

**AN ASSESSMENT OF CARBON SOURCES
FOR THE PRODUCTION OF SYNTHETIC FUELS FROM
NUCLEAR HYDROGEN**

By

MinWah Leung

Submitted to the Department of Nuclear Science and Engineering in partial fulfillment of
the requirements for the degree of

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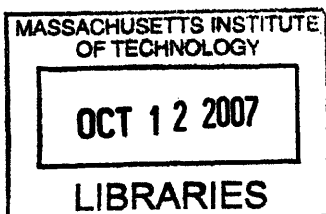
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ABSTRACT

In the transportation sector, the current dependence on petroleum to satisfy large transportation fuel demand in the US is unsustainable. Oil resources are finite, and causing heavy US reliance on oil imports. Therefore, the development of alternative transportation fuels that do not depend on oil is becoming increasingly necessary.

Our research investigates the feasibility of producing gasoline synthetically from nuclear hydrogen and two carbon sources: carbon dioxide emissions and municipal solid waste. These synthetic fuels have the potential to satisfy the large demand for gasoline, while reducing CO₂ emissions. The nuclear hydrogen is produced through High Temperature Steam Electrolysis (HTSE), with heat and electricity provided by a supercritical CO₂ cooled gas fast reactor. Through this study, we determine the suitable components for gasoline production from CO₂ emissions and MSW. The feasibility of these methods of gasoline production was assessed by performing material and energy balances for the involved processes, determining preliminary cost estimates, and evaluating production scale and environmental impact.

The material balances were compatible with our gasoline production scheme. By-product oxygen from the HTSE was especially beneficial for both production schemes, leading to various efficiency improvements. Water that is generated in the production processes can also displace a portion of water input for HTSE. By matching HTSE H₂ output with H₂ requirement of each production scheme, gasoline can be produced on a large scale. Gasoline output from MSW and coal plant CO₂ emissions was about 1 million gallons/day and 550,000 gallons/day, respectively. These gasoline outputs are similar to SASOL Fischer-Tropsch plant in South Africa and the New Zealand methanol-to-gasoline plant.

The base price of our synthetic gasoline was \$4.35/gallon and \$4.04/gallon for gasoline produced from CO₂ and MSW, respectively. These costs will not be competitive with current US oil prices, but has high potential to compete with unconventional oil sources if oil prices rise significantly in the future. Carbon dioxide emissions can be significantly reduced with both production schemes, with MSW producing zero net emissions.

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1 Introduction

1.1 Overview

Today, the world is faced with an increasingly urgent and severe energy situation. The tremendous level of energy consumption is depleting our natural resources and causing a variety of environmental consequences. We are heavily dependent on a finite amount of non-renewable resources such as coal and oil. Meanwhile, the large amounts of greenhouse gas emissions that are released from burning fossil fuels are leading to global warming. As energy demand is growing rapidly with the emergence of developing countries such as India and China, these concerns are becoming even more pressing. In light of these issues, we must find new solutions to energy security and limiting greenhouse gas emissions for a sustainable future.

The issue of finite resources is particularly relevant to the transportation industry. Currently, 90% of all transportation fuels are derived from crude oil [1]. Furthermore, the need for transportation fuel is the main driver of rapid growth in oil consumption today. The magnitude of this consumption has generated major concerns over the dependence on foreign oil and the effects of carbon dioxide emissions on climate change. As a result, there is a need for alternative sources of transportation fuel that do not depend on oil.

This research investigates a solution for producing gasoline that both mediates the environmental concerns and satisfies the large gasoline demand in the US. Gasoline can be made synthetically from sources besides fossil fuels, where the primary method of producing these synthetic fuels requires hydrogen and a carbon feedstock. Our proposed system for synthetic fuel production involves hydrogen produced using nuclear reactors, and two potential carbon feedstock: carbon dioxide emissions from power plants and municipal solid waste.

The idea of producing synthetic fuels from these sources has been previously suggested in literature [2,3,4]. However, the details of the integrated process have not been examined. The full gasoline production scheme consists of many subprocesses, such as hydrogen production, carbon extraction from the carbon source, and conversion of these materials into gasoline. While the technologies of these subprocesses are known, the feasibility of linking these subprocesses together remains unknown. For example, the

hydrogen produced may not be enough to react with the amount of carbon dioxide, or the amount of energy required may be impractical. Therefore, determining the energy and material balance for each subprocess is essential for assessing the feasibility of the integrated process.

The objectives of our research are therefore to assess the feasibility of the integrated production scheme in three ways:

- Determine the energy and material balance for each subprocess, as well as how these processes need to be scaled
- Perform preliminary cost estimates to determine the competitiveness of our synthetic gasoline with current gasoline costs
- Finally, analyze the environmental impact and potential for large scale gasoline production

1.2 Relevant Energy Conditions

1.2.1 Transportation Fuel Consumption

Transportation undoubtedly plays a significant role in our lives today. As a result, we consume a great amount of energy for transportation purposes. In 2005, the transportation sector accounted for 28.11 quadrillion BTU, about 28% of total US energy consumption [1]. Comparatively, this is only second to the electric power sector, which accounted for 39% of total US energy consumption. Transportation energy use is expected to increase 1.4% per year until 2030 [1]. With our heavy reliance on transportation today, the demand for transportation fuel will undoubtedly continue to grow. As 98% of transportation fuels are currently derived from oil, we have also developed a dependence on crude oil.

In 2005, Americans consumed 9159 thousand barrels per day (or 400 million gallons per day) in motor gasoline alone, with about 200 million gallons per day from personal vehicles [1]. An additional 4580 thousand barrels per day of jet fuel and diesel vehicle fuel are produced. Oil consumption for transportation fuel was 13.5 million barrels per day in 2005.

With an increase in transportation energy use, liquid fuel demand is also expected to increase since vehicle efficiencies are not projected to increase as rapidly as vehicle use in the country [1]. Figure 1-1 shows projected US energy consumption from 1980-2030 by fuel. As seen in this figure, liquid fuels are expected to lead growth in total US energy consumption.

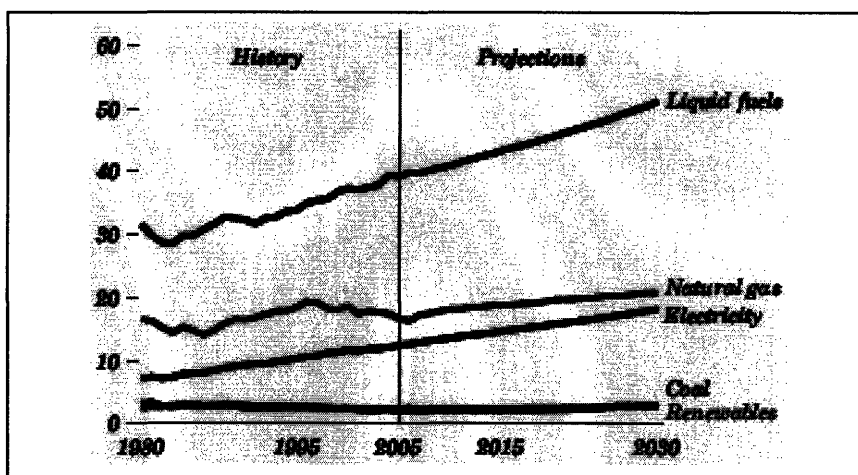


Figure 1-1. Delivered Energy Use by Fuel , 1980-2030. Source:[1]

According to EIA predictions [1], oil consumption for transportation will exceed 10 million barrels/day in 2014. Total US oil consumption is projected to grow at rate of 1.3%. All projections in this report are based on the reference case, which considers average level oil prices and economic growth rate. The immensity of transportation fuel consumption today presents several major concerns for the future, primarily energy security and carbon dioxide emissions.

1.2.2 Energy Security

From the growing needs in transportation, we are rapidly depleting our crude oil resources. Although the amount of oil available in the future is debatable, oil is a non-renewable resource, and the supply is ultimately limited. With the emergence of rapidly developing countries such as India and China, world oil reserves are expected to deplete at an even higher rate. Oil consumption for transportation in China and India are expected

to grow at a rate of 4.2% and 2.8%, respectively [1]. This growth rate is two to three times greater than the increase in the US.

In addition, the upgrading of oil into usable transportation fuels requires additional fossil fuel resources. As this current solution is not sustainable, we need to seek alternative transportation fuels that do not depend on oil. In the short term, alternative fuels can assist in reducing oil consumption, and in the long term, they can exclusively replace petroleum-derived fuels.

A second aspect of energy security is US dependence on oil imports. As a result of the large oil consumption dominated by the transportation sector, the US relies heavily on foreign oil. Currently, the US imports 12 million barrels per day. With the increase in transportation fuel demand, this value is expected to increase to 17 million barrels per day in 2030 [1]. On the contrary, domestic oil supply is only expected to grow 20% by 2030, showing that oil supply will become increasingly reliant on foreign oil. Political instability of the Middle East makes this supply volatile and unpredictable. Therefore, the US government has expressed hopes of reducing this dependency on oil [5].

1.2.3 Carbon Dioxide Emissions

Carbon dioxide (CO₂) emissions have become a major environmental concern in recent years. As a greenhouse gas, carbon dioxide traps solar radiation within the Earth's atmosphere. This leads to a gradual increase in the Earth's temperature—global warming. CO₂ emissions from fossil fuel burning is the largest contributor to the annual rise in global temperature. This is especially true because rapidly growing countries such as India and China are expected to raise world CO₂ emissions by a tremendous amount within the next decade [1].

Global warming indirectly leads to various imbalances in the environment. The melting of the polar ice caps, and subsequent rise in ocean levels is likely to cause increased flooding around the world. Additionally, an imbalanced distribution of solar radiation may cause more extreme weather. Many more indirect feedback effects on climate change remain unknown.

The transportation sector accounts for over 30% of CO₂ emissions in the US each year. The fraction of emissions from transportation is expected to increase [1], emphasizing the need to focus on reducing CO₂ emissions from the transportation sector.

Our proposal of making gasoline from nuclear hydrogen and carbon source can reduce carbon dioxide emissions. With hydrogen produced from nuclear energy, carbon dioxide emissions are negligible in the production of hydrogen. Recycling carbon dioxide emissions from power plants has a high potential for reducing CO₂ emissions. By recycling the emissions, the CO₂ emissions are essentially halved. Instead of CO₂ released from both power plants and gasoline consumption, CO₂ would only be released from gasoline consumption.

The second option with a high potential for CO₂ reduction is using biomass as a carbon feedstock. In the case of biomass, although CO₂ is emitted in the burning of gasoline, CO₂ is absorbed in the photosynthesis process when biomass is grown. As a result, the net CO₂ emissions is zero.

2 Synthetic Fuels

The technology for producing synthetic fuels is known and well developed. It was mainly developed during World War II to convert coal into gasoline in locations where oil resources were not accessible. The conversion processes were further advanced and commercialized during the energy crisis and rise in oil prices in the 1970s. However, the subsequent decrease of oil prices in the 1980s halted the need and interest in synthetic fuels. Thus, many of the demonstration and commercialized plants were shut down [2]. As the energy problem becomes more urgent, synthetic fuels provides an option for the future. This research involves the two synthetic fuel production processes that output gasoline: Fischer-Tropsch (F-T) and Mobil M.

2.1 Fischer-Tropsch

The Fischer-Tropsch process converts a mixture of CO/CO₂/H₂ into gasoline. This mixture of CO/CO₂/H₂ is commonly known as syngas, and is derived from gasifying

carbon feedstock such as coal or biomass. However, often the H₂ to CO ratio of the syngas from coal and biomass gasification is not sufficient for producing gasoline products. Gasoline products require a syngas H₂ to CO ratio of about 2. As a result, hydrogen from an external source is often necessary to increase the syngas ratio.

The only remaining commercialized plants utilizing the Fischer-Tropsch process are the SASOL plants in South Africa. First established in 1950, the SASOL plants has been converting coal into gasoline, and is the main source of gasoline supply for the country [6]. The SASOL plants have experienced great success in South Africa since oil resources are limited, but coal resources are abundant. SASOL I produced 850 tonnes of gasoline per day, or 300,000 gallons of gasoline per day. The development of SASOL II increased gasoline output to 50,000 barrels of gasoline per day, or 2 million gallons of gasoline per day [2].

2.2 Mobil M

Mobil M is a process that converts methanol to gasoline. As methods of producing methanol have been well established, Mobil M allows the further conversion of this product into gasoline. Methanol can be readily synthesized from syngas, or solely from CO₂. Similarly to F-T, a certain amount of external hydrogen is necessary to produce methanol, depending on whether the reactant is syngas or solely CO₂. The Mobil M process then utilizes a catalyst to select for the large hydrocarbon molecules present in gasoline.

The Mobil M process was discovered in the 1970s and commercialized in New Zealand. As natural gas is readily available in New Zealand, the Mobil M plant produced gasoline from syngas made by reforming natural gas. Methanol output was 4400 tonnes of methanol per day, while gasoline output was 7.5 million gallons gasoline per day [2]. However, the plant was ultimately shut down when the synthetic gasoline produced could not compete with the decrease of world oil prices during the 1980s.

3 Sources of Carbon

Many carbon sources for the production of gasoline have been identified in previous literature [2,4,7]. This study investigates two carbon sources: carbon dioxide emissions from coal plants and municipal solid waste. We focus on these two carbon sources due to their potential for practical implementation in the future. These carbon sources can lead to a significant reduction in CO₂ emissions, and can be employed on a large scale. In addition, the technologies to extract the carbon from these sources and convert these materials to gasoline have been established and are well developed.

3.1 CO₂ Emissions from Coal Plants

Although coal plants are the largest producers of CO₂ emissions in the energy sector, coal is projected to remain the primary fuel for energy generation in the next century [1]. This is because coal is abundant and available at low cost in the US, as well as in China. With the growing energy demands in the US and China, the availability of coal resources on a large scale will undoubtedly continue to play a large role in energy generation.

Nonetheless, significant amounts of CO₂ will be released if measures for mitigation are not taken. According to the MIT Coal Study, over 500 coal fired power plants produce 3 million tonnes of CO₂ per year in the US [8]. Coal plants are the largest contributors to total CO₂ emissions, accounting for 33% in 2005 [1]. Projected CO₂ emissions from coal plants are displayed in Table 1. The values in Table 1 correspond to an increase of 1.6% per year. By 2030, the CO₂ emissions from coal plants will total almost 3000 million tonnes per year.

Table 3-1. Projected CO₂ emissions from coal plants. Source: [1]

Year	2005	2015	2030
CO ₂ (million tonnes)	1944	2203	2927

The major method of CO₂ mitigation discussed in recent literature is carbon capture and sequestration. However, sequestration is characterized by several

disadvantages. The captured CO₂ can only be stored at suitable sequestration geological sites, such as coal beds and empty oil fields. CO₂ must therefore be transported from the site of emissions to the sequestration site. The required infrastructure for pipeline transportation and injection into geological formations is vast and expensive. In addition, CO₂ leaks in this vast infrastructure is inevitable, and difficult to detect.

A more effective method of mitigation is recycling of the CO₂ emissions into useful products. As CO₂ emissions contain carbon, they can be combined with H₂ to produce synthetic fuels. By converting the CO₂ emissions from coal plants into gasoline, the amount of CO₂ emitted into the atmosphere is greatly reduced. The reduction of emitted CO₂ is approximately half, as CO₂ is captured from the power plants, but still emitted when the gasoline is combusted in vehicles.

Several previous studies have suggested methods of the using CO₂ to make synthetic fuels [3,4]. Middleton et al [9] discusses the production of ethanol and methanol from CO₂ emissions. General Atomics has suggested converting CO₂ into gasoline through the Fischer-Tropsch process. Our research details the conversion of CO₂ and H₂ to produce methanol, and then conversion of methanol into gasoline. The production of methanol as an intermediate step provides the option of using methanol as the end product fuel, or a fuel additive. Additionally, the intermediate step is convenient, as the methods of converting CO₂ into methanol are well established [10,11]. The optimal types of coal plants for CO₂ capture and conversion into gasoline is described through the next sections.

Before CO₂ emissions can be used, it must first be captured from the flue gases which exit the power plant. The capture process includes CO₂ isolation followed by a purification and compression system. Of the different methods of capture, monoethanolamine (MEA) is the most considered technology for capture in air-blown plants [8]. CO₂ capture lowers efficiency and adds significant cost to a typical air-blown plant. CO₂ capture requires a 37% increase in plant size and coal feed rate [8]. The difficulty in isolating CO₂ is mostly due to the low CO₂ concentration in the flue gases.

Another method of carbon capture is through oxygen combustion in a power plant, examples being IGCC and oxyfuel supercritical PC plants. The cost of the carbon capture system is lower for oxygen combustion, mostly a result of the high CO₂ concentration in

the flue gases. The carbon capture system for oxygen combustion only consists of a purification and compression system. However, oxygen production is expensive and has high energy requirements.

3.2 Municipal Solid Waste

There has been much recent interest in using biomass as an alternative energy source. Biomass is renewable, and produces zero net CO₂ emissions. Any CO₂ emitted from biomass is absorbed by the biomass when it is grown. In addition, sulfur and nitrogen concentrations in biomass are low, preventing harmful SO_x and NO_x emissions into the atmosphere. There exists many ways for biomass conversion to transportation fuels. Figure 3-1 shows the possible methods of conversion.

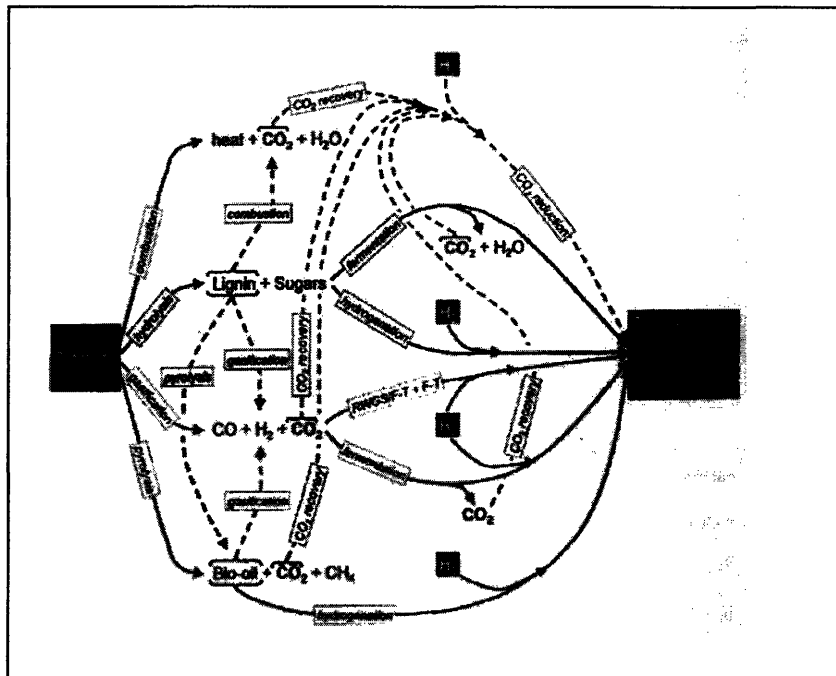


Figure 3-1. Biomass conversion to synthetic fuels. Source: [12]

In recent years, the conversion of corn to ethanol has received wide attention in the media. However, several major disadvantages have prevented biomass from becoming a cost-effective and viable energy source. Crops have immense land and water requirements. This prevents large-scale conversion of biomass into combustible products.

With the scale of gasoline consumption in the US today, the land needed to grow the amount of energy crops is not feasible. Furthermore, the growth of energy crops competes with the national food supply.

One form of biomass is an exception to these disadvantages: municipal solid waste (MSW). MSW is defined as non-hazardous waste generated by the residential, commercial, and industrial sectors. This includes paper, food scrap, and yard trimmings, but does not however include residual wastes such as agricultural waste, sewage sludge, or batteries. Figure 3-2 depicts the composition of MSW. The organic component of MSW that can be converted to syngas is approximately 60% by mass. As also seen from this figure, sulfur and nitrogen content is low, indicating low emissions of air pollutants such, as SO_x and NO_x.

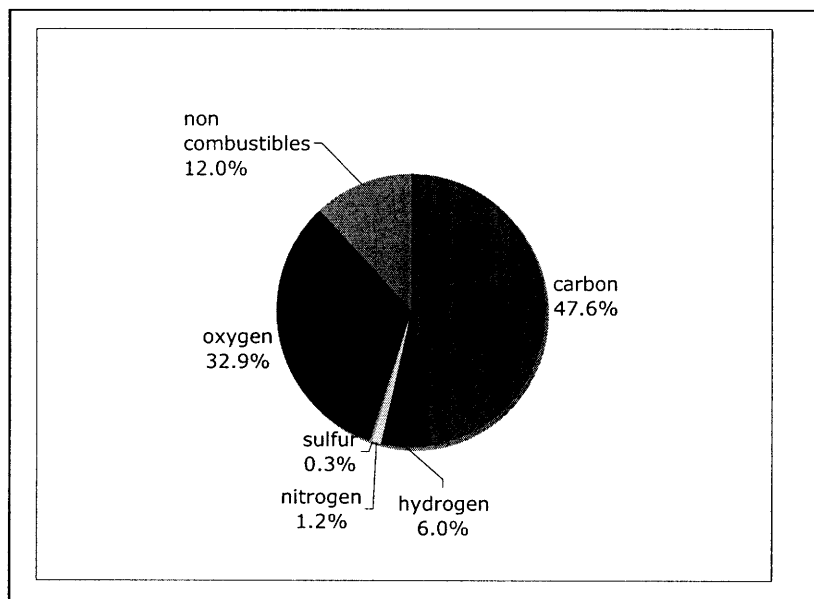


Figure 3-2. Composition of MSW. Adapted from [13]

Approximately 245 million tons of MSW is produced each year in the US [13]. Of the 245 million tons, 79 million tons are recycled. This leaves about 166 million tons that is sent to landfills or incinerated. The magnitude of these values indicate that the large supply of MSW is capable of supporting large-scale gasoline production.

The advantages of converting MSW to gasoline are manifold. MSW is abundant and generated on a steady basis. Conventionally, MSW is a waste that must be disposed

of in landfills or through incineration. The conversion of MSW into gasoline recycles the waste, creates a second useful product, and eliminates the need for disposal. Land for landfills will become more constrained in the future, and require more incineration of MSW. However, incineration is expensive and releases toxic emissions. A second major advantage of MSW as a carbon source for fuel production is that as a biomass feedstock, MSW produces zero net CO₂ emissions. Lastly, the infrastructure for MSW collection is already established. As a result, unlike other energy sources, MSW does not require the development of a vast new infrastructure.

The most efficient method of converting MSW into gasoline is through MSW gasification. The gasification of MSW produces synthetic gas, which can be subsequently converted to gasoline. Such gasifiers have already been studied and developed in the past, with the Union Carbide PUROX process having the most success [14]. Although several demonstration plants were built in the US and Europe, the high cost of oxygen production was one of the major reasons for plant discontinuation.

4 Gasoline Production

4.1 Proposed Production Schemes

Two production schemes are proposed for synthesizing gasoline from hydrogen and coal plant CO₂ emissions and municipal solid waste as carbon feedstocks. In both production schemes, hydrogen is produced from High Temperature Steam Electrolysis. A nuclear power plant provides the heat and electrical energy required to boil and split water entering the HTSE unit.

Figure 4-1 shows the integrated gasoline production scheme for using CO₂ from coal plants as the carbon source. Coal is burned in the power plant for electricity generation, and CO₂ is emitted and captured. By-product oxygen from the HTSE feeds into the coal power plant to improve combustion efficiency, as well as facilitate carbon capture. Captured CO₂ emissions from a coal plant feed into a methanol synthesis plant along with hydrogen output from the HTSE unit. Under proper reaction conditions, the H₂ and CO₂ combine to form methanol. The methanol is finally converted to gasoline in a Mobil M plant.

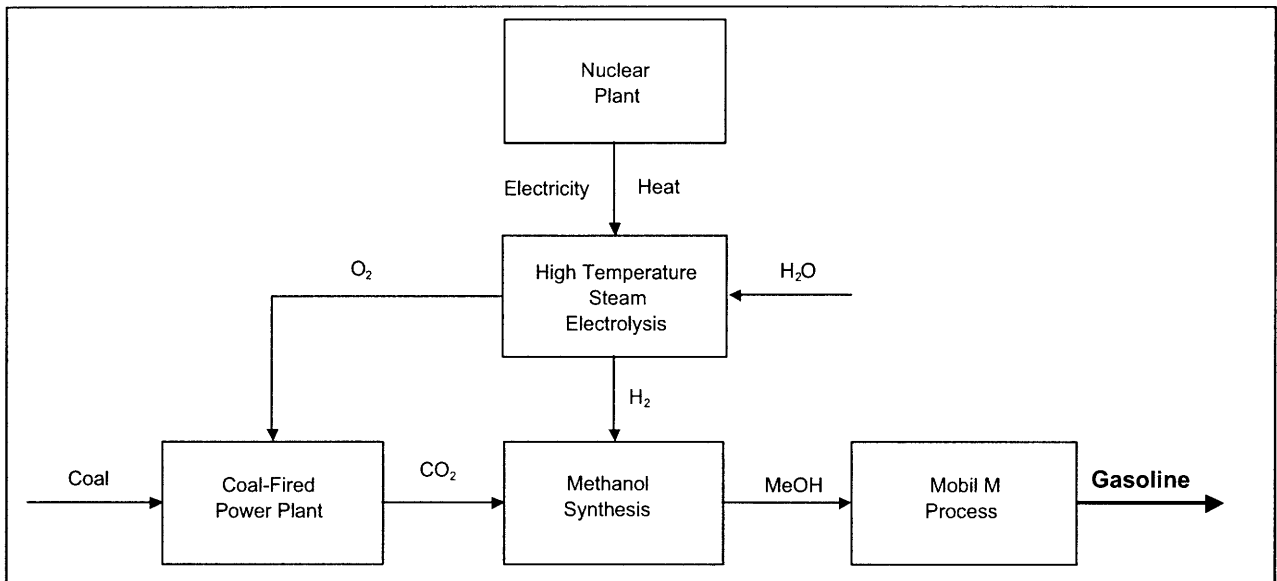


Figure 4-1. Gasoline production using CO₂ emissions from a coal plant as the carbon source

Figure 4-2 depicts the schematic of a gasoline production system using MSW as the carbon source. As MSW contain non-organic material, the metals and non-organic material must first be separated from the combustible, organic portion of the MSW. The filtered MSW then feeds into a gasifier. The by-product oxygen from HTSE feeds into the gasifier with the MSW, converting the carbon content of MSW into syngas.

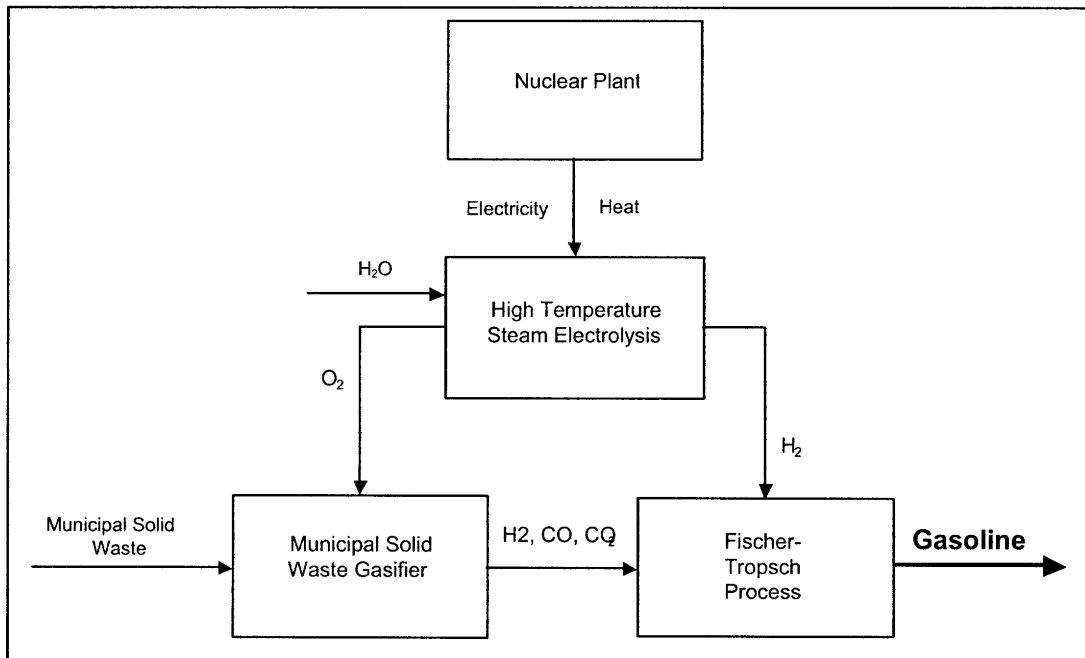


Figure 4-2. Gasoline production from MSW as carbon feedstock.

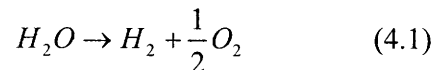
Although H₂ is present in the syngas, the H₂/CO mole ratio is not suitable for the production of gasoline. As a result, H₂ must be added from the HTSE to increase the H₂/CO ratio to approximately 2. The syngas is then transformed into gasoline through the Fischer Tropsch process.

Syngas from the gasifier can also be used to produce methanol before conversion to gasoline, with the Mobil M process discussed above. However, as CO is one of our gasification products and an optimal reactant for F-T conversion, we focus on MSW conversion to gasoline through the F-T process. Moreover, the final gasoline yield is higher without an intermediate methanol step.

4.2 High Temperature Steam Electrolysis (HTSE)

The High Temperature Steam Electrolysis (HTSE) unit produces hydrogen for fuel production. The heat and electricity required by the HTSE process is supplied with a nuclear power plant. Much recent effort has focused on the development of HTSE units coupled with Gas Fast Reactors [12]. Such HTSE units have been tested on a small scale and optimized to achieve high efficiency heat and electricity generation.

The electrolysis reaction is described by Eq. (4.1):



Conventional electrolysis has relatively low efficiencies, as it requires large amounts of electricity. However, the amount of electricity needed to split water in the electrolytic process decreases as a function of increasing reaction temperature. As a result, high temperature steam electrolysis allows for higher hydrogen production efficiencies.

The HTSE-GFR system chosen for hydrogen production is described by Memmott et al [12]. The nuclear plant is a 2700 MWth GFR, cooled with supercritical-CO₂. A visualization of the complete HTSE-GFR system is shown in Figure 4-3. The main heating of the steam to high temperatures occurs directly before the HTSE unit, where the heat is supplied by recuperated heat from the output oxygen and hydrogen streams. Steam enters the HTSE unit at 870°C.

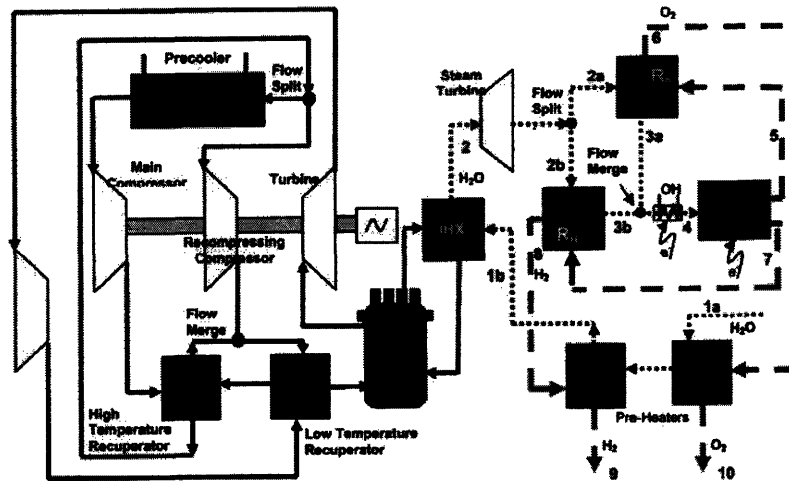


Figure 4-3. Schematic of HTSE-GFR. Source: [12]

The 2700 MWth GFR provides the necessary heat and electricity for the electrolysis process. Figure 4-4 shows the energy balance of the reactor. Of the 2700 MWth that is output by the reactor, 234.7 MWth is extracted through the water boiler loop to boil the feedwater into steam. The remaining thermal energy output from the reactor is converted into 108 MWe of electricity in the reactor's power conversion system.

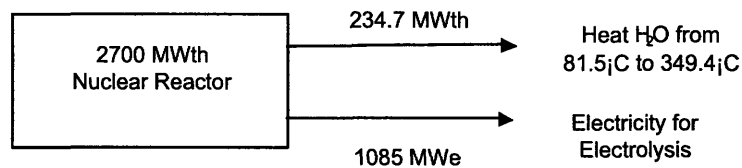


Figure 4-4. Energy balance of nuclear reactor for HTSE

The HTSE unit uses the 1085 MW of reactor output electricity to split high temperature steam into hydrogen and oxygen. Figure 4-5 shows the input and outputs of the electrolysis process.

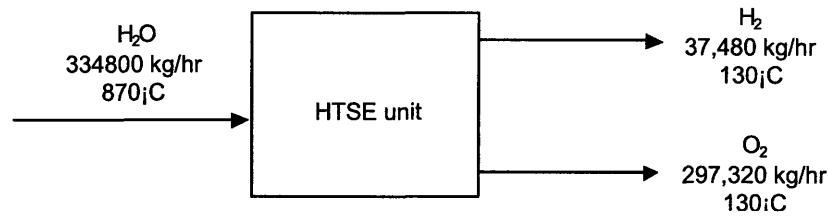


Figure 4-5. Material balance of HTSE unit. Adapted from [12].

The HTSE-GFR arrangement produces 37,480 kg/hr, or 900 tonnes H₂ per day. Based on the stoichiometry of Eq. (1), the amount of water needed is 93 kg/s, corresponding to 93 L/s. Although the water requirement is large, water can be considered readily available. Furthermore, recycling water output from other parts of the fuel production process can satisfy approximately 60% of the water requirement.

As seen from the output streams, 297,320 kg/hr of oxygen is produced as a by-product of hydrogen production from HTSE. This oxygen output is advantageous in our fuel production schemes, as a large amount of oxygen is required for combustion in coal plants and MSW gasification. Conventional methods of oxygen production, such as air separation units, are expensive and require a significant amount of energy. The details of oxygen fired coal plants and MSW gasifiers are further discussed in Sections 4.3.1 and 4.4.1.

4.3 CO₂ emissions production components

4.3.1 Coal Plant

As coal resources remain abundant and cheap, coal is expected to continue as the preferred option for electricity production. However, coal plants release unmitigated amounts of CO₂ into the atmosphere. In our proposed solution, these carbon emissions are utilized as the carbon source for producing gasoline.

With heightened concerns about global warming and air pollutants, many of the recent coal initiatives have pursued higher efficiency plants with cleaner combustion of coal. In particular, two types of plants have been in development to achieve these goals: oxygen-fired Supercritical PC plants (or oxy-fuel plants) and Integrated Gasification Combined Cycle (IGCC). These two plants burn coal in oxygen, instead of air. The major

advantages of oxygen combustion are facilitated CO₂ capture and more efficient combustion. CO₂ capture is difficult in air-blown plants because the partial pressure of CO₂ in the exit stream is low. In addition, oxygen combustion is more efficient because much fewer harmful emissions are generated and therefore much less energy is needed to remove the emissions. However, oxygen production is expensive and energy intensive.

Oxygen is generally generated via an air separation unit, in which oxygen is filtered from nitrogen. The major cost and energy disadvantages have prevented oxygen-fired plants from being implemented. For a 500 MWe oxygen-fuel pulverized coal combustion, the air separation unit requires an additional 105 MWe [8]. In this type of plant, the efficiency reduction due to the energy required for oxygen production exceeds the noted efficiency improvements. As oxygen is a by-product of the HTSE, it can be supplied to these plants for combustion. Such an arrangement eliminates the large energy requirements for oxygen generation by air separation.

In comparing oxy-fuel supercritical PC plants and IGCC plants, the oxy-fuel plant is more suitable for our synthetic fuel production process. The oxy-fuel plant is an established and less sophisticated technology compared to IGCC. Oxyfuel plants are simply conventional PC plants supplied with oxygen instead of air, while IGCC is a less developed technology. Additionally, the capital cost of the IGCC plant is much higher than conventional PC plants [8]. Oxy-fuel supercritical PC combustion is currently in pilot-scale development, with projects in the Europe and Canada [8,16].

Table 4-1 notes the essential material balances for a 500 MWe Oxy-Fuel Supercritical PC coal plant, as presented in the MIT *The Future of Coal* study [8]. The plant produces an additional 105 MWe required for oxygen generation from an air separation unit. The coal feed is generalized to be Illinois #6 bituminous coal.

Table 4-1. Material flows for a 500 MWe Oxy-Fuel Supercritical PC coal plant. Source: [8]

<i>Input</i>	Material flow kg/hr
Coal feed	233 000
Oxygen	480 000
<i>Output</i>	
Captured CO ₂	470 000

The oxygen output of the HTSE unit is 297,300 kg/hr. This value is approximately 60% of the oxygen input for a 500 MWe Oxy-Fuel Supercritical PC coal plant. The plant can be scaled down 60% to 300 MWe to match the oxygen and hydrogen output from the HTSE. Based on the values in Table 4-1, the material flow of the same oxygen fired coal plant rated at 300 MWe is shown in Figure 4-6. Full calculations of the material and energy flows for gasoline production from coal plant CO₂ are in Appendix A.

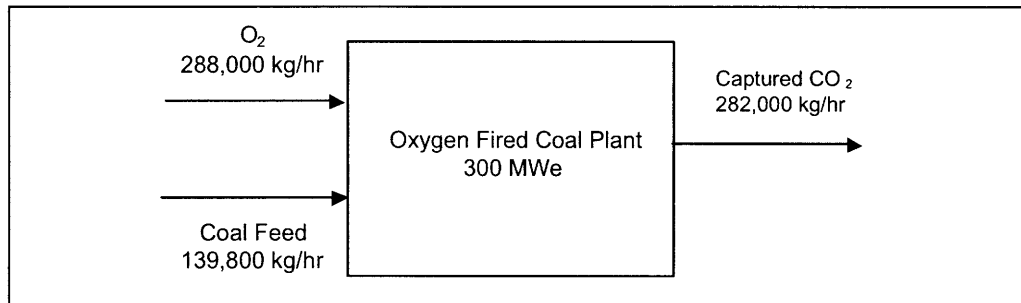


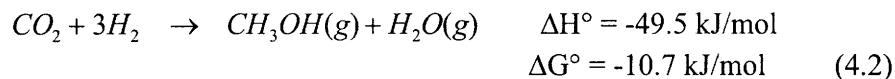
Figure 4-6. Material flow of 300 MWe oxy-fuel supercritical PC coal plant

The oxygen supplied by HTSE saves the coal plant 63 MWe that would be used to generate oxygen. With this oxygen supply, the oxy-fuel supercritical PC plant becomes an attractive option for future sustainable electricity production. The plant no longer has a 6.4 percentage point efficiency reduction from oxygen generation, and the efficiency improvements dominate over conventional air-blown coal plants. The oxy-fuel plant also releases significantly less particulate emissions and employs a simpler and cheaper carbon capture system.

4.3.2 Methanol Synthesis

In the next step of gasoline production from CO₂, methanol is synthesized from the nuclear hydrogen and the CO₂ captured from coal plants. The process of converting CO₂ and H₂ to methanol has been demonstrated, and considerable research has been done previously [2,10,11]. Additionally, catalysts have been developed for the practical application of this conversion. In Japan, several bench-scale plants producing methanol from CO₂ and H₂ have been built to test the conversion under different catalysts and reaction conditions [11].

The mass and energy balances of CO₂ and H₂ conversion to methanol are governed by Eq. (4.2):



This reaction is exothermic at all temperatures and pressures. However, the temperature and pressure at which the reaction occurs affect the yield of methanol. An increase in reaction pressure leads to a more negative Gibbs free energy, corresponding to a more spontaneous reaction. At conventional reaction conditions, the yield of methanol is relatively low. The maximum yield, which occurs when the reaction is at 423K and 15 MPa, is only about 70%. In order to produce a higher yield, the unreacted gases must be recycled. In one Japanese bench plant using a Cu/ZnO/Al₂O₃ catalyst, the yield of methanol was more than 90% at 512 K, 8 MPa, and a recycle ratio of 4 [10]. For calculation purposes, the methanol yield was therefore assumed to be 90% in our analysis.

The Japan bench plants [10] used a 3:1 H₂/CO₂ feed gas ratio, agreeing with the stoichiometry in Eq. (4.2). The gaseous phase of the methanol output is also compatible with the Mobil M process, whose input is gaseous methanol.

Figure 1 shows a block diagram of methanol synthesis from nuclear hydrogen and CO₂ emissions. The flow rates of each reactant are taken from the rates of carbon capture and hydrogen production.

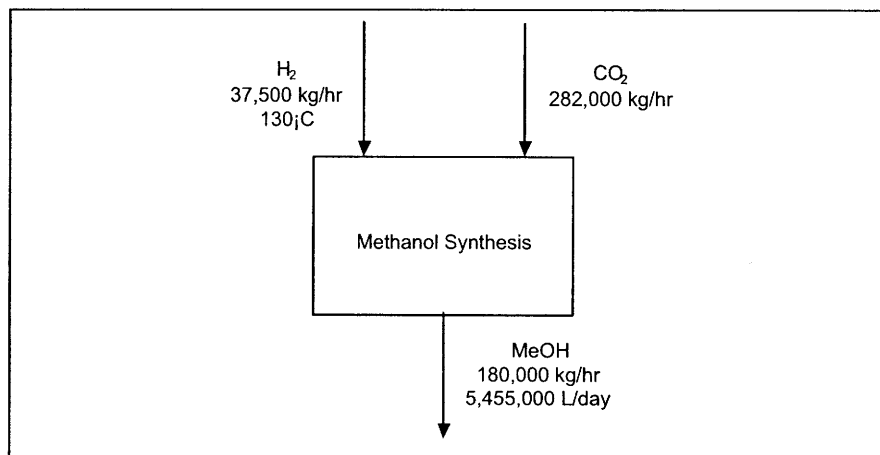


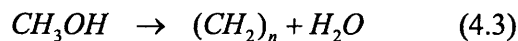
Figure 4-7. Methanol synthesis from nuclear hydrogen and CO₂ emissions.

As discussed above, three moles of hydrogen are required for each mole of CO₂ to produce one mole of methanol. Using this stoichiometric relation, 38,500 kg/hr of hydrogen is needed to completely react with the 282,000 kg/hr of CO₂. The hydrogen output from the HTSE of 37,500 kg/hr is similar in value to the 38,500 kg/hr hydrogen requirement to completely react with the CO₂ produced. The 3% difference between these values is within the uncertainty of our calculations. With H₂ as the limiting reactant, 180,000 kg/hr of methanol is produced. Our plant would therefore produce 4320 tonnes per day, which is similar to the 4400 tonnes of methanol per day produced by the New Zealand plant.

The output methanol can then be easily converted to gasoline through the Mobil M process. However, the output methanol can also be used as an end-product fuel or as a fuel additive. Middleton et. al. discusses the implications of methanol production from this method for use as an end-product fuel to replace gasoline [9].

4.3.3 Methanol to Gasoline

The final step of the proposed production of synthetic fuels is the conversion of methanol into gasoline through the Mobil M process. The overall reaction for the Mobil M process is shown in Eq. (4.3):



A mixture of hydrocarbons and water are produced from methanol. Table 1 shows the material and thermal balances of the Mobil M process. The products of our fuel production system were calculated from the shown material balance. The thermal balance indicates that 10,600 MJ of heat is lost in the reaction. The strong exothermic nature of this reaction is a potential advantage for the proposed fuel production system. The heat released from the reaction can be recuperated for the heating processes in the HTSE system, thereby improving the efficiency of the integrated fuel production complex.

Table 4-2. Material and thermal balances of Mobil M process. Source: [2]

	Material Balance [kmol]	Thermal Balance [MJ]
<i>Input</i>		
Methanol (gas)	100	76400
<i>Output</i>		
Gasoline	11.8	52500
Gases	5.7	13300
Water	100	---
Losses	---	10600

Using the values of Table 4-2, the material balance for the Mobil M process of our system was determined and is shown in Figure 4-8. With an input of 180,000 kg/hr of methanol from the previous methanol synthesis step, 63,700 kg/hr of gasoline is produced. This is equivalent to 552,700 gallons per day, or 13,200 barrels/day.

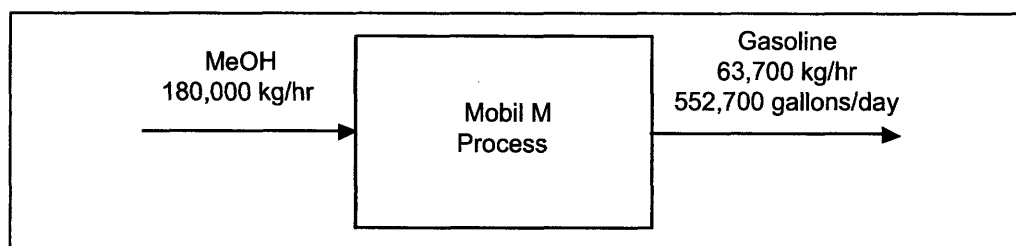


Figure 4-8. Gasoline production from methanol via the Mobil M process

Given that current gasoline consumption is 9159 thousand barrels/day, about 700 reactors would be needed to produce enough gasoline to replace current consumption. The size of our Mobil M plant would be comparable to the capacity of the New Zealand plant. The New Zealand plant produced about 600,000 tonnes of gasoline per year, while our plant would produce about the same amount.

4.4 Components of MSW Production

4.4.1 MSW Gasifier

The carbon content of MSW is extracted through gasification. This process converts MSW into synthetic gas, a mixture of H₂, CO, and CO₂. The synthetic gas can then be

converted into useful products such as gasoline. The main chemical reactions of gasification are represented by Eqs. (4.4), (4.5), and (4.6):



Although there exist many developed biomass gasification processes, the Union Carbide PUROX process was found to be most compatible with our gasoline production scheme. The PUROX plant is a fixed-bed gasifier which operates at high temperatures and utilizes oxygen as the reactant. These characteristics have several advantages for MSW gasification and synthetic fuel production.

MSW is highly heterogeneous and not fully composed of organic material. For many other biomass gasification processes, these properties generate a number of flow and thermal problems. However, the high operating temperature of the PUROX process leads to complete melting of non-combustible material in the MSW [14], which can then be removed. As a result, the MSW feedstock does not require extensive treatment before entering the PUROX reactor.

Second, the use of oxygen instead of air in gasification allows for a higher concentration of H₂ and CO in the output stream. This leads to a higher heating value of the synthetic gas. The synthetic gas is a medium heating value gas with sufficient energy content for conversion to synthetic fuels. In addition, oxygen gasification eliminates the need for external heat energy, since the process is strongly exothermic. Furthermore, oxygen gasification is particularly compatible with our proposed production scheme, as it utilizes the by-product oxygen from our HTSE unit.

The PUROX process was demonstrated successfully and several plants were built in the US and Europe in the 1970s. However, most of the plants were ultimately shut down due to the expensive cost of oxygen production [14]. The by-product oxygen from the HTSE unit is therefore especially relevant for the future dissemination of this process. Table 4-3 details key properties of the PUROX demonstration plant.

Table 4-3. Key properties of the PUROX demonstration plant. Source: [14]

Feed rate (tonne MSW/day)	181
Oxygen rate (kg/kg feed)	0.2
Output Gas rate (kg/tonne MSW)	808
Output Gas Heating Value (MJ/kg)	13.7
Reaction Temperature(°C)	1100
Output Gas Composition (Mass %)	
H ₂	3
CO	59
CO ₂	28
H ₂ O	5

Based on the feed rates and gas compositions given in Table 4-9, the material balance was determined for the MSW gasifier. Detailed calculations for MSW conversion to gasoline can be found in Appendix B. Figure 2 shows a block diagram of the syngas production in a demonstration sized PUROX plant. One may notice that the H₂/CO ratio of the synthetic gas is only 0.7. In order to produce Fischer Tropsch liquid products, this ratio must be about 2. This ratio is increased by adding H₂ from the HTSE unit to the synthetic gas mixture.

Another noticeable fact from Figure 4-9 is that the material flow rates are much lower than those in fuel production from coal plant CO₂ emissions. Similarly, the oxygen flow rate is 1,500 kg/hr, almost 200 times lower than the oxygen supply output from the HTSE unit is 297,000 kg/hr. With the amount of synthetic gas produced from this demonstration plant, the gasoline output would only be 16,400 gallons of gasoline per day. This is an order of magnitude less than the 552,700 gallons of gasoline output from fuel production using CO₂ emissions.

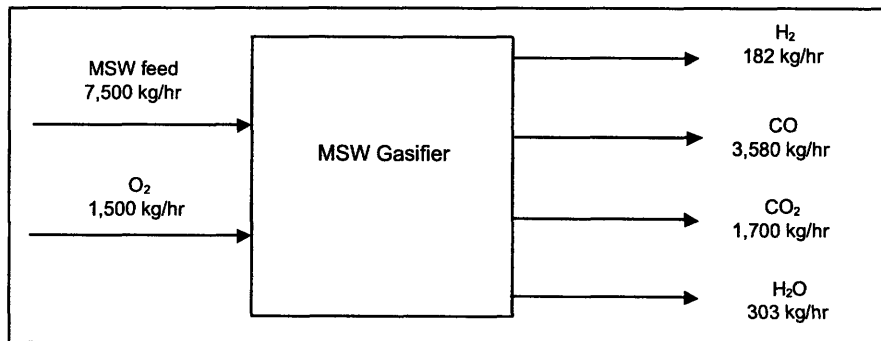


Figure 4-9. MSW gasifier based on demonstration sized unit

For large scale production of gasoline, the MSW gasifier must be scaled up. Figure 4-10 shows a block diagram of the PUROX process scaled up by a factor of 60, from 180 tonne/day to 11,500 tonne/day. This processing rate would produce enough synthetic gas to fully utilize the HTSE hydrogen output. However, similar to methanol production from coal CO₂ emissions, H₂ is the limiting reactant. The MSW gasifier only requires a fraction of the oxygen output from the HTSE. The oxygen required for the gasifier is 96,000 kg/hr, while the oxygen supply from the HTSE is 297,000.

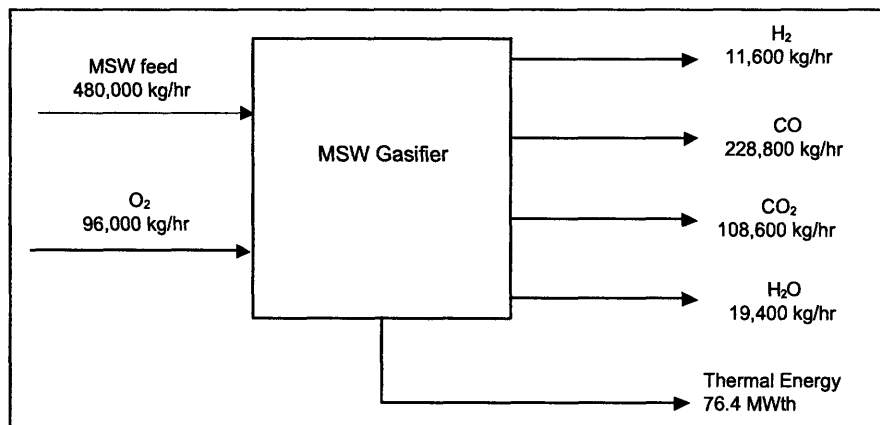


Figure 4-10. MSW gasifier for large-scale gasoline production

4.4.2 Fischer-Tropsch

The Fischer-Tropsch process converts synthetic gas to gasoline. However, the H₂ to CO ratio of the synthetic gas must have a value of 2 for a gasoline product. As the synthetic gas output from the MSW gasifier is only about 0.7, H₂ must be added from an external source. Given CO and CO₂ quantities, the amount of H₂ required by the F-T process is determined by Eq. (4.7) [2]:

$$\frac{H_2}{2CO + 3CO_2} = 1.03 \quad (4.7)$$

The H₂ present in the synthetic gas offsets some of the H₂ requirements of the F-T process. The size of the MSW gasifier was chosen to fully utilize the H₂ from the HTSE.

The overall F-T process can be represented by Eq. (4.8) [2]:



As can be seen from Eq. (4.8), gasoline production is mostly dependent on CO content. The CO₂ in the synthetic gas that reacts in the F-T plant is considered negligible. Additionally, the synthetic gas does not react to completion in the F-T plant. The unreacted gases are fed back into the F-T plant to improve output gains. Using Eq. (4.8), the amount of gasoline and water output from the F-T plant can be determined. Figure 4-11 is a block diagram of large scale gasoline production showing our results.

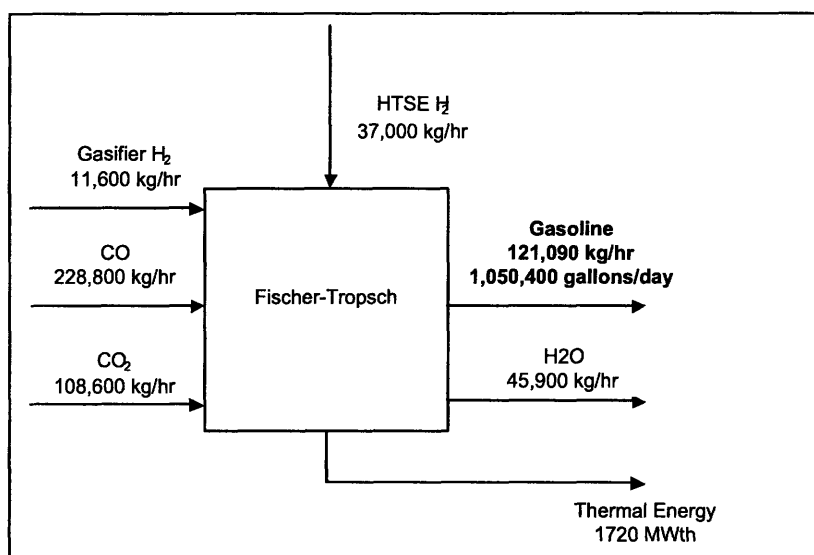


Figure 4-11. Block diagram of large scale gasoline production through Fischer-Tropsch process

One may notice that the F-T process is highly exothermic, releasing 1720 MW of thermal energy. The dissipation of this large amount of heat has been a major challenge in previous experience with the F-T process. In the context of our production scheme, this heat energy could potentially be recuperated in hydrogen production.

The inputs from the MSW gasifier and H₂ HTSE produce approximately one million gallons of gasoline per day, or 25,000 barrels per day. Therefore, the F-T plant of our production scheme is half the size of the current SASOL II plant, which produces 50,000 barrels per day. Moreover, the gasoline production from MSW is nearly double that from coal plant CO₂ emissions. With this gasoline output, about 366 plants would be

needed to completely replace gasoline consumption in the US. From this preliminary analysis, it is seen that gasification of MSW results in high gasoline output.

5 Cost Analysis

The following section estimates the potential price of gasoline that is output from our fuel production scheme. The cost analysis is presented here to gain some perspective on the potential cost feasibility of these fuels. As a result, the prices determined here are only intended to be rough estimates. Detailed calculations of the costs and prices are in Appendix C.

5.1 Current Gasoline Prices

In order to provide a comparison for the price of gasoline from our production schemes, it is necessary to discuss current gasoline prices. According to the EIA [1], the retail price of gasoline price is \$2.60 per gallon. Table 5-1 details the projections of retail gasoline prices in the future.

Table 5-1. Projected retail gasoline prices in the US. Source: [1]

\$/gallon	2006	2010	2020	2030
Reference Case	2.60	2.17	2.02	2.15
High Price Case	--	2.50	2.86	3.20

As seen from Table 5-1, gasoline prices are projected to decrease to \$2/gallon and remain below \$2.20/gallon by 2030. However, in a high price case, gasoline prices are projected to exceed \$3.00/gallon by 2030.

5.2 Fuel Production using CO₂ emissions from Coal Plants

The breakdown of the total production cost of gasoline produced from coal plant CO₂ emissions is shown in Figure 5-1.

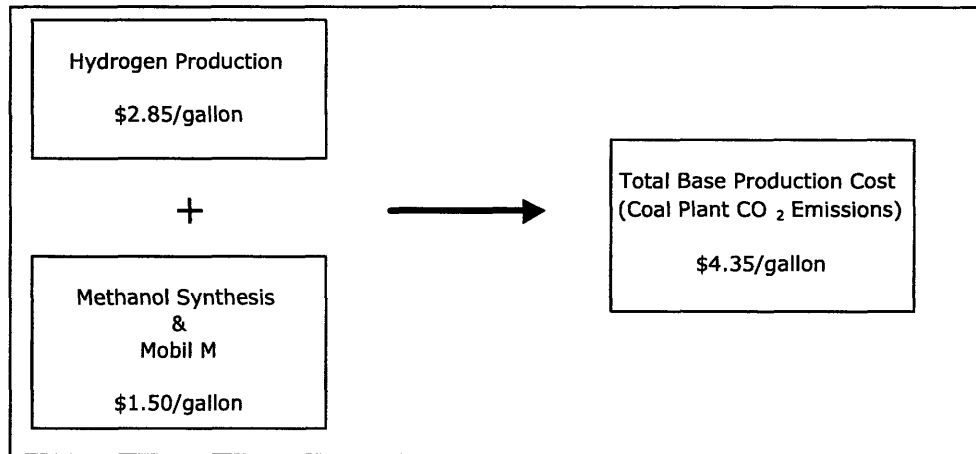


Figure 5-1. Total base production cost for gasoline from coal plant CO₂ emissions.

According to Yildiz et al, the low and high estimate for hydrogen production from the HTSE-GFR unit range is \$1.18 and \$2.37 per kg H₂, respectively [15]. These estimates include the capital and operating costs for both the nuclear plant and the HTSE unit. For approximate calculations, we use the average of these values (\$1.75 / kg H₂) as the cost for hydrogen production. From the amount of hydrogen and gasoline produced in our gasoline production scheme, the corresponding partial cost is \$2.85 per gallon of gasoline produced.

Current literature contains limited information regarding methanol synthesis and methanol-to-gasoline costs. A rough estimate of \$1.50 per gallon gasoline was assumed for the conversion of CO₂ into methanol and then gasoline.

By adding these production costs, the base price of gasoline from production is \$4.35 per gallon, as shown in Figure 5-1. Compared to the current gasoline prices discussed in Section 5.1, the cost of our synthetic fuels are significantly higher. However, our production scheme also eliminates many associated costs. When these costs are considered, the price of our gasoline is lowered.

5.2.1 Carbon Sequestration

One major cost that we face in the future is that of carbon sequestration. As we are becoming more urgently faced with the problem of increasing CO₂ emissions, many recent efforts have focused on carbon capture and sequestration. Of the several potential methods of sequestration, geological storage is the cheapest and most feasible method. Geological storage involves the injection of CO₂ into suitable storage sites such as oil and gas reservoirs, deep saline formations, and unminable coal beds. Preliminary estimates for injection range from \$0.5-8/tCO₂ [17]. Our production scheme eliminates the need to sequester CO₂. Therefore with the low estimate for injection, we save \$0.01 per gallon gasoline produced, while a high estimate of geological injection would result in a saving of \$0.17 per gallon gasoline.

Another disadvantage of carbon sequestration is the need to transport CO₂ from the emission sites to suitable geological storage locations, which may be a considerable distance away. As our production scheme utilizes CO₂ emissions on site, the cost of pipe transport is also eliminated. The cost of pipe transport is approximated to be \$1/tCO₂/100 km. However, the cost is highly variable depending on the distance, route, and quantity of CO₂ transported [17], and is therefore not included in cost saved from eliminating the need for sequestration.

5.2.2 Carbon Tax Credit

CO₂ emissions that are not sequestered are emitted into the atmosphere. In recent years, the rising levels of CO₂ in the atmosphere have prompted global discussions on implementing carbon taxes [8]. These taxes are paid for every tonne of CO₂ emitted and aimed towards reducing the unrestricted amounts of CO₂ emissions produced everyday. According to the recent MIT Coal Study [8], the cost of CO₂ emissions in a high case scenario would be \$25/tCO₂, with a price increase of 4% per year. In a low carbon price scenario, the emission cost is \$7/tCO₂. Compared to a typical supercritical PC plant without capture, we avoid 5900 tCO₂ emissions per day by using an oxyfuel plant. The amount saved for avoiding carbon taxes is 23.6 cents per gallon gasoline in a high case scenario, and 6.61 cents per gallon gasoline in a low case scenario.

5.2.3 Improvements in Plant Efficiency and Capture

Although the oxy-fuel plants employ many advantages such as simple carbon capture and improved combustion efficiency, the major drawbacks of the oxy-fuel plant are the high cost and power consumption of oxygen production by the ASU. However, the HTSE unit in our production scheme produces by-product oxygen to supply the oxy-fuel plant, thereby resolving these two issues. Without the energy requirement of the ASU, the plant is able to produce more electricity, thus improving the efficiency of the plant by 6.4%. This leads to an overall oxy-fuel plant efficiency of 37%, which is highly comparable to the efficiency of a typical supercritical CO₂ plant without capture (38.5%).

Additionally, the cost of the overall plant is reduced, as the ASU has an associated capital cost. The cost improvements associated with efficiency and capital cost can be approximated by considering the cost of electricity (COE). The cost of electricity is mostly attributed to the capital cost, but also include fuel costs and operation and maintenance. The capital cost of the oxy-fuel plant without the ASU is assumed to be similar to that of the supercritical CO₂ plant without capture. This assumption is based on the fact that the oxy-fuel plant is simply an oxygen-blown instead of air-blown supercritical CO₂ plant without capture. The COE from an oxy-fuel plant with the ASU is 6.98 cents/kWh, while the COE from the reference supercritical PC plant without capture is 4.78 cents/kWh. Assuming the similarity in overall efficiencies and plant costs, the COE of our oxy-fuel plant without the ASU is reduced by 2.2 cents/kWh. This corresponds to a saving of \$0.29 per gallon gasoline.

The \$0.29 per gallon gasoline savings is also representative of the amount saved from carbon capture. With a typical supercritical PC plant, carbon capture significantly lowers the efficiency and increases the cost of the plant. The COE for a supercritical PC plant without capture is 4.78 cents/kWh, while that with capture is 7.69 cents/kWh, or a 60% increase in cost. This is a result of the low concentration of CO₂ in the flue gas of air-blown plants. However, the oxy-fuel plant without ASU in our production scheme achieves the same efficiency as the reference supercritical PC plant without capture.

Thus, one can say there is no additional carbon capture cost by using the oxy-fuel plant without ASU.

5.2.4 Implications of Cost Reduction from Credits

The resulting cost of our gasoline with the savings discussed in the sections above is summarized in Table 5-2. These prices show that even the optimistic savings from future sequestration and carbon tax costs were not comparable to the significant production cost of gasoline.

Table 5-2. Gasoline price under different future carbon tax and sequestration costs

	High Cost Sequestration	Low Cost Sequestration	High Carbon Tax	Low Carbon Tax
Base Production Price (\$/gallon)	4.35	4.35	4.35	4.35
SAVINGS(\$/gallon gasoline)				
Efficiency Improvement	-0.29	-0.29	-0.29	-0.29
Credit under future cost scenario	-0.17	-0.01	-0.24	-0.07
Net Gasoline Price (\$/gallon)	3.89	4.05	3.83	3.99

Despite the high prices, it is possible that future conditions will allow the implementation of this technology. The savings due to carbon sequestration does not include the price of CO₂ transport. The development of the pipeline infrastructure for CO₂ may prove expensive. In addition, the more expensive forms of sequestration were not considered. The rapid increase in CO₂ emissions worldwide may lead to necessary implementation of expensive methods of sequestration, such as ocean storage (\$5-30/tCO₂).

In addition, these estimates are based on a cost of \$1.5/gallon gasoline for CO₂ conversion to methanol then gasoline. Further research is needed to verify this cost. The

methane to methanol to gasoline plant that was built in New Zealand is a possible source for estimates.

5.3 Fuel Production using MSW

The breakdown of the total base cost for gasoline production from MSW is shown in Figure the full process involving MSW consists of hydrogen production, MSW gasification, and the Fischer-Tropsch plant.

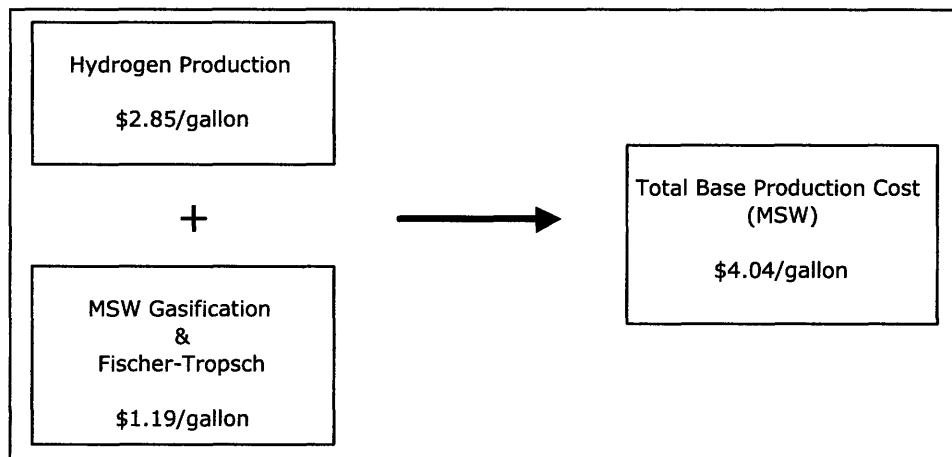


Figure 5-2. Total base production cost for gasoline from MSW.

As there are few commercialized F-T plants, cost estimates are limited. However, the cost of MSW gasification and the F-T plant can be approximated from the cost of coal-to-liquids conversion, as coal-to-liquids is the gasification of coal instead of MSW. In addition, since the infrastructure for MSW collection is long developed, the cost of MSW is not expected to be significantly higher than the cost of coal. According to the MIT Coal Study, the cost of coal-to-liquids conversion without capture is estimated as \$1.19 per gallon gasoline [8].

Often coal-to-liquids conversion is discussed with carbon capture. Coal-to-liquids conversion releases large quantities of CO₂ emissions, almost three times as much as emissions from a typical coal plant. However, we exclude carbon capture in our MSW gasification process because the capture of CO₂ is already inherently included in the natural process of MSW generation. Although MSW releases CO₂ in the gasification

process, MSW absorbs CO₂ when the organic material is grown. The net CO₂ emitted is zero.

Including the partial cost of hydrogen production, the total production price using MSW as the carbon feedstock is \$4.04 per gallon gasoline, as seen in Figure 5-2. Moreover, there are also associated costs that can be saved by using this method to produce gasoline.

The cost estimate for coal-to-liquids conversion includes the cost of oxygen production for the gasification process. As discussed earlier, oxygen production using the ASU is expensive and requires a great deal of energy. Unlike the cost analysis for CO₂ emissions from coal plants, there is no credit associated with efficiency improvements. In the coal plant, the energy required for the ASU is otherwise used to produce electricity for sale. While in MSW gasification, the energy requirement drives up the cost of gasification. For a rough approximation, only the savings from the capital cost of the ASU was included. Eliminating the capital cost of the ASU corresponds to a \$0.13 saving per gallon gasoline.

The enforcement of a carbon tax in the future will also reduce the price of gasoline. Although CO₂ is released from the end combustion of gasoline in vehicles, the CO₂ is absorbed when the organic material in the MSW is grown, resulting in zero net CO₂ emissions. Credit can be taken for the CO₂ emissions that are not released. Table 5-3 summarizes the net gasoline prices with savings from oxygen plant efficiency improvement and avoidance of carbon taxes.

Table 5-3. Net gasoline prices under different carbon tax scenarios for MSW.

	High Carbon Tax	Low Carbon Tax
Production Price (\$/gallon)	4.04	4.04
SAVINGS(\$/gallon gasoline)		
Credit under different carbon taxes	-0.24	-0.07
Oxygen Plant Cost	-0.13	-0.13
Net Gasoline Price (\$/gallon)	3.67	3.84

5.3.1 Implications of Net Prices

The net price for gasoline produced from MSW is \$3.67 per gallon gasoline if a high carbon tax is implemented, and \$3.84 for a low carbon tax.

Other credits could also potentially have an impact on the net gasoline price. One example is waste disposal. With the amount of energy we consume, we also generate a lot of waste, leading to increasing need for landfill area in the country. As waste continues to grow, land constraints will cause the disposal of waste to become more expensive. Furthermore, methods of disposal other than landfilling, such as incineration, are expensive and have toxic emissions. Although the prices of these concerns in the future are unclear, this gasoline production scheme may satisfy a need in the future.

5.4 Cost Implications

The price of gasoline from MSW was slightly lower than that from coal plant CO₂ emissions. However, as the difference is within the uncertainty of the cost estimate, conclusions regarding which production scheme is cheaper cannot be made. Nevertheless, the price of gasoline produced under these two production schemes is undoubtedly much higher than current gasoline.

An important driving factor for the implementation of this technology is the price of oil. The gasoline cannot compete with the low price of oil that is currently on the market. However, it may be viable option when oil prices increase. As seen in Table 5-1, under a high oil price case, gasoline prices are projected to rise above \$3/gallon, making our gasoline cost more competitive. Oil prices may rise for a variety of other reasons. With the rapid development of China and India, we will have to compete with China and India for world oil resources, driving up the cost of oil. In addition, as the US relies heavily on oil imports from politically unstable regions, causing our oil supply to be volatile.

When oil prices increase, we will be looking towards unconventional oil sources, such as tar sands and oil shale. Further work would need to be done to determine whether

the costs of these synthetic fuels are competitive with gasoline produced from unconventional oil sources. One of the major benefits of these synthetic fuels over unconventional oil sources is the significant reduction in CO₂ emissions. In this manner, synthetic fuel may be preferred over these unconventional oil sources.

The cost of synthetic fuels can also depend on technological breakthroughs in the near future. One possible breakthrough technology is co-electrolysis. Co-electrolysis is a process which electrolyzes CO₂ and water simultaneously to output syngas [18]. This technology would eliminate the need for the intermediate methanol production step in CO₂ conversion to gasoline.

6 Conclusion

6.1 Summary

Synthetic fuels created from a hydrogen and carbon source are viable alternatives to petroleum-derived gasoline. This can offset the amount of oil imported from politically unstable countries and reduce CO₂ emissions while decreasing the rate at which we are consuming fossil fuel resources. Two carbon sources, municipal solid waste and CO₂ emissions from coal plants, were investigated for the production of gasoline with nuclear hydrogen. A production scheme was proposed for each carbon source, where components were chosen from already developed technologies. The feasibility of these two synthetic gasoline production processes was assessed on the basis of material and energy balance, cost competitiveness, scale, and reduction in CO₂ emissions.

The energy and material balances of each production step were strongly compatible. Table 6-1 summarizes the key conclusions from the material and energy balance of the subprocess from each production scheme.

Table 6-1. Comparison of key conclusions from material balance of production schemes from each carbon source.

Coal Plant CO ₂ emissions	MSW
<ul style="list-style-type: none"> • Oxygen input improves combustion efficiency, carbon capture ease, and decreases release of air pollutants • Typical 500 MWe coal plant is scaled down to 300 MWe, utilizing 282,000 kg/hr of captured CO₂ • Methanol synthesis and Mobil M plant are on the same scale as the New Zealand methanol-to-gasoline plant, processing 4400 tonnes methanol/day into 13,000 barrels gasoline/day • Requires 700 plants to replace US gasoline consumption • Coal plant fully utilizes O₂ and H₂ output from HTSE • Water recycled is 60% required HTSE input 	<ul style="list-style-type: none"> • Oxygen input results in higher syngas energy content and no external heat is required • Demonstration MSW gasifier plant is scaled up by a factor of 60, processing 11,500 tonnes MSW/day • F-T plant is half the size of SASOL II, producing 25,000 barrels gasoline/day • Requires 370 plants to replace US gasoline consumption • MSW utilizes 30% of O₂ output from HTSE, but fully utilizes H₂ output • Water recycled 20% required HTSE input

As seen from this table, by matching the H₂ requirements for each production scheme with the output H₂ from HTSE, gasoline is produced on large scale. The amount of gasoline produced is similar to the output from currently established synthetic fuel plants. This table also shows that the by-product oxygen from the HTSE is a very useful and convenient for gasoline production from these carbon sources. Furthermore, many of the components generated water as a by-product. This water can be recycled and satisfy a portion of the HTSE water input.

Table 6-2 summarizes the essential properties of the two production schemes. The gasoline price includes energy efficiency improvements from eliminating the need for oxygen production, and excludes savings from carbon credits.

Table 6-2. Summary of essential properties of gasoline production from each carbon source.

	Coal plant CO ₂ Emissions	MSW
Gasoline generated per plant [gallons/day]	552,700	1,050,400
Gasoline price [\$/gallon]	4.06	3.91
Carbon dioxide emission	Reduce total emissions from power plants and transportation by half	Zero net emissions

From our preliminary cost analysis, it is seen that MSW-derived gasoline is much more expensive than current prices due to the low cost of oil in the US. The intention in further studying synthetic fuels is therefore not for these fuels to compete with current oil supply, but to compete with unconventional oil sources in the future. Additionally, the price of synthetic gasoline can be competitive when oil prices become high. As the US relies heavily on imports, oil supply is volatile and prices may rise, similar to the jump in natural gas prices in 2005. Furthermore, if higher oil prices are coupled with harsher restrictions on CO₂ emissions, the technology can be a viable option.

Despite these drawbacks, synthetic gasoline provides a sustainable option for the future. Producing gasoline from MSW results in zero net emissions, as the organic material in MSW absorbs CO₂ when it is cultivated. In addition, with improvements in CO₂ capture in the future, CO₂ can be captured from the atmosphere. Our proposed production scheme for coal plant CO₂ emissions would be able to adapt easily to CO₂ captured from air, thus allowing for a sustainable recycle of CO₂ in the atmosphere. Fuel production from both CO₂ emissions and MSW allow for the recycling of material, thus limiting the amount of harmful substances placed into the environment. With our resources is growing more limited, recycling and reusing of materials will become increasingly necessary for a sustainable future.

6.2 Future Work

Several areas of research are suggested for further analysis of the feasibility of synthetic fuel production from various carbon sources in the future.

1) A more detailed cost analysis would allow for a better understanding of the extent to which synthetic fuels produced from these two carbon sources are cost competitive. Further research can be done on the cost estimates of components such as the methanol-to-gasoline plant and MSW gasifier.

2) As synthetic fuel production is likely to compete with unconventional oil sources, the economic and environmental aspects of both should be compared. Initiatives towards unconventional oil sources are currently present in Canada and Venezuela.

3) The process of co-electrolysis can eliminate the need for separate hydrogen and methanol production steps in the conversion of CO₂ emissions to gasoline. The cost of co-electrolysis should be examined to determine the reduction in synthetic fuel cost.

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Appendix A: Calculations for Coal Plant CO₂ emissions

Coal Plant

Oxygen requirement to 500 MWe oxyfuel coal plant: 480,000 kg/hr

Oxygen output from HTSE: 297,000 kg/hr

$$\frac{HTSE\ O_2\ output}{coal\ plant\ O_2\ required} = 0.61$$

Scale 500 MWe down 60% to 300 MWe:

O₂: (480,000 kg/hr)(.6) = 288,000 kg/hr

Coal Feed: (233,000 kg/hr)(.6) = 139,800 kg/hr

CO₂: (470,000 kg/hr)(.6) = 282,000 kg/hr

Methanol Synthesis

Methanol produced with 90% yield, using CO₂ input:

$$\left(\frac{282000\ kg\ CO_2}{hr}\right) \left(\frac{1\ mol\ CO_2}{.044\ kg\ CO_2}\right) \left(\frac{1\ mol\ MeOH}{1\ mol\ CO_2}\right) \left(\frac{.032\ kg\ MeOH}{1\ mol\ MeOH}\right) (.9) = 184,600\ kg\ MeOH/hr$$

Methanol produced with 90% yield, using H₂ input:

$$\left(\frac{37500\ kg\ H_2}{hr}\right) \left(\frac{1\ mol\ H_2}{.002\ kg\ H_2}\right) \left(\frac{1\ mol\ MeOH}{3\ mol\ H_2}\right) \left(\frac{.032\ kg\ MeOH}{1\ mol\ MeOH}\right) (.9) = 180,000\ kg\ MeOH/hr$$

H₂ is therefore limiting reactant, and final methanol output = 180,000 kg MeOH/hr

In volume:

density of MeOH: 792 kg/m³

$$\left(\frac{180000\ kg\ MeOH}{hr}\right) \left(\frac{1\ m^3}{792\ kg\ MeOH}\right) \left(\frac{1000\ L}{1\ m^3}\right) \left(\frac{24\ hr}{1\ d}\right) = 5,455,000\ L\ MeOH/day$$

Water produced:

$$\left(\frac{37500\ kg\ H_2}{hr}\right) \left(\frac{1\ mol\ H_2}{.002\ kg\ H_2}\right) \left(\frac{1\ mol\ H_2O}{3\ mol\ H_2}\right) \left(\frac{.018\ kg\ H_2O}{1\ mol\ H_2O}\right) (.9) = 101,250\ kg\ H_2O/hr$$

Heat released:

ΔH° = -49.5 kJ/mol

$$49.5 \text{ kJ/mol} \left(\frac{6250000 \text{ mol MeOH}}{\text{hr}} \right) \left(\frac{\text{hr}}{3600 \text{ sec}} \right) = 86 \text{ MWth}$$

Mobil M Gasoline Synthesis

Gasoline produced from methanol:

$$\left(\frac{180000 \text{ kg MeOH}}{\text{hr}} \right) \left(\frac{1 \text{ mol MeOH}}{.032 \text{ kg MeOH}} \right) \left(\frac{11.8 \text{ mol gasoline}}{100 \text{ mol MeOH}} \right) \left(\frac{.096 \text{ kg gasoline}}{1 \text{ mol gasoline}} \right) = 63,700 \text{ kg gasoline/hr}$$

In volume:

$$\left(\frac{63700 \text{ kg gasoline}}{\text{hr}} \right) \left(\frac{1 \text{ m}^3}{730 \text{ kg gasoline}} \right) \left(\frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left(\frac{1 \text{ gallon}}{3.79 \text{ L}} \right) = 552,700 \text{ gallons gasoline/day}$$

With total US gasoline consumption as 9159 thousand barrels/day, number of processing plants required to replace total gasoline production:

$$\frac{9159000 \text{ barrels/day}}{\left(\frac{552700 \text{ gallons}}{\text{day-plant}} \right) \left(\frac{1 \text{ barrel}}{42 \text{ gallons}} \right)} = 700 \text{ plants}$$

Water Produced:

$$\left(\frac{180000 \text{ kg MeOH}}{\text{hr}} \right) \left(\frac{1 \text{ mol MeOH}}{.032 \text{ kg MeOH}} \right) \left(\frac{1 \text{ mol H}_2\text{O}}{1 \text{ mol MeOH}} \right) \left(\frac{.018 \text{ kg H}_2\text{O}}{1 \text{ mol H}_2\text{O}} \right) = 101,250 \text{ kg H}_2\text{O/hr}$$

Appendix B: Gasoline Production from MSW gasification

MSW gasification

Demonstration plant

MSW feed based on processing rate of 180 tonnes/day:

$$\left(\frac{180 \text{ tonnes MSW}}{\text{day}} \right) \left(\frac{1 \text{ day}}{24 \text{ hr}} \right) \left(\frac{1000 \text{ tonnes}}{1 \text{ kg}} \right) = 7500 \text{ kg MSW / hr}$$

Oxygen required based on 20 mass% of MSW feed:

$$0.2 (7500 \text{ kg MSW/hr}) = 1500 \text{ kg O}_2/\text{hr}$$

Syngas produced:

Gas rate=808 kg/tonne MSW

$$\left(\frac{808 \text{ kg syngas}}{1 \text{ tonne MSW}} \right) \left(\frac{7500 \text{ tonne MSW}}{\text{hr}} \right) = 6060 \text{ kg syngas / hr}$$

Composition of syngas:

$$\text{CO: } (.59)(6060 \text{ kg syngas/hr}) = 3575 \text{ kg CO/hr} = 127,700 \text{ mol CO/hr}$$

$$\text{CO}_2: (.28)(6060 \text{ kg syngas/hr}) = 1697 \text{ kg CO}_2/\text{hr} = 38,560 \text{ mol CO}_2/\text{hr}$$

$$\text{H}_2: (.03) (6060 \text{ kg syngas/hr}) = 182 \text{ kg H}_2/\text{hr} = 90,900 \text{ mol H}_2/\text{hr}$$

Amount of hydrogen required by Fischer Tropsch equation:

$$\frac{H_2}{2CO + 3CO_2} = 1.03$$

$$\frac{H_2}{2(127700 \text{ mol CO/hr}) + 3(38560 \text{ mol CO}_2/\text{hr})} = 1.03$$

$$H_2 \text{ required} = 382,200 \text{ mol H}_2/\text{hr}$$

Amount of H2 that must be supplied by HTSE:

$$H_2 \text{ supplied by HTSE} = (382200 - 90900)(\text{mol H}_2/\text{hr})(.002\text{g/mol H}_2) = 583 \text{ kg H}_2/\text{hr}$$

$$\left(\frac{127693 \text{ mol CO}}{\text{hr}} \right) \left(\frac{486 \text{ mol gasoline}}{1558 \text{ mol CO}} \right) \left(\frac{.0475 \text{ kg gasoline}}{1 \text{ mol gasoline}} \right) \left(\frac{1 \text{ m}^3}{730 \text{ kg}} \right) \left(\frac{1000\text{L}}{1 \text{ m}^3} \right) \left(\frac{1 \text{ gallon}}{3.79\text{L}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) = 16,400 \text{ gallon gasoline / day}$$

Plant to match HTSE hydrogen output

Hydrogen output from HTSE = 37000 kg H₂/hr

Scaling factor:

$$\frac{\text{HTSE H}_2 \text{ output}}{\text{required external H}_2 \text{ input for demo plant}} = \frac{37000 \text{ kg/hr}}{583 \text{ kg/hr}} = 64$$

MSW feed = 180 tonne/day (64) = 480,000 kg/hr

Syngas Composition

CO: (64)(3575 kg CO/hr) = 8,172,800 mol CO/hr = 228,800 kg CO/hr

CO₂: (64)(1697 kg CO₂/hr) = 2,467,800 mol CO₂/hr = 108,600 kg CO₂/hr

H₂: (64)(182 kg H₂/hr) = 5,817,600 mol H₂/hr =

H₂ required for FT reaction = (64)(382,200 mol H₂/hr) = 244,601,000 mol H₂/hr

H₂ supplied by HTSE = (244601000 – 5817600) (mol H₂/hr) = 37000 kg H₂/hr

Gasoline produced:

The material balance for a nominal F-T plant producing 10⁸ MJ/d based on Eq. (4.8) is shown in Table B.1.

Table B.1. Material balance for a nominal F-T plant. Source: [2]

Mol/s	IN	OUT	
		From Reaction	Unreacted Gases
H ₂	3731		494
CO	1558		31
CO ₂	168		168
Gasoline		486	
H ₂ O		1451	

$$\left(\frac{8172800 \text{ mol CO}}{\text{hr}} \right) \left(\frac{486 \text{ mol gasoline}}{1558 \text{ mol CO}} \right) \left(\frac{.0475 \text{ kg gasoline}}{1 \text{ mol gasoline}} \right) = 121,090 \text{ kg gasoline/hr}$$

$$\left(\frac{121090 \text{ kg gasoline}}{\text{hr}} \right) \left(\frac{1 \text{ m}^3}{730 \text{ kg gasoline}} \right) \left(\frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left(\frac{1 \text{ gallon}}{3.79 \text{ L}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) = 1,050,400 \text{ gallons gasoline/day}$$

Number of plants to replace gasoline consumption:

$$\frac{9159000 \text{ barrels/day}}{\left(\frac{1050400 \text{ gallons}}{\text{day - plant}} \right) \left(\frac{1 \text{ barrel}}{42 \text{ gallons}} \right)} = 370 \text{ plants}$$

Heat Energy released:

The amount of thermal energy produced is calculated from the heat of formation for the hydrocarbons in gasoline. Results are shown in Table B.2.

Table B.2. Thermal energy released in F-T reaction. Enthalpies from [2].

	Mass fraction	Flow rate (kg/s)	Enthalpy (-MJ/kg)	MW
Methane	0.11	3.699972222	55.5	2.05E+02
Ethene	0.04	1.345444444	50.3	6.77E+01
Ethane	0.06	2.018166667	51.9	1.05E+02
Propene	0.11	3.699972222	49	1.81E+02
Propane	0.02	0.672722222	50.4	3.39E+01
Butene	0.08	2.690888889	48.5	1.31E+02
C5-C7 HCs	0.08	2.690888889	46.9	1.26E+02
Light oils	0.33	11.09991667	47.4	5.26E+02
Heavy oils	0.06	2.018166667	47.1	9.51E+01
Alcohols	0.09	3.02725	71.1	2.15E+02
Acids	0.02	0.672722222	57.6	3.87E+01
Total	1			1.72E+03

Appendix C: Cost Analysis

Coal Plant CO₂ emissions

Hydrogen Production Cost per gallon gasoline:

$$\$1.75/\text{kgH}_2 \left(\frac{37500 \text{ kgH}_2}{\text{hr}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons gasoline}} \right) = \$2.85/\text{gallon}$$

Carbon Sequestration:

Typical Supercritical PC coal plant would capture 490662 kg CO₂/hr

$$490662 \text{ kgCO}_2/\text{hr} \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1000 \text{ kg}}{1 \text{ tonne}} \right) \left(\frac{\$0.5}{\text{tonne CO}_2} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.01/\text{gallon}$$

$$490662 \text{ kgCO}_2/\text{hr} \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1000 \text{ kg}}{1 \text{ tonne}} \right) \left(\frac{\$8}{\text{tonne CO}_2} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.17/\text{gallon}$$

Carbon Taxes:

CO₂ emitted from typical Supercritical PC power plant: 414903 kg/hr

CO₂ emitted from oxy-fuel plant with capture: 52202 kg/hr

$$(414903 - 52202 \text{ kgCO}_2/\text{hr}) \left(\frac{500 \text{ MWe}}{300 \text{ MWe}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1000 \text{ kg}}{1 \text{ tonne}} \right) \left(\frac{\$7}{\text{tonne CO}_2} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.07/\text{gallon}$$

$$(414903 - 52202 \text{ kgCO}_2/\text{hr}) \left(\frac{500 \text{ MWe}}{300 \text{ MWe}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1000 \text{ kg}}{1 \text{ tonne}} \right) \left(\frac{\$25}{\text{tonne CO}_2} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.24/\text{gallon}$$

Oxygen Improvements:

COE of oxy-fuel plant is 6.98 cents/kWh. We assume COE of oxy-fuel plant without ASU is 4.78 cents/kWh.

$$(6.98 - 4.78 \text{ cents/kWh}) (300 \cdot 10^3 \text{ kW}) \left(\frac{\$8730}{1 \text{ hr}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.29/\text{gallon}$$

MSW Production Scheme

Oxygen plant credit calculation:

COE of 500 MWe oxyfuel coal plant with ASU is 6.98 cents/kWh. 105 MWe is consumed for the ASU. Without the ASU, this electricity can be sold, lowering the COE to 5.77 cents/kWh.

$$(6.98 - 5.77 \text{ cents/kWh})(300 \cdot 10^3 \text{ kW}) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.16/\text{gallon}$$

$$(6.98 - 4.78 \text{ cents/kWh})(300 \cdot 10^3 \text{ kW}) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{1 \text{ day}}{552745 \text{ gallons}} \right) = \$0.29/\text{gallon}$$

$$\$0.29 - 0.16 = \$0.13/\text{gallon}$$