Background

Generating power is a long standing issue due to the disadvantages of many of the modern techniques that require large amounts of energy or fuel. Energy consumption and population are always increasing, so it is essential for engineers and scientists to come up with natural and affordable ways to produce power with minimal effect on the environment. One of these methods includes utilizing the physical properties of water and how it naturally acts in our environment. This is known as hydropower, or hydroelectric power, and is an environmentally friendly and efficient way to supply surrounding areas with power and electricity to live their daily lives.

Engineers have the ability to produce mechanisms or create environments that cause water to produce energy naturally, which can be transferred directly to an object to cause mechanical work. This work can be transferred into a generator to produce electricity. One way of producing this water energy is through use of a turbine. A turbine is a mechanism that accepts moving water, and contains a wheel or rotor that spins as the water impacts one of its blades. The faster the flow rate of water, the higher the frequency of the wheel or rotor. This rotation drives a shaft connected to the generator which ultimately produces power. There are often guide vanes or wicket gates that can control the flow of water impacting the blades and therefore output power, which ultimately controls the efficiency of the turbine.

Figure 1. Diagram of typical Kaplan turbine.
The most common and preferred type of turbine is the Francis turbine, invented by James Francis in Lowell, MA in 1848. (Hydroelectric, 2014) Francis turbines are used to generate about 60% of the global hydropower in the world, making them the most widely used type of turbine (Alstom). This type of turbine receives water at high pressure and causes the water exiting the turbine to leave at a much lower pressure. This change in momentum is transferred to the blades and causes the shaft to rotate at a much greater frequency. This causes the Francis turbine to be capable of much greater power output and therefore higher efficiency than other types of turbines as seen below in Chart 1.

![Chart 1. Turbine selection chart of typical turbine types.](http://example.com/chart.png)

*Figure from Heinzmann HydroTech Private Limited, India*

Turbines types are classified based on the mechanism by which water interacts with the turbine propeller. There are two general classes, either impulse or reaction. Reaction turbines are further classified as radial and mixed-flow turbines, or as axial-flow or propeller turbines. Francis turbines fall under the mixed-flow (reaction) category because they effectively alter the directional flow of the water from radial to axial (Hield).
The main components of a Francis Turbine are the runner, runner blades, guide/stay vanes, spiral casing, and draft tube. The runner blades are the component of the turbine which the water strikes. The impact force of the water on the blades causes rotation of the runner, which causes the shaft to rotate as well. The guide or stay vanes are fixed in place at the entrance, and control the angle of the flow of water towards the runner blades. They also cause the pressure energy created by the water to convert to kinetic energy and momentum and reduce whirling caused by water entering the turbine at high pressures. Since these guide vanes control the flow of water impacting the runner, they indirectly can affect the power production of the generator. This is important, since the power demand changes on a daily basis. The guide vanes can be controlled and synchronized as best as possible with the power demand in that local area. The runner itself is placed inside of the spiral casing, which allows the water that enters the runner region during the process to remain at a relatively constant velocity. This is achieved due to the decrease in spiral diameter as the fluid flows through. The water exits the turbine through the draft tube. This is one of the most crucial aspects of the Francis turbine when it comes to design. This is due to the possibility of cavitation, meaning the pressure drops so drastically that at the exit, the local pressure drops below the vapor pressure of water. This causes the water to boil and form bubbles, and after the water exits this region it rapidly increases in pressure and causes the bubbles to burst. This can cause severe damage to equipment or the environment, so is very crucial to avoid. The draft tube can prevent this from happening due to its very large increase in cross sectional area. The velocity decreases due to continuity, and all of the velocity head gets reduced. (How Does, 2014)

![Diagram of Francis Turbine Components](image)

**Figure 2.** Major Components of a Francis Turbine
Design Advantages

Selecting a turbine type for a particular application often depends on existing site characteristics. As shown previously in Chart 1, Francis turbines operate over the largest range for both flow and head parameters. Table 1 summarizes these and additional turbine design parameters for the three most common turbine types: Pelton, Francis, and Kaplan (Drtina & Sallaberger, Hield).

<table>
<thead>
<tr>
<th></th>
<th>Pelton Wheel</th>
<th>Francis Turbine</th>
<th>Kaplan Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating specific speed, $N_s$</td>
<td>0.5 - 20</td>
<td>15 - 85</td>
<td>65 - 185</td>
</tr>
<tr>
<td>Operating flow (m/s)</td>
<td>0.5 - 50</td>
<td>0.7 - 950</td>
<td>1.5 - 1000</td>
</tr>
<tr>
<td>Operating head (m)</td>
<td>100 - 1800</td>
<td>20 - 800</td>
<td>0 - 100</td>
</tr>
<tr>
<td>Maximum Power (MW)</td>
<td>300</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>Highest Efficiency (%)</td>
<td>93</td>
<td>94</td>
<td>94</td>
</tr>
</tbody>
</table>

All three types are capable of achieving >90% efficiency. However, the Francis turbine can produce 700 MW more power than a Pelton wheel and 800 MW more than a Kaplan turbine. In the past, Francis turbines have typically been used to generate moderate power outputs, ranging from 0.025 to 30 MW. Newer companies, such as Voith Hydro, have developed enhanced Francis turbines capable of achieving 1000 MW (Voith Hydro). This makes the Francis turbine an ideal choice in high energy demanding projects with low to medium head resources. Though Francis turbines are capable of achieving up to 94% efficiency, output performance depends highly upon percent of actual flow to design flow, illustrated in Chart 2 (Hield; Smith et al.).

![Chart 2. Francis Turbine Efficiency Curve](https://example.com/image.png)

*Graph from Smith et al., 2002*
As seen in Chart 2, Francis turbines achieve 90% efficiency at flows greater than or equal to 75% design flow, but performance drops drastically at flows below 40% design flow. Severe loss in efficiency at low flow can be attributed to low pressure in the draft tube. Average losses at ideal operating conditions are shown in Figure 2.

![Figure 2. Energy Losses in a Francis Turbine](image)

Displayed in Figure 2, gap and draft tube losses normally account for the smallest percent (0.3% each). Typically, largest energy losses occur in the runner and guide vanes. As velocity head decreases, these losses, as well as losses due to friction, remain relatively constant. Losses in the draft tube are more variable due to pressure decreases with low flow (Drtina & Sallabarger). Variability of losses with respect to total head is shown in Chart 3.
Even under low head conditions, the Francis turbine is able to operate at 93% efficiency. Minimal losses are achieved through careful design of turbine components. As seen in the top right image in Figure 3, depicted below, the spiral-casing tapers from a larger inlet diameter to a smaller diameter near the end. This maintains constant velocity to achieve optimum energy output. Stationary vanes are not adjustable, and are designed to steer the flow toward the runner. Guide vanes are the intermediate between the runner and spiral-casing, and are adjustable to a small degree. Guide vanes can be adjusted, depending on flow conditions to alter flow rate and maximize power output by achieving radial flow at the runner exit, as shown in the left image in Figure 3 (Hield; How Does, 2014).

![Chart 3. Variability of Losses with Head in a Francis Turbine](image1)

![Figure 3. Flow Path in a Francis Turbine](image2)
Case Studies

Three Gorges Dam

The Three Gorges Dam Project, as seen in Figure 4, is the world’s largest hydropower project, located on the Yangtze River in China. Three Gorges Dam Project Development Corporation (GTGPC), the legal entity who is in charge of financing the project, began construction in of a hydroelectric power plant in 1993. After 15 years, the dam was finally opened in 2008 (Tarantola, 2011).

The Three Gorges Reservoir has a total capacity of nearly 32,000,000 acre-ft, and the constructed concrete gravity dam has a length of 7,660ft with a height of 610ft. This massive project had a total construction cost of around $26 billion.

Three Gorges Dam includes a total of 32 Francis turbines, each with the ability to produce 700MW of power. These turbines are massive, as seen in Figure 5, each with a diameter of 32ft and a weight of about 6,000 tons. The blades of the turbines spin at 75 revolutions every minute, passing between 21,000cfs and 34,000cfs of water. The efficiency of each turbine is roughly 95%. Altogether, the Three Gorges Dam has a hydroelectric generator capacity of 18,300MW.

Brazil’s Itaipu Dam, the next largest dam in the world, only produces 12,600MW in comparison (Three Gorges, 2014).

The Three Gorges Dam was designed to provide many benefits to this region of China. Beyond having the ability to generate nearly 10% of current Chinese power requirements, the dam also has the ability to control flooding along the river, something that has been a giant problem for the area in the past. Navigability improvements have also been seen, which has aided in China’s domestic and export trade. Finally, support for the project includes emissions reduction, which limits the soaring Chinese emissions that cause acid rain.

Although there are some tremendous benefits that Three Gorges Dam provides, there are also some problematic issues that have led some to consider the project a detriment to society. The
dam has led to a sharp decrease in water quality of the river, which as a result, has impacted wildlife and biodiversity of the area. This problem is not limited to Three Gorges, but many large dams across the world. In addition to this, some actually feel that there has been even more flooding now than there ever was before the dam was constructed. Finally, construction of the dam also forced nearly 1.25 million people to leave their homes and relocate (Tarantola, 2011).

**Grand Coulee Dam**

![Figure 6. The Grand Coulee Dam](image)

The Grand Coulee Dam project, as seen in Figure 6, is the largest power plant in the United States, located in the state of Washington on the Columbia River. The owner of the project is the U.S. Bureau of Reclamation and construction began in 1933 as part of President Roosevelt’s New Deal Public Works Administration.

The dam originally began with a right powerhouse, but today the dam includes the Right Powerhouse, Left Powerhouse, and the Third Power Plant. The reservoir has a total capacity of about 9,600,000 acre-feet while the concrete gravity dam is roughly 550ft high and has a length of nearly 5,230ft. The total cost of the project has equated to about $7.5 billion in today’s dollar (Grand Coulee, 2012).

The Grand Coulee Dam includes 33 turbines, 27 of which are Francis turbines, as seen in Figure 7. The Right Powerhouse includes nine 125 MW Francis turbines, the Left Powerhouse includes three 10 MW and nine 125 MW Francis turbines, and the Third Power Plant includes three 690MW and three 805 MW Francis turbines. The Third Power Plant was the most recent component of the dam project to be completed, so it makes sense that the higher capacity turbines are located there. The Grand Coulee Dam produces nearly 21.6 billion GWH every year.

![Figure 7. Francis Inlet Scroll (Grand Coulee Project)](image)

As a result of the Grand Coulee Dam project, there were many benefits to the United States. The project began during the Great Depression, a time when many people were out of work. This
project, although it was met with large amounts of controversy, was able to create new jobs. In addition, farming opportunities were expanded and electricity was produced at a low cost.

Today, there has been discussion about rehabilitation to the six Francis turbines in the Third Power Plant, including the potential of uprating three of them. The purpose of this rehabilitation is to ensure reliable operations of the turbines in the future, as the six units are reaching the end of their design life. The Bureau of Reclamation has scheduled that the overhaul of three of the units will be completed by September 2017, while the remaining three units will be overhauled by December 2022. Once the needed rehabilitation is completed, the plant will be able to operate for the next 40 years (Vick, 2013).

**Glen Canyon Dam**

The Glen Canyon Dam project, as seen in Figure 8, is located along the Colorado River in Arizona, California. Owner of the project is U.S. Bureau of Reclamation; the project began mid 1950’s. After nearly 10 years of construction, the dam was completed in 1966. The dam’s reservoir is called Lake Powell and is the second largest artificial lake in the country.

Lake Powell has a total capacity of roughly 26,000,000 acre-feet, and the associated concrete gravity dam has a height of 726ft, second only to the Hoover Dam. This large project had a total construction cost of roughly $980 million in today’s dollars.

Glen Canyon Dam is made up of eight Francis turbines, five of which are 165 MW turbines and three that are 157 MW turbines. In total, the power station has an ability to generate roughly 3.50 billion KWH each year. a tremendous amount.

With such a large capacity of water, Lake Powell serves as a “bank account” of water during times of drought, which has a significant helps cities, industries, and agriculture in the West meet their needs. In addition, Lake Powell is a giant recreational attraction and nearly 2 million people visit the Glen Canyon National Recreation Area every year (Glen Canyon, 2014).

Although there are many benefits to areas around the Glen Canyon Dam, this project has been met with controversy. Controversy first began when the dam nearly collapsed due to giant floods in 1983 that caused Lake Powell to reach its highest recorded water level in history. Massive damage due to cavitation was a result of this. Although the concrete damages were repaired and reinforced, the public image of the dam dropped significantly. In addition to this, there are large water losses each year due to evaporation and seepage because the Glen Canyon Dam is located in a desert. This has upset environmentalists and an ongoing battle to keep or remove the dam continues today.
References: Unknown Author


References: Known Author


