American University of Beirut

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ENST 300

Project on Clean Coal Technologies

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Abstract:

In this paper, the feasibility of coal power plants is tackled from several perspectives, including environmental, economic, and regional standpoints. It provides a detailed study on the history and composition of coal and the negative impacts caused by its use in power generation. The thermodynamic cycles used to generate power using coal are explained, along with their expected thermal efficiencies. The innovations to enhance their efficiencies are displayed, with their advantages and disadvantages. The methods of inhibiting carbon dioxide and other toxins from being released into the atmosphere have been explained in detail with a thorough explanation of carbon capture and storage types. A comparison between coal power generation and some renewable energy systems from an economic and environmental view is presented. The paper concludes that coal power generation use should be limited to coal power plants incorporating carbon capture and storage with the utilization of the stored carbon dioxide in industrial usage. Otherwise, it is recommended to use renewable energy technologies to generate power due to the cheaper cost and near zero carbon dioxide emissions.

Introduction:

History of Coal:

Coal has been used as a fuel for multiple millennia; however, it wasn't fully utilized until the start of the industrial revolution at the start of the 19th century due to the invention of the steam engine. The increase in the consumption of coal led to a significant increase in its supply as a primary energy source for the production of electricity; this can be seen in Figure 1.[1]

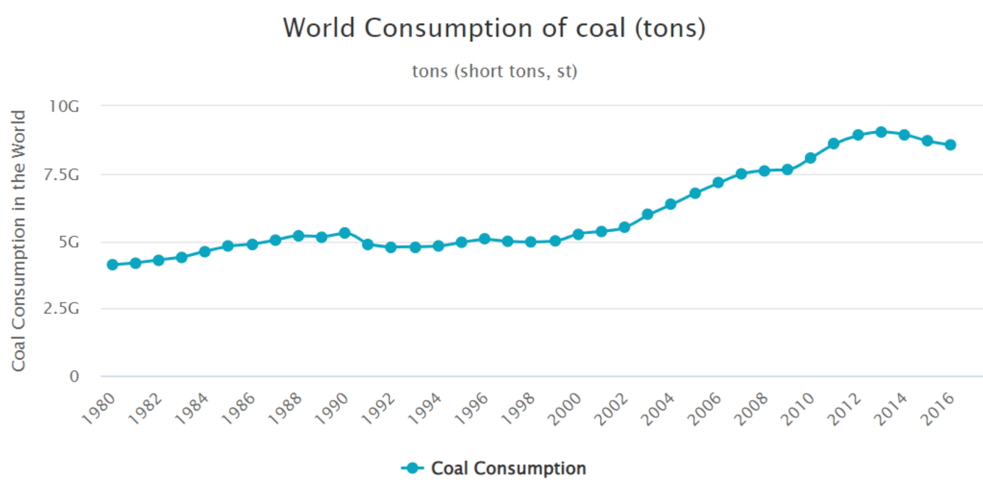

Figure 1: Coal Consumption per Year. [35]

Coal Composition and Formation:

Coal is formed of several elements mainly Carbon, hydrogen, sulfur, oxygen, and nitrogen.[2] Coal is originally produced when dead plant matter decomposes into turf, also known as peat, it is then transformed into coal by thermal energy and high pressure due to the geological forces in the Earth's crust. This process takes place over millions of years.[3]

Coal is classified into different types depending on the amount of energy that it possesses. Anthracite is considered to have the highest carbon content among the different types of coal, thus the highest energy output due to combustion. It is followed by Bituminous, sub-bituminous, and lignite, as observed in Figure 2.[4]

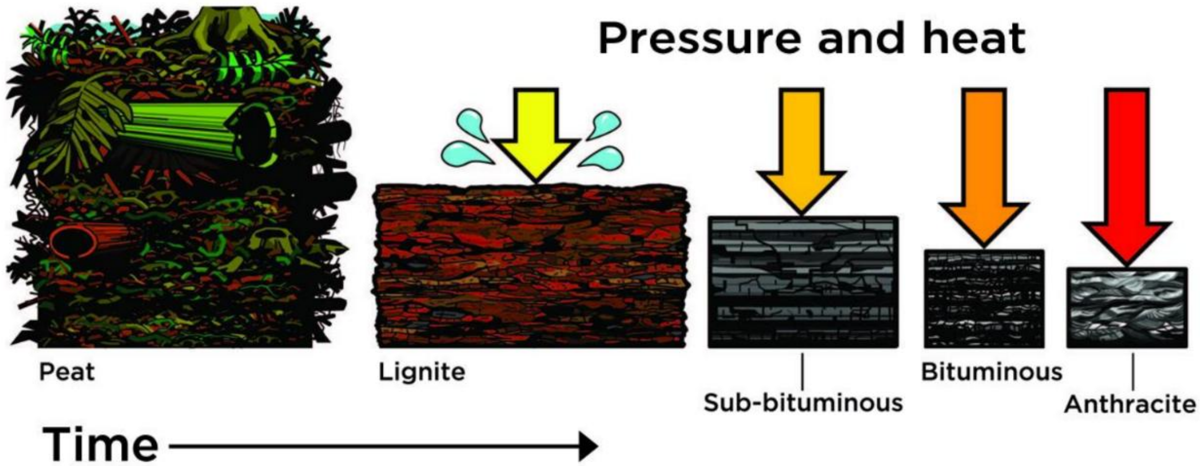

Figure 2: Coal Formation. [3]

Availability and Consumption of Coal:

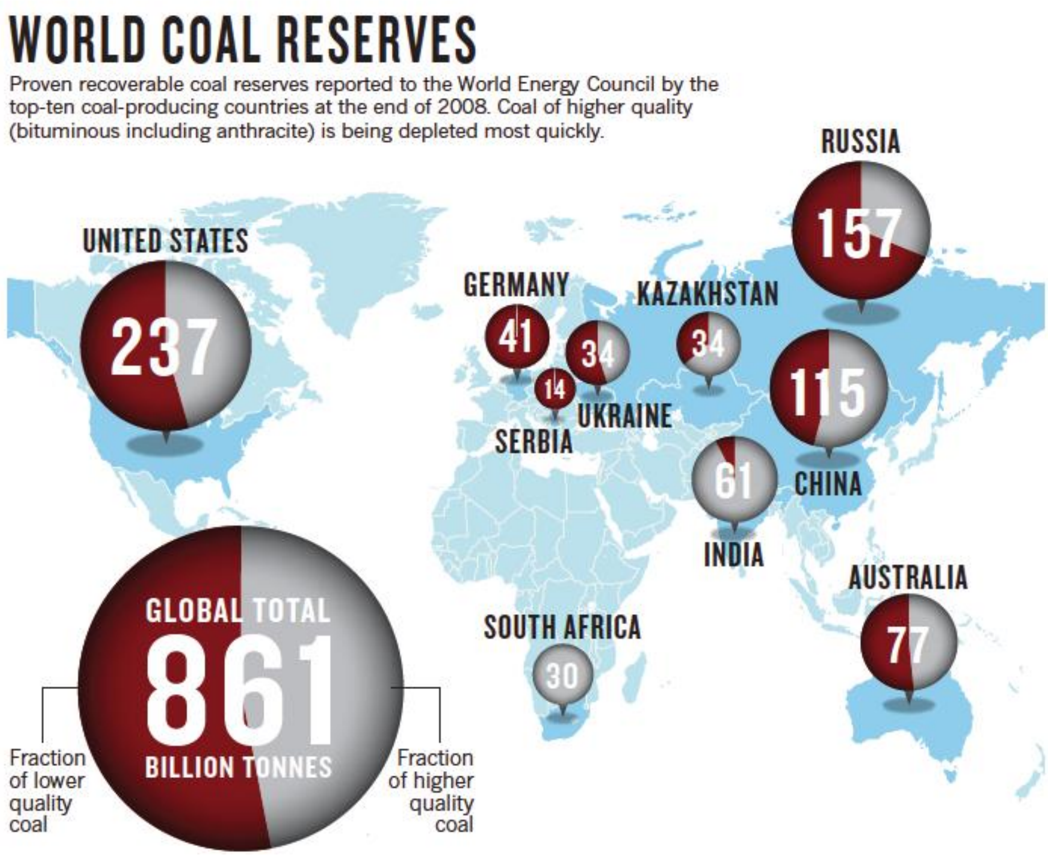

Figure 3: World Coal Reserves. [4]

Coal is considered one of the most abundant fossil fuels, with more than one trillion tons of reserves equivalent to over 5 trillion barrels of oil equivalent and a consumption of 8.5 billion tons only. This results in enough reserves of coal allowing it to last approximately 133 years if consumption of coal continues at its current pace.[5]

In Figure 3, we can observe the distribution of the countries with the highest coal reserves, with the United States reporting the highest reserves, followed by Russia and then China. China as a country rich with coal reserves consumes more than 50% of the total yearly world share.[6]

Carbon Dioxide and Green House Gases:

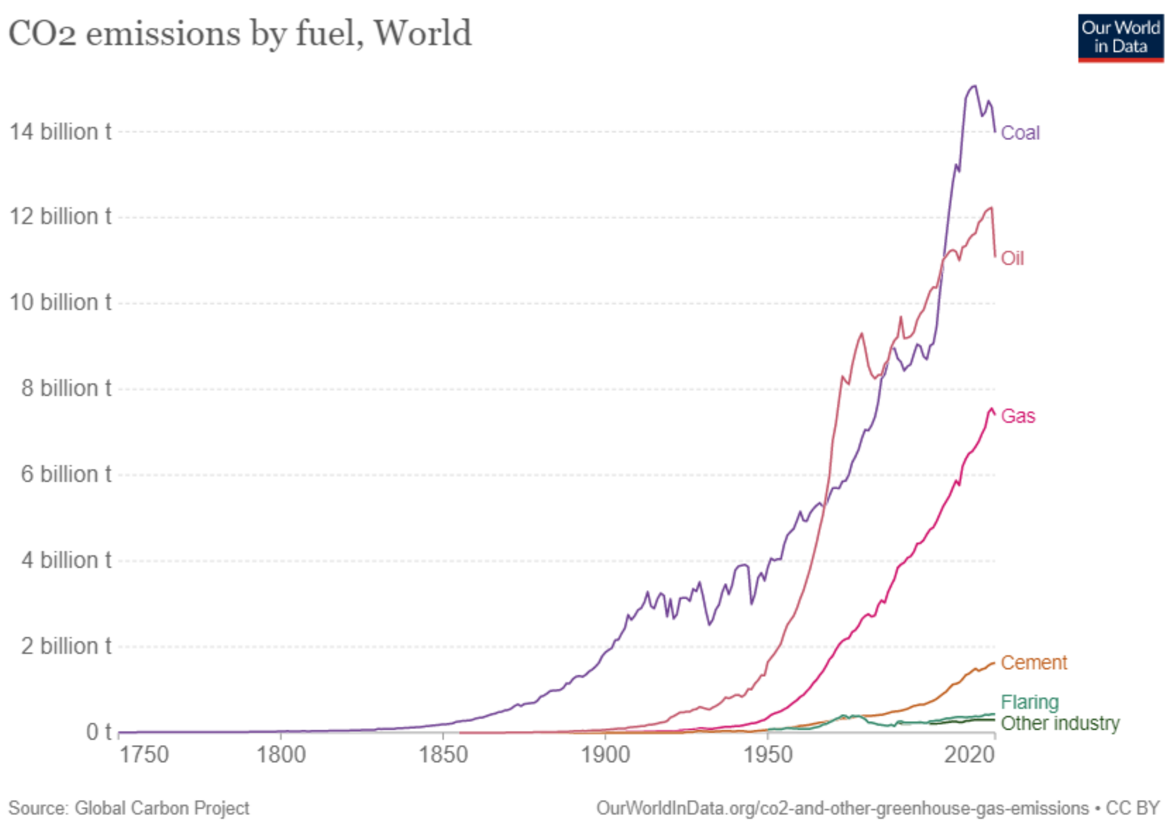

Figure 4: CO2 Emissions by Fuel per Year. [36]

The problem with using coal is the effect it has on the environment. Coal worsens air pollution, water pollution, and global warming; it emits the highest amount of CO_2 compared to all other energy sources as seen in Figure 4 . Once the coal is released into the air, a number of toxins are released with it including mercury, lead, sulfur, particulates such as ashes, and many other heavy metals. These toxins impact the health of people causing some to suffer from asthma, breathing difficulties, brain damage, cancer, and premature death. It also pollutes water significantly; when charcoal is burnt, ash is produced making coal power plants produce more than 100 million tons of coal ash per year. More than half of it is thrown into lakes, ponds, and landfills contaminating water sources and draining the rocks from acid. As for global warming, the carbon emissions, resulting from coal burning, are released into the atmosphere creating a layer around it that can lead to drought, sea level rise, flooding, and extreme weather conditions.[7] Coal power plants have been even classified as the largest contributor to the increase in greenhouse gas emissions, as well as carbon dioxide emissions in 2018 [9]. Coal electricity generation has been the cause of 30% of CO_2 emissions in 2018. [9] As seen by the figure above, coal is the biggest contributor of CO_2 emissions compared to all other fuels used.

The United Nations have taken important measures to prevent extreme climate change by dedicating the 13th sustainable development goal to taking "urgent action to combat climate change and its impacts". The Race to Zero campaign was launched with the goal of forming a coalition to projects for net-zero carbon emission, and to establish clime change goals for around 20 sectors of the global economy. This has led to the rise of "net zero by 2050" targets for multiple countries that cover over half of the world's population. [44]

The concept of carbon taxes has also been introduced by many governments worldwide. This concept entails the government setting a price that carbon emitters must pay per every ton of greenhouse gas emissions they emit. This will encourage producers and consumers to act towards reducing their emissions, such as switching to cleaner fuels or adopting and researching new technologies. Implementing such changes in their production procedure will help them avoid paying the tax, while simultaneously decreasing their carbon emissions.

Dirty power sources, mainly coal, lead to almost 465,000 deaths every year. This fatal effect can be reduced with the help of mandatory "scrubbers", removing air toxins from the power plant; however, this requires an additional cost.[23]

To tackle these environmental consequences of coal burning without replacing coal as a fossil fuel, many methods and techniques have been developed in the past decades; they are known as clean coal technologies (CCT).

Body:

Operation of Coal Power Plants:

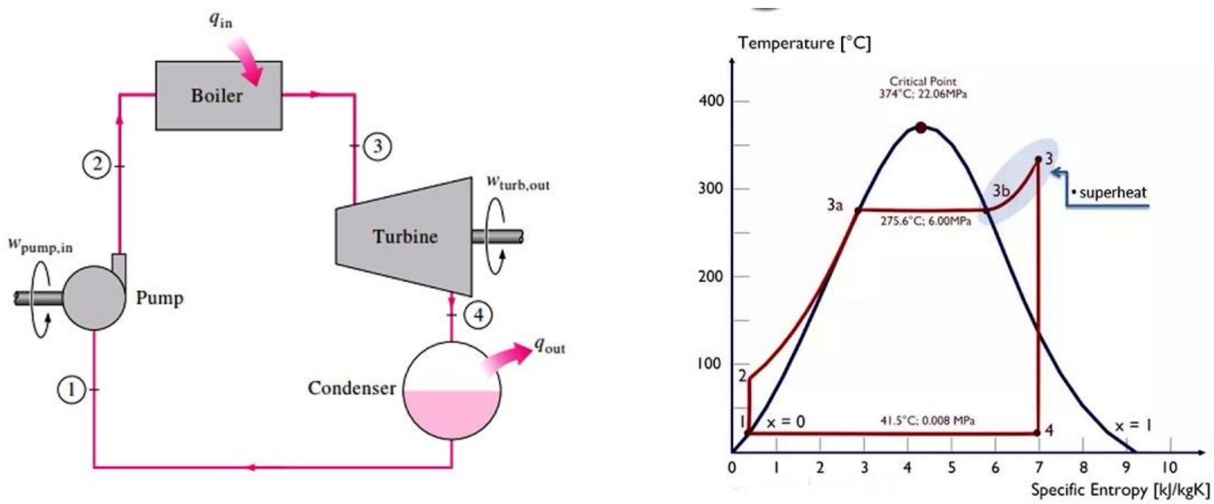

Figure 5: The Rankine Cycle. [8]

Thermal coal, used in power plants to generate electricity, is used to produce very high temperatures. This high temperature is needed for the Rankine cycle used to produce electric power, as observed in the T-s diagram in Figure 5. This cycle has four main components: a turbine, condenser, pump, and boiler. Water is present in the cycle throughout all stages. First, water is pumped into the boiler, where it is heated by an external source, reaching very high temperatures, and transforming the water into steam which then passes into the turbine that turns the generator, where the mechanical energy produced is converted to electrical energy. This reduces the temperature and pressure of the water that now needs to be condensed to repeat the cycle again.

In our case, coal is burned in the furnace and the heat produced is used to boil the water. Coal has a high concentration of carbon, hence its combustion releases high amounts of energy according to the following chemical equation.

$$C + O_2 \rightarrow CO_2 \quad (1)$$

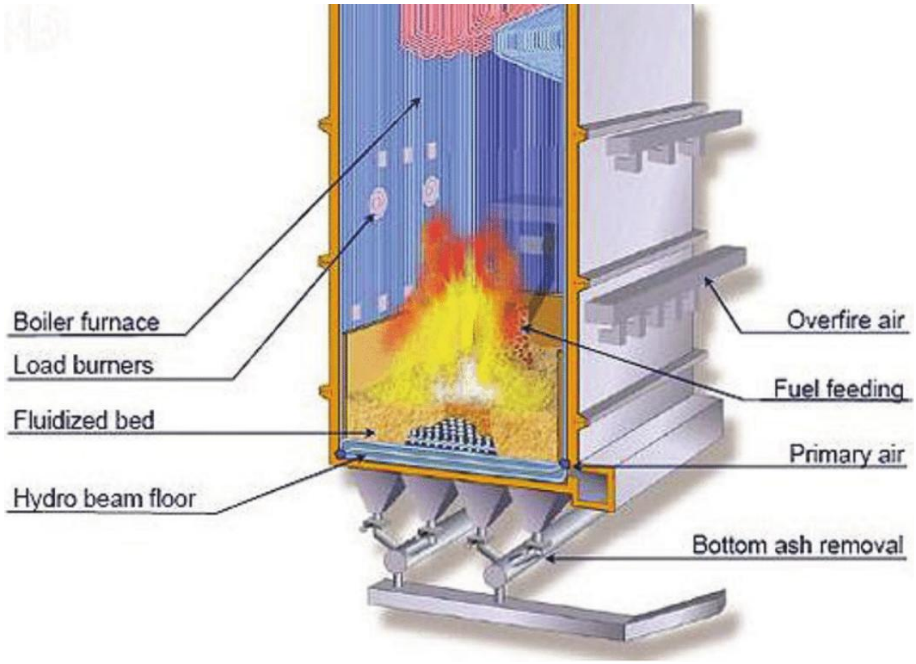

Figure 6: The Standard Coal Furnace. [10]

The typical coal furnace consists of the different components shown in Figure 6, water running through the tubes passes through the fire and rises in temperature rapidly. After the burning of the coal, the remaining ash is collected and removed from the bottom of the furnace. There are two methods of ash removal at the bottom of the furnace: dry bottom boiler and wet bottom boiler.[11] A sufficient supply of air is also needed to have enough oxygen for the combustion process.

The thermodynamic efficiency of the Rankine cycle ranges from 25 to 50% depending on several factors including the age of the power plant, the turbine power, and the pre-combustion treatment of coal. The thermodynamic efficiency is equal to the amount of energy the system outputs divided by the amount of energy input into the system. [12] As shown in equation (2).

$$\eta = \frac{W_{out}}{W_{in}} = \frac{W_{turbine} - W_{pump}}{Q_{in}} \quad (2)$$

The work we obtain from the turbine and the work used up by the pump can be calculated by the equations (3) and (4):

$$W_{turbine} = \dot{m}(h_3 - h_4) \quad (3)$$

$$W_{pump} = \dot{m}(h_1 - h_2) \quad (4)$$

Where:

h is the enthalpy of the steam or water and can be thought of as its internal energy for simplicity. $\dot{m}$ is the mass flow rate of steam or water in the system.

The W_{net} can also be represented by the area enclosed in T-s diagram if this area increases the net-work increases.

The temperature of the water or steam at states 1, 2, 3, and 4 are integral to obtaining energy and consume less energy in each cycle since the enthalpy h at a certain state is proportional to the temperature at that state. Therefore, if we can obtain higher temperatures of steam coming out of the boiler (state 4), we can produce more energy from each cycle; however, the power plant has limitations preventing this, such as the price of material capable of withstanding such high temperature, the amount of air, hence oxygen, introduced into the burning chamber, etc... Many power plants use compressors to push air into the burning chamber to increase the amount of heat input in the boiler, thus increasing the temperatures at state 3.

Integrated Gasification Combined Cycle:

More efficient cycles have been developed to increase the thermal efficiency of the coal power plant. One of those cycles is the integrated gasification combined cycle (IGCC), shown in Figure 7. Unlike the traditional ranking cycle, this cycle gasifies coal to produce syngas, which is a mixture of Hydrogen and Carbon Monoxide.[13] The syngas is burned, and the products of the combustion are passed into a gas turbine, thus generating electricity. A heat recovery steam generator is used at the exhaust of the gas turbine to raise the temperature of the steam being fed to the steam turbine, thus generating more electricity due to the higher steam temperature. This method increases the overall thermal efficiency of the power plant to 48%. [15]

This increase in thermal efficiency is due to the combined power generation of the Rankine cycle and the Brayton cycle, shown in Figures 7 and 8; this combination makes use of the lost energy in the condenser of the Brayton cycle and used as the energy input for the boiler in the Rankine cycle, rather than the conventional coal-powered thermal generation that is composed of the Rankine cycle only.[15]

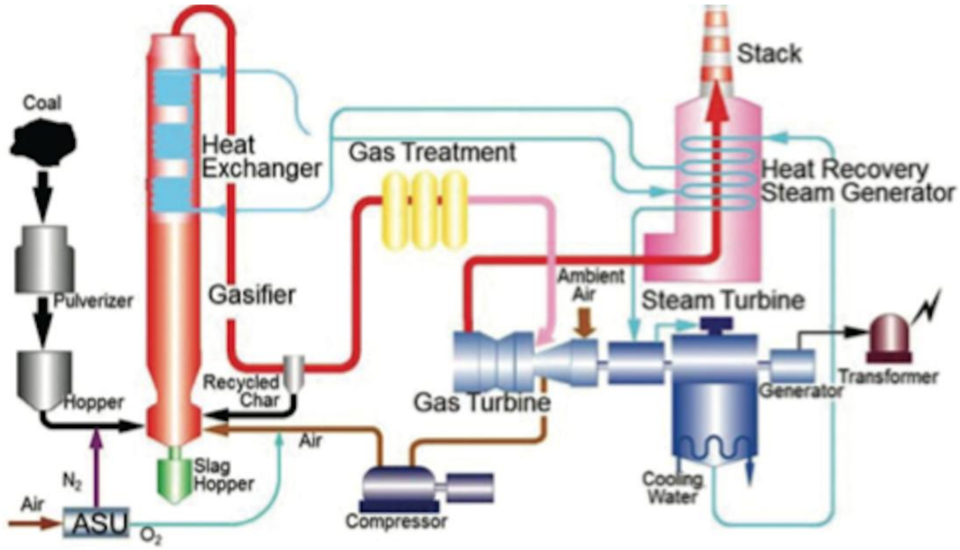

Figure 7: Integrated Gasification Combined Cycle (IGCC). [14]

The gasification process consists of several procedures. First, the coal is fed into the gasifier using air as a gasification agent. Then, desulfurization and dedusting treatment take place in the gas clean-up unit. Afterward, the clean gas is inputted into the gas turbine combined cycle. Gasification aided by air results in less power consumption that is needed for oxygen production resulting in higher net thermal efficiencies. This process produces syngas, which is much cleaner than coal due to the removal of sulfur and dust from it. [15]

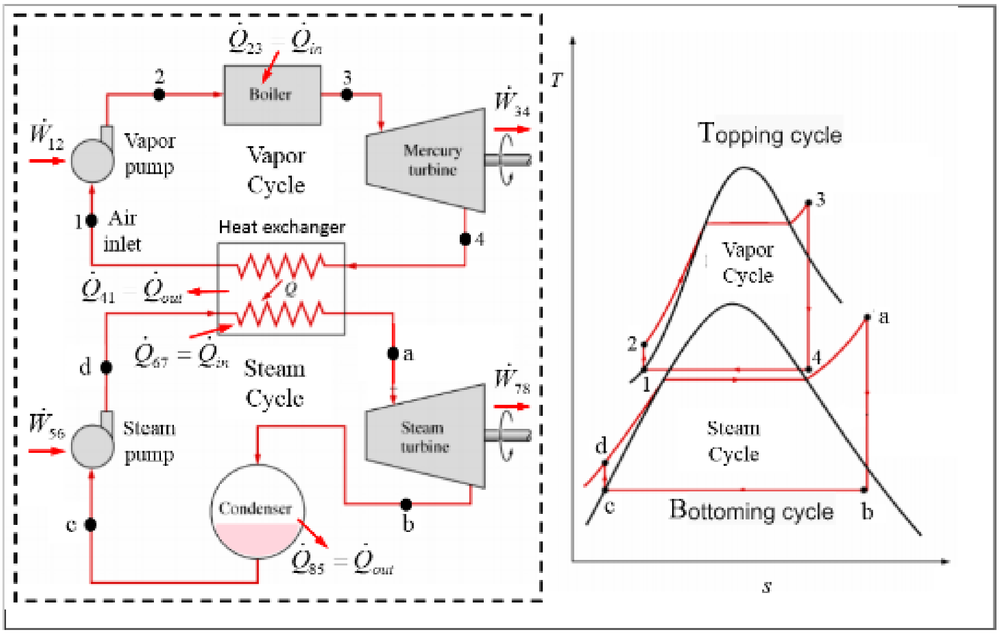

Figure 8: Combined Brayton-Rankine Cycle. [37]

Although IGCC's thermal efficiency is higher than that of a typical coal power plant Rankine cycle, it is approximately 35% more expensive. The addition of the carbon capture and storage (CCS) technology, which is not initially integrated into it, adds to its cost. Studies show that at least $ 20 billion have been invested in IGCC projects in the USA in the previous decade. This resulted in one IGCC power plant facing technical issues and the anticipation of another one opening after many years due to cost overruns and delays. Furthermore, an IGCC coal power plant costs around 4.4 billion $ per gigawatt of the capacity of build, according to the US Energy Information Administration.[16]

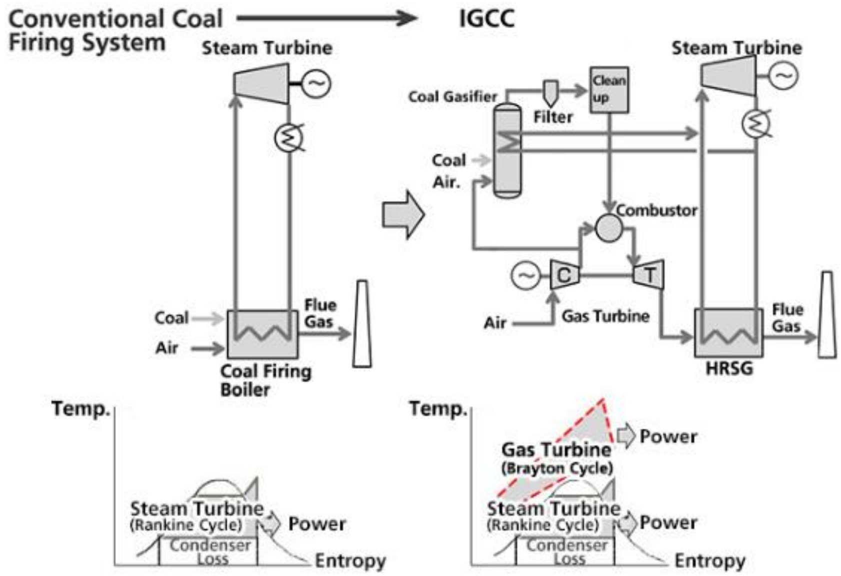

Figure 9: T-s diagrams of IGCC power plant. [15]

From an environmental perspective, conventional coal produces twice the amount of carbon that IGCC stations do and is almost ten times more polluting than renewable energy sources such as wind and solar energy. This reduces coal's emissions by a decent but not sufficient amount of 20% considering how much it costs.[17]

Regeneration methods:

Waste heat and water recovery technology were enhanced where a portion of water vapor and its latent heat from flue gases, also known as exhaust gases, was based on a nanoporous ceramic membrane capillary condensation separation mechanism. It consists of a 2-stage design specifically for coal power plant flue gas application. This recovered water can be used to replace the boiler of the power plant and increase its efficiency. In coal power plants, water vapor exits with flue gases at a volume of 12-16% which is lost into the atmosphere. If we can recover about 40-60% of this water vapor with its latent heat, the thermal efficiency of the process can increase to more than 5%. Levy et al. designed a pilot scale water recovery system for boiler gas based on multiple condensing heat exchangers where the results showed that the flue gas can be cooled to below 40 $°C$ and water capture efficiencies are 10-35% by using makeup water and combustion air as cooling sources.[18]

In order to achieve this water recovery process, we need a special anti-corrosion tubing material for the condensing heat exchanger. Copen on the other hand designed a Water Extraction from Turbine Exhaust (WETEX) that can remove up to 23-63% of the water vapor from the flue gas by volume. However, it is a very costly process. The new technology is based on a nanoporous ceramic separation membrane to extract a portion of the recovered water and its heat returning it to the steam cycle. This water vapor passes through the membrane and then condenses in direct contact with low-temperature water. Contaminants such as CO2, O2, NOx, and SO2 are inhibited from passing due to the high selectivity of the membrane. [18]

Since water is high in energy state (vapor state) its recovery from high moisture elevated temperature waste streams is energy efficient. This energy can be recovered with the liquid water increasing the efficiency of the system.[18]

The process shown in Figure 10, operates as follows: the water vapor from the flue gas is transported through the membrane structure by condensing inside the inner membrane layer through the substrate. This condensed water along with its latent heat combines with cold boiler makeup water raising its temperature before entering the boiler feed water tank. There is a small vacuum layer that is maintained on the waterside to prevent the backflow of water.[18]

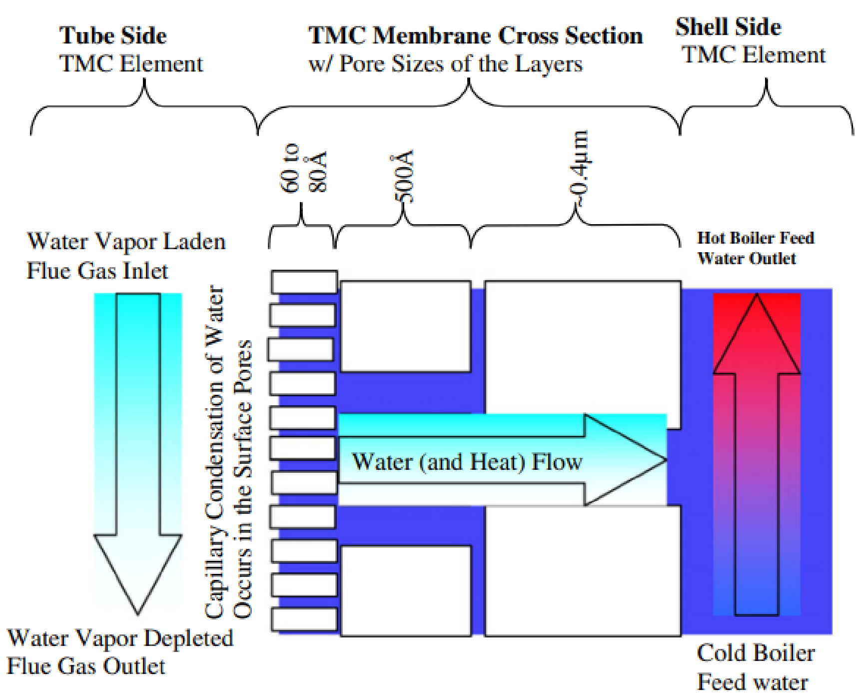

Figure 10: Capillary Condensation of Water. [18]

This recovered water and its heat can be used to replace power plant boiler makeup water. It will be beneficial to coal-powered plants that use high moisture flue gas to recover their water vapor increasing the boilers' efficiency and decreasing their water consumption.[18]

Removing Pollutants:

Coal power plants produce many solid wastes and uncontrolled ash disposal that leads to environmental contamination due to the major and trace elements (Al, Fe, Ca, Mg, As, Cd, etc.). In general, coal has a high concentration of trace elements so, during combustion, ashes enriched 3 to 10 times with trace elements are produced. The major components in coal ashes are silica, alumina, ferric oxide, and calcium oxide. These elements are not released during combustion since the same concentration of them is present in both ash and original coal. The trace elements are easily filtered from acid ashes, leading to soil pollution and consequent groundwater contamination. [19]

Arsenic, a chemical compound associated with sulfur, is released from the structure of coal, and tends to be adsorbed into the small ash particles, increasing its availability from 25% in coal to 70% in ash. The results showed that all the traces of these elements tend to enhance their concentration in the same sequence. A lot of toxic metals were associated with coal combustion by-products, the most concerning ones are Molybdenum and Arsenic. Metal polluted soils lead to human and animal contamination through plants which is very harmful.[19]

Due to this problem, new methods for cleaning coal need to be investigated. One of these methods is carbon capture and separation. Multiple methods exist for capturing carbon dioxide from gas streams; however, these methods have not yet been used on the scale needed for coal-burning power plants. Previously, the main goal of this technique was to obtain CO_2 for industrial use rather than reducing its emission. Capturing CO_2 from the exhaust of coal power plants requires a lot more difficult and energy-consuming than that from natural gas. Nowadays, this process consumes 20 to 25% of the enhanced powerplant's energy output, reducing the plant's thermal efficiency significantly. [20]

The process of coal CCS starts by burning the coal and having it in powdered form, it is then mixed with pure oxygen that ignites the mixture, making CO_2 the main constituent of the exhaust gases and everything else being soot, which we also don't want to release into the atmosphere. Thus, this exhaust mixture is stored underground or in other storage systems; however, these systems are very expensive and dangerous, since if this mixture leaks it could suffocate people. This can be more economical if we use this stored mixture in industrial applications. [21]

Other ways of capturing CO_2 exist, such as mixing the exhaust gases with Monoethanolamide, shown in Figure 11. This compound reacts with CO_2 and the liquid mixture allows the storage and pumping of CO_2 underground [22]. The chemical equation of carbon capture using this method is shown below:

$$CO_2 + 2RNH_2 \rightarrow \mathrm{RNHCOO^-} + RNH_3^+ \quad (5)$$

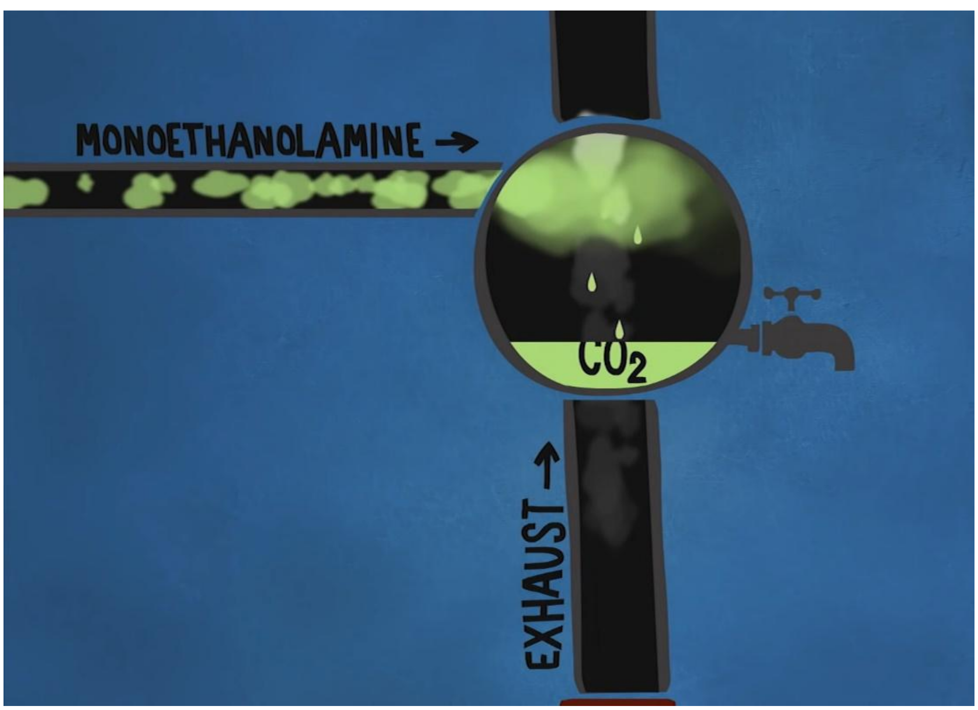

Figure 11: CO2 capture using Monoethanolamide. [22]

Methods of Storing CO2:

CO_2 can be stored underground in the form of supercritical fluid: at a temperature (31.1 $°C$) and pressure (72.9 atm), which characterizes the critical point of CO_2. At these special conditions, CO_2 is in an unsaturated form, where it acts as dense as a liquid and as viscous as a gas. The most important advantage of storing CO_2 in this form is that it decreases the required volume needed to store it compared to that needed at its normal state. As we go deep into the earth's crust, temperature and pressure of fluids increase, where at a depth below 800 meters the expected temperature and pressure are higher than that needed for CO_2 to maintain a supercritical state.[42]

In order to ensure that the CO_2 stays in the position where it was injected, four mechanisms are described.[42]

1. Structural trapping: traps the largest amount of CO_2 in rocks physically. The layers of the rocks above and below the CO_2 storage formation acts as seals which prevents the CO_2 from exiting out of the storage formation. However, the CO_2 can be more buoyant that other liquids in the space, so it can move upwards through the porous rocks until it hits the layer of seal rocks.[42]

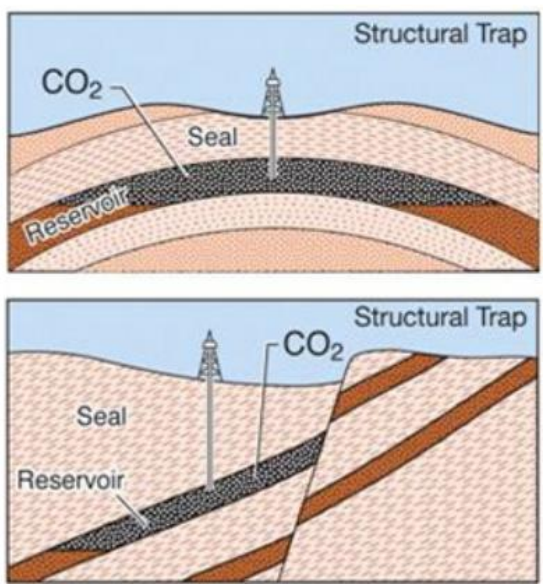

Figure 12: Structural trapping of Co2. [42]

2. Residual trapping: this trapping occurs where the remaining trapped CO_2 in the pores between rock grains stays trapped between these grains as the CO_2 plume moves through the

rocks. While the CO_2 propagates, some of it might be left behind as residual in the pore spaces, which are essentially motionless.[42]

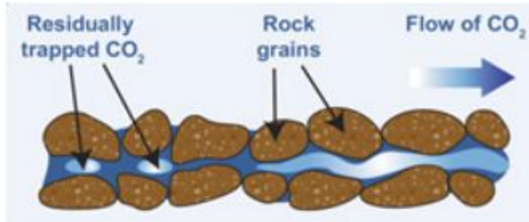

Figure 13: Residual Trapping of CO2. [42]

3. Solubility trapping: in this form of trapping, injected CO_2 will be absorbed into the brine water between the pores within the rocks as shown in the below figure. The rest of particles of CO_2 react with hydrogen forming HCO_3^-. [42]

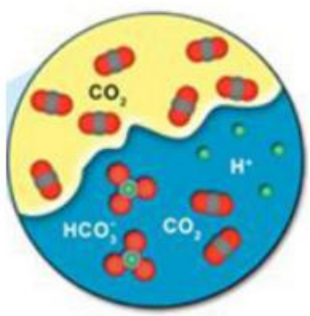

Figure 14: Solubility Trapping of CO2. [42]

4. Mineral Trapping: it occurs when the CO_2 dissolved in the rocks' brine water reacts with the minerals found in these rocks. Upon the dissolvement of CO_2 in water, it produces a weak carbonic acid H_2CO_3 and eventually bicarbonate HCO_3^-. With time, this carbonic acid reacts with the minerals in the rocks, leading to the formation of solid carbonate minerals that will ensure the trapping and storage of the injected CO_2. The magnesium in the rock reacts with CO_3 found in the water to produce $MgCO_3$ on the surface.[42]

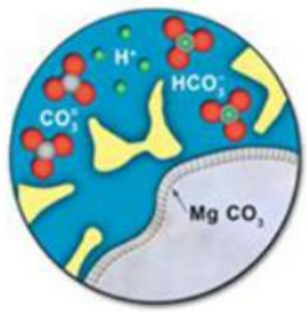

Figure 15: Mineral Trapping of CO2. [42]

Sulfur Removal:

Sulfur present in coal turns into sulfur dioxide after combustion. Sulfur dioxide in the atmosphere reacts with water vapor, as shown in the chemical equation below, to produce acid rain, which harms crops, animals, and sedimentary rocks. Sulfur extraction from coal can be achieved by three methods: physical, chemical, and biological. However, the most cost-effective method is the physical method, which can remove phytic sulfur; but it fails to remove organic sulfur. Chemical methods, on the other hand, ensure the extraction of both organic and inorganic sulfur. Another method to extract sulfur is by powderizing coal and running water over it to get rid of all the sulfur. Sulfuric water, obtained from this procedure, will be treated separately; hence, the left over powderized coal can be burned without any sulfur leaking into the atmosphere.[43]

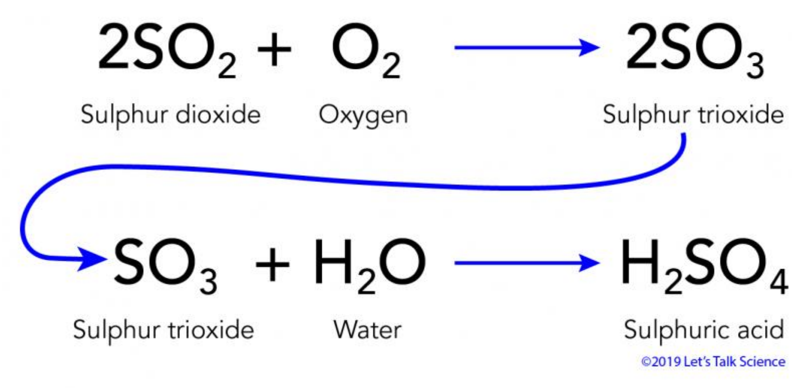

Figure 16: Sulfur to Sulfuric Acid Chemical Equations. [38]

Coal vs Renewable Energies:

Due to decades of research and technological advancements, the thermal efficiency of coal power plants has increased from 30% to almost 50%. This has also reduced the CO_2 emissions of such plants by 40%.[23] Coal power generation is cleaner than ever. NETL's research study has indicated that recent coal power plants with pollution controls decreases nitrogen oxides emissions by 83%, sulfur dioxide emissions by 98%, particulate matter emissions by 99.8% compared ones without pollution controls.[26]

Although this is significant, it is still not sufficient for coal to compete with renewable energies that emit 30 times less CO_2, such as wind and hydropower, and others that emit 20 times less, like solar and geothermal energy. Even among fossil fuels, coal still emits double the amount of CO_2 emitted by natural gas. [23]

A recent research study, done in 2022, calculated the optimal cost of substituting coal with renewable energies, incorporating the social implications that will be caused by this transition. The estimate of replacing all coal power plants with renewable energy sources is a net gain of almost $ 78 trillion by 2100. This amount is equivalent to four-fifths of the global gross domestic product (GDP) today.[24]

In order to have an estimate for the number of avoided emissions, the research group relied on a dataset produced by "Asset Resolution", including companies' previous and expected global coal production.[24]

The cost of switching to renewable energy includes the capital spending for new energy generation equivalent to that which will be lost from coal power plants. In addition, the compensation due to lost earning by coal companies forced to close because of the switch shall be considered. However, the estimate obtained will not include compensation for affected workers. [24]

In order to achieve this, we start by approximating the reduction in emissions by removing coal, and by setting a carbon price for those emissions. Other assumptions are made in the study, keeping in mind that they are conservative assumptions to avoid overshooting the estimate, considering the multiple decades of uncertainty included.[24]

The study yielded to the limiting of the global temperature increase to 1.5 °. It also found that the global cost of eradicating coal power generation is about $29 trillion; this cost is distributed globally in Figure 17. This requires a lot of funding from private sectors, since no government will be capable of affording such huge costs.[24]

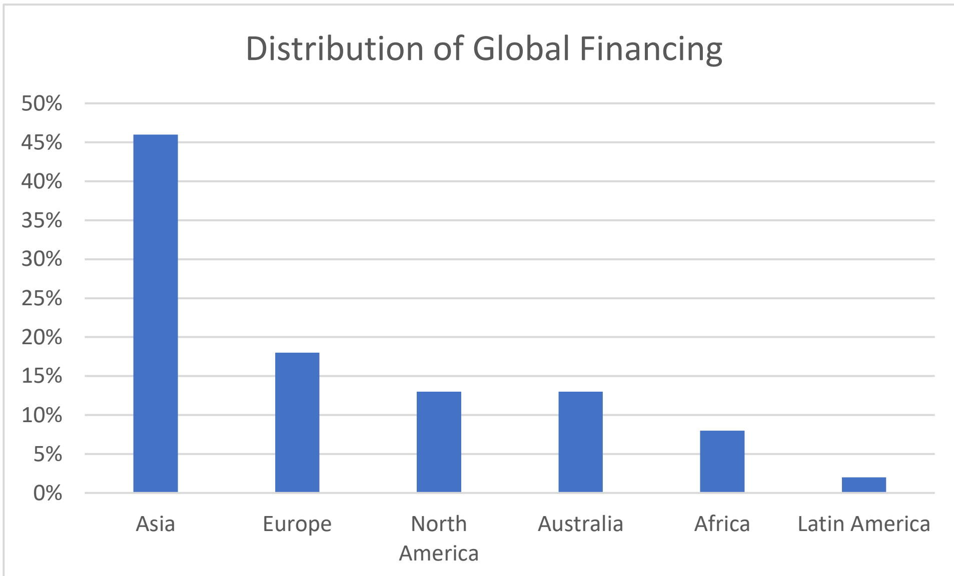

Figure 17: Global Distribution of Percentage Cost for Eliminating Coal Power Generation. [24]

Another study has shown the switch from coal to renewable energy has plunged by 99% since 2010 compared to the transition of coal to natural gas.[25]

This study encourages switching from coal to clean-renewable energy than to natural gas, since the CO_2 cost will be much lower. This is shown in Table 1.[25]

Region	Coal to Gas ($/tCO2)	Coal to Clean ($/tCO2)
Global Weighted Average	235	-62
China	40	11
EU	288	-90
India	64	38

Japan	69	59
South Korea	90	38
Philippines	44	57
UK	216	-98
US	15	50
Vietnam	-27	23

Table 1:Regional Breakdown For Switching from Coal to Other Energy Sources, 2022 Average. [25]

In Table 2, it can be concluded that coal power generation is much more polluting and contributing to global warming than all methods of renewable energy listed. It is also much more expensive than solar and wind energy.

Power Type	$/kWh	g of CO2/kWh
Coal (US 2020)	0.167647603	1011.5
Solar	0.06	50
Hydro	0.85	24
Wind	0.053	11

Table 2: Price and CO2 Emissions per kWh of Coal, Solar, Hydro and Wind power generation. [27],[28],[29],[30],[31],[32],[33],[34],[35]

However, we need to consider the limitations of the listed renewable energies. For solar energy, we need a significant exposure area to solar radiation to produce large amounts of power. For example, in the US we would need 21,250 square miles to produce its energy needs using solar energy.[36] For hydropower, we would need high mountain with water reservoirs or very fast flowing rivers limiting the capability of producing large amounts of energy. It should also be noted that hydro power is more expensive than coal power generation, according to the table above.

Some hydroelectric water dams have been built in the US similar to the one shown in Figure 18. Some limitations to wind energy are the very high noise and visual pollution it cases, the intermittency of it, due to the variability of wind speeds. This requires wind turbines to be built away from populations, restricting its potential.[40]

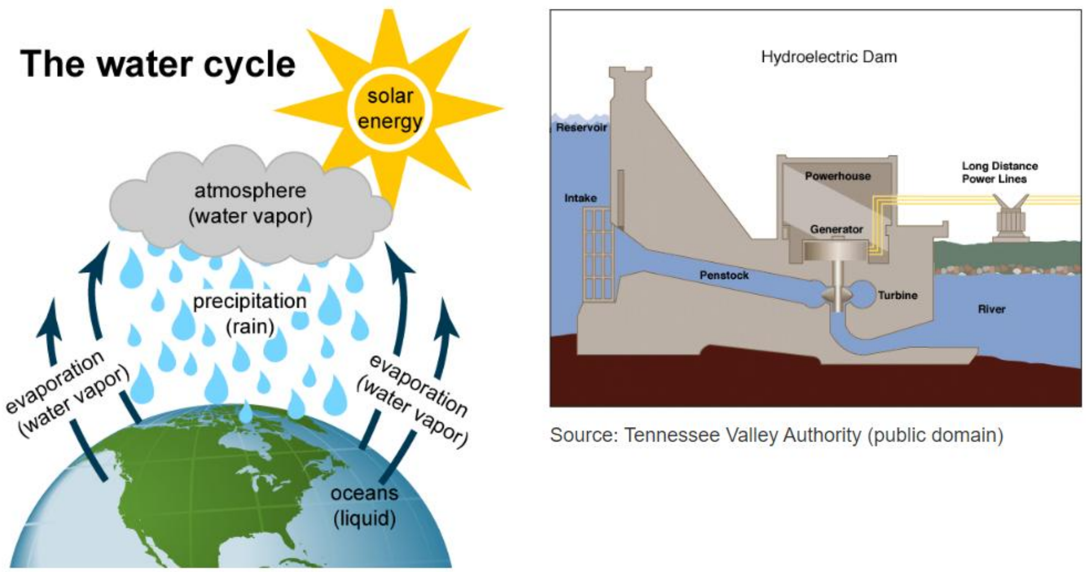

Figure 18: Hydroelectric Dam Schematic and Water Cycle. [40]

Conclusion:

From what we have discussed in this paper, we can infer that IGCC coal power plants are too expensive to use and using carbon capture and storage methods without reusing the captured CO_2 is also very costly. We have also deduced that coal power plants are not the cheapest power generation method available and that other fossil fuels such as natural gas are a cleaner option when taking greenhouse gas and carbon dioxide emissions into account. We have found that removing sulfur and ash is common in coal power plants and is added to most coal power plants today. It is recommended to use coal power plants with carbon capture and storage technologies, while simultaneously using the carbon dioxide in industrial use by the chemical or oil industry. They should also be using sulfur removal technologies and particulate material removal.

However, we do not recommend the usage of IGCC coal power plants, because it is very expensive, although it increases the thermal efficiency of the system.

In the case of being able to introduce different power generation systems, it is recommended to either incorporate natural gas or renewable energies based on which is less expensive for the region. However, if our main goal is to minimize the carbon emissions, we would like to use renewable energies completely.

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