# Coal Gasification: A Clean Alternative to Combustion

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*I am thinking of adding more of an introduction here with a brief outline of the whole paper. Yes? No?*

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## 1 Coal is Damaging

A large component of the damage done by coal comes from traditional power plants. The most common of which are pulverized coal plants. The process of coal in a pulverized coal plant 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.

The problem with this traditional design is the pollution from combustion. When coal dust is burned it creates a large amount of pollutants, some of which are: carbon dioxide, methane, nitrogen oxides, and sulfur dioxide.[3] These pollutants cause lots of environmental damage. For example, carbon dioxide and methane are widely known green house gases. Nitrogen oxides damage fresh water ecosystems, and carbon dioxide causes acidification of oceans.[4] The pollution caused from the combustion of coal can seem "far away" when talking about these environmental damages, but these pollutants also have a direct effect on our lives. 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

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`.
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).

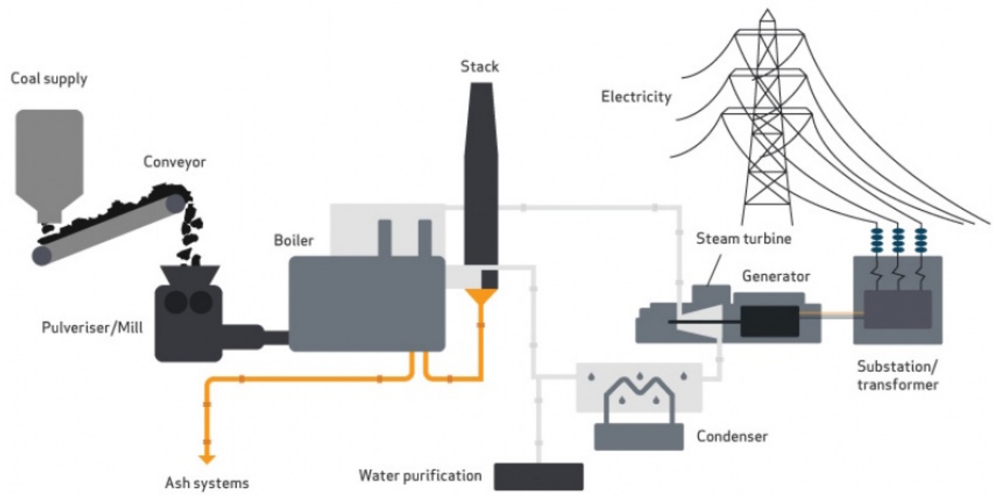


Figure 1: Pulverized Coal Plant[2]

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, but it is also important to consumers and businesses. When fuel prices rise so will the cost of electricity for consumers and businesses.

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. It turns out that traditional coal is actually more expensive that natural gas. In fact, this is not even a fair comparison because traditional coal is way more polluting than natural gas is. From this plot it seems that natural gas is actually a clear winner. However, this bar plot does not tell the whole story. Natural gas prices are currently

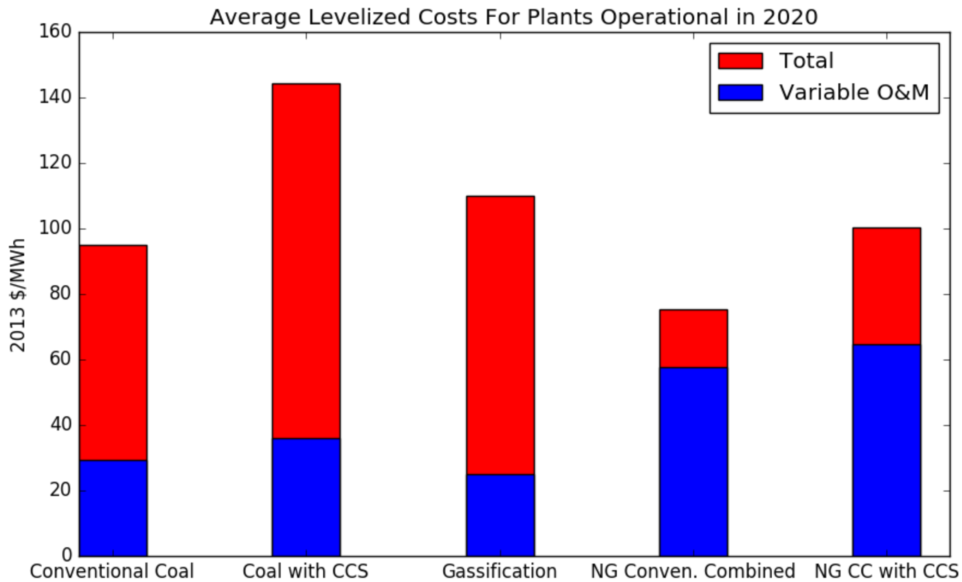


Figure 2: Levelized Costs[6]

at an incredible low because of the recent increase in fracking. This sudden increase in supply has not been caught up with by demand, which has caused many storage centers to near capacity, and drive prices way down.[7] These low prices are likely not to stay. Both the rising environmental concerns of fracking and low oil prices make these fracking wells unlikely to continue producing at the rate they currently are. When natural gas production falls, natural gas prices will rise again and may make coal the cheaper source again. Furthermore, the two of these that pollute the least are gasification and natural gas with carbon capture and storage. It can be seen that natural gas with CCS still has a slight edge on gasification, but it is very small. Either way, coal is definitely in the fight for the cheapest resource to generate electricity.

Another aspect that makes coal appealing is its steady price. This recent volatility of natural gas prices is not uncommon. As can be seen in figure 3, the price of history of natural gas (green) is much more unstable than the price history coal (red). This long term price security of coal is important for investors because power plants tend to have a relatively large upfront cost, and therefore, need to produce consistent income for several years to come. This price security of fuel also leads to a price security of electricity. The price security of electricity is very important to the economy because it is used in nearly ever commercial operation and is integral to nearly every citizen's life. The stability of coal's price gives security to the investor, businesses manager, and

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`.

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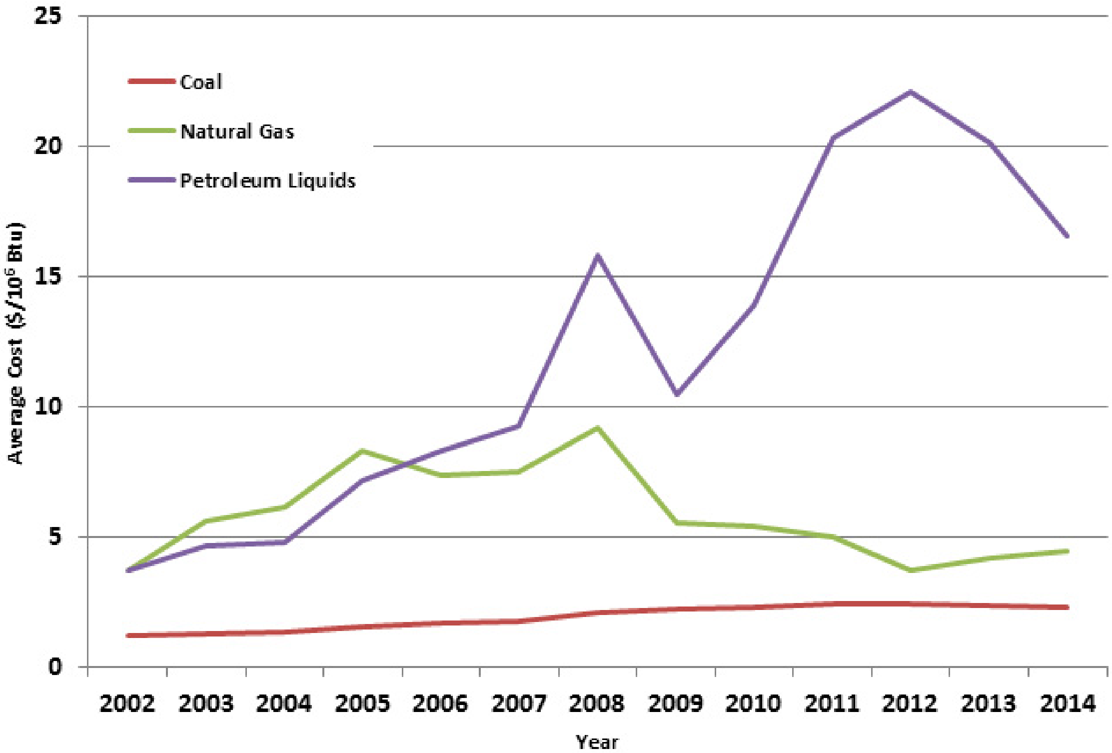


Figure 3: Price Histories[8]

This historical price security of coal is also not likely to change because its supply is plentiful. Not only is coal's supply plentiful in the world, but specifically in the United States. The US Department of Energy estimates that the US has coal reserves of about 480 billion short tonnes.[9] 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 about 95 years of coal left,

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

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.

9. "U.S. Coal Reserves," US Department of Energy, accessed March 2016, `http://www.eia.gov/coal/reserves/`.

Despite the enormous damage that coal pollution causes, it seems unreasonable to not utilize such an inexpensive and stable resource for generating electricity.

## 3 How Gasification Works

A potential solution to this conundrum is gasification. The precess of gasification is shown in figure 4. 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.[10] (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.

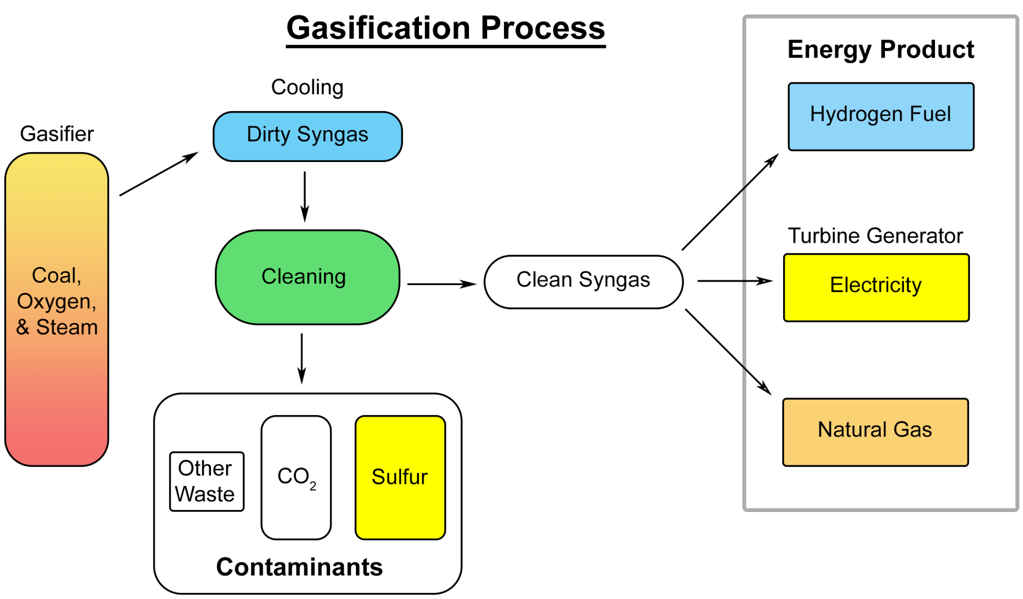


Figure 4: Gasification Process

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

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.[11] This now clean 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, since the reaction is much more controlled in gasification, 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.[12] 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 clean syngas can be used in a variety of ways to produce energy. Operations entirely focused on electricity generation will now burn the syngas as a fuel in an on site turbine.[13] However, there are two other commonly utilized options. One, is to further process the syngas into synthetic natural gas. This is done in the Great Plains Dakota Gasification Plant.[14] Another is to further purify the syngas into just hydrogen gas. The natural gas or hydrogen gas can then be sold as a fuel. Regardless of the route chosen, gasification has successfully converted the energy contained in the original coal to a clean energy source.

## 4 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 all the coal it is converted into syngas. This syngas is nearly all hydrogen gas. When hydrogen gas is burned it just 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.

11. "GASIFICATION INTRODUCTION."
12. "CO2 Capture and Storage," Dakota Gasification Company, accessed March 2016, `http://www.dakotagas.com/CO2_Capture_and_Storage/index.html`.
13. 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).
14. "Gasification," Dakota Gasification Company, accessed March 2016, `http://www.dakotagas.com/Gasification/`.

Chemically this is possible because the reaction takes place in a highly controlled environment. Nitrogen oxides are not produced because, unlike combustion, the coal is not burned in the presence of raw air, which contains nitrogen. Instead, the ingredients are limited to calculated amounts of oxygen, steam, and coal. This means there is virtually no nitrogen exposed to the reaction and nearly eliminates the concentration of NOx.[15] 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.[16] 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. In fact, these qualities of gasification can make it a cleaner process than burning natural gas.[17]

Besides not producing nearly any gaseous pollutants, gasification also offers an improvement in efficiency over traditional coal. First, 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.[18] Meaning about 32.7% of the energy in the coal they burn becomes electricity. Then we can compare this to the efficiency of gasification plants which 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.[19] 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.[20]

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.

15. "Emission Advantages of Gasification," US Department of Energy, accessed March 2016, http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/low-emissions.
16. Ibid.
17. "Gasification," US Department of Energy, accessed March 2016, http://energy.gov/fe/science-innovation/clean-coal-research/gasification.
18. "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.
19. "Gasification."
20. Ibid.

Second, it means the coal reserve will last longer because it will be used slower. Furthermore, some criticism of coal argue that coal scrubbing technology will decrease the efficiency of generation by $25\% - 40\%$, which may be true for traditional coal plants, but gasification actually increases efficiency.[21]

## 5 Economics of Gasification

Gasification is clearly 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. But, 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.[22] 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.[23] However, since there are so many proposed plants, this lack of momentum is clearly not a big enough hurdle to prevent any startups. Thus the adoption of gasification plants might be slow to start up, but eventually the momentum issue will not be problem.

The current low natural gas prices are likely to change in the near future. 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 actually 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.

Even more beneficial for gasification 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

21. Epstein et al., "Full cost accounting for the life cycle of coal."

22. "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`.

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

can be cleaner 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 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.

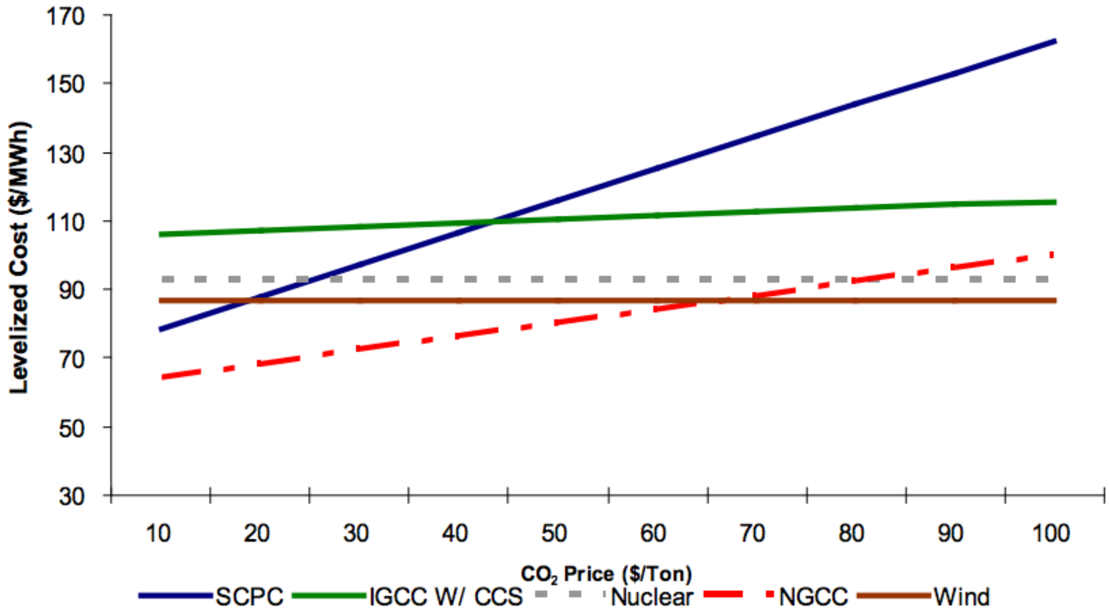


Figure 5: Levelized Cost vs. Pollution Cost[24]

Another advantage that gasification has is its ability to be dynamic in what it produces. This kind of flexibility is typically thought of as an advantage that natural gas has over coal. Natural gas plants are very good at adjusting their power output to meet the current demand. Whereas, traditional coal plants cannot quickly adjust their power output, and therefore, must produce enough electricity 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. However, Gasification also has the potential to be dynamic because it can produce things other than electricity. A dynamic gasification plant produces the maximum amount of syngas it can at any time, but it only burns enough syngas to meet the current electricity demanded.[25] The gasification plant can then use whatever excess syngas it produces to make hydrogen gas (or synthetic natural gas). This flexibility is even better than natural gas's because a gasification plant can always be operating at maximum output. This allows gasification to take advantage of more profit opportunities than natural gas.[26] When natural gas lowers its power output to meet demand, it lowers its potential

25. 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).

26. Ibid.

profits. Gasification uses its extra capacity to make fuel, which it later sells. This dynamic potential of gasification gives it incredibly flexibility which translates into increased efficiency and increased profits.

## 6 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 still need to utilize fossil fuels.

Many people think of natural gas as the cleanest alternative to utilizing fossil fuels as we transition. Yet, gasification is even cleaner.[27] 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.[28] 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 allows them to provide just the right amount of electricity required. As we transition to renewable power this flexibility is very important 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 flexibility too, but instead of wasting its extra capacity gasification plants can use it to produce hydrogen fuel.[29] 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 take advantage of the inexpensiveness and price security

27. "Gasification."
28. 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/.
29. 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."

of coal. It will hold us to together as we conquer the hurdles of transitioning to renewable sources.

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