Coal Gasification: A Clean Alternative to Combustion

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HSA10—Economics of Oil and Energy
May 5, 2016

1 Coal is Damaging

Coal is an incredibly damaging fuel for energy production when used in a traditional coal plant. Traditional coal combustion plants are mostly pulverized coal plants. The process a pulverized coal plant uses to turn coal into electricity is shown in figure 1. Pulverized coal plants work by first grinding the coal dust into a fine powder. Then injecting it into a firebox where it is combusted to boil water. The boiled water is heated and compressed to temperatures of up to 1000 degrees Fahrenheit and $3,500$ pounds per square inch.[1] The resulting steam drives a turbine that generates electricity.

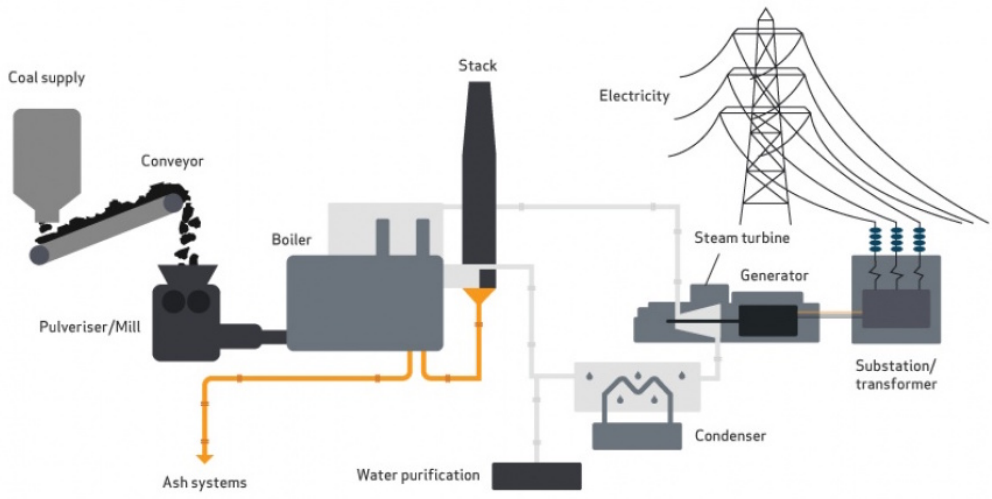

Figure 1: Pulverized Coal Plant[2]

1. "How Do Coal-Fired Plants Work?," Duke Energy, accessed March 2016, `https://www.duke-energy.com/about-energy/generating-electricity/coal-fired-how.asp`.
2. "Coal & electricty," World Coal Association, accessed April 2016, `https://www.worldcoal.org/coal/uses-coal/coal-electricity`.

The problem with this traditional design is the pollution from combustion. When coal dust is burned it creates a large amount of pollutants, including: carbon dioxide, methane, nitrogen oxides, and sulfur dioxide.[3] These pollutants cause lots of environmental damage. Carbon dioxide and methane are widely known green house gases. Nitrogen oxides damage fresh water ecosystems, and carbon dioxide causes acidification of oceans.[4] A Harvard study estimated that damages from coal pollution caused up to "24,475 excess deaths in 2005, with a cost of $187.5 billion" from "damages to public health, property, crops, forests, foregone recreation, and visibility".[5] The pollution caused from the combustion of coal can seem "far away" when talking about these environmental damages, but the Harvard study shows coal pollutants have a direct effect on our lives. The damages from coal combustion mean that it actually costs the public more than it seems, and makes its continued use as an energy source unsustainable.

2 Coal is Plentiful

Despite coal combustion being an incredibly damaging method of generating electricity, coal has good qualities as a resource. Coal is inexpensive and plentiful. These two qualities offer stability and security. This is important for investors and utilities who desire to make profits from energy production. And is also important for consumers and businesses, most of which use electricity every second of the day.

To compare the cost of coal to alternative resources we will need to look at the levelized costs of the power plants that use them. The levelized cost of a power plant is a kind of amortized cost which attempts to determine the average price of the power generated over the plant's lifetime. The big expenditures that contribute to a levelized cost are: initial capital investment, fuel, maintenance, and operation.

Coal's main competitor for electricity generation is natural gas. The levelized costs of various coal and natural gas technologies are shown in figure 2. We can see from figure 2 that traditional coal is more expensive that natural gas. Furthermore, traditional coal is way more polluting than natural

3. "Environmental impacts of coal power: air pollution," Union of Concerned Scientists, accessed March 2016, http://www.ucsusa.org/clean_energy/coalvswind/c02c.html#.VtfVX5MrKRs.

4. Paul R. Epstein et al., "Full cost accounting for the life cycle of coal," *Annals Of The New York Academy Of Sciences* 30 (Ecological Economics Reviews 2005).

5. *The Hidden Costs of Energy: Unpriced Consequences of Energy Production* (National Research Council, 2005).

6. "Investment Decisions for Baseload Power Plants," National Energy Technology Laboratory, accessed April 2016, http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/InvestmtDecsnsBsldPP4.pdf; "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015," Energy Information Administration, accessed April 2016, https://www.eia.gov/forecasts/aeo/electricity_generation.cfm#3.

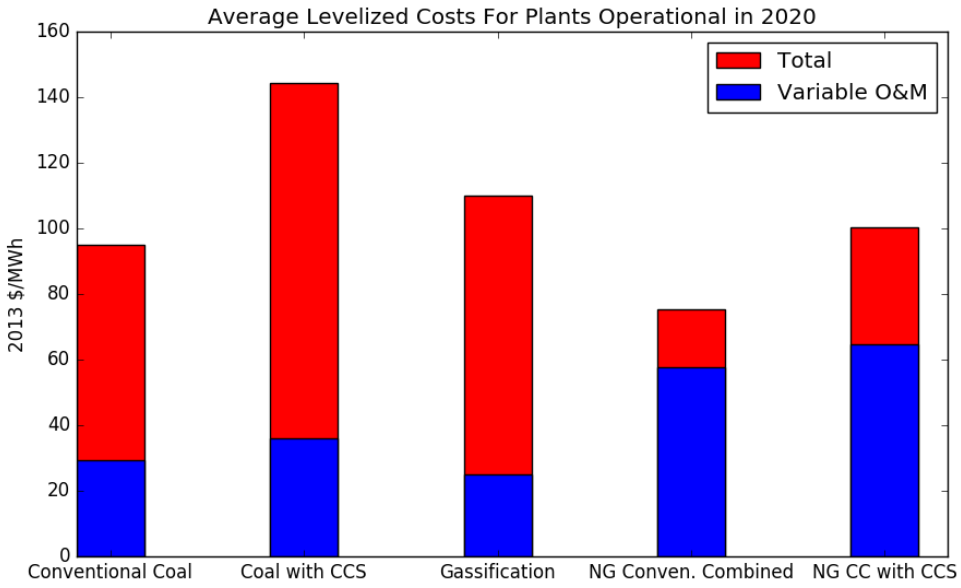

Figure 2: Levelized Costs[6]

gas is. This makes it seem that natural gas is the best option.

However, this bar plot does not tell the whole story. Natural gas prices are currently at an incredible low because of the recent boom of fracking. This sudden increase in supply has caused many storage centers to near capacity, driving prices down.[7] These low prices are likely not to stay in the long term. Both the rising environmental concerns of fracking and low oil prices make these fracking wells unlikely to continue producing at their current rate.[8] When natural gas production falls, natural gas prices will rise. This will make the levelized cost of the two natural gas options rise, which will shrink the price gap between coal and natural gas.

Although conventional natural gas is cleaner than conventional coal, it is not cleaner than gasification or coal with carbon capture and storage (CCS). If we are looking for an option cleaner than conventional natural gas, then our options are natural gas with CCS, coal with CCS, or gasification.[9] Coal with CCS is too expensive to be competitive. However, the gap between gasification and natural gas with CCS is relatively small. This means the natural gas price would not have to rise much to make gasification the cheapest clean option.

7. Keith Robinson, "Natural gas prices expected to stay low, too," Purdue University, April 2016, `https://www.purdue.edu/newsroom/releases/2015/Q4/tyner-natural-gas-prices-expected-to-stay-low,-too.html`.

8. KSE Focus, "States Take Wait and See Approach on Fracking Regulation," Congress.org, accessed April 2016, `http://congress.org/2015/07/09/states-take-wait-and-see-approach-on-fracking-regulation/`.

9. "Gasification," US Department of Energy, accessed March 2016, `http://energy.gov/fe/science-innovation/clean-coal-research/gasification`.

Considering all of these factors: raw cost, pollution, and environmental concerns, it can be seen that coal is in the fight for the cheapest resource.

Another aspect that makes coal appealing is its large supply. The US Department of Energy estimates that the US has coal reserves of about 480 billion short tonnes.[10] To get an idea of how much that is we will make a rough estimate of how long it would take the US to use that coal. The United States processed about 980 million short tonnes of coal in 2013, and the high estimates of coal production are about 1250 million tonnes by 2040. Suppose that because of property rights and or technology barriers, only 380 tonnes of the coal reserve is obtainable (about 80 %). Now suppose our coal production instantly rose to $4,000$ million short tonnes a year. Even with these unlikely estimates we still have 95 years of coal left,

$$\frac{380 \cdot 10^9 \cdot \text{tonnes}}{4 \cdot 10^9 \cdot \text{tonnes} \ / \ \text{year}} = 95 \cdot \text{years}.$$

This should be plenty of time to fully transition to renewable energy.

Furthermore, this reserve being in the United States ensures that the US government has the ability to control the price of the coal during an international crisis; thus, providing even more security by reducing the chance of a shortage of supply.

This large supply is important because it means coal is likely to have a steady price in the future. Coal's steady price is apparent when compared to natural gas's. As can be seen in figure 3, the price of history of coal (red) is much more stable than that of natural gas (green). This figure only shows price histories, but this price security of coal is not likely to change because its supply is plentiful, especially in the United States.

It might seem that this long term price security of coal is only important for investors because power plants tend to have a large upfront cost, and therefore, need to produce consistent income for several years to come. Yet, this price security is important to everyone because of how ubiquitous the use of electricity is. Average citizens rely on electricity in nearly every facet of their lives. Furthermore, electricity is integral to nearly every commercial and industrial business, making the price security of electricity important to the whole economy. The stability of coal's price gives security to the investor, businesses manager, and citizen.

Despite the enormous damage that coal pollution causes, it seems unreasonable to not utilize such

10. "U.S. Coal Reserves," US Department of Energy, accessed March 2016, `http://www.eia.gov/coal/reserves/`.
11. "Economic Competitiveness," US Department of Energy, accessed March 2016, `http://www.netl.doe.gov/research/coal/energy-systems/gasification/economic-competitiveness`.

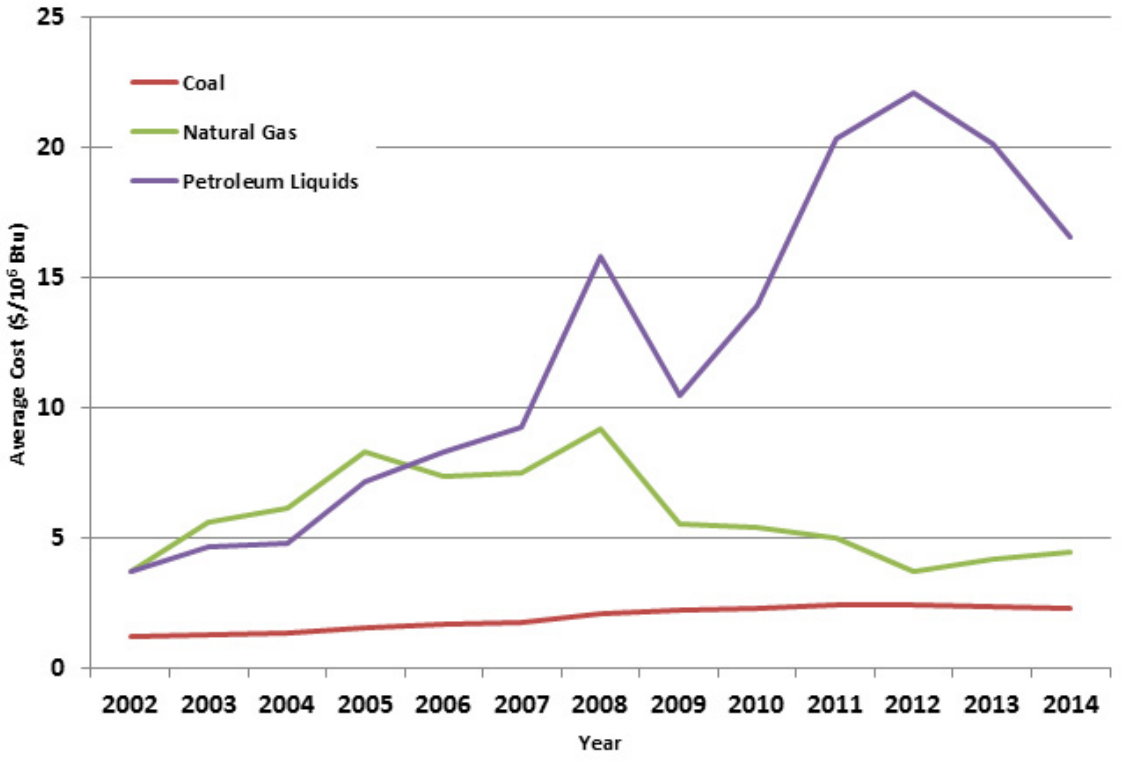

Figure 3: Price Histories[11]

an inexpensive and stable resource for generating electricity.

3 Gasification Process

Coal has historically been an extremely damaging fuel for power generation. In many old cities the buildings have become coated with a layer of the particulate exhaust from coal combustion. In addition, to making the buildings look dirty and disgusting it caused corrosive damage to their structures. In modern cities this kind of pollution is no longer as apparent as it once was. However, modern coal plants that still use the traditional method of burning coal in a fire box produce less visible, but, as discussed in section 1, still harmful pollutants.

Yet, as was just discussed in section 2, coal has great qualities of inexpensiveness and security. A potential solution to this conundrum is gasification. Gasification does not burn the coal to generate power. Instead it decomposes the coal into syngas so that is can be burned cleanly. Gasification is a new clean way to utilize the benefits of coal.

3.1 How Gasification Works

The process of gasification is shown in figure 4. Gasification starts in the gasifier where extreme heat and pressure cause the coal to decompose into syngas. Unlike traditional combustion, the vast majority of the coal is not burned in gasification. Instead just a small amount of the coal is burned. The heat and pressure from this small amount of coal causes the coal to decomposes into syngas: a mixture of hydrogen, carbon monoxide, and small amounts of carbon dioxide.[12] (Coal has a large amount of hydrogen, and is where most of the hydrogen gas comes from.) To fuel this combustion there is a controlled amount of oxygen added to the mixture. The final ingredient in the chemical reaction of the decomposition of coal is steam. This mixture of coal, oxygen, and steam proceeds through several chemical reactions in the gasifier to produce the desired syngas.

Just after the syngas is produced is the first step that generates power. Although the syngas is unprocessed and not ready to be used, it is still incredibly hot. This excess heat is captured in water and used for power generation.

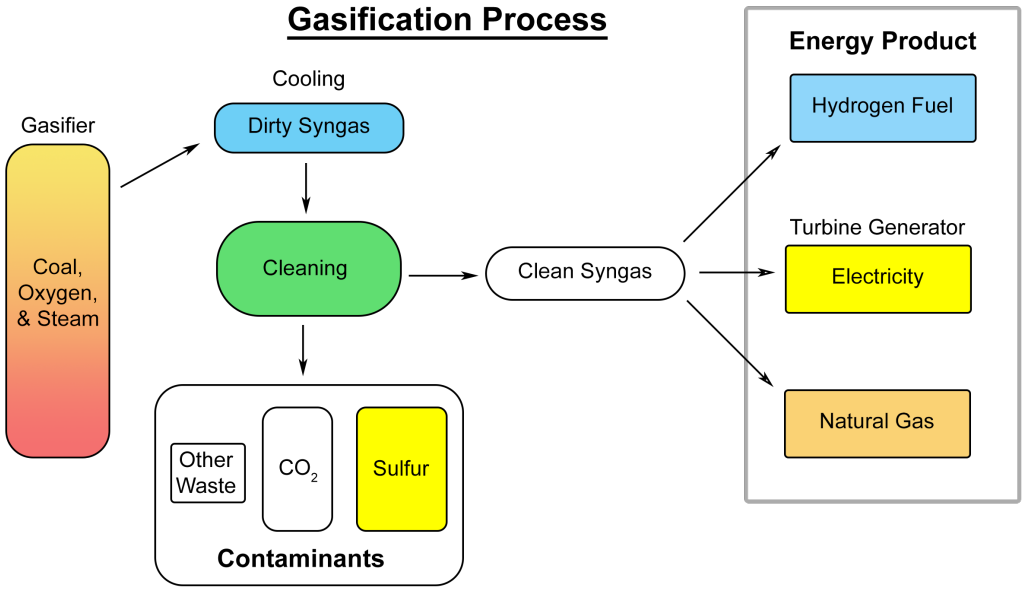

Figure 4: Gasification Process

To be utilized further the syngas produced from the gasifier needs to be cleaned. First, particulate matter still remaining in the gas is removed. Then, the gas is cleaned of remaining contaminants. The two most voluminous gases removed are carbon dioxide and hydrogen sulfide.[13] This now clean

12. "GASIFICATION INTRODUCTION," US Department of Energy, accessed March 2016, `http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/intro-to-gasification`.
13. Ibid.

syngas is almost all hydrogen gas and is ready to be utilized for energy generation.

This cleaning process is similar to techniques that modern pulverized coal plants use to reduce their pollution. However, the reaction is much more controlled in gasification, so the contaminants are much more concentrated. This may seem bad at first, but depending on the method used the contaminant sulfur may be obtained in either a solid or liquid form. Either way, the sulfur is at a high enough concentration to be sold as a commercial product—an additional income source. The carbon dioxide may seem to be a waste. Yet, in some cases it can also be sold for profit. One, such commercial use of carbon dioxide is to improve yields from oil drilling.[14] If there are no commercial markets for the carbon dioxide, then it can be safely piped into under ground storage and not be released as a pollutant.

The now clean syngas can be used in a variety of ways to produce energy. Operations entirely focused on electricity generation will burn the syngas as a fuel in an on-site turbine.[15] However, there are two other commonly utilized options. One is to further process the syngas into synthetic natural gas, how the Great Plains Dakota Gasification Plant processes its syngas.[16] Another is to further purify the syngas into hydrogen gas. The natural gas or hydrogen gas can then be sold as a fuel. Regardless of the route chosen, gasification successfully converts the energy contained in the original coal to a clean energy source.

3.2 Gasification is Cleaner

Gasification offers a clean way to take advantage of the benefits of coal because it hardly pollutes when compared to traditional coal combustion. Gasification makes this possible because instead of burning the coal, it is converted into syngas. This syngas is nearly all hydrogen gas. When hydrogen gas is burned it becomes water. Thus when the syngas is burned to generate electricity it does not produce the pollutants that burning the coal from the start would have produced.

Chemically this is possible because the reaction takes place in a highly controlled environment. The ingredients in the gasification reaction are limited to calculated amounts of oxygen, steam, and coal. This means nitrogen oxides are not produced because, unlike combustion, the coal is not burned in

14. "CO2 Capture and Storage," Dakota Gasification Company, accessed March 2016, `http://www.dakotagas.com/CO2_Capture_and_Storage/index.html`.

15. Evangelos Tzimas and Stathis D. Peteves, "The impact of carbon sequestration on the production cost of electricity and hydrogen from coal and natural-gas technologies in Europe in the medium term," *Energy* 30 (14 2005).

16. "Gasification," Dakota Gasification Company, accessed March 2016, `http://www.dakotagas.com/Gasification/`.

the presence of raw air, which contains nitrogen.[17] Furthermore, the remaining contaminants that do get produced, mainly carbon dioxide and sulfur compounds, are at a much higher concentration and at a much higher pressure. The higher pressure means less volume to clean compared to the near atmospheric pressure of a traditional plant. The higher concentration of pollutants makes the filtering more effective.[18] This high concentration also has the benefit of allowing for the these toxins to be gathered in large enough quantities at high enough purities to be sold. This means they do not need to be sent to and stored in a toxic waste facility. Together, these qualities of gasification can make it a cleaner process than burning natural gas.[19]

Besides not producing nearly any gaseous pollutants, gasification also offers an improvement in efficiency over traditional coal. For comparison, we can calculate the efficiency of a coal fired power plant by taking the number of Btus in a kWh (3,412 Btu) and dividing it by the heat rate of the power plant. The United States department of energy reports that the average heat rate of coal power generation in 2014 was 10428 Btu, so,

$$\frac{3,412}{10,428} \approx 32.7\%,$$

traditional coal power plants are about 32.7% efficient.[20] Meaning about 32.7% of the energy in the coal they burn becomes electricity. On the other hand, gasification plants currently offer about 40% efficiency. This might not seem like much, but it is about a 22% increase in efficiency, and means that gasification requires about 18% less coal to produce the same amount of electricity as a traditional coal plant.[21] Furthermore, the US DOE expects this could rise to 80% in the next couple of years, which means gasification would use about 60% less coal.[22]

This increased efficiency has two major benefits. First, it reduces emissions even more by consuming less coal to produce the same amount of power—potentially less than half of what is currently used. Second, it means the coal reserve will last longer because it will be used slower. Although, some criticisms of coal argue that coal scrubbing technology will decrease the efficiency of generation, gasification plants actually have higher efficiency than traditional coal plants.[23]

Gasification offers a clean way to utilize coal as an inexpensive and stable source of fuel. Unlike

17. "Emission Advantages of Gasification," US Department of Energy, accessed March 2016, `http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/low-emissions`.
18. Ibid.
19. "Gasification."
20. "What is the efficiency of different types of power plants?," US Department of Energy, accessed April 2016, `https://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3`.
21. "Gasification."
22. Ibid.
23. Epstein et al., "Full cost accounting for the life cycle of coal."

traditional combustion, it does not burn the coal, which normally release large amount of pollutants. Instead it decomposes the coal in to syngas, which is mostly hydrogen gas, and can be burned cleanly. Together these qualities make gasification pollute even less than natural gas.

4 Economics of Gasification

Gasification is far superior to traditional combustion when you look at how much they pollute. However, there are currently only four coal gasification plants operating in the United States. The main force preventing the widespread adoption of the technology are momentum, low natural gas prices, and the lack of stronger pollution regulations.

The momentum to adopt the technology is low because there is a lack of previously successful commercial examples. This has two effects. One, it dissuades investors because the lack of previous successful examples makes the investment's success less certain. Two, the equipment and facilities that gasification plants require are more expensive than they could be because they must be custom designed and built for gasification.[24] However, the National Energy Technology Laboratory has a list of 61 proposed projects in the United States, 24 of which are in active construction as of March 2016.[25] These proposed plants show this lack of momentum is not a big enough hurdle to prevent further adoption of gasification. The adoption of gasification plants might be slow to start up, but eventually the momentum issue will not be problem.

The current issue of low natural gas prices is likely to change in the next couple of years. As discussed in section 2, natural gas prices are not likely to stay as low as they currently are. If you look back at figure 2 than you can see that natural gas with carbon capture is just barely cheaper than gasification. Since coal and natural gas are so close in price just a small rise in natural gas prices could make gasification the more economically successful option.

Another benefit that will come in the next couple of years is more stringent pollution regulations. These will be a big help because gasification is expensive when its free to pollute, as seen in figure 2. However, gasification can be less polluting than natural gas. Thus, when a price is put on pollution it costs gasification less than it does natural gas. As seen in figure 5, as carbon dioxide pollution becomes more expensive, the gap between the cost of gasification (green) and natural

24. "Challenges For Gasification," US Department of Energy, accessed March 2016, `http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/challenges`.

25. "United States Proposed Gasification Plant Database," National Energy Technology Laboratory, accessed April 2016, `http://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/gasification/worldwide%20database/US-Gasification-Database.xlsx`.

26. "Investment Decisions for Baseload Power Plants."

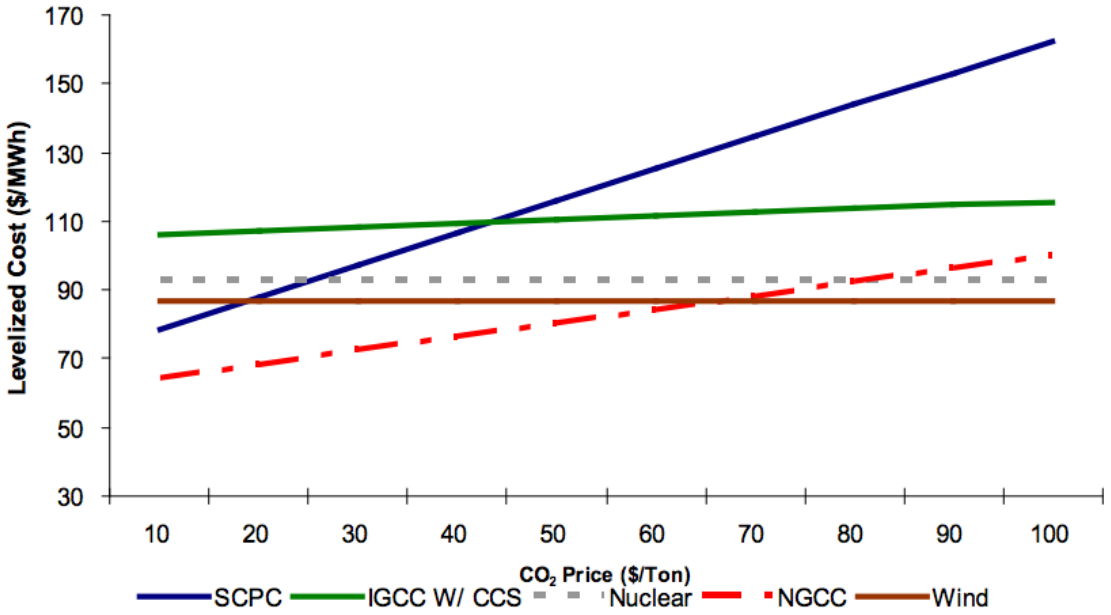

Figure 5: Levelized Cost vs. Pollution Cost[26]

gas (red dashed) decreases. Thus gasification becomes more and more economically viable as the cost of pollution rises, which it is likely to do as the world becomes more concerned with global warming.

4.1 Hybrid Plants

A final benefit of gasification is its ability to be flexible in what it produces. As briefly discussed in section 3.1, gasification is not limited to one output. It can produce a multitude of products; the most common being electricity, hydrogen, and synthetic natural gas. Since the process to produce these products is the same until the last step, it is relatively easy to make a plant that can produce multiple products.[27] The main benefit of this is to flexible in the amount of electricity produced. This is important because in our current grids excess electricity generated is just wasted. Whereas fuels like hydrogen and natural gas do not need to be consumed immediately and can be stored until purchased.

This kind of flexibility is typically thought of as an advantage that natural gas has over coal. Natural gas plants are good at adjusting their output to meet the current demand. Whereas, traditional coal plants cannot quickly adjust their power output, and therefore, must produce enough electricity

27. F. Starr, E. Tzimas, and S. Peteves, "Critical factors in the design, operation and economics of coal gasification plants: The case of the flexible co-production of hydrogen and electricity," *International Journal of Hydrogen Energy* 32 (10-11 2007).

for peak demand. This makes natural gas plants more efficient because they do not need to always generate enough electricity for peak demand, which wastes electricity.

Gasification also has the potential to be flexible, but in a better way than natural gas. The main difference is, unlike natural gas plants, gasification plants are not limited to producing electricity. This allows gasification plants to run at maximum output all the time. The plant only burns enough syngas to meet the current electricity demanded.[28] The excess syngas it produces can then be used to make hydrogen gas (or synthetic natural gas). Since gasification plants can run at maximum outpu all the time, they can take advantage of more profit opportunities than natural gas.[29] When natural gas lowers its power output to meet demand, it lowers its potential profits. Gasification uses its extra capacity to make fuel, which it later sells. This dynamic potential of gasification gives it incredible flexibility which translates into increased efficiency and increased profits.

5 Future of Gasification

The ultimate energy goal is, of course, to transition to all renewable power. Most of these technologies create virtually no pollution and will never run out. However, we still have a long way to go before this is possible. In the mean time we will need to utilize fossil fuels.

Many people think of natural gas as the cleanest process to utilize fossil fuels as we transition. Yet, gasification is even cleaner.[30] Currently, gasification is more expensive than natural gas. However, this is likely to change in the near future because the natural gas fracking boom is likely to bust from environmental concerns. In fact, two states have already banned fracking along with many other municipal districts in the United States.[31] Furthermore, gasification uses coal as a fuel which has a much more stable price history. Gasification is a cleaner and more secure way to take advantage of fossil fuels than natural gas.

The flexibility of hybrid gasification plants makes them integrate better with renewable technology. Hybrid gasification plants have the ability to generate electricity and hydrogen fuel. This flexibility is important as we transition to renewable power because many renewable technologies, such as solar and wind, are not constant sources of power. For example, when the wind dies down, or when it is night time, the wind or solar generators may not produce enough electricity to meet demand, but the gasification plant can increase its output to maintain demand. Natural gas can have this

28. Starr, Tzimas, and Peteves, "Critical factors in the design, operation and economics of coal gasification plants: The case of the flexible co-production of hydrogen and electricity."
29. Ibid.
30. "Gasification."
31. Focus, "States Take Wait and See Approach on Fracking Regulation."

flexibility too, but instead of wasting their extra capacity, gasification plants can use it to produce hydrogen fuel.[32] This hydrogen fuel fits in perfectly with many other new clean technologies such as the Toyota Mirai, a hydrogen powered car. Gasification offers the flexibility that will be required as we transition to renewable power.

Gasification is not a perfect solution, but in the years to come it will help bridge the gap to a fully renewable society. It is the cleanest way to utilize fossil fuels as we transition to renewable technology and allows us to take advantage of coal as an inexpensive and stable fuel source. Gasification will keep our electricity flowing as we conquer the hurdles of transitioning to renewable sources.

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32. Starr, Tzimas, and Peteves, "Critical factors in the design, operation and economics of coal gasification plants: The case of the flexible co-production of hydrogen and electricity."

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