barrage with a 200m *x* 250m basin, if the difference in water level between low and high tide is 6 meters, determine the amount of potential energy that can be converted to electricity.

Thus, assuming a 3-meter average level differential (head), the amount of potential energy available from the water that enters or exits the basin is:

$$W = 10{,}000 \cdot V \cdot H_{avg} = 10{,}000 \cdot 300{,}000 \cdot 3 = 9x10^9 \text{ Joules}$$

Thus, the total electric energy available per tidal cycle is:

$$W_{total} = W_{In} + W_{Out} = 9x10^9 \text{ J} + 9x10^9 \text{ J} = 18x10^9 \text{ Joules}$$

Potential Energy System Example

Given a barrage with a 200m *x* 250m basin, if the difference in water level between low and high tide is 6 meters, determine the amount of potential energy that can be converted to electricity.

Assuming a 90% turbine efficiency, the total potential energy converted to electricity per tidal cycle will be:

$$W_{electric} = (0.9)\cdot(18x10^9) = 16.2x10^9 \text{ Joules}$$
$$= 16.2x10^9 \text{ J} \cdot \frac{1\text{kWh}}{3.6\text{x}10^6 \text{J}} = 4{,}500 \text{ kWh}$$

If valued at $0.12/kWh, then:

$$4{,}500 \,\tfrac{\text{kWh}}{\text{cycle}} \cdot 0.12 \,\tfrac{\$}{\text{kWh}} = 540 \,\tfrac{\$}{\text{cycle}}$$

Tidal Potential Energy Systems

If a large, naturally occurring inlet is available, a barrage can be placed across its entrance, forming a huge reservoir, in-turn offering a huge source of renewable energy.

https://gambarsurat.com/ppt-energy-resources-coal-tidal-powerpoint-presentation.html

Tidal Potential Energy Systems

Sihwa Lake Tidal Power Station, South Korea – 254MW

(the world's biggest tidal power plant)

Opened in August 2011, the facility utilizes a 12.5km long seawall that was originally constructed for flood mitigation and agricultural purposes.

Power is generated on tidal inflows into a 30km^2 basin with the help of ten 25.4MW turbines.

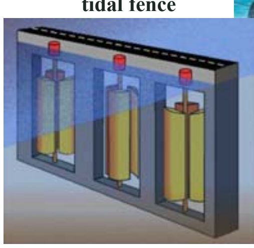
Eight culvert type sluice gates are used for the water outflow.

https://www.power-technology.com/features/featuretidal-giants-the-worlds-five-biggest-tidal-power-plants-4211218/

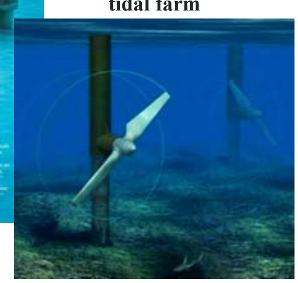
Kinetic Energy Systems

Various Systems (Current and Wave)

tidal fence



tidal farm



https://gambarsurat.com/ppt-energy-resources-coal-tidal-powerpoint-presentation.html

https://www.nationalgeographic.org/encyclopedia/tidal-energy/

Kinetic Energy Turbines

<u>Kinetic energy turbines</u>, also called free-flow turbines, can be used to generate electricity from the kinetic energy of the water flowing in rivers, tides, and ocean currents.

Kinetic energy systems have less environmental impact than potential-energy (dam-based) systems because they do not require large civil works or areas of land to form a reservoir.

Additionally, kinetic energy systems are modular allowing them to be installed incrementally and be operational in a short time compared to potential-energy systems.

Introduction to Renewable Energy, Vaughn Nelson

Kinetic Energy Due to Flow

The <u>kinetic energy</u> contained in a moving mass of water is:

$$KE = \tfrac{1}{2} \cdot m \cdot v^2 = \tfrac{1}{2} \cdot \rho \cdot V \cdot v^2 \ \text{ Joules}$$

where: $\rho = 1000 \ {}^{\text{kg}}\!/_{\text{m}^3}$ is the density of water, and
V is the volume of the water in meters^3.

If a volume of the material is forced to move through a given area-sized opening, then:

$$KE = \tfrac{1}{2} \cdot (\rho \cdot V) \cdot v^2 = \tfrac{1}{2} \cdot \rho \cdot (Q \cdot t) \cdot v^2 = \tfrac{1}{2} \cdot \rho \cdot (A \cdot v) \cdot t \cdot v^2$$
$$= \tfrac{1}{2} \cdot \rho \cdot A \cdot t \cdot v^3 \ \text{ Joules}$$

Kinetic Energy Due to Flow

Since <u>power</u> is a rate of energy conversion (J/sec), the power available from the flowing water is:

$$P = \frac{KE}{t} = \frac{\frac{1}{2}\cdot\rho\cdot A\cdot t\cdot v^3}{t} = \frac{1}{2}\cdot\rho\cdot A\cdot v^3 \text{ Watts}$$

Thus, as long as there is a constant volume of water is flowing through the cross-sectional area *A*, the available power per unit area is:

$$\frac{P}{A} = \frac{\frac{1}{2}\cdot\rho\cdot A\cdot v^3}{A} = \frac{1}{2}\cdot\rho\cdot v^3 \ \frac{\text{Watts}}{\text{meter}^2}$$

Kinetic Energy Due to Flow

The following shows the average speed of the ocean currents around the US mainland:

$$\frac{P}{A} = \frac{1}{2}\cdot\rho\cdot v^3 \ \frac{\text{Watts}}{\text{meter}^2}$$

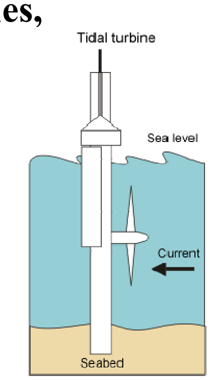
https://maps.nrel.gov/mhk-atlas/

Kinetic Energy System Example

Determine the energy that could be generated annually by a single kinetic energy system in south Florida, where coastal currents near the shoreline can easily have an average velocity of 0.3 m/sec, if the system utilizes two turbines, each having a blade radius of 4 meters.

Given an average velocity of 0.3 m/sec, the theoretical power per unit area available from the currents is:

$$\frac{P}{A} = \tfrac{1}{2} \cdot \rho \cdot v^3 = \tfrac{1}{2} \cdot (1000 \tfrac{\text{kg}}{\text{m}^3}) \cdot (0.3 \tfrac{\text{m}}{\text{sec}})^3 = 13.5 \tfrac{\text{Watts}}{\text{meter}^2}$$



https://www.eia.gov/energyexplained/index.php?page=hydropower_tidal

Kinetic Energy System Example

Determine the energy that could be generated annually by a kinetic energy system that utilizes two turbines, each with a blade radius of 4 meters, if the currents have an average velocity of 0.3 m/sec.

Additionally, if the turbines each have a 4 meter blade radius, then its blades will sweep a total cross-sectional area of:

$$A = 2 \cdot \pi \cdot r^2 = \pi \cdot (4)^2 = 100.6 \text{ meter}^2$$

Thus, the theoretical power available to the turbines is:

$$P = \left(\frac{P}{A}\right) \cdot A = (13.5 \tfrac{\text{W}}{\text{m}^{\text{s}}}) \cdot (100.6 \text{m}^2) = 1{,}358 \text{ Watts}$$

Kinetic Energy System Example

Determine the energy that could be generated annually by a kinetic energy system that utilizes two turbines, each with a blade radius of 4 meters, if the currents have an average velocity of 0.3 m/sec.

If the system runs 24 hours per day for a year, then:

$$\text{Energy} = P \cdot t = (1.358\text{kW}) \cdot (24\,\tfrac{\text{hours}}{\text{day}}) \cdot (365\,\tfrac{\text{days}}{\text{year}}) = 11{,}896\,\tfrac{\text{kWh}}{\text{year}}$$

Note that this assumes 100% of the available kinetic energy is converted to electricity.

If valued at $0.12/kWh, then:

$$11{,}896\,\tfrac{\text{kWh}}{\text{year}} \cdot 0.12\,\tfrac{\$}{\text{kWh}} = 1427.5\,\tfrac{\$}{\text{year}}$$

2MW OpenHydro tidal turbine installed in Canada in July 2018

https://marineenergy.biz/2018/07/26/eu-nods-yes-for-raz-blanchard-tidal-energy-demonstration/

Betz's Law

Betz's Law indicates the maximum power that can be extracted from Newtonian fluid* flow through a turbine, independent of the design of a turbine in open flow.

According to Betz's law, no turbine can capture more than 59.3% of the kinetic energy of water.

* – Both water and air can be considered Newtonian for practical calculations under ordinary conditions.

Betz's Law is typically accounted for by including a power coefficient, C_p, in the calculations, where C_p is the ratio of the captured power and the available power:

Modern large wind turbines achieve peak values for C_p in the range of 0.45 to 0.50

$$C_p = \frac{P_{captured}}{P_{available}}$$

$$C_{p,max} = \frac{16}{27} = 0.593$$

https://en.wikipedia.org/wiki/Betz%27s_law

Kinetic Energy System Revisited

Determine the energy that could be generated annually by a kinetic energy system that utilizes two turbines, each with a blade radius of 4 meters, if the currents have an average velocity of 0.3 m/sec.

If the turbines have a power coefficient of C_p = 0.45, then:

$$P_{captured} = \tfrac{1}{2} \cdot C_p \cdot \rho \cdot v^3 \cdot A = \tfrac{1}{2} \cdot (0.45) \cdot (1000\,\tfrac{\text{kg}}{\text{m}^3}) \cdot (0.3\,\tfrac{\text{m}}{\text{sec}})^3 \cdot (100.6\text{m}^2) = 611\text{ Watts}$$

$$\text{Energy} = P_{captured} \cdot t = (0.611\text{kW}) \cdot (24\,\tfrac{\text{hours}}{\text{day}}) \cdot (365\,\tfrac{\text{days}}{\text{year}}) = 5{,}350\,\tfrac{\text{kWh}}{\text{year}}$$

$$5{,}350\,\tfrac{\text{kWh}}{\text{year}} \cdot 0.12\,\tfrac{\$}{\text{kWh}} = 642\,\tfrac{\$}{\text{year}}$$

Since power ≡ velocity³, exposing the systems to stronger currents would greatly increase their energy production. Additionally, a tidal farm composed of *N* systems would produce *N*-times more energy.

Kinetic Energy Tidal Farm Example

What if a <u>tidal farm</u>, consisting of 24, 4-meter, dual-turbine systems (C_p = 0.45) is located further off the coast where the ocean currents have an average velocity of 1.5 m/sec?

$$P_{captured} = N \cdot \tfrac{1}{2} \cdot C_p \cdot \rho \cdot v^3 \cdot A$$
$$= (24) \cdot \tfrac{1}{2} \cdot (0.45) \cdot (1000\,\tfrac{\text{kg}}{\text{m}^3}) \cdot (1.5\,\tfrac{\text{m}}{\text{sec}})^3 \cdot (100.6\text{m}^2) = 1{,}833{,}000\text{ Watts}$$

$$\text{Energy} = P_{captured} \cdot t$$
$$= (1{,}833\text{kW}) \cdot (24\,\tfrac{\text{hours}}{\text{day}}) \cdot (365\,\tfrac{\text{days}}{\text{year}})$$
$$= 16{,}057{,}000\,\tfrac{\text{kWh}}{\text{year}}$$

$$16{,}057{,}000\,\tfrac{\text{kWh}}{\text{year}} \cdot 0.12\,\tfrac{\$}{\text{kWh}} = 1{,}927{,}000\,\tfrac{\$}{\text{year}}$$

http://www.esru.strath.ac.uk/EandE/Web_sites/13-14/Tidal/technologies.html