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Fossil Fuel Power Plants

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Abstract

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Traditional Coal-Fired Power Plant

Description of Coal Fuel

Coal is a combustible rock that is formed from the buildup of decayed organic material, after years of intense heat and pressure. It has been used for centuries as a form of heating in early world empires but was popularized during the Industrial Revolution as a source of energy. The scope of this research will focus on the uses of lignite, bituminous and sub-bituminous coal for their use in electrical power generation.

The by-products of burning coal include flue gases such as nitrogen oxide (NO_x), carbon dioxide (CO_2), sulfur dioxide (SO_x) and water vapor. SO_x and NO_x are toxic gases that have been regulated in some countries to prevent air pollution. In Ontario, discharges from flaring-type incidents in a 24-hour period are limited to a threshold of 225 kg[2]. CO_2 is a greenhouse gas and is a contributing factor to climate change causing it to also be heavily regulated. In Canada, emitters must track and limit their carbon emissions to 420,000 kg/GWh of electricity generated[4].

The advantages of using coal are that it is relatively inexpensive and readily available worldwide. To evaluate its relative price against other resources the Levelized Cost of Electricity (LCOE) can be used as an accurate metric for comparison. It is an economic assessment of the average total cost to build and operate a power source over its lifetime while factoring its total energy output over the same period (Figure 1). Coal is approximately 50% cheaper than conventional technologies such as natural gas and nuclear and is also competitive with alternative renewable energies[1]. With a levelized cost of $60/MWh, coal ranks 3rd in price among the energy sources accounted in the study. However, the only cheaper sources of energy, solar thermal and PV, are only capable of small-scale power generation.

Energy density is the amount of energy that can be stored in a given mass. Higher energy density fuels are sought after less because mass is required to produce a given demand, reducing transportation and storage costs. Bituminous and lignite coal have a fuel density of 30 MJ/kg, which is relatively low compared to other non-renewable fuel sources (Table 1). Fuel properties also carry significance in determining fuel efficiency. Optimum characteristics of coal includes:

- Moisture content be 12 - 14%
- Grindability between 40 – 100 Hardgrove Grindability Index (HGI)
- High carbon content

Availability and Global Perception

There are an estimated 1.1 trillion tons of proven coal reserves available in the world. This supply will last 150 years at the current production rates. Coal is the most abundant fossil fuel in the world, available on virtually every continent in some capacity (Figure 2).

In the 2015 Paris Agreement on climate change, 25 nations and states confirmed to accelerate clean energy growth and climate protection through the rapid phase-out of coal power through three specific actions[6]:

1. Government partners commit to phasing out existing coal power without any operational carbon capture or storage.
2. Business and non-government partners commit to powering their operations without coal.
3. All partners commit to supporting clean power through their policies and investments to restrict financing coal power without carbon capture strategies

This was one of the most significant announcements for global commitment to climate change however, the new anti-coal alliance only accounts for less than 3 percent of coal use worldwide. The trends between major coal producers and consumers are that China, India and the United States lead both categories by a substantial margin (Table 2). China is a global leader in coal mining, representing approximately 50% and is also the largest consumer. The global coal market is largely dependent on Chinese energy policy, which recently has seen a significant investment in clean renewable energies[5]. For the immediate future, China will be the global leader in coal power.

How is it obtained?

Coal can be extracted from the Earth through surface or underground mining. It is considered Surface mining if the coal is less than 60 metres below the ground and Underground mining can be as deep as 300 metres. There are three variances of surface coal mining. Strip mining is used where coal can be removed in larger layers (Figure 7). Sediment covering the coal is removed using explosives and towed away using large vehicles. Strip mining can be used when the landscape is flat and jagged, making it relatively versatile. Open-pit mining is used when coal is located slightly deeper than the surface. A large pit is excavated and coal is extracted until the cost of removing sediment is greater than the overall investment in the mine (Figure 8). This type of surface mining is generally limited to flat landscapes to reduce the cost of transportation. Lastly is mountaintop removal mining (MTR). In this procedure the entire summit of a mountain is stripped of overburden, including rocks, trees and topsoil. MTR is the most controversial technique due to the severe environmental consequences. Toxic by-products of the mining and explosive processes can drain into waterways and pollute nearby communities and ecosystems.

There are also three types of underground mining. Longwall mining slice large panels of coal that are 1 metre thick, 3-4 kilometres long and 300 metres wide. It is among the oldest and most frequently used methods of underground mining due to the efficiency of moving large quantities of coal by conveyor belt to the surface. Room-and-pillar mining carve a section that can be 9 metres wide and 30 metres high. Coal is extracted using a sophisticated tool called a continuous miner. Lastly, Retreat mining is a variation of the room-and-pillar method. When all available coal has been extracted from the room, miners carefully destroy the pillars and let the ceiling collapse and the remains add to the supply. This method is considered dangerous because if pillars are not removed in the correct order, miners can be trapped underground.

Pulverized Coal Power Plants

Pulverized coal power plants account for approximately 97% of the world’s coal-fire capacity and obtain an operating efficiency of 35%. To generate electricity, coal is first pulverized into a fine power less than 100 μm in size, then burned in a controlled environment (Figure 3). The resulting heat released in the furnace and rapid combustion occurs at high temperatures. The furnace walls are covered with water tubes that are then super-heated to begin the conversion of water to steam. At the same time, flue gas rises in the furnace through a bank of heat exchangers to also heat the tubes. Remaining material, called bottom ash, collects at the bottom of the furnace and is disposed of through either a wet or dry bottom boiler. The finer ash mixed in the flue gas, called fly ash, is separated using electrostatic precipitators before being discharged into the atmosphere. Maintaining ash collection is critical in boiler operation and design. The pressurized steam then turns a turbine inducing an electrical current in a generator which is connected to the electrical grid and capable of supplying power.

Pulverized coal technology can be optimized by increasing pressure and operating temperature of the boiler. Subcritical, supercritical and ultra-supercritical operate at increasing standards up to 34 MPa and 1033 Kelvin[7]. These boilers are capable of higher efficiencies of 40-50% but are more susceptible to inner tube failure and lower reliability as a tradeoff. The majority of modern coal power plants have implemented deviations from traditional designs to improve efficiency and cooperate with emissions standards. An example is the Huaneng Yuhuan power station, China's 1,000 MW ultra-supercritical boilers[17]. The plant cost €900 million, and the runs at about 45% efficiency. China is now building around ten similar coal-fired plants using different international manufacturers, and amassing its own design and construction expertise.

Pollution and Waste By-products from Coal

Damage to Human Health

Exposure to coal can have serious health effects on human beings at all stages of the fuel's useful lifecycle. This neglects the risk of physical injury due to mining, and focuses on toxins that can lead to a variety of illnesses. Carbon monoxide is released from explosives used to clear overburden before mining, but often lingers in pockets around the area. It is a colourless, odorless and tasteless gas that poses a risk to workers particularly in mountaintop mining. During the mining process and transportation, coal dust is released in the area and can cause black lung. It is estimated that over the past decade, the disease has claimed over 10,000 lives of coal miners worldwide[11]. As previously mentioned, coal combustion releases NO_x, SO_x, particulate matter and mercury, all of which are known to be hazardous to human health. The combination of all these toxins contribute to lung damage, formation of smog, increased risk of bronchitis and freshwater pollution. This is particularly taxing on a country's population in terms of increased health costs and reduced life expectancy.

The 2010 report from the Clean Air Task Force provided an update on the burden of death and disease from coal-based electricity production across the United States. It deemed that among all industrial sources of air pollution, none pose a greater risk to human health than coal-fired power plants[12]. The study emphasized the concerning link between coal power induced air pollution and public health. The results show that declining particulate emissions after passing Clean Air Interstate Rule (CAIR) have had negligible effect in reducing air quality-induced fatalities among Americans. This demonstrates the current air pollution regulations are not restrictive enough to sufficiently protect public health. This is dramatically more concerning for countries such as China and India considering they are global leaders in coal consumption and have an infamous reputation for poor air quality. The analysis indicates that even after the first phase of CAIR, power plants are still linked to premature mortality and disease proportionally more across the coal-burning Midwest, South and Mid-Atlantic regions (Figure 7). States with large population centres in close proximity to coal-fired power plants fare worse such as in West Virginia. However, the state of California has reputably poor air quality due to smog but ranks low in mortality due to their little reliance on coal electricity.

Damage to Environment

There are numerous damaging environmental impacts of coal separate from the health hazards it has on human beings. The processes of mining, storage and its waste by-product all contribute to coal being the most damaging fossil fuel to the environment.

During the mining process, coal is crushed and washed to remove surrounding soil and rock. This washing process generates significant amounts of liquid waste called Coal Sludge. It is typically disposed of in landfills near mines, however residual waste can often be leftover in the environment. Acid Mine Drainage (AMD) is the outflow of coal sludge from coal mines where rainwater has been exposed to sulfur and mixed with nearby rivers. AMD tends to occur after mines have been decommissioned and over time waste rocks come in contact with air and water. This causes heavy metals such as lead and mercury to dissolve into water sources threatening organisms using it as a resource.

After the combustion process, it was mentioned that one type of waste remains in the boiler called bottom ash. This is the second largest industrial waste and requires disposal in customized containers that are lined with clay and plastic. This does not prevent rainwater from mixing with its contents and leaks can transfer toxic metals into the environment.

The most damaging and wide-spread environmental effect of coal-fired power plants are its contributions to climate change. Coal contains more carbon than oil or natural gas fossil fuels resulting in larger volumes of CO_2 emissions per kilowatt generated. The threats of climate change vary by location but no country will be completely unaffected. An increase in global temperature can cause rising ocean level, which can displace significant amounts of coastal resident. It also causes an increase in extreme weather such as hurricanes, heat waves, extreme rainfall[13].

Future Developments

Integrated Gasification Combined Cycle (IGCC)

In IGCC plants, carbon capture can be completed before combustion when it is more concentrated and easier to separate from the fuel[9]. The synthetic gas includes filters to remove particulates, such as mercury, that are released as toxins in the pulverized coal-plants. IGCC also consumes less water than pulverized coal plants because it is only used to capture heat from the combustion turbine exhaust for use in a secondary steam turbine. A lot of water is lost due to evaporation in the condenser of pulverized coal-plants. Its overall efficiency ranges from 40-50%. The major drawback of IGCC plants are its high capital costs, holding a levelized cost of $90/MWh[10]; an LCOE 150% larger than pulverized coal-fired plants. This is the largest obstacle for its integration into the power market however, the increasing pressure on carbon regulation may incentivize the technology in the future.

This technology uses a high-pressure gasifier to convert carbon fuels into a synthetic gas. Impurities can be removed before beginning the power generation cycle, allowing for lower emissions of toxins such as sulfur dioxide, mercury and carbon dioxide. The sulfur dioxide can be reprocessed through the Claus Process[8] to make sulfuric acid, a usable resource in the manufacturing of medicine, and fertilizers. To increase efficiency, a water-gas shift reaction is incorporated in the system. In this process carbon dioxide from the shift reaction can be separated, compressed and stored. The resulting excess heat from the primary combustion is passed to a similar steam cycle as the pulverized coal-fired plant (Figure 6).

Carbon Capture and Storage

Replacing coal power may not be the ideal solution for many countries at the moment due to its low cost and ability to reliably meet energy demands. A method of reducing the pollutants involved in coal energy while retaining its energy capabilities is through Carbon Capture and Storage (CCS). This technology can curb the increment in emissions levels to comply with political regulations while also remaining capable of supplying power for a lower cost[14].

CCS involves capture of CO_2 during power generation, its compression, transportation and long-term storage. CO_2 capture can occur before or after combustion and depends on the state of the fuel. Usually pre-combustion capture is used in IGCC plants due to coal being gasified. Post-combustion capture is ideal in an oxygen-rich environment where an air separation unit can be used[15]. CO_2 is then transported for safe use or storage using similar methods as oil such as pipeline, tanker or commercial ship. The infrastructure is largely available in countries that already rely on oil, petroleum and natural gas fuels. CO_2 long-term storage entails pumping the gas deep underground where the high pressures convert it into a liquid. A number of geological trapping mechanisms can be used for this type of storage with minimal risk to human or environmental safety. CO_2 can be used as a value-added commodity. It is already used for enhanced oil recovery to help maintain pressure in reservoirs by injecting CO_2 into mature oilfields. This increases production of crude oil therefore having a positive commercial value for carbon capture where it can sustain future deployments of the technology.

The process of incorporating CCS into coal-fired power plants adds higher capital and operating costs as well as lowering efficiencies[16]. This makes the technology difficult to sell to investors given its upfront deficiencies. Despite growing concerns of the coal power, many global consumers often do not have the capability of completely phasing this fuel out soon. It is more reasonable to promote the use of CCS as a compromise. This allows the technology to become more efficient and less costly over time while also appealing to the reduced risk on the environment.

Fluidized bed combustion (FBC)

Fluidized bed combustion (FBC) uses coal fuel for energy production and is able to operate at an efficient rate without significantly damaging the environment. The conventional coal firing technology requires pulverized fuel before entering the furnace but are not needed for FBC. Instead, coal is coarsely crushed and dropped in the lower section onto bedding materials. Unlike the conventional boiler which burns the fuel at high temperature, the concept of FBC keeps fuel in an air-suspended bed of inert particles on the bottom of the reactor vessel to create a flameless combustion process. By choosing the appropriate bed material to absorb sulfur, flue gas can pass through while controlling SO_x and NO_x emissions to achieve the acceptable limits of environmental legislation.

Comparing the fluidized mechanism over the pulverized power plant, the floating particles have a reduced chance of hot and cold spots in the furnace during combustion. This results in the inert bed absorbing and retaining most of the gases which promotes a safer and more stable process. Due to the turbulent mixture of fuels and the hot inert particles of the fluidized bed, wasted ash does not melt. This makes heat transfer surfaces stay clean and minimize corrosion which ultimately increases the efficiency and reliability, lowering the price of maintenance.

The solid bed materials often consist of inert materials (ash or silica sand) that are mixed with sorbents, such as limestone. These particles are placing on top of the air distribution nozzle at the bottom of the boiler. There are three types of beds (Figure 8). For the low primary air flow rate, the bed particles are static. The air flow rate depends on the size of particles and density of the air fuel mixture. The air is fed through nozzles and if lower than the minimum fluidization velocity (the flue gas passing between the particles), it is called the static or fixed bed. Increasing the primary air velocity will produce drag forces on the particles to counteract the gravitational force. The bed particles move with respect to each other in the form of bubbles. This form is called Bubbling Fluidized Bed (BFB). Increasing the air velocity higher than the terminal velocity of the bed particles will suspend them midair and extend itself over the entire vessel of the combustion chamber.

Bubbling Fluidized Bed and Circulating Fluidized Bed

Although there are three types of beds, energy can only be harvested from two variances. Bubbling Fluidized Beds (BFB) are used for lower capacity applications (air velocities in the range of 1.0–3.0 m/s). The characteristic of BFB is that the inert bed particles form a non-uniform, bubbling fluid and do not leave the bottom bedding area. On the other hand, Circulating Fluidized Beds (CFB) is controlled by higher air velocities, normally in the range of 3.0–6.0 m/s (Figure 10 a) is BFB and b) is CFB). It is used for applications that are over 0.4MW energy loads.

Higher air velocities, circulates bedding particles around the bed area while extending and suspending themselves over the entire furnace. In order to keep the bed material in a constant fuel ratio, all the particles are collected by steam cooled solid cyclone separators (Figure 11) which recycle more of them back to the furnace. Before re-entering the furnace, the particles pass through a high-performance heat exchanger where a steam coil is submerged into bubbling bed to produce high temperature steam. There is no clear distinction between burning fuels in the bottom bedding areas and the upper diluted zone but due to the density of the bedding particle being proportional to the height of the furnace, operating conditions for BFB and CFB are varied (Figure 12).

Benefits and Implementations of Fluidized Bed Technology

There are a few advantages of FBC compared to other fossil fuel burning methods. FBC possesses a stable and low temperature combustion condition. Both FBC concepts use water injection, boiling vessel’s internal heat exchange surface and recirculation of flue gas to control operating temperatures. It is also beneficial that once the combustion chamber is fully functioning, the reactor is flexible enough to adjust the quantity of moisture, load and heating value of the fuel. CFB is often represented by a high energy output and a high heat transfer efficiency between the bedding materials and the heat exchangers. Unlike nuclear station, the FBC process can be interrupted and there will not be any waiting time to restart the plant. Lastly, the emission of NO_x, CO_2 and SO_x is relatively low due to the mixture of bedding materials absorption. The use of limestone and dolomite for desulfurization can greatly reduce the SO_x as flue gas (Figure 12). Over 90% of the resulting sulfur oxides can be removed before the emission.

Modern technology has emphasized the use of FBC for CO-firing plants, which has demonstrated promising results to reduce the CO_2 And NO_x emission. FBC co-firing plants are compatible with retrofitting old coal firing plants without the need for new burners. The oxidizer composition requires a high O_2 concentration and mixture of correct fuels. To mitigate the NO_x, emissions need to lower the volatile matter of the fuels. The formation of the NO_x is very sensitive to excess oxygen, so volatile oxidation increases the temperature and formation of NO_2 during combustion. Operators are allowed to manipulate char particles in the NO_x reduction mechanism (Figure 13). There is a high NO_x formation in the lower part of the furnace that decreases significantly moving up. This phenomenon is explained by the high amount char in the fluidized bed during coal combustion. There are a few disadvantages for the FBC design. Primarily, it requires an advanced gas and solid particle separation system for its high dust concentration. There will be some solid bedding particles agglomerations, leading to the erosion of the inner surface (mostly for CFB combustion chamber). Both of these constraints add to the maintenance requirements of FBC technology.

Future Development and Applications

In Belarus where energy resources are lacking, low grade coals and biomass are considered the main fuels of choice. FBC plays a significant role to provide power in their industrial and commercial sectors. The Institute of the National Academy of Sciences of Belarus has successfully developed an FBC implementation with a capacity of 1.25MW (Figure 14). The fuel is a mixture of anthracite and silesian coal. The design is most similar to the BFB offering a much simpler process, and low power consumption. A 1.25MW steam boiler was used to produce 6,620GJ of the heat. A system was developed for controlling the fluidized bed height and allows operation with different fuel to produce various levels of ash. Technology from CBC was also implemented that collects and transports ashes to recirculate back in to the bed to increase combustion efficiency. For cleaning flue gases, sufficient multi-cyclones equipment are added to reduce SO_x and NO_x. The system can react rapidly to the fluctuation in load demand, with little or no downtime and is simple to establish the thermal equilibrium between fuels and air temperature in the reactor. The development of FBC emerges as an alternative that is available around the world. The drawback is the requirement to constantly apply high pressure to the bedding particles in order to maintain efficiency, but can be considered minor. It is part of the solution to meet the world energy need while conserving resources and preserving air quality.

FBC has two future development approaches. The first one will be oxyfuel combustion, that uses a mixture of oxygen and recycled flue gas to limit the temperature. Thus, the combustion air will be denser and more compact which significantly reduces the cost. The other process is chemical looping combustion (Figure 15). This system consists of two separate reactors. The advantage for this combustion is the CO_2 does not dilute with nitrogen gas, can be received and stored from the flue gas without additional cost.

Natural Gas

The use of traditional natural gas as an energy source is well utilized throughout the world. Approximately 21% of the world's energy is produced from natural gas with North America leading the charge with 26% of the continent's energy produced from natural gas.[18] As seen in figure 16 in the appendix, natural gas use is widespread among countries around the world and continues to grow due to its fuel efficiency and burns cleaner than coal or petroleum products[19].

Efficiency

Natural gas can be used in several ways including power generation, heating for residential and commercial buildings as well as in residential appliances such as stoves and water heaters[20]. In the case of power generation, natural gas is mainly used in two methods to produce electricity. First, it can be simply burned to produce steam that is used to turn a turbine. Alternatively, it can be used in a gas turbine where hot gasses produced from the burning of natural gas is used to turn a turbine rather than the heating steam method. Gas turbines are generally used in combined cycle plants were the excess heat is used to generated steam and turn a secondary turbine. This method of power generation is significantly more efficient than the singular gas or steam turbine setup. A combined cycle plant approaches 60% efficiency which is almost double that of a nuclear or coal power plant which is only about 30% efficient. Figure 17 in the appendix shows the layout of a combined cycle plant[21].

Principles of Operation and Components

Natural gas can be classified into three main groups that are widely used. In the first group, non-hydrocarbons are used in to power helium plants. This group includes gasses such as nitrogen, helium, carbon dioxide, and hydrogen sulfide. The second group is used to power natural gas liquid plants. These gasses include Ethane (C_2) and heavier fractions such as natural gasoline and pentanes plus (C_{5+}). The third group is used to power liquified petroleum gas plants. The main gasses in this group are Propane (C_3) and Butane (C_4)[22].

Before natural gas can be used as a fuel source in generation plants, it must undergo a pre-treatment stage. This process begins with an inlet facility removing heavy ends. Next, the gas goes through 3 steps which include mercury removal, sour gas removal, and dehydration[23]. This process is performed to remove impurities such as water, mercury, and sulfur. At the end of this process, the natural gas is then split into gas that will be used for power generation and gas that will be used in residential homes[24].

The natural gas is then burned to produce steam to turn a steam turbine or used in a combined cycle plant to turn a gas turbine. This lifecycle of natural gas produces less emissions than a coal or petroleum-based power plant and if used in a combined cycle plant, has double the efficiency than a coal or nuclear based power plant[25]. Due to these advantages, the world has seen a continuous growth in natural gas use over the past 20 years and is expected to continually grow for the foreseeable future[26].

Resources and Financial Cost

Natural gas is found deep within the Earth in underground rock formations or in combination with other reservoirs such as coal beds. There are two different types of reserves that are available, conventional, and deep. Conventional deposits are found closer to the surface of the Earth, while deep deposits can go down as far as 15,000 feet into the Earth. Liquid nitrogen is then used to cool the natural gas so that it is converted into its liquid state. The liquid natural gas is pumped to the surface where it is either stored or transported to where it is needed[27].

Currently, the United States has enough natural gas reserves to continue its use for the next 90 years. The world's largest deposits of natural gas are in Russia, Iran, Qatar, and the United States with Russia having approximately 48 trillion cubic meters of reserves. At the moment, the United States has enough natural gas reserves to last for the next 90 years of current usage[28]. Canada has the 17th largest natural gas reserve in the world at 2,056 billion m^3. Natural gas is used to provide approximately 35% of all energy in Canada. It is used to supply 50% of space heating, 65% of water heating, and 80% of businesses use natural gas for heating both[29]. Figure 18 in the appendix below shows the countries with the most natural gas reserves in the world.

Since 2003, the price of natural gas has dropped from a high of $18.48 per thousand cubic metres to today's price of $2.90 per thousand cubic metres[30]. This has been a significant decrease in the price of natural gas which has been driven by increased output and use around the world. The cost of mining natural gas has remained low but more recently, costs have begun to rise due to deeper reserves and more advanced technology[31].

Technology

There have been several advancements in the field of natural gas mining and energy production. As the demand for natural gas has grown over the past two decades, the industry has made several technological advancements to keep pace with demand. The most notable advancements that have been made are 3-D and 4-D seismic imaging, coiled tubing, slimhole drilling, and hydraulic fracturing also known as "fracking"[32].

3-D and 4-D seismic imaging has changed the nature of natural gas exploration. A 3-D model is generated and then using time to create a 4-D seismology, exploration teams can identify natural gas reserves more easily, reduce the number of holes drilled, reduce drilling costs, and minimize exploration time. All these factors lead to both ecological and financial benefits[33].

Coiled tubing has replaced the traditional rigid, jointed drill pipe with a longer and more flexible coiled pipe. This advancement significantly reduces the cost of drilling and allows for a smaller drilling footprint. Additionally, the coiled pipe requires less drilling which in turn reduces the time needed for drill pipe connection. Together, the new coiled tubing leads to an economic and environmental benefit[34].

Slimhole drilling is the drilling of smaller holes in the ground to get to the natural gas reserves. This can be done because of the coiled pipe. Due to the smaller hole drilled, there is a significant decrease in the time required to complete the project. Drilling costs can be reduced by 50% due to the smaller hole and the drilling footprint can be reduced by up to 75%. Due to its lower cost and reduced environmental impact, slimhole drilling can be performed in new areas and in pre-existing wells that can be drilled deeper[35].

Hydraulic Fracturing, also known as fracking, is the process of removing trapped natural gas from shale rock formations. Fracking consists of injecting a mixture of sand and water into the shale rock formation to create fractures. This allows the natural gas to flow to the wellhead to be extracted. Over 90% of natural gas wells in the United States have used this method to increase the natural gas reserves and enhance production. Figure 19 in the appendix below shows an example of fracking in the United States[36].

Environmental Considerations

With all the benefits that natural gas provides us in our everyday lives, there are also negative consequences from the extraction and energy provided by natural gas. Natural gas has a negative impact on air quality, land use and wildlife, water use and pollution, and earthquakes.

The burning of natural gas results in the release of nitrogen oxides which are precursors to smog. In addition, areas where natural gas drilling occurs have seen an increase in hazardous air pollutants. These pollutants can lead to respiratory issues, cardiovascular disease, and cancer. However, the combustion of natural gas produces significantly less pollutants than the combustion of other fossil fuels such as coal and petroleum. A study performed by the US Department of Energy found that for every 10,000 homes powered with natural gas instead of coal circumvents the annual emission of 1,900 tons of NOx, 3,900 tons of SO_x, and 5,200 tons of particulates[37]. This reduction is harmful emissions helps improve air quality and overall public health.

Natural gas mining causes a disruption in land use and wildlife as the construction required for drilling can harm local ecosystems by causing erosion and disintegrating wildlife habitats. During construction, there is the possibility of erosion of dirt, minerals, and other pollutants into nearby water sources[38]. Figure 20 in the appendix below shows the climate risks of natural gas.

Natural gas development poses a health risk to adjoining communities through the contamination of drinking water sources with chemicals that are used during construction, drilling, and processing. There is a strong risk of groundwater sources near natural gas wells being contaminated with gases and fracking fluids[39]. Additionally, the use of fracking as a method of extracting natural gas requires abundant amounts of water per well which may cause a strain on local water supplies. The water used for fracking cannot be returned to its source as it is contaminated with chemicals which further strains local water resources. The US Environmental Protection Agency estimated that approximately 400 billion litres of water were used in fracking processes in 2011[40]. This represents a significant amount of water that is lost each year due to fracking activities.

Fracking shale rock formations for natural gas is a significant advancement in natural gas mining, however, it has been reported that fracking increases the chances of low-magnitude seismic activity in the fracking areas. Most of the seismic activity related to fracking are mild events that are undetectable at the surface, but some have been linked to larger earthquakes[41]. Over half of the magnitude 4.5 or larger earthquakes in the past decade in the US have occurred in regions of fracking events and in most cases the coincidence is supported by the location and timing of the seismic incident[42].

Mitigation of Environmental Impact

Natural gas mining and its use in energy production produces negative effects which were covered in the previous section. In order to minimize those negative effects, individuals and companies have attempted advancements in technology to mitigate the consequence on the environment.

The oil and gas industry have made strides in attempting to reduce the pollution caused by natural gas by new advancements such as progressive modelling, coiled tubing, and slimhole drilling which all reduce the adverse result on the environment. In conjunction with new policies to reduce harmful emission created, the continued developments in technology will further reduce the footprint created by natural gas mining and energy production[43].

Natural gas used as an energy source will always produce harmful pollution but if continued design and technology improvements transpire, the negative effect on the environment can be further mitigated and the benefits of natural gas will greatly outweigh the negatives.

Micro Turbines

Distributed Generation

Distributed generation (DG) is a form of power generation different from the traditional centralized method, characterized by long distance transmission and an interconnected network. DG is defined as micro-generator sets installed near a load to meet special user demands. It can help reduce transmission and distribution losses, and improve the stability of the power network.

DG offer increased load flexibility, safety, stability, and diversity of energy utilization. In sum, it is cost effective with low risk, making it more attractive to those seeking reliability and independence by self-generating. DG offers diverse power source options includes energy-transforming devices, such low power internal combustion turbine, micro gas turbines, fuel cells, photovoltaic, and wind turbine.

Given the current electric utility restructuring and public environmental policy, on-site DGs may be the most practical approach to address increasing power demand and power quality requirements[44]. Micro gas turbines are can offer higher stability in generation. Its small size and light-weight, efficient fuel makes it versatile for use in many regions. It has low noise and emission pollution offering a more environmentally friendly option that benefits from low maintenance cost due to not being a water-cooled system. Microturbines are the most popular and competitive commercial DG as it has become a hotspot of scientific research and market development.

What are Microturbines?

Definition & History

Microturbines (MTs) are simple-cycle gas turbines energy generators with outputs ranging typically from about 15 to 300 KW. MTs are also incorporated with performance improvement techniques such as recuperation, that offer low NOx emission and use advanced ceramics for hot sectionals common to large-scale gas turbine units. MTs are designed to operate for long periods with less maintenance. They can be used for base-load requirements, peak shaving and cogeneration applications. Presently, MTs generally have the following features[45]:

- Relatively smaller in size
- High efficiency - fuel-to-electricity conversion range of 25%-30%
- Environmental superiority - NOx emissions lower than 7 p.p.m.
- Durability - designed for 11,000 hours of operation between major overhauls
- Economy of operation - system costs lower than $500 per KW.
- Fuel flexibility - capable of using alternative fuels

MTs came into the automotive market between 1950 and 1970. The first microturbines were based on gas turbine designed to be used in generators of missile launching stations, aircraft and bus engines, among other commercial means of transport. The use of this equipment in the energy market increased between 1980 and 1990, when the demand for distributed generating technologies increased as well[46].

Some companies in the United States, England and Sweden have recently introduced them in the commercial world market. Among these companies are: AlliedSignal, Capstone, Ingersoll-Rand Energy Systems & Power Recuperators WorksTM and ABB Distributed Generation & Volvo Aero Corporation.

State of the Art Microturbines

There are two types of microturbine designs. One is a high-speed single shaft design with a turbine and compressor mounted on a shaft attached to the permanent magnet synchronous generator. The generator can produce high frequency three phase signals ranging from 1.5-4kHz.

Another is a split shaft design uses a gas turbine rotating at 3600 rpm and a conventional generator connected via a gearbox[47].

MTs are similar in set-up to small, medium and large size, as they are composed of a compressor, combustion chamber and a turbine, as shown in the simplified scheme of Figure 21[46]. The state-of-the-art MTs have had significant improvement in recent years. Manufacturers developed different MT configurations based on their application, even though they keep the same components.

Gas MTs' operating principle is similar to the open cycle gas turbines principle (Brayton open cycle). At the beginning of this cycle, air is compressed before going through the combustion chamber, where it receives energy from the fuel thus raising its temperature. Leaving the combustion chamber, the high temperature working fluid is directed to the turbine, where it is expanded by supplying power to turn the turbine which drives the electric generator[46].

MTs cycle can be made with or without recuperation. To improve efficiency, the heat at the turbine exhaust can be recovered and used to preheat air supply before entering the combustor in an air-to-air heat exchanger called recuperator. By adding a recuperator to the cycle, the net efficiency can be increased by 30% while the usual average net efficiency of unrecovered MTs is 17 %.

The performance of MTs are affected by components efficiency, mainly gas temperatures at the turbine inlet, and the AC-DC conversion. This is because MTs usually employ permanent magnet variable-speed alternators generating very high frequency and alternating current that must be rectified first and then converted to AC to match the required supply rate.

MTs can operate in different modes: grid connect, stand-alone, dual mode and multiple units for potentially enhanced reliability. In grid connection, the system locks to the grid's voltage and frequency. Grid connected applications include base load, peak shaving and load following. One of the benefits of MTs grid connect mode is that the synchronization and the protective relay functions required to reliably and safely interconnect with the network can be integrated directly into the MT control and power electronic systems. This eliminates the need for expensive and cumbersome external equipment needed in conventional generation technologies. In the stand-alone mode, the system behaves as an independent voltage source and supplies the current demanded by the load. For the stand-alone mode, MTs can be equipped with a large battery which will be used for unassisted black start and for transient electrical load management.

Dual mode means that the MTs have the capability to switch automatically between grid connect mode and stand-alone mode. To enhance reliability and have large power generation multiple MTs can be connected in parallel or to other DG systems. By integrating this capability in the MT, the need for external equipment will be eliminated.

Fuels used and Emissions

MTs are flexible in term of the type of fuel can be used, they can operate with gas, liquid fuels and biogas. The flexibility and the adaptability enabled by digital control software allow this to happen with no significant changes to the hardware.

The Capstone MT, shown in Figure 22, uses a lean premix combustion system to achieve low emissions levels at a full power range[46]. Lean premix operation requires operating at high air-fuel ratio within the primary combustion zone. The large amount of air is thoroughly mixed with fuel before combustion. This premixing of air and fuel enables clean combustion to occur at a relatively low temperature. Injectors control the air-fuel ratio and the air fuel mixture in the primary zone to ensure that the optimal temperature is achieved for the NO_x minimization. The higher air-fuel ratio results in a lower flame temperature, leading to lower NO_x levels. In order to achieve low levels of CO and Hydrocarbons simultaneously with low NO_x levels, the air-fuel mixture is retained in the combustion chamber for a relatively long period. This process allows for a more complete combustion of CO and Hydrocarbons.

In addition, the exhaust of MTs can be used in direct heating or as an air pre-heater for downstream burners, once it has a high concentration of oxygen. Clean burning combustion is the key to both low emissions and highly durable designs.

The most effective fuel to minimize emissions is natural gas. Natural gas is also the fuel choice for small businesses. Usually the natural gas requires compression to the ambient pressure at the compressor inlet of the MT. The compressor outlet pressure is nominally three to four atmospheres.

Future developments

Aging power infrastructure, poor grid connectivity in several parts of the world, strict environment protection policy and increasing electrical loads are all factors that will increase demand for DG. As a result, there is an anticipated increase in demand for MTs globally especially because of their capability to be used as Combined Heat and Power (CHP) systems and Combined Cooling and Heating Power (CCHP) systems. This can offset the the low fuel-to-electric efficiency, which is a major restraint for the market.

Furthermore, the flexibility offered by MTs in terms of fuel can facilitate its use of renewable energy sources (biogas and biomass) which have lower environmental impacts.

Wabash River Coal Gasification Project

Coal will remain the dominant source for electricity generation in the near future. With power generation being the primary source of CO_2 emissions, clean and efficient use of fuel should be the key route for a balanced solution. Carbon capture and storage technology is the only method that can align increased use of fossil fuels with the regulatory constraints being implemented worldwide. Many countries have begun transitioning traditional coal-fired power plants to use an Integrated Gasification Combined Cycle for its economical and environmental benefits. The Wabash River Coal Gasification Repowering Project was an IGCC plant built to incorporate parts of a pulverized coal facility in the United States[48]. It was the largest single train gasification plant in the world, generating 300 MW of energy.

Analysis

World energy demand is expected to rise 45% by 2030 and 90% of it used by developing nations. It is unrealistic to expect that these nations will be able to completely phase-out their use of fossil fuels due to their low cost and ability to reliably supply energy demands. A genuine expectation is to implement carbon capture and storage techniques such as at Wabash River. The goals for this project was to begin pushing gasification programs in the United States to start to modernize their old plants. Its secondary goal was to demonstrate superior environmental performance for reducing emissions from an existing coal plant.

Based on the IGCC's plant operating in its first year, there was an increased runtime contributing to a 5.5x larger production. NO_x and SO_x pollutants were also reduced by 1,200 and 5,500 tons of particulates in the same year[49]. The gasification plant produced very little solid ash waste, which was a significant issue with the pulverized process. The ash content becomes a vitrified slag but has been used by the Indiana Department of Transportation for asphalt mix and construction backfill, rather than traditionally being disposed in a landfill.

The US Department of Energy subsidized a significant amount of the costs of development and construction ($219M). On a dollar-per-kilowatt scale, the estimated installation cost of the project was $1700/kW. This is 140% larger than conventional coal plants, prompting the tradeoff of added cost for efficiency and environmental benefits[50].

Future Developments

The Wabash River Repowering Project was deemed a groundbreaking success, achieving all of its environmental and efficiency goals for retrofitting the existing conventional bituminous coal fired plant. The project also showed a conversion to zero liquid waste for the gasification and was exceptional flexible to perform under multiple market demands. The project earned Power Magazine's *Plant of the Year* in 1996 for its top performance in electricity generation and innovative design.

After its initial success, IGCC power generation has been further studied to improve its efficiency so that it could be standardized across the United States. The three main areas of focus are:

- Increasing the temperature of gasifiers to promote optimized oxidation reactions
- Select proper steam concentration in the gasification agent
- Optimize the inlet temperature of the gas turbine

Appendices

Figures

Figure 1 - Levelized Cost of Electricity Formula

$$Levelized\ Cost\ of\ Electricity = \frac{\Sigma Cost\ over\ Lifetime}{\Sigma\ Electrical\ Energy\ Produced\ Over\ Time}$$

Figure 2 - Location of World's Fossil Fuel Reserves

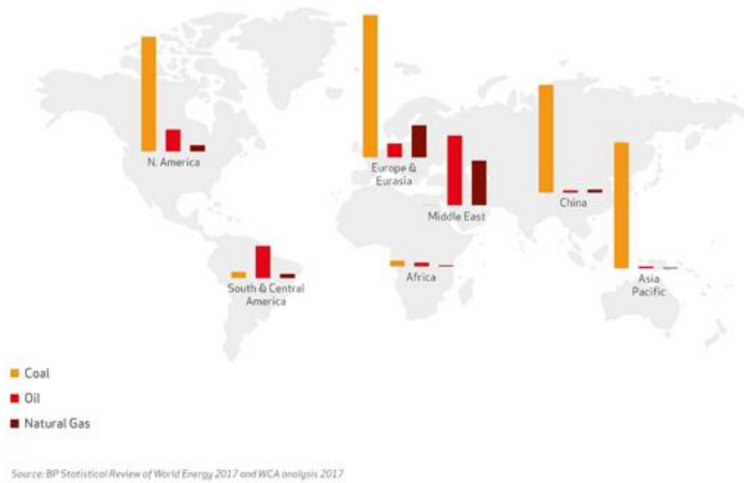


Figure 4 - Strip Mining Diagram

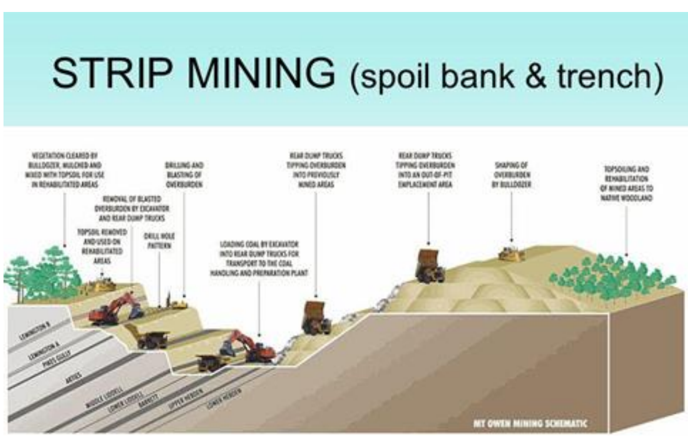


Figure 3 - Open Pit Mining Diagram

Figure 5 - Coal Plant Mortality Per 100,000 Adults

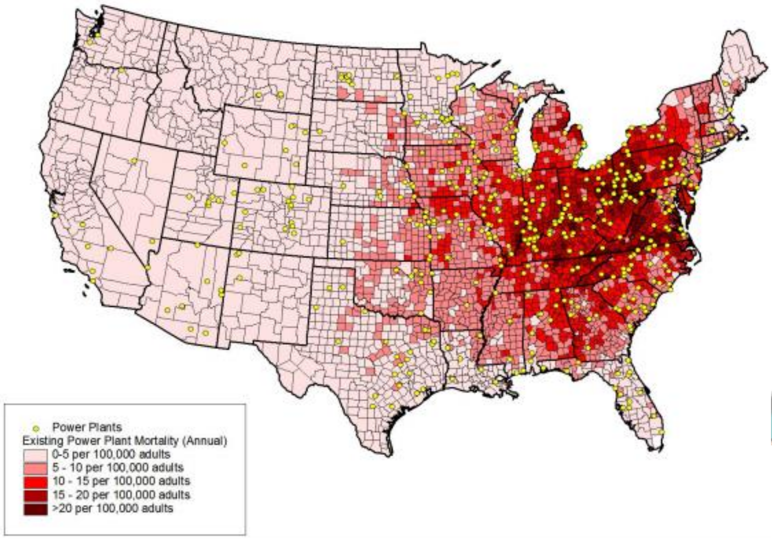


Figure 6 - Pulverized Coal Plant Diagram

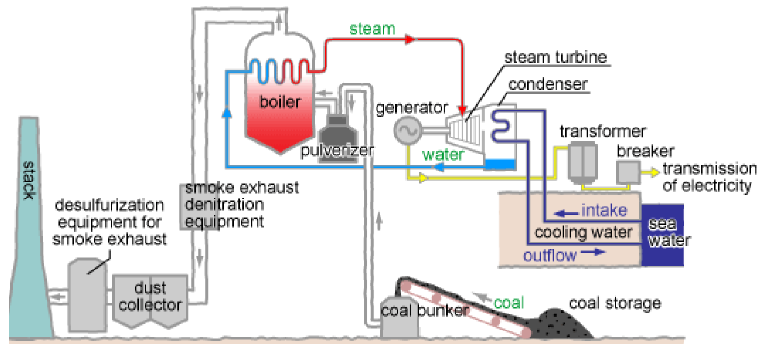


Figure 5 - Integrated Gasification Combined Cycle Diagram

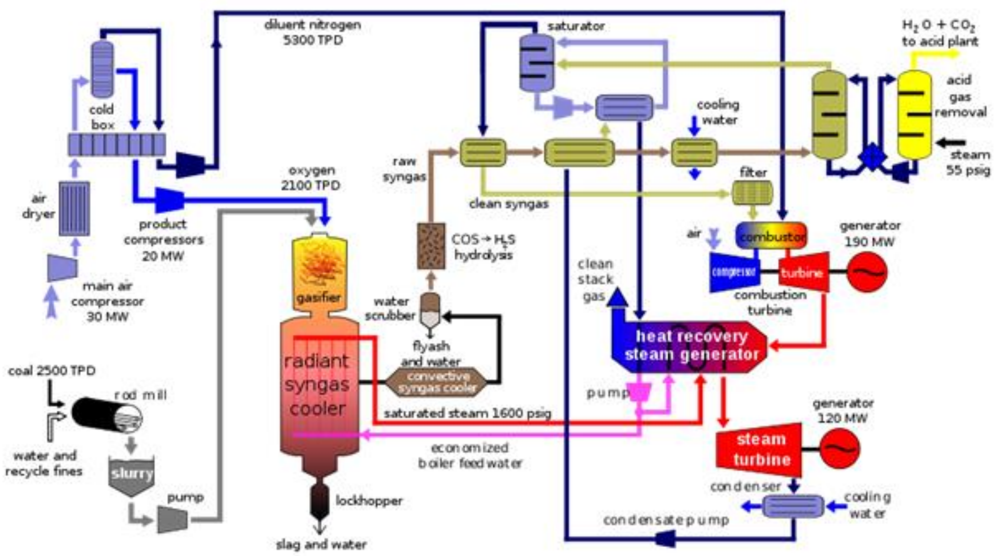


Figure 8 - Types of Fluidized Beds

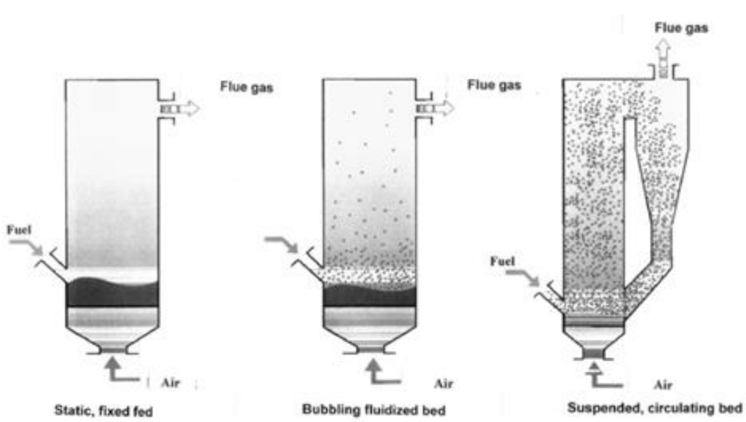


Figure 9 - Bubbling and Circulating Fluidized Bed Diagrams

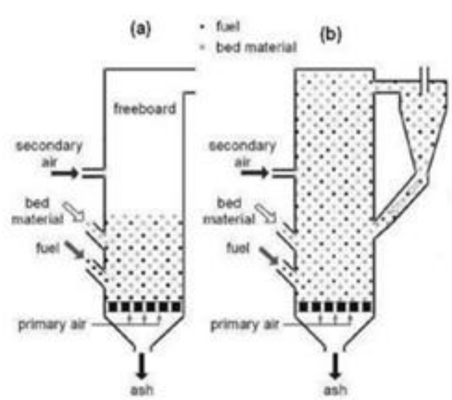


Figure 7 - Solid Cyclone Separator Diagram

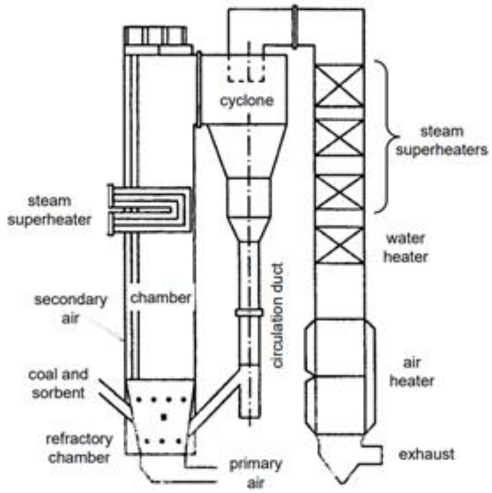


Figure 6 - Operating Conditions for BFB and CFB

Table 6.1 Comparison of BFB and CFB technologies

	Bubbling Fluidized Beds	Circulating Fluidized Beds
Air velocity (m/s)	1.0–3.0	3.0–6.0
Bed material size (mm)	<0.5–1.0	<0.2–0.4
Fuel particle diameter (mm)	<80	<40
Excess air (%)	20–30	10–20
Bed Temperature (°C)	650–850	750–900
Capacity (MW_{th})	>20	>30
Tar in flue gas	Moderate	Low
Dust load in flue gas	Very high	Very high (higher than BFB)
Combustion efficiency (%)	90–96	95–99.5
Heat transfer rate (MW/m^2)	0.5–1.5	3.0–4.5
Specific investment[a]	Lower	Increased[a]

[a]Due to increased boiler size and possible requirements for fuel pre-treatment

Figure 82 - Chemical Reactions of FBC

$$CaCO_3 = CaO + CO_2 \qquad \Delta H = 182.1 \text{ kJ/gmol}$$

$$CaO + SO_2 + \tfrac{1}{2}O_2 = CaSO_4 \quad \Delta H = -481.4 \text{ kJ/gmol}$$

Figure 93 - NOx Reduction Mechanism

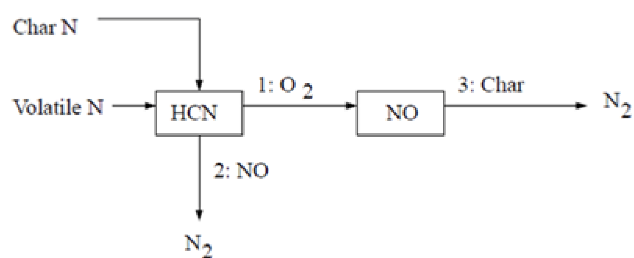


Figure 10 - Scheme of Fluidized Bed Steam Boiler

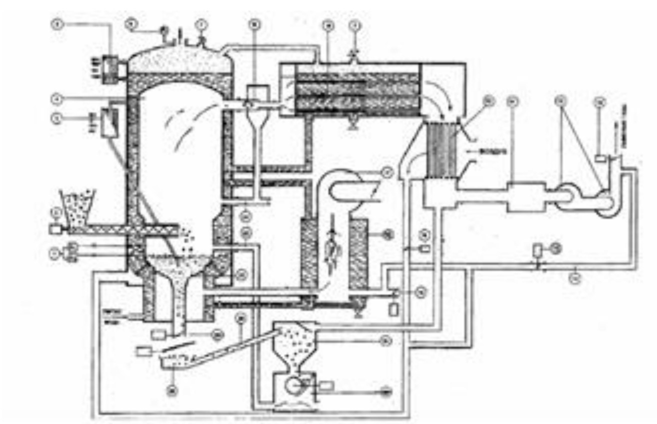


Figure 3. Scheme of 1.25 MWth fluidized bed steam boiler: 1 – bed temperature regulator, 2 – coal screw feeder, 3 – bed level sensor, 4 – furnace chamber, 5 – gauge-glass, 6 – manometer, 7 – safety-valve, 8 – precipitator (cyclone), 9 – superheater, 10 – recuperator, 11 – fly ash filter, 12 – exhaust fan, 13 – exhaust fan vent, 14 – line for recirculation flue gases, 15 – recirculation vent system for maintaining required fractional composition of the bed material, 16 – air vent, 17 – start-up burner, 18 – lighting chamber, 19 – ash hopper, 20 – ash crusher, 21 – ejector, 22 – line for feeding inert material, 23 – gas distributor, 24 – ash draining line, 25 – ash draining system, 26 – ash separator

Figure 11 - Chemical Looping Combustion Process

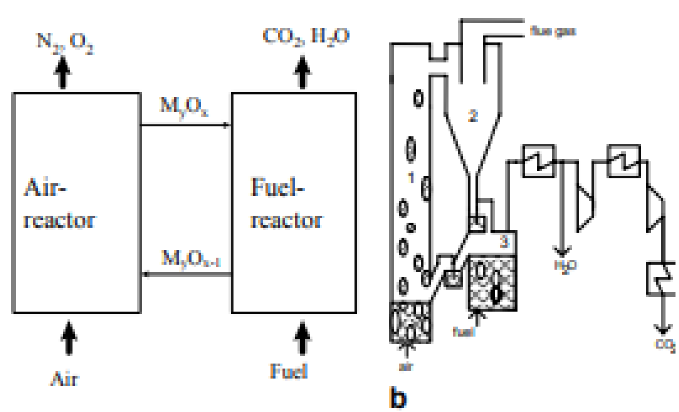


Figure 12 - Worldwide Usage of Natural Gas

Figure 13 - Combined Cycle Plant Diagram

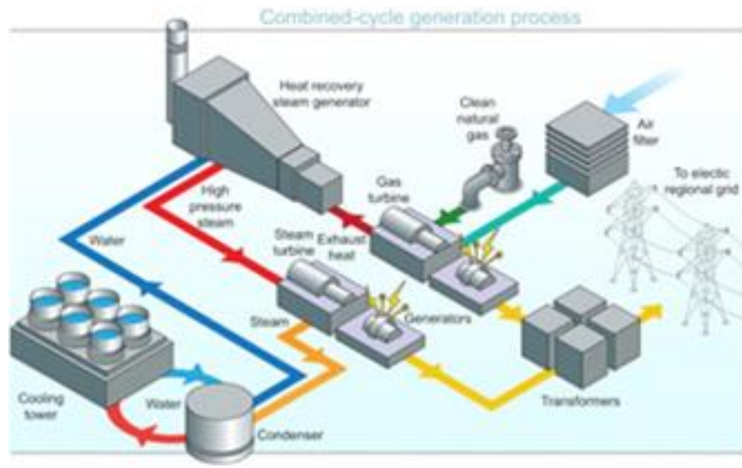


Figure 14 - Natural Gas Reserves

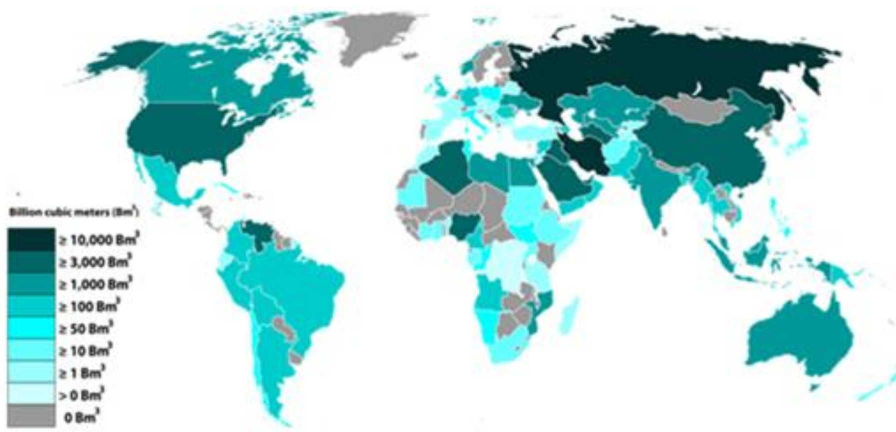


Figure 19 - Fracking in the United States

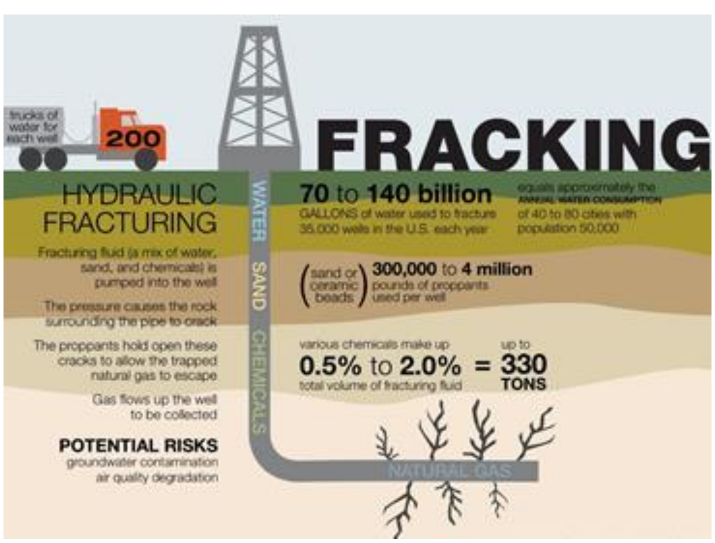


Figure 20 - Climate Risks of Natural Gas

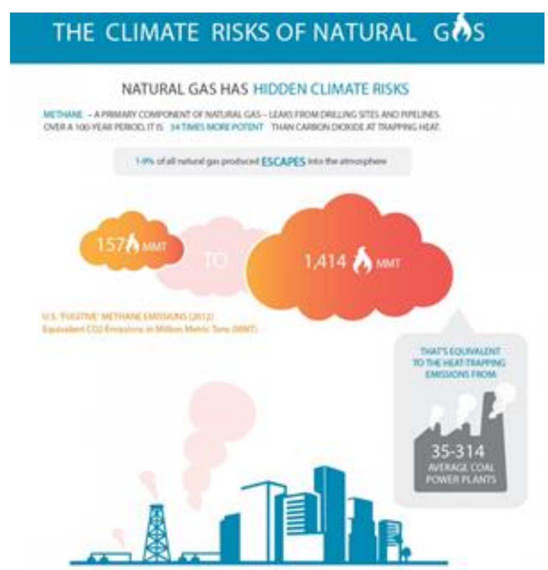


Figure 16 - Simple Open Cycle Gas Turbine Scheme

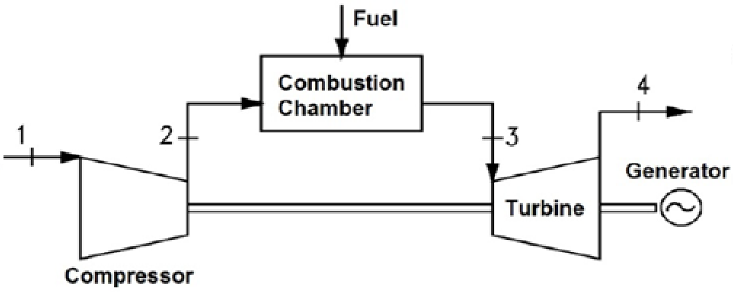
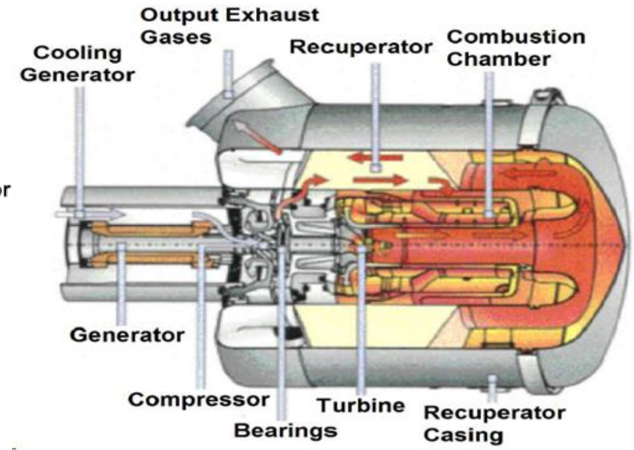


Figure 15 - Capstone Microturbine



Tables

Table 1 - Energy Density of Various Fuel[52]

Fuel	Energy Density (MJ/kg)	Typical Uses
Natural Gas	55	Power generation, heating
Gasoline	46	Gasoline engines
Diesel	45	Diesel engines
Crude Oil	44	Refinery, petroleum products
Biodiesel	38	Automotive engines
Uranium-235	3,900,000	Power generation
Coal	30	Power generation
Ethanol	27	Gasoline mixture, alcohol
Wood	16	Cooking, heating

Table 2 – Major Coal Consumers and Producers[51]

Country	Production of Coal (million tons)	Consumption of Coal (million tons)
China	3,523	4,214
India	716	914
USA	702	673
World Total	7,727	8,261

References

1. https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf
2. https://ero.ontario.ca/notice/013-4126
3. https://www.nasa.gov/feature/goddard/2017/chinas-sulfur-dioxide-emissions-drop-indias-grow-over-last-decade
4. https://laws-lois.justice.gc.ca/eng/acts/c-15.31/
5. Song Yunchang, Song Zhaozheng, Wang Yiyun, Chen Lei, Xu Chunming and Jiang Qingzhe, "Development situation and policy suggestions of Chinese renewable energy," *2011 International Conference on Materials for Renewable Energy & Environment*, Shanghai, 2011, pp. 1-4.
doi: 10.1109/ICMREE.2011.5930750
keywords: {government policies;renewable energy sources;Chinese renewable energy policy;Chinese sustainable energy strategy;Production;Silicon compounds;Earth;Biomass;Renewable energy;Development;Potential;Suggestions},
URL:http://ieeexplore.ieee.org.proxy1.lib.uwo.ca/stamp/stamp.jsp?tp=&arnumber=5930750&isnumber=5930749
6. https://www.nytimes.com/interactive/2017/11/16/climate/alliance-phase-out-coal.html
7. Kowalczyk, Łukasz & Elsner, Witold & Niegodajew, Paweł & Marek, Maciej. (2016). Gradient-free methods applied to optimisation of advanced ultra-supercritical power plant. Applied Thermal Engineering. 96. 10.1016/j.applthermaleng.2015.11.091.
8. Ralf Steudel, Lorraine West, *Vita of Carl Friedrich Claus - inventor of the Claus process for production of sulfur from hydrogen sulfide*, online document of 2015 on the platform ResearchGate.net
9. I. Burdon, "Winning combination [integrated gasification combined-cycle process]," in *IEE Review*, vol. 52, no. 2, pp. 32-36, Feb. 2006.
doi: 10.1049/ir:20060202
keywords: {combined cycle power stations;coal gasification;gas turbines;air pollution control;coal-burning power station;integrated gasification combined-cycle;large-scale integration;power generation;CO/sub 2/ emission reduction;combined-cycle gas turbines;synthetic gas},
URL: http://ieeexplore.ieee.org.proxy1.lib.uwo.ca/stamp/stamp.jsp?tp=&arnumber=1599353&isnumber=33628
10. K. Park, I. Kim, N. Jang, M. Jeong, Y. Lim and E. S. Yoon, "Cost of energy analysis of integrated gasification combined cycle (IGCC) power plant with respect to CO2 capture ratio under climate change scenarios," *2011 International Symposium on Advanced Control of Industrial Processes (ADCONIP)*, Hangzhou, 2011, pp. 662-665.
keywords: {air pollution control;carbon compounds;climate mitigation;combined cycle power stations;power generation economics;power generation reliability;pricing;cost of energy analysis;integrated gasification combined cycle power plant;IGCC power plant;CO2 capture ratio;climate change scenarios;carbon capture and sequestration power plant;COE analysis;Aspen Plus;fuel price;economic reliability;syngas stream power plant;CO2;Power generation;Coal;Meteorology;Biological system modeling;Analytical models;Economics;Data models},
URL:http://ieeexplore.ieee.org.proxy1.lib.uwo.ca/stamp/stamp.jsp?tp=&arnumber=5930508&isnumber=5930387
11. Jeff Biggers,"What Killed the Miners? Profits Over Safety?", Huffington Post, April 6, 2010.
12. “The Toll from Coal” – Clean Air Task Force
13.https://www.academia.edu/19418589/A_Review_of_Greenhouse_Gas_Emission_Liabilities_as_the_Value_of_Renewable_Energy_for_Mitigating_Lawsuits_for_Climate_Change_Related_Damages
14. A. Sood and S. Vyas, "Carbon dioxide capture efficiency determination for post combustion capture through MEA using Aspen HYSYS at low pressure," *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, Chennai, 2017, pp. 1695-1700.
doi: 10.1109/ICECDS.2017.8389738
keywords: {adsorption;air pollution;carbon capture and storage;carbon compounds;chemical engineering computing;chemical technology;coal;combustion;global warming;solvents (industrial);global warming;anthropogenic carbon emissions;sequestration plant;Aspen HYSYS;coal based power plants;carbon dioxide capture;post combustion carbon capture;oil based power plants;monoethanolamine;carbon capture and sequestration plant;sieve type absorber column;MEA corrosive properties;solvent usage;Fluid flow;Carbon

dioxide;Bars;Absorption;Data analysis;Power generation;Combustion;Aspen;Carbon capture;Global warming;MEA;Monoethanolamine;Post combustion},
URL:http://ieeexplore.ieee.org.proxy1.lib.uwo.ca/stamp/stamp.jsp?tp=&arnumber=8389738&isnumber=8389494
15. U. Singh and A. B. Rao, "Estimating the environmental implications of implementing carbon capture and storage in Indian coal power plants," *2014 International Conference on Advances in Green Energy (ICAGE)*, Thiruvananthapuram, 2014, pp. 226-232.
doi: 10.1109/ICAGE.2014.7050169
keywords: {boilers;carbon capture and storage;coal;steam power stations;environmental implication;carbon capture and storage;Indian coal power plants;environmental resources;super-critical plant;environmental impact;particulate matter;coal property;boiler efficiency;power 500 MW;power 660 MW;CO_2;SO_2;NO_x;HCl;Coal;Boilers;Power generation;Green products;Air pollution;Carbon capture and storage;Carbon Dioxide;Carbon Capture and Storage;Environmental Effects;Indian coal power plants},
URL:http://ieeexplore.ieee.org.proxy1.lib.uwo.ca/stamp/stamp.jsp?tp=&arnumber=7050169&isnumber=7050131
16. https://www.worldcoal.org/reducing-co2-emissions/carbon-capture-use-storage
17. https://www.power-technology.com/projects/yuhuancoal/
18. Natural Gas Demand and Uses. (n.d.). Retrieved March 5, 2019, from https://www.e-education.psu.edu/eme444/node/341
19. How Natural Gas Works. (n.d.). Retrieved March 5, 2019, from https://www.ucsusa.org/clean_energy/our-energy-choices/coal-and-other-fossil-fuels/how-natural-gas-works.html
20. Use of Natural Gas. (n.d.). Retrieved March 5, 2019, from https://www.eia.gov/energyexplained/index.php?page=natural_gas_use
21. Biresselioglu et al., 2015 M.E. Biresselioglu, T. Yelkenci, I.O. Oz: Investigating the natural gas supply security: a new perspective. Energy, 80 (2015), pp. 162-174
22. Faramawy et al., 2016 S. Faramawy, T. Zaki, A.A.E. Sakr Natural gas origin, composition, and processing: a review. J. Nat. Gas. Sci. Eng., 34 (2016), pp. 41-52
23. Ibid
24. Ibid
25. C. Biliyok, R. Canepa, M. Wang, H. Yeung. Techno-economic analysis of a natural gas combined cycle power plant with CO2 capture. K. Andrzej, T. Ilkka (Eds.), Computer aided chemical engineering, vol. 32, Elsevier (2013), pp. 190-194
26. Ayhan Demirbas, Mohammad Rehan, Basil Omar Al-Sasi & Abdul-Sattar Nizami (2016) Evaluation of natural gas hydrates as a future methane source, Petroleum Science and Technology, 34:13, 1204-1208
27. Natural Gas Facts. (2018, August 21). Retrieved March 8, 2019, from https://www.nrcan.gc.ca/energy/facts/natural-gas/20067
28. Ibid
29. Ibid
30. Natural Gas Prices - Historical Chart. (n.d.). Retrieved March 10, 2019, from https://www.macrotrends.net/2478/natural-gas-prices-historical-chart
31. U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved March 10, 2019, from
https://www.eia.gov/beta/international/data/browser/#/?pa=g&c=ruvvvvvfvtvnvv1urvvvvfvvvvvvfvvvou20evvvvvvvvvnvvuvo&ct=0&tl_id=3002-A&vs=INTL.3-1-AFG-BCF.A&cy=2011&vo=0&v=H&end=2017
32. Upgrading Natural Gas Technology. (2018, July 23). Retrieved March 10, 2019, from https://www.aiche.org/chenected/2018/07/upgrading-natural-gas-technology
33. Waite, M.W., Rusdinadar, S., Jenkins, S.D., and Bee, M.F., "Using 4D Seismic to Monitor and Improve Steamflood Efficiency," World Oil, November 1998, pp. 51-53.
34. Duplantis, S., "Slide Drilling—Farther and Faster," Oilfield Review (May 2016) 28, No.2: 48-54.
35. Ibid

36. Carter et al., 2011. K.M. Carter, J.A. Harper, K.W. Schmid, J. Kostelnik. Unconventional natural gas resources in Pennsylvania: The backstory of the modern Marcellus shale play. Environmental Geosciences, 18 (2011), pp. 224-229.
37. Environmental Impacts of Natural Gas. (n.d.). Retrieved March 12, 2019, from https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/environmental-impacts-of-natural-gas
38. Ibid
39. Ibid
40. L. Gandossi & U. Von Estorff; An overview of hydraulic fracturing and other formation stimulation technologies for shale gas production – Update 2015; EUR 26347; doi: 10.2790/379646.
41. Kim, W.-Y. (2013), Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. J. Geophys. Res. Solid Earth, 118, doi:10.1002/jgrb.50247.
42. Ibid
43. National Renewable Energy Laboratory (NREL). 2012. Renewable electricity futures study. NREL/TP-6A20-52409. Golden, CO.
44. A. K. Saha, S. Chowdhury and S. P. Chowdhury, "Modeling and simulation of microturbine," *2010 International Conference on Power System Technology*, Hangzhou, 2010, pp. 1-5.
doi: 10.1109/POWERCON.2010.5666085
45. A. Al-Hinai and A. Feliachi, "Dynamic model of a microturbine used as a distributed generator," *Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory (Cat. No.02EX540)*, Huntsville, AL, USA, 2002, pp. 209-213. doi: 10.1109/SSST.2002.1027036
46. Progress in Gas Turbine Performance, Edited by Ernesto Benini, DOI: 10.5772/54444:
https://www.intechopen.com/books/progress-in-gas-turbine-performance/micro-gas-turbine-engine-a-review
47. J. J. Li, "Modeling and Simulation of Micro Gas turbine Generation System for Grid Connected Operation," 2010 Asia-Pacific Power and Energy Engineering Conference, Chengdu, 2010, pp. 1-4. doi: 10.1109/APPEEC.2010.5449304
48. T. Wang and G. Stiegel, Integrated gasification combined cycle (IGCC) technologies. Duxford, United Kingdom: Woodhead Publishing, 2017.
49. Ibid.
50. Ibid.
51. https://www.iea.org/statistics/
52. B. E. Layton, "A comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter," *Int. J. Green Energy*, vol. 5, no. 6, pp. 438-455, Dec. 2008.