Greenhouse Gas Emissions from the Petrochemical Industry in the Greater Houston Area

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Abstract

The Greater Houston Area is the leading manufacturer of petrochemicals in the world. This sector is also a significant contributor to greenhouse gas emissions, raising environmental concerns and warranting urgent mitigations strategies. This research paper investigates the extent of greenhouse gas emissions in the petrochemical industry within the Greater Houston Area, examining key sources and their impact. The report utilizes emissions data and on-site assessments to quantify the emissions of petrochemical facilities in the region. The findings reveal the need for innovative technologies to address these emissions associated with petrochemical production. The research evaluates existing and proposed technologies that have the potential to reduce greenhouse gas emissions. Alternative fuels, electrification, and carbon capture technologies are among the solutions explored in this paper. The paper also assesses the economic feasibility and practicality of implementing these technologies, considering the characteristics of the Greater Houston Area's petrochemical landscape.

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Background

The impacts of climate change were first addressed in the 1990s when scientific reports proved that the earth was warming due to human activity.[1] Since then, there has been research to understand and combat the negative effects of global warming. The effects include imbalances in nature including hotter temperatures, more intense storms, increased drought, rising sea levels, loss of biodiversity and more. These consequences also affect humans by disrupting agriculture and food supply, destroying homes and infrastructure with extreme weather events such as wildfires and floods, harming human health and more.[37] The main cause of global warming has been the accumulation of greenhouse gases—such as carbon dioxide, methane, nitrous oxide, and fluorinated gases—which absorb the heat from the sun and trap it within the atmosphere causing an increase in Earth's temperature. In 2021, data provided by the Environmental Protection Agency (EPA) showed that carbon dioxide has had the largest impact on global warming with human activity accounting for 79% of total carbon emissions.[17] While carbon dioxide is naturally occurring, 73% of total greenhouse gas emissions were caused by the combustion of fossil fuels with 32% being from the combustion of petroleum specifically.[17] Due to the impact of petroleum combustion, this report focuses on the emissions produced by the petrochemical industry within the greater Houston area as well as efforts that support the reduction of their carbon footprint.

Introduction

Before investigating the effects of the petrochemical industry, it is important to understand what petrochemicals are and how they are incorporated into the market. Petrochemicals are derived from fossil fuels—mainly petroleum (crude oil), natural gas, and coal, which are composed of hydrocarbon mixtures. Petroleum has various uses, one of them being a main source of energy[6]; it is also the building block for many other products. While the two most common petrochemicals categories are olefins and aromatic hydrocarbons, this report will focus on the production of olefins.

Introduction to Olefins

Olefins are alkenes, hydrocarbons with double bonds between the carbon atoms, such as ethylene (C_2H_4), propylene (C_3H_6), butylene (C_4H_8) and more. They are widely used as feedstock to produce various chemicals. The most common products made from olefins are plastics or polymers—long chemical chains composed of repeating units—that have become essential in modern society. Table 1 below demonstrates the applications of polymers and other chemicals derived from olefins.

Table 1. Products Made from Olefins

Olefins	**Chemical Product**	**Application**
Ethylene	Polyethylene	Food packaging, grocery bags, wire insulation, toys, household products, piping[36]
	Ethylene oxide	Antifreeze, pesticide, sterilizing agent[8]
Propylene	Polypropylene	Packaging, bottles, fibers, textile, furniture[28]
	Acrylonitrile	Fabric, carpet fibers, automotive parts, electronics, wastewater treatment[28]
	Propylene oxide	Furniture, automotive parts, appliances, resins[29]
	Isopropanol	Solvent, cosmetics, pharmaceuticals, household cleaners[29]
	Cumene (for phenol & acetone)	Wood adhesives, coatings, medical equipment, helmets[29]
Butylene	Butadiene	Synthetic rubbers

Olefins Production Process

The production of olefins is a highly energy-intensive process. It consists of four main parts: furnaces, quenching, compression/cooling, and separation. In the furnace, thermal cracking occurs. It is the process of “cracking” single-bond hydrocarbons (ethane, propane, etc.) and converting them into double-bond hydrocarbons (ethylene, propylene, etc.). It is highly endothermic with combustion temperatures reaching up to 1200°C.[12] The fuel for furnaces is usually natural gas; therefore, emissions are being produced both from the process gas and fuel gas, increasing the greenhouse gas emissions concentration in this section of the production process. Once the hot gas leaves the furnace, it is quickly cooled—or quenched—to about 300-450°C with cooling water via heat exchangers to prevent secondary reactions.[12] Quenching is done to maintain the properties of the desired products. The stream is then dried to remove excess water and sent to a 4-6 stage centrifugal compression section. After the gas is compressed, it enters a distillation column to be separated into the desired light hydrocarbons, which are then sent to be converted into other products like polymers and more.

Emissions from Houston's Petrochemical Industry

The Greater Houston area was chosen for this report as it is recognized as the leading manufacturer of petrochemicals in the world and accounts for over 42% of the country's petrochemical capacity.[16] While researching the petrochemical facilities in the region, the EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT) demonstrated that the highest concentrations of petrochemical facilities are located in three counties: Harris, Brazoria, and Jefferson. Emissions data from 2010 to 2022 was gathered from FLIGHT and was investigated for the three counties with a total of 24 facilities. This data was initially compared among them to see the impact of each county on the overall region.

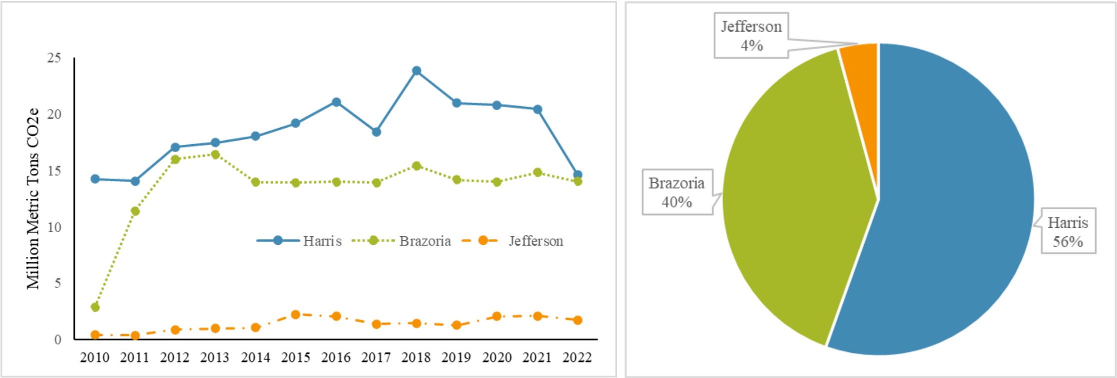


Figure 1. *The line graph (left) shows the annual overall emissions, which include carbon dioxide, methane, and nitrous oxide, of all three counties. The pie chart (right) shows the contribution of overall emissions of each county with Brazoria and Harris counties accounting for most emissions. Percentages were calculated with the data gathered from the EPA's FLIGHT for the years 2010 to 2022.*

Each of the 24 facilities was mapped, with a detailed overview of the top 3 facilities' greenhouse gas (GHG) emissions. To determine the top GHG-emitting facilities, the facilities were ranked by looking at their total GHG emissions from 2010 – 2022. For an accurate comparison, each GHG was converted into CO_2e (carbon dioxide equivalent) by multiplying by their corresponding Global Warming Potential (GWP), a measure of how much global warming is caused by a gas over 100 years. The GWP for the gases in the data are 1 for CO_2, 25 for CH_4, and 273 for N_2O.[26]

Table 2. Petrochemical Facilities Ranked by Total Emissions for 2010 – 2022. The total includes the summation of greenhouse gas emissions (carbon dioxide, nitrous oxide and methane) for each facility. The data was gathered from EPA FLIGHT.

Rank	Facility	13-Year Total Emissions (MT CO2e)
1	Shell Deer Park Refinery	50,110,840
2	Dow Texas Operations	41,756,623
3	INEOS Chocolate Bayou	29,734,570
4	Channelview Complex	25,307,978
5	Chevron Phillips Cedar Bayou Plant	18,785,726
6	Olin Blue Cube	16,174,183
7	Oxy Vinyls LP La Porte	15,997,391
8	Chevron Phillips - Sweeny Complex	15,037,663
9	Equistar Chemicals La Porte	13,640,644
10	Clearlake Plant	8,481,685
11	Ascend Performance	7,789,577
12	OCI Beaumont LLC	5,496,700
13	Indorama Ventures Oxides LLC	5,114,906
14	Natgasoline LLC	1,342,533
15	Oxy Vinyls LP Deer Park	1,305,671
16	BASF TOTALEnergies Petrochemicals LLC	901,828
17	Equistar Chemicals	879,035
18	Bayport Polymers LLC Ethane Crackers	830,092
19	ExxonMobil (Bt Site)	731,303
20	Chevron Phillips Chemical Company	567,396
21	ExxonMobil Beaumont Refinery	559,857
22	Motiva Chemicals LLC	549,292
23	MEGlobal Oyster Creek	313,478
24	LyondellBasell (La Porte)	98,879

The top three facilities in the region are shown in Table 2. For each of these top facilities, the GHG emissions of each unit operation related to petrochemical production were analyzed. With this assessment, the key contributors to GHG emissions in the region were identified, including specific unit operations, which allows for the development of targeted strategies to implement emission reduction technologies.

Top 3 Emitters

Average Annual Emissions

The top three emitters from in decreasing order are Shell Deer Park Refinery (Harris), Dow Texas Operations (Brazoria), and INEOS Chocolate Bayou Plant (Brazoria). The average annual data per facility during the 12-year span was calculated for comparison. In conclusion, Shell has the highest overall CO_2, CH_4 and N_2O emissions. Dow has the second highest CO_2 emissions but has the lowest overall, N_2O and CH_4.

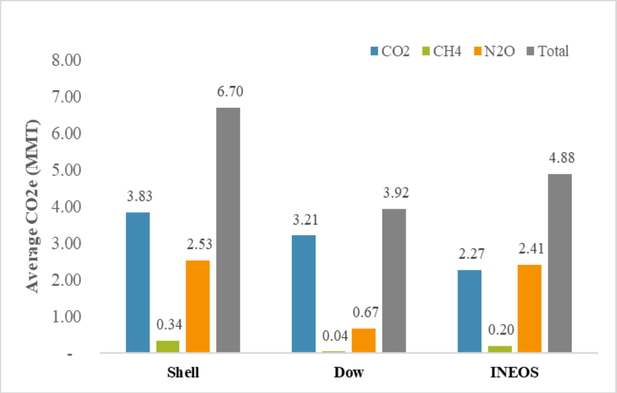


Figure 1. *The average annual emissions in million metric tons per GHG type per facility. Data was gathered from EPA FLIGHT and converted to CO_2e with the corresponding Global Warming Potential unit for each GHG gas: 1 for CO_2, 25 for CH_4, and 273 for N_2O.* [26]

Shell Deer Park Chemical

Nitrous oxide and methane emissions reported increased from 2011 to 2012. Before 2012, the facility was not measuring such emissions in any unit operations except for flares. Since then, N_2O emissions account for about one-third and CO_2 for about one-half of total emissions. In 2022, CO_2 and N_2O emissions decreased significantly due to the transfer of ownership of the facility from Shell Oil Company to PEMEX.

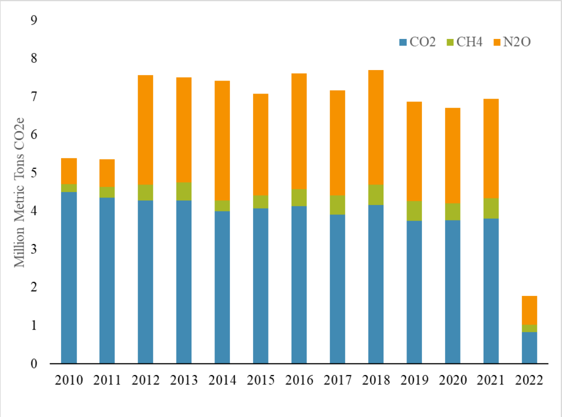


Figure 2. *Bar graph indicating the emission types in million metric tons CO_2e for Shell Deer Park Chemical for the years 2010-2022. Data was gathered from EPA FLIGHT and converted to CO_2e*

Dow Texas Operations

Emissions for this facility are mostly composed of CO_2. No emissions were reported in 2010. Since 2015, emissions reported have been well below those of the years prior.

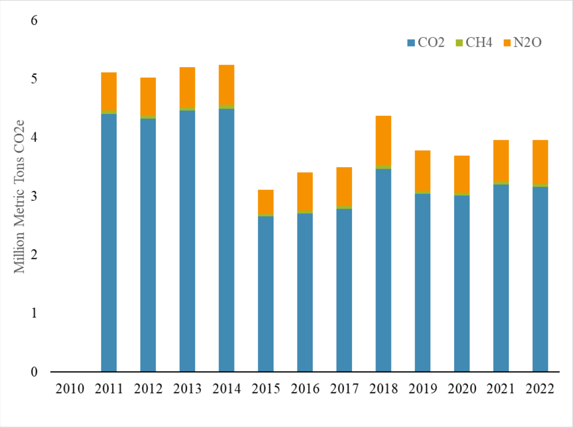


Figure 3. *Bar graph indicating the emission types in million metric tons CO_2e for Dow Texas Operations for the years 2010-2022.*

INEOS Chocolate Bayou Plant

Before 2012, N_2O and CH_4 emissions were only accounted for in flares. Since then, they have been measured in flares and other combustion sources, resulting in a spike in 2012 and 2013. However, these emissions diminished starting in 2014 and account for about half of total emissions.

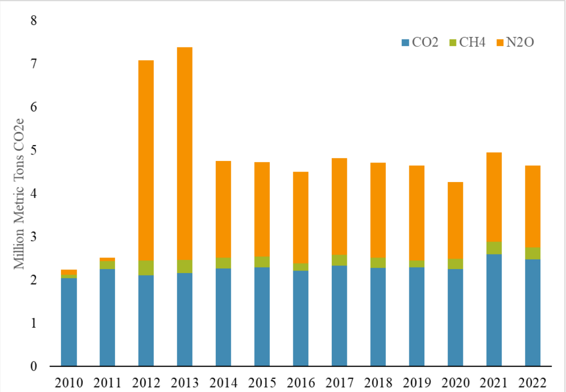


Figure 4. *Bar graph indicating the emission types in million metric tons CO_2e for INEOS for the years 2010-2022.*

Emissions Sources

Data from 2020 to 2022 was gathered and analyzed for specific unit operations of each of the three facilities to determine the source within the process with the highest emissions. The sources include furnaces, flares, heaters, boilers (OB), simple-cycle combustion turbines (SCCT), and other combustion sources (OCS). For Shell, the highest emissions sources are furnaces accounting for over 80% of total emissions. For Dow, furnaces also account for most emissions with heaters accounting for slightly over 20% and other combustion sources for less than 10%. For

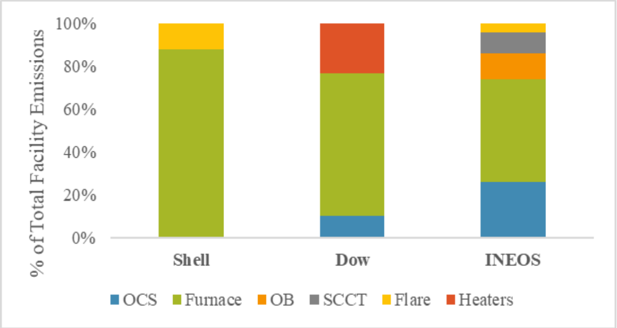


Figure 5. *The chart above displays the percentage of total emissions produced by the sections in the process where GHG are emitted and measured.*

INEOS, about half of emissions are from furnaces, with the other half being divided amongst SCCT, OB, flares, and OCS.

In conclusion, furnaces account for most of the total emissions for the top three emitters. Analysis of new furnace technologies was conducted in order to provide a recommendation that could lead to a significant reduction in CO_2 emissions.

Technologies

Hydrogen-Natural gas Blend Fuel

Decarbonization of cracking furnaces used in olefins production has emerged as a compelling avenue for innovation. Cracking furnaces are traditionally operated using hydrocarbon fuels, such as natural gas (NG), which release significant amounts of carbon dioxide (CO_2) into the atmosphere. An innovative and progressive approach involves partially replacing hydrocarbon fuels with hydrogen, a clean and energy-dense gas that, when combusted, produces only water vapor. The integration of hydrogen as a fuel source in cracking furnaces presents the potential to revolutionize olefin production, offering a dual advantage of reduced greenhouse gas emissions and increased energy efficiency. However, to substantiate this idea, several critical aspects such as performance and economics must be considered.

Performance

While the goal is to ultimately reduce greenhouse gas emissions from the olefins process, the performance of the furnaces cannot be jeopardized. Natural gas is primarily used as a fuel in industrial heating applications for its energy content, affordability, and flame reliability so it is important to analyze these aspects after a blend with hydrogen.

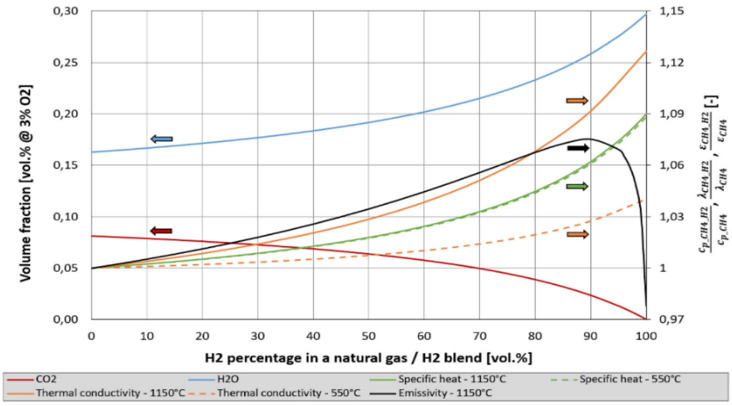


Figure 6. *Shows volume fraction of CO_2 and water vapor emissions, specific heat capacity at different temperatures, emissivity, and thermal conductivity. [24]*

In a study performed by Markus Mayrhofer et al, the focus was on flue gas to determine heat transfer and overall furnace efficiency leading to emission reduction with a hydrogen-natural gas blend for fuel. A key parameter to be studied in this context is specific heat capacity, which directly links to flue gas losses [24]. A good representation of efficient heat transfer is a decrease in flue gas losses, which according to the study, decreases by 7% going from pure natural gas to pure hydrogen due to an increase in flue gas-specific heat capacity. Additionally, heat conductivity was measured at different hydrogen-NG blends to further evaluate heat transfer, results at two different flue gas temperatures can be seen in Figure 7 below. It can be seen that thermal conductivity also rises by 12%, contributing to an improved convective heat transfer in typical stainless-steel furnaces. Overall, the study concluded that a furnace efficiency improvement of 1.2% can be accomplished with hydrogen content between 0%-40% in natural gas mixture with a total CO_2 reduction of about 16% [24].

However, while there was a reduction in CO_2 emissions, there are concerns about nitrous oxides, otherwise known as NO_x. NO_x emissions significantly increased as the content of hydrogen in the fuel mixture increased and would require large amounts of burner power to reduce the emissions, an unattractive strategy. Other potential solutions to reduce NO_x emissions would be to not use combustion preheated air but it comes at the cost of reducing combustion efficiency.

Additionally, the same study revealed that when considering the adiabatic flame temperature of the fuel mixture, the temperature value would rise significantly as it approached a 100% hydrogen content. However, due to hydrogen gas properties, the lower heating value of the mixture simultaneously decreased linearly, meaning less energy per unit of volume.

A separate study by [21] found that adding hydrogen gas to hydrocarbon fuel reduces the ignition delay of methane, increases the flame velocity, and speeds up the relatively slow reaction rate of methane to improve the flame stability. Additionally, a journal written by Choudhuri et al shows the relationship between the percentage of hydrogen in the mixture with natural gas to a few key flame parameters. Firstly, according to the trends, flame length decreases as hydrogen content increases, a sign of improved combustion efficiency. Additionally, the data reveals that the flame residence time decreases as hydrogen percentage increases, in other words, the fuel travels a shorter length before combusting.

Another key parameter to monitor is the burner temperature. Burner temperature is crucial in the cracking process to ensure reaching the desired yield of the high-value product; in this case it is ethylene. Burner temperature is the initial temperature at which the fuel and air mixture ignites, a vital factor in combustion efficiency but also for maintenance purposes. A study on the effect of hydrogen-blended natural gas on the combustion stability and emission of domestic gas water heaters by Xinyi Zhan et al [38] showed that burner temperatures varied depending on the heat load applied to the H_2/CH_4 mixture as seen in Figure 8.

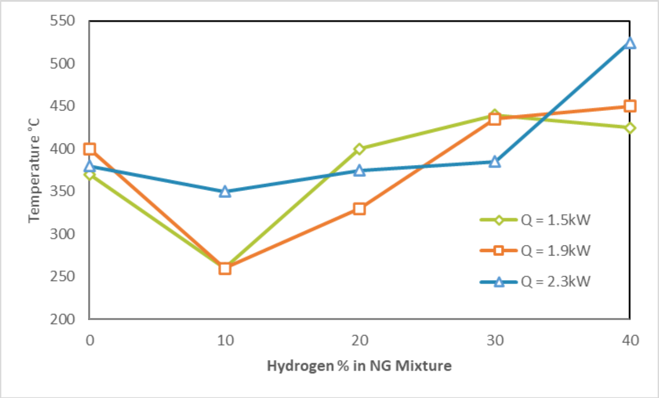


Figure 8. *Burner temperature in degrees Celsius at different Hydrogen-Natural Gas ratio when applying three different heat loads from an experiment conducted by Xinyi Zhan et al. Heat load is defined as the amount of energy required to ignite the mixture.*

Furthermore, as can be seen in Figure 8, the temperature of the burner with any given heat load, decreases at 10% hydrogen but then rises with the addition of hydrogen to the mix. In particular, the data for a 2.3 kW (7,900 BTU/hour) heat load showed a temperature of 522 degrees Celsius at 40% hydrogen mix compared to a temperature of around 380 degrees Celsius using 0% hydrogen, shows that burner tips for industrial furnaces such as the ones required in olefins would undergo extreme heat conditions, leading to more frequent burner maintenance. Based on the study, it can be concluded that blending hydrogen and natural gas does not jeopardize the performance of the burner temperature, in fact, it increases the temperature which can positively impact the olefins process, however, could lead to higher tip corrosion as they undergo higher thermal stress.

The feasibility of using hydrogen as a fuel for olefin furnaces, whether via H_2-NG blending or fully H_2, does not depend purely on the performance of the combustion itself. The technical and safety challenges associated with hydrogen storage management also introduce limitations to many facilities that would consider this option. Hydrogen has a very high energy content with a lower heating value (LHV) of 52,000 BTU per pound which is nearly 2.5 times that of natural gas. However, by volume it has a value of 275 BTU per standard cubic feet, nearly 4 times less than that of natural gas [13]. Having such a low energy content per volume in addition to its low absolute density requires very large and complex high pressure storage systems that many petrochemical facilities cannot implement efficiently or economically.

Economic Assessment

The use of hydrogen as a fuel really depends on the hydrogen economy and how fast it can develop. The source of hydrogen is one of the biggest factors that plays a major role in the decarbonization of major industries. Hydrogen can be produced by many different methods and with various feedstocks as can be seen in table #. The feasibility of introducing hydrogen into fuel systems heavily depends on the development of these technologies as well as the overall carbon footprint of hydrogen production. A study by the Royal Society of Chemistry [39] examined the costs of carbon mitigation from a life cycle perspective for all 12 different hydrogen production techniques. Table 3 shows the names of common hydrogen production technologies and their respective energy vector, input materials, and technology readiness levels (TRL). TRL scale is from 0 to 10 with a score of 10 being fully developed and in practice. [39]

Table 3. Common Hydrogen Production Technologies

Technology name	Energy vector	Input material	TRL
Steam methane reforming	Thermal	Natural gas	9
Steam methane reforming with CCS		Natural gas	8
Coal gasification		Coal	9
Coal gasification with CCS		Coal	7
Methane pyrolysis		Natural gas	5
Biomass gasification		Biomass	6
Biomass gasification with CCS		Biomass	5
Electrolysis — wind	Electrical	Water	9
Electrolysis — solar		water	9
Electrolysis — nuclear		water	9
Thermochemical water splitting (S—I) cycle	Electrical + thermal	water	4
Thermochemical water splitting (Cu—Cl) cycle		Water	4

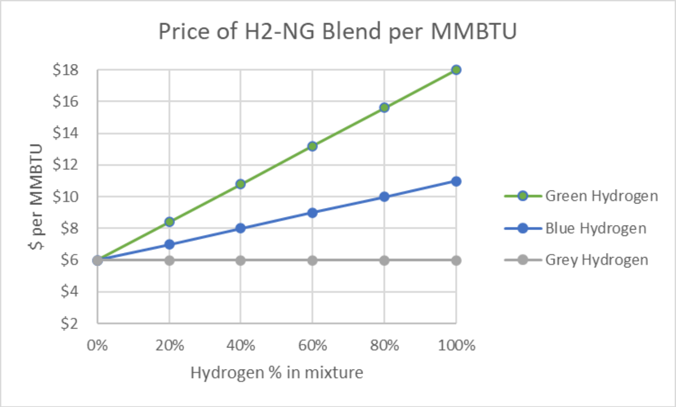


Figure 9. *Cost per MMBTU of mixture depending on H2 % content with the three main types of hydrogen, assuming a natural gas cost of $6 per MMBTU. [Reference]*

The study resulted in methane pyrolysis showing to be the most cost-effective solution to decarbonize hydrogen production and simultaneously encourage building infrastructure for a future hydrogen economy. A major milestone in the hydrogen economy is for the price of hydrogen produced via renewable energy electrolysis, also known as green hydrogen, to become competitive with natural gas prices. Currently the cost of green hydrogen is roaming $3 per kg of H2, roughly $18 per MMBTU, and needs to be reduced at least threefold for cost parity with fossil fuels [10].

Figure 9 illustrates an approximate cost per million British thermal units (MMBTU) using different kinds of hydrogen. Grey hydrogen would be the most economical when compared to traditional natural gas fuel but the overall carbon footprint of grey hydrogen would nullify any carbon emission reduction mentioned in this report from process efficiency improvement.

Notably, the steam cracking process itself yields hydrogen as a valuable byproduct, which can be directly harnessed to fuel the furnace [7]. This approach is one that lacks literature and a lot of clarity on the economic opportunity that lies with purifying the byproduct hydrogen for clean combustion. Overall, the proposition of using hydrogen as an alternative fuel to natural gas seems to be technically feasible as it slightly improves process efficiency while reducing greenhouse gas emissions but is very dependent on the development of a strong hydrogen economy. Additionally, the properties of hydrogen introduce safety risks that must be mitigated and prevented, potentially resulting in additional costs.

Electric Furnaces

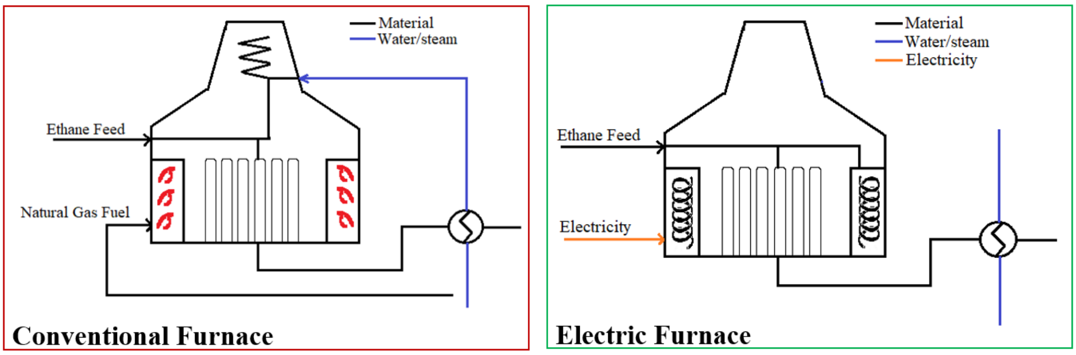


Figure 10. *Comparison of conventional & electric furnaces. The figure on the left (outlined in red) depicts a conventional furnace with natural gas fuel. The figure on the right (outlined in green) shows an electric furnace (eFurnace) providing the heat duty through electricity. [35]*

Another development in decarbonizing cracking furnaces is electrification. As mentioned above, conventional cracking furnaces combust hydrocarbon fuels to generate heat. Electric furnaces in olefins production vary from conventional furnaces, as they use electricity to generate heat instead of the combustion of hydrocarbon fuels. Conventionally, radiative heat is applied to the process tubes from heating elements that surround the tubes. In an electric furnace, the tubes can be heated in a couple of different ways, and experimental testing will determine the more effective method. The first is similar to the conventional furnace where the radiative heat from electrical heating elements is applied to the process tubes. The other method includes applying an electric current directly to the process tubes in the furnace. So, while further testing will determine the more practical method, it has been stated that this technology consumes 21% less energy than conventional furnaces, making it a cleaner and more energy efficient choice for olefins production [35]. While the implementation of electric furnaces would lead to a significant reduction in GHG emissions from a facility, it would also require significant increases in a facility's electricity consumption.

Since the electric furnace has not yet been implemented on a commercial scale, the available design and performance data are currently based on pilot units manufactured by select companies. There are multiple joint ventures actively engaged in the development and execution of design and implementation plans for electric steam cracking furnaces. In the Netherlands, Shell and Dow have started up an experimental unit to test and generate data to validate the model before constructing a pilot plant as early as 2025 [33]. Also in Europe, SABIC, Linde, and BASF are close to completing construction of the world's first demonstration plant for large-scale electric steam cracking furnaces at BASF's Ludwigshafen Verbund site in Germany [19]. In the United States, more specifically in Channelview, Texas, Technip Energies, LyondellBasell, and Chevron Phillips Chemical are collaborating to design, construct, and operate a demonstration unit [23]. These experimental and demonstration units will help prove if electricity as a heat source can sustain continuous operation for the olefins production. The validation of the electric steam cracking furnace technology will affect the global landscape when it comes to olefins production.

Economic Viability

When looking at the costs associated with an electric steam cracking furnace, the two main expenses to consider are capital and operating costs. It is assumed that the capital costs of a conventional and electric steam cracking furnace would be similar to each other. Though most facilities would likely need to add some infrastructure to deal with the increasing electricity demand [9]. This technology would have a high capital cost, and depending on the region, a high operating cost as well.

One of the main operating costs for electric steam cracking furnaces is electricity. The cost of electricity plays a pivotal role in the development of these electric steam cracking furnaces, significantly influencing their economic viability and sustainability.

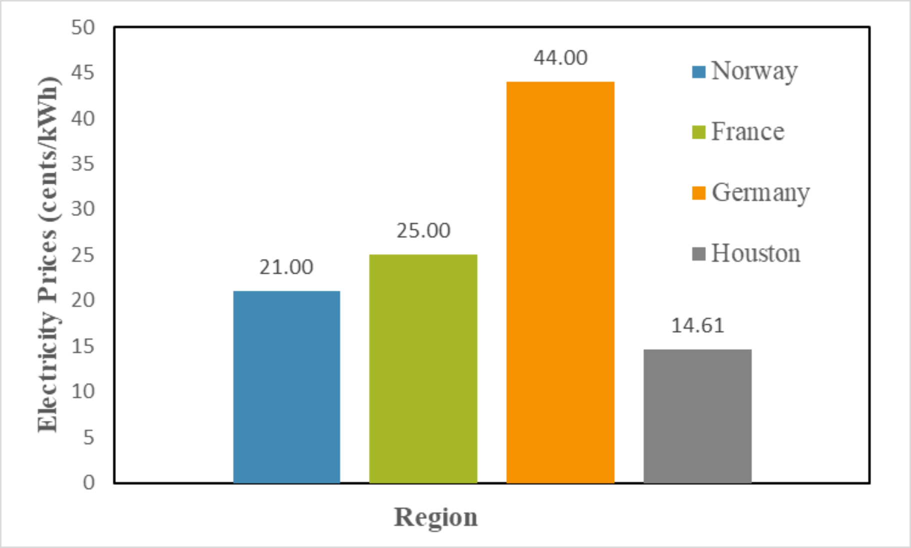


Figure 11. *The electricity prices (cents / kWh) were provided for three separate European countries (Norway, Germany, and France) as well for the Houston area to provide a comparison between the regions. Values for the European countries in the first half of 2023 are shown [11]. The data for electricity prices in the Houston area comes from the retail price from Reliant Energy in June 2023 [2].*

Figure # above highlights the regional differences in electricity prices. The figure shows the Houston area has low electricity costs when compared to the European region. This can be attributed to the fact that natural gas prices have increased significantly, which is tied to the price of electricity. The United States, more specifically Texas, can export a surplus of natural gas due to shale drilling, while Europe need to import the bulk of its gas. Natural gas is used to generate electricity, so the regions where the cost of natural gas is lower the cost of electricity is lower as well [31]. Due to the high electricity demands of the electric steam cracking furnace technology, the lower electricity costs would help make it more economically viable.

Environmental Impact

Electric steam cracking furnaces have the potential to significantly reduce the environmental impact of olefins production compared to traditional furnaces. Multiple sources have stated that electric furnace technology could reduce furnace GHG emissions by up to 90% [35]. So, in terms of scope 1 emissions, this technology will provide a substantial reduction in the facility’s GHG emissions. Scope 2 emissions are also important to consider for this technology, as the source of the electricity is vital in shaping its environmental impact. The sources of electricity are different from region to region, with varying profiles when it comes to the use of renewable energy sources. Examining the diversity of electricity sources in different regions is particularly important when considering the energy landscape in the Texas region.

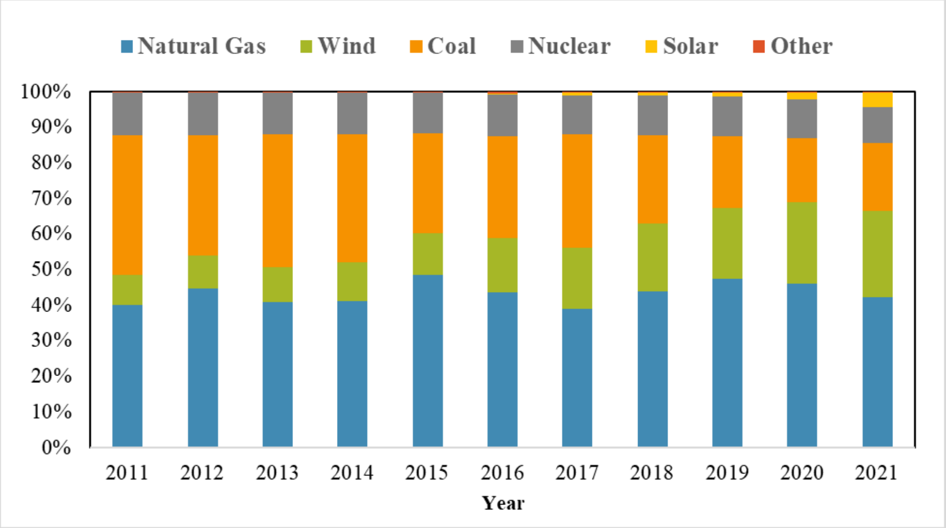


Figure 12. *Energy use by fuel source in Texas from the Electric Reliability Council of Texas (ERCOT) for 2011 to 2021 [2].*

For the last decade, Texas has led the nation in wind-powered electricity generation, but the state also relies heavily on fossil fuel-based sources, such as natural gas and coal. Analyzing the data in Figure # reveals a noticeable shift in Texas towards an increasing reliance on renewable sources, such as wind and solar, for electricity generation. The percentage of electricity generation attributed to wind and solar sources increased from 8.5% in 2011 to 28% in 2021 [2]. Shifting towards renewable sources for electricity generation will significantly reduce the carbon footprint associated with scope 2 emissions. Renewable sources, such as wind and solar, produce electricity with minimal GHG emissions, making them an effective way to lower the indirect emissions of electric furnaces.

So, while electric furnaces absolutely lead to a substantial reduction in scope 1 GHG emissions, their carbon footprint is significantly influenced by the source of electricity due to their high electricity consumption.

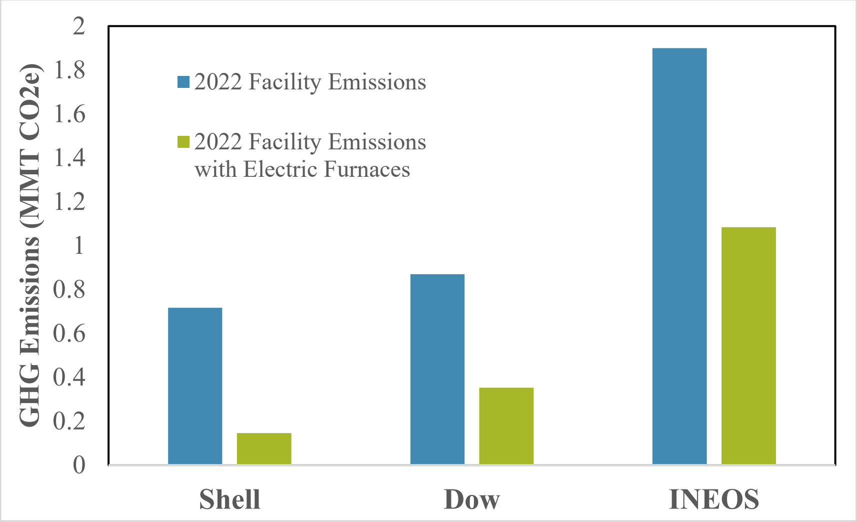


Figure 13. *Comparison of scope 1 GHG emissions, in MMT CO2e, between conventional and electric furnaces. The 2022 facility emissions data is coming from the EPA's FLIGHT tool. The top three highest emitting facilities in the region are shown above. The assumption was made that all conventional furnaces were replaced with electric furnaces at each of the facilities, and that electric furnaces reduce furnace GHG emissions by 90% [23].*

Figure 13 shows the impact that electric steam cracking furnaces would have on a facility's scope 1 GHG emissions. In 2022, if the Shell Deer Park Refinery was operating electric furnaces instead of conventional, then there would have been a scope 1 GHG emissions reduction of 80% related to petrochemical production. In terms of scope 1 GHG emissions, the reductions for Dow Texas Operations and INEOS Chocolate Bayou are 59% and 43%, respectively. It is clear to see that making improvements to steam cracking furnaces will have a significant impact on the emissions profiles at a facility, regarding their scope 1 emissions. It is also important to understand that scope 2 emissions are a key factor in the environmental impact of electric furnaces. If the technology was to be implemented using green electricity sources, then it would be an effective option for GHG emissions reduction.

Post-Combustion Solutions

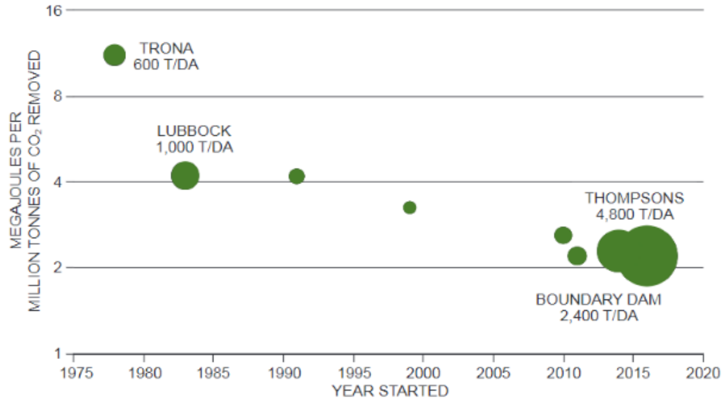
Carbon Capture

Point source carbon capture is the process of capturing CO_2 from a large emitting source, like petrochemical plants. There are four main methods of separating CO_2 at a low concentration from a flue gas: absorption into another material, adsorption onto the surface of another material, membrane separation, and cryogenic processes [27]. Of these four, the most widely used method in industrial applications is absorption, particularly absorption using an amine absorbent. For olefin production, CO_2 flue gas emissions mainly come from fuel burning used in the production of superheated steam. The purity of CO_2 in the flue gas is typically between 7-12% [27], which validates the use of amine absorption since the CO_2 concentration is low. An amine absorption process will always consist of an absorption column for capture of the CO_2 and a stripping column for regeneration of the amine absorbent.

Techno-Economic assessment

Amine absorption is the most mature CO_2 capture process which has gone over half a century of cost optimization in terms of energy requirements. Amine solvent selection depends on four properties which directly relate to the energy requirement of operation, which are as follows [27]: the solvent capacity for CO_2, the rate of CO_2 absorption, the heat of CO_2 absorption, and lastly the thermal degradation of the solvent. Figure 14 shows the advancements made in energy consumption requirements with amine absorption over the decades.

Absorption systems using amine solvents, particularly MEA, could potentially have a 90% CO_2 removal efficiency in settings with flue gas compositions similar to furnace cracking byproducts in the petrochemical industry [32]. The biggest tradeoff for this efficiency is the power requirement needed to regenerate the absorbent. The US Department of Energy estimates that the CO_2 mitigation cost is \$59.1/tonne CO_2 avoided for a plant with a 941g CO_2 /kWh emission generation rate [32].



ource: Rochelle, G. T. (2014). "From Lubbock, TX to Thompsons, TX: A technical review of the progress in amine scrubbing," plenary presentation at 12th Greenhouse Gas Control Technologies Conference, Austin, Texas.

Figure 14. *Improvement of amine absorption system power requirements over time starting with the first plant scale implementation. [27]*

Environmental Impact

Amine absorption has the potential to reduce at least 90% of emissions in the petrochemical industry since most emissions come from steam furnace systems that use combustion to generate heat. However, this percentage does not take into account the power requirement needed to keep an amine absorption operation running, which has heat exchangers that need steam to be generated. Therefore, steam generation requirements in these processes make it difficult to fully mitigate petrochemical plant emissions, although they can be greatly reduced.

The CO_2 captured in an amine absorption process could be produced in the liquid phase at a high pressure. This product could be used in upstream operations to mobilize oil and gas underground to increase production [4], or the product could even be sequestered in a Class VI well, which are used to inject CO_2 deep underground into an empty fossil fuel reservoir. Class VI wells are regulated to ensure that Underground Sources of Drinking Water (USDWs) are not compromised [34]. The Underground Injection Control Program protects USDWs by: modeling injected CO_2 plume to predict its movement underground, constantly monitoring the injection well to ensure its integrity, ensuring well owners have appropriate means to account for emergencies and shut down of the operation which includes plugging up the well at the end of its life cycle.

Economic Evaluation

Government Incentives & Sanctions

A pivotal player in the pursuit of decarbonizing the petrochemical industry and the olefins process in specific, is the federal government. The United States federal government has introduced a crucial bill named The Inflation Reduction Act (IRA) in 2022 which will assist in reducing emission footprint while also making these decarbonizing ventures economically attractive. The IRA includes incentives such as the revision of the 45Q tax credit, designed to incentivize and promote investments in carbon capture, utilization, and storage (CCUS) projects [15]. The credit values each ton of captured CO_2 in industrial facilities at $85 per ton. Additionally, a tax credit of $60 per ton can be awarded for the utilization of captured CO_2 and/or CO to produce low and zero-carbon fuels, chemicals, and other products, or for enhanced oil recovery (EOR) [15]. The table below shows an estimate of tax credits attained by each facility mentioned in this report assuming a carbon capture efficiency of 90%.

On March 8th, 2023, the U.S Department of Energy (DOE) Office of Clean Energy Demonstrations (OCED) issued a Funding Opportunity Announcement (FOA) for $6 billion to reduce emissions through commercial-scale demonstration projects in energy-intensive industries [14]. The goal of the opportunity is to demonstrate the technical and commercial feasibility of industrial decarbonization approaches, promoting widespread technology adoption, including those involving hydrogen fueling and electric furnace technologies. Companies were able to apply and receive financial assistance covering up to 50% of the project costs. The awards would range in value from $35 - 500 million each. The funding opportunity had three topic areas:

- Near-Net-Zero Facility Building Projects
- Facility-level Large Installations and Overhaul Retrofits
- System Upgrades and Retrofits for Critical Unit Operations or Single Process Lines Within Existing Facilities

This contributes to the broader goal of reducing GHG emissions in energy-intensive industrial sectors, such as chemicals and more specifically olefins production.

Conclusion/Recommendation

Hydrogen blended with natural gas is a promising short-term solution to reducing greenhouse gas emissions in the petrochemical industry. Specifically, the olefins process can highly benefit from the properties of a hydrogen-natural gas blend combustion as it increases flame temperature, reduces flue gas losses, and improves overall furnace efficiency leading to a significant reduction in CO_2 emissions. Ultimately, the recommendation for hydrogen as a fuel depends on the maturity of a hydrogen economy as well as a cheap mitigation to a slight increase in nitrous oxide emissions.

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Greenhouse Gas Emissions from the Petrochemical Industry in the Greater Houston Area

Hugh Irvine, Karla Solis, Juan Sanchez and Carlos Garcia

UNIVERSITY OF HOUSTON

Agenda

☐ About Us

☐ Introduction to Petrochemicals

☐ Petrochemical Facilities

☐ Emission Sources

☐ Technologies

☐ Q & A

About Us

Hugh Irvine

Junior

LyondellBasell

Karla Solis

Senior

Dow, Chevron Phillips & Air Products

Juan Sanchez

Senior

Shell & Air Products

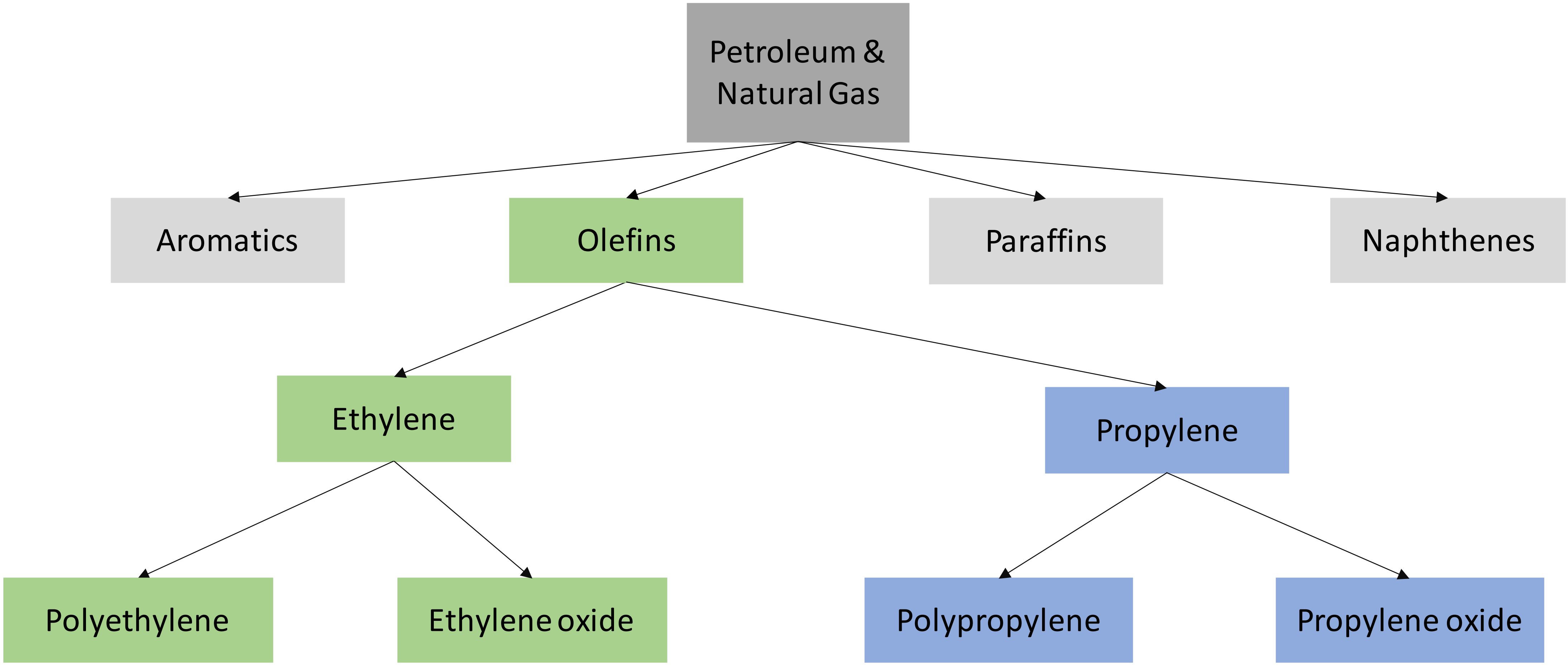
Carlos Garcia

Senior

CDM Smith

Petrochemical Industry

What are petrochemicals?



Petroleum & Natural Gas

Aromatics

Olefins

Paraffins

Naphthenes

Ethylene

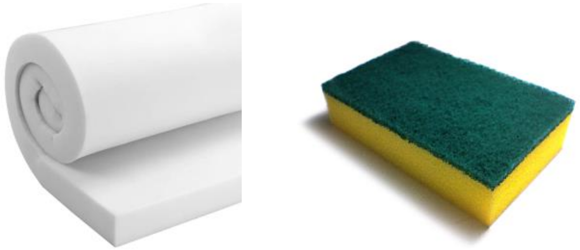
Propylene

Polyethylene

Ethylene oxide

Polypropylene

Propylene oxide



Petrochemical Industry in Houston

The Houston Ship Channel is considered the largest petrochemical complex in the country

The Greater Houston area is the leading manufacturer of petrochemicals in the world

Produces over 42% of the country’s total petrochemical capacity

Petrochemical Facilities

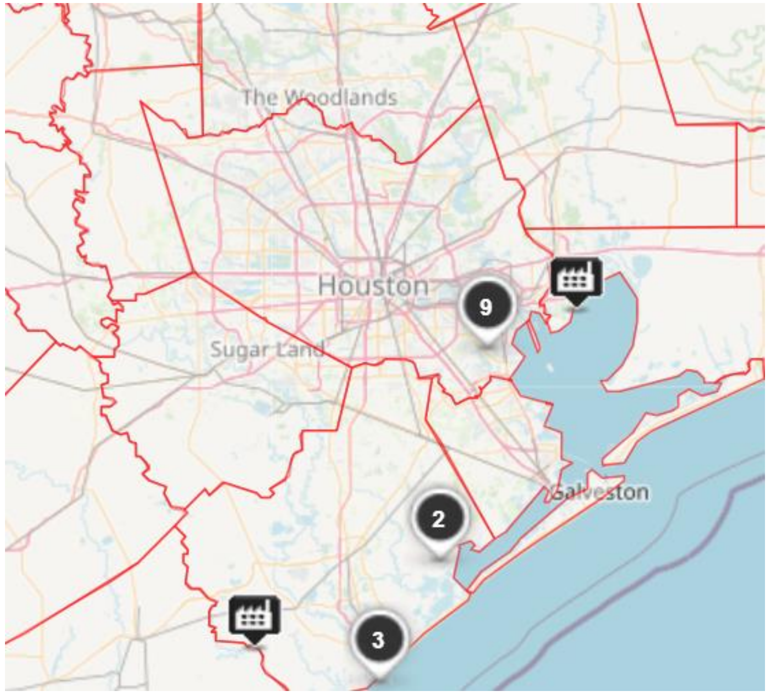
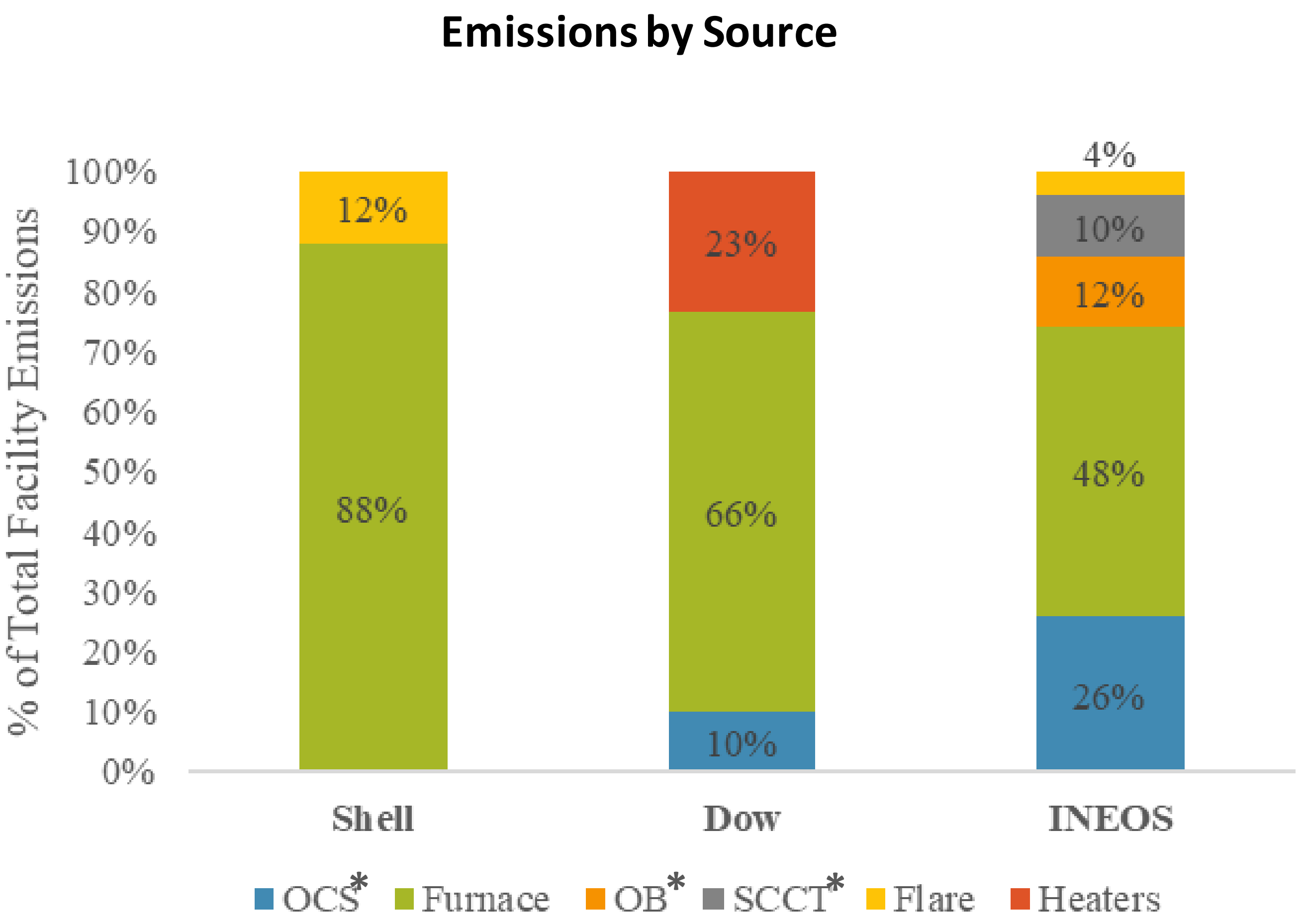


Figure 1. Facilities from EPA FLIGHT in the Greater Houston Area

Table 1. Petrochemical Facilities Ranked. Total emissions include carbon dioxide, methane and nitrous oxide for 2010-2022.

Rank	Facility	13-Year Total Emissions (MT CO2e)
1	Shell Deer Park Refinery	50,110,840
2	Dow Texas Operations	41,756,623
3	INEOS Chocolate Bayou	29,734,570
4	Channelview Complex	25,307,978
5	Chevron Phillips Cedar Bayou Plant	18,785,726
6	Olin Blue Cube	16,174,183
7	Oxy Vinyls LP La Porte	15,997,391
8	Chevron Phillips - Sweeny Complex	15,037,663
9	Equistar Chemicals La Porte	13,640,644
10	Clearlake Plant	8,481,685
11	Ascend Performance	7,789,577
12	OCI Beaumont LLC	5,496,700
13	Indorama Ventures Oxides LLC	5,114,906
14	Natgasoline LLC	1,342,533
15	Oxy Vinyls LP Deer Park	1,305,671
16	BASF TOTALEnergies Petrochemicals LLC	901,828
17	Equistar Chemicals	879,035
18	Bayport Polymers LLC Ethane Crackers	830,092
19	ExxonMobil (Bt Site)	731,303
20	Chevron Phillips Chemical Company	567,396
21	ExxonMobil Beaumont Refinery	559,857
22	Motiva Chemicals LLC	549,292
23	MEGlobal Oyster Creek	313,478
24	LyondellBasell (La Porte)	98,879

Emission Sources



*OCS = other combustion source
OB* = boiler, other
SCCT* = simple-cycle combustion turbine

Cracking Furnace

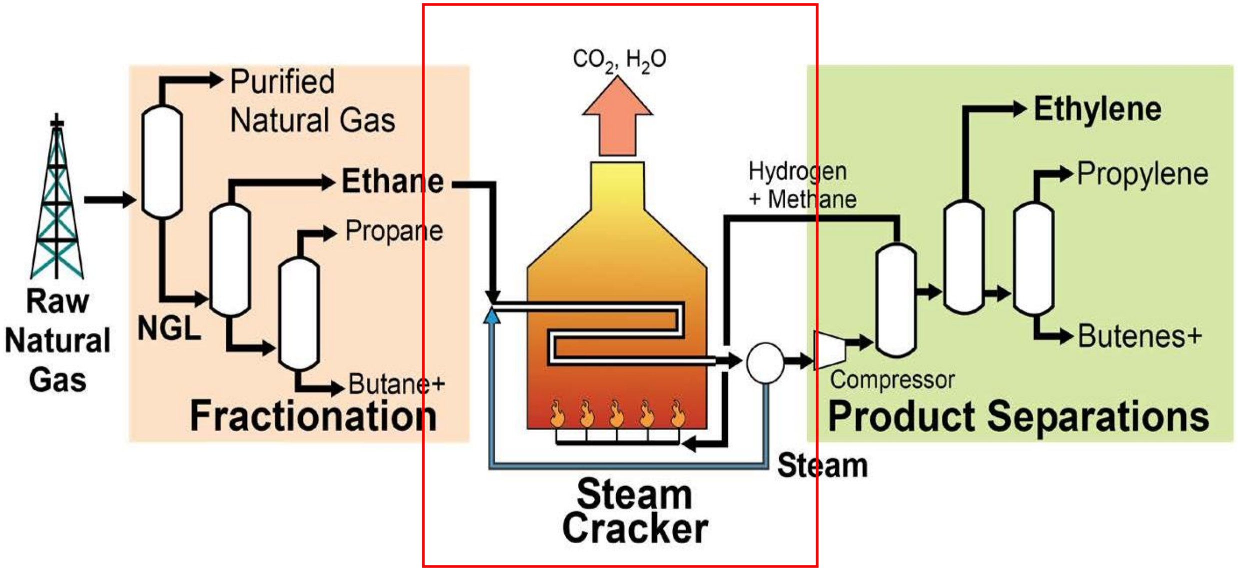
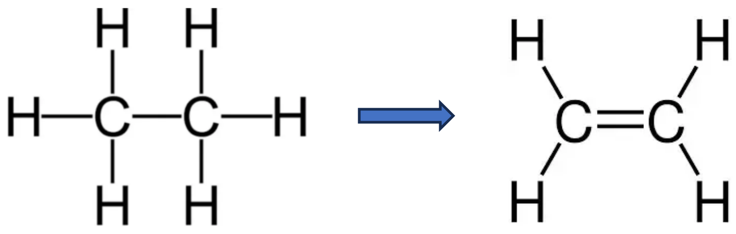
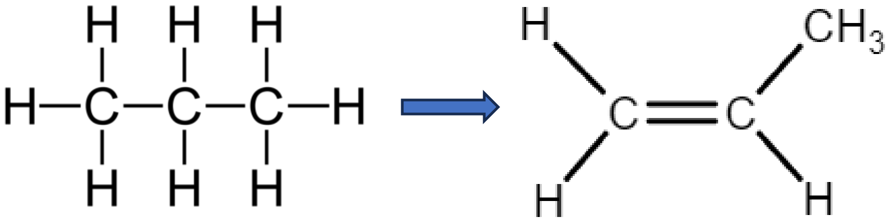


Figure 2. Ethylene & Propylene Production Process *(American Chemical Society, Sept. 2021)*



Ethane

Ethylene



Propane

Propylene

Technologies

Hydrogen-NG Fuel

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Furnace Performance (per 40% H2)

☐ Furnace Efficiency increases by 1.2%

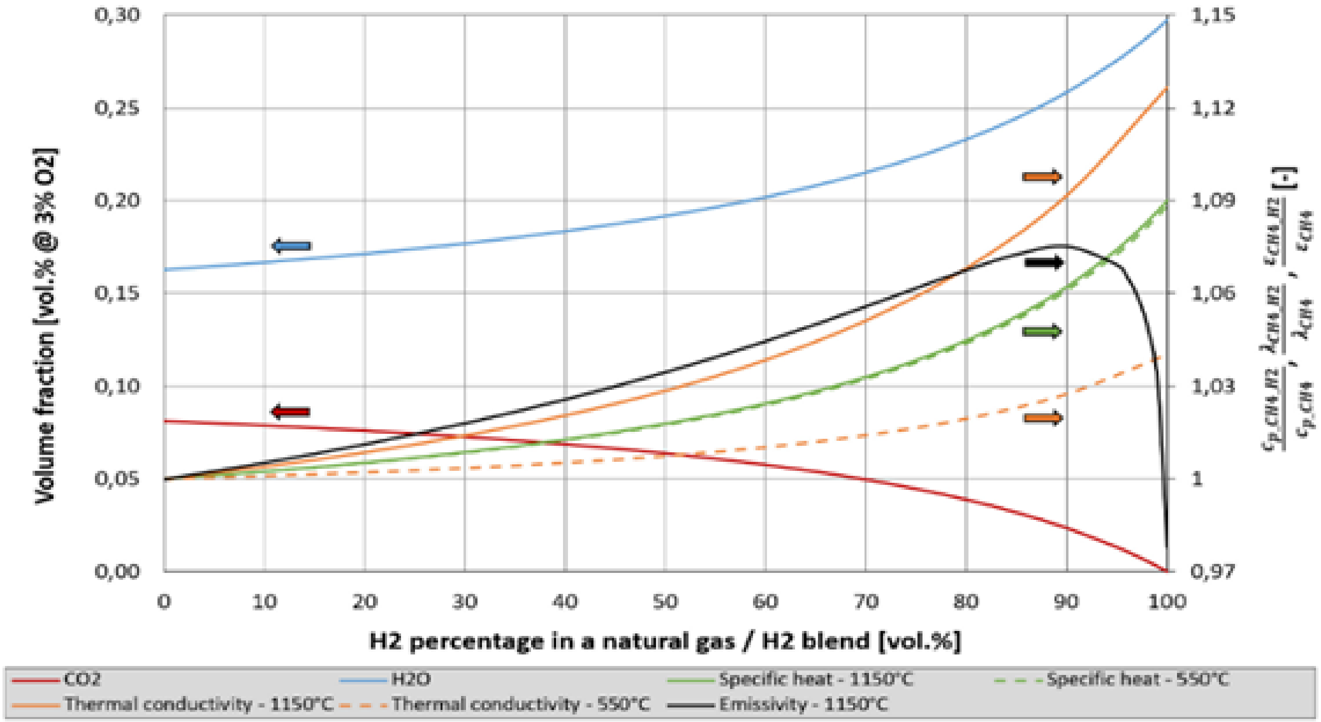
- 12% thermal conductivity improvement
- 7% decrease in flue gas losses

☐ CO2 emissions decrease by 16%

☐ NOx emissions increase by 9.5%

Natural Gas + Hydrogen Combustion

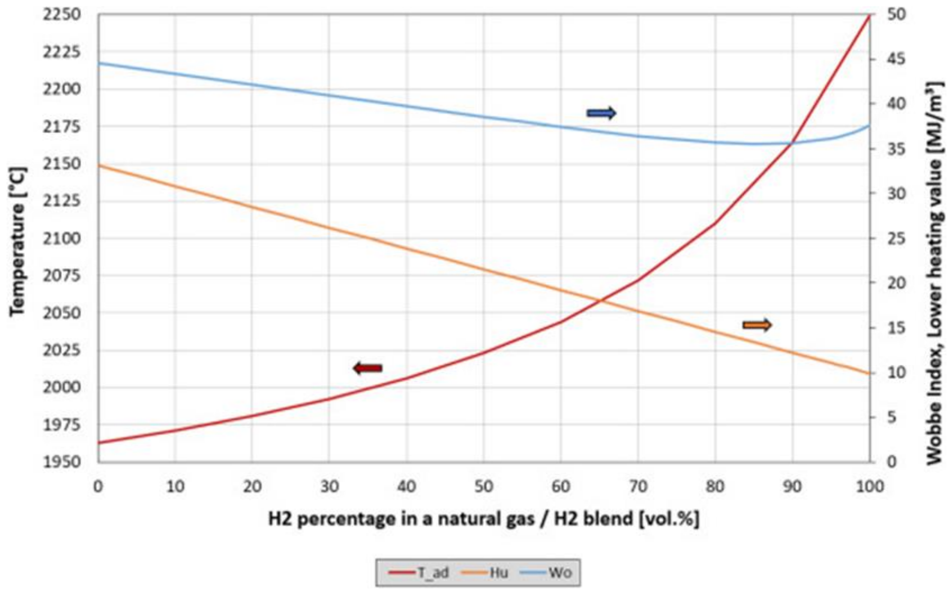
$$2H_2 + CH_4 + 3O_2 \rightarrow CO_2 + 4H_2O$$



Hydrogen-NG Fuel

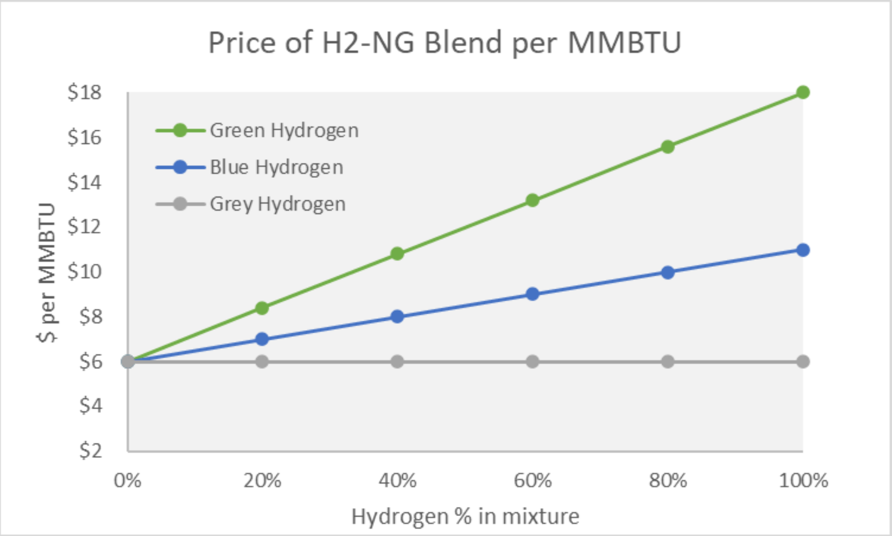
Combustion Characteristics

- ❑ Flame temperature greatly increases
- ❑ Energy content per unit volume decreases resulting in large volumetric flowrate requirements



Economics

- ❑ Green hydrogen cost must decrease at least by factor of 3 for zero carbon footprint
- ❑ Methane Pyrolysis is most cost-effective method to promote hydrogen infrastructure



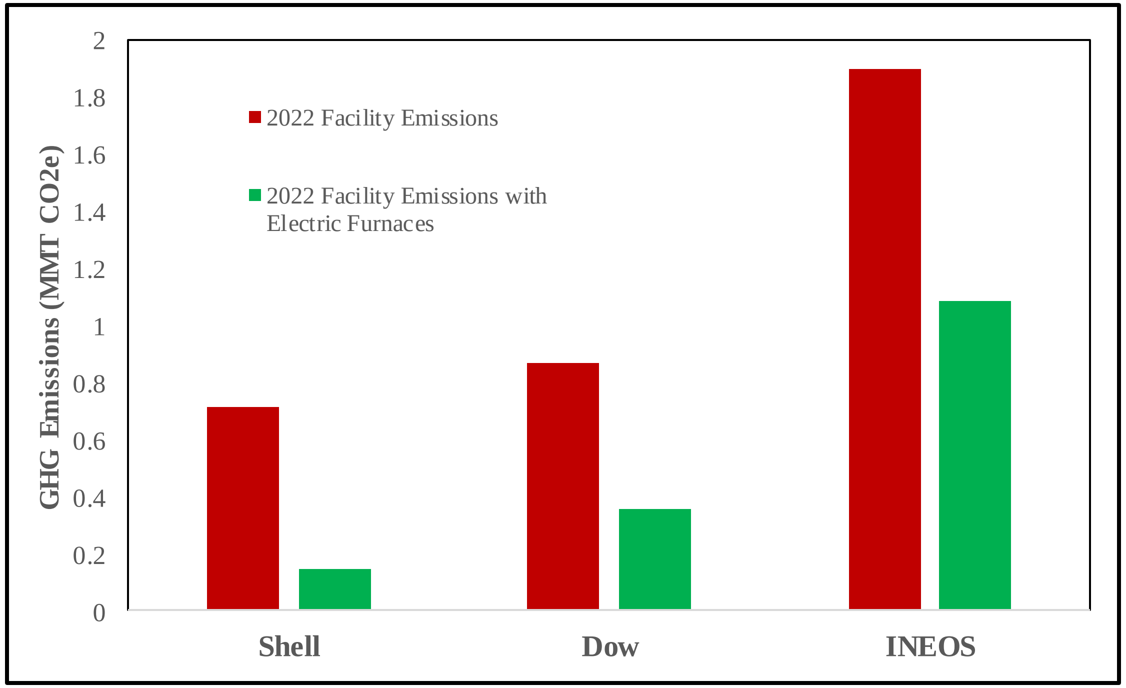
Assuming $6/MMBTU price for NG & 2022 H2 prices

Electric Furnaces

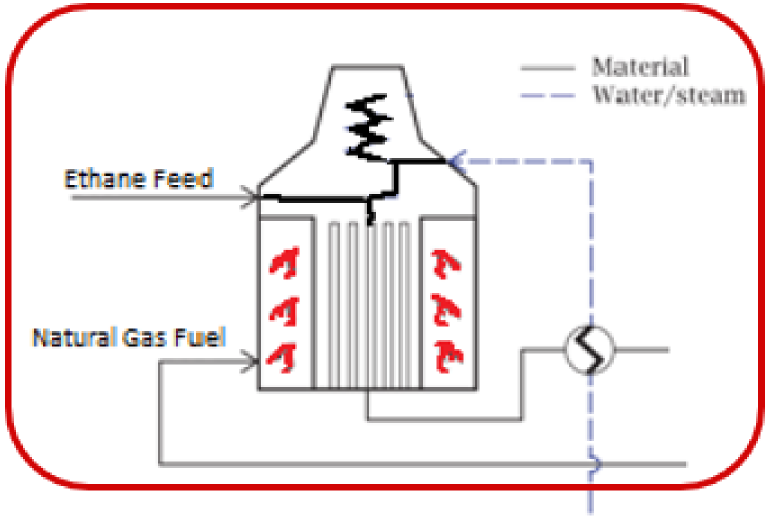
Environmental Impact

- ☐ Combustion of Natural Gas Fuel → Electric Heat Duty
- ☐ High Scope 1 GHG Emission Reduction
  - Reduces furnace GHG emissions by 90%
  - More energy efficient than conventional furnaces

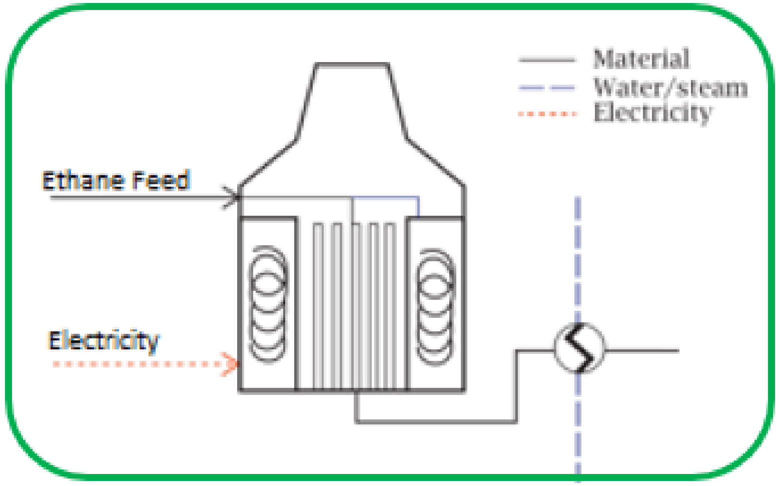
Scope 1 Emissions Reduction



Conventional



Electric

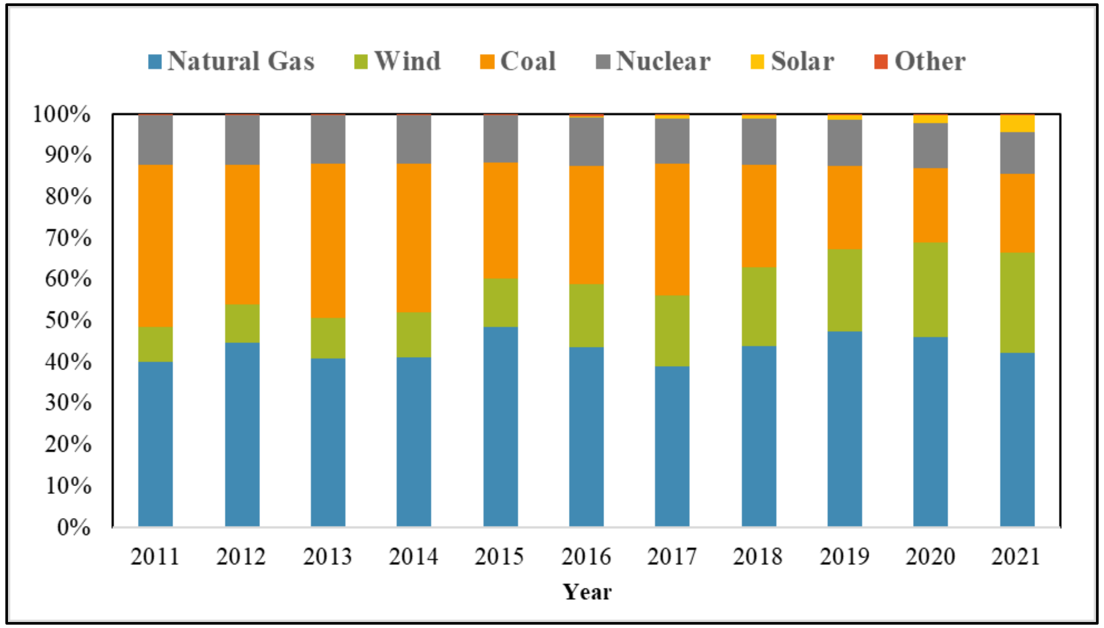


Electric Furnaces

Scope 2 Emissions

- ☐ Source of electricity is important when considering the environmental impact of the electric furnace
- ☐ Texas grid: ~28% from renewable sources (wind and solar)
- ☐ Natural gas and coal: ~61%

Energy Use in Texas by Fuel Source from 2011 to 2021 (ERCOT)

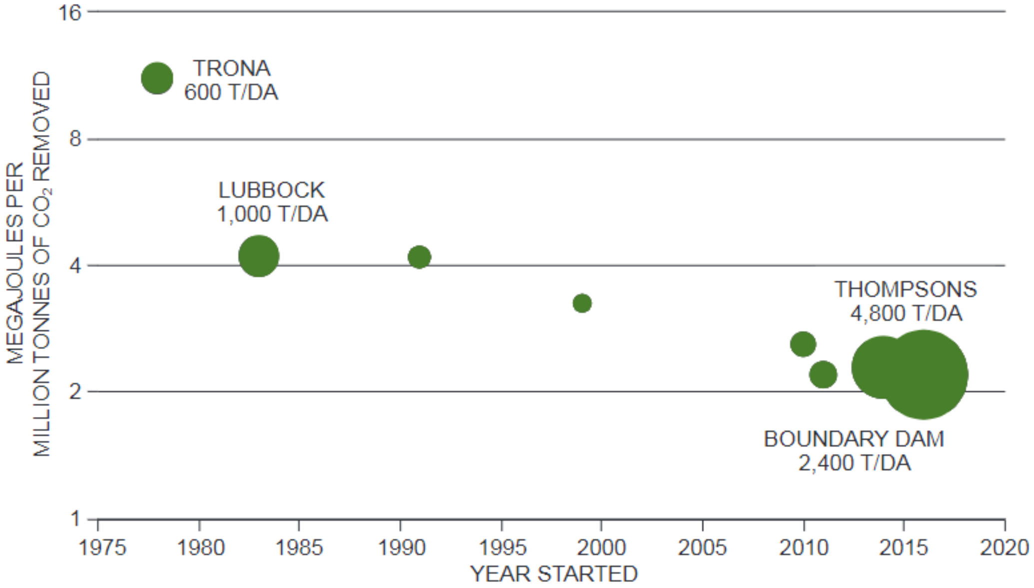


Economics

- ☐ High capital expense, would need to purchase a brand-new furnace
- ☐ Operating costs dependent on electricity prices
  - Increase in electricity generation from renewable sources would increase the price of electricity

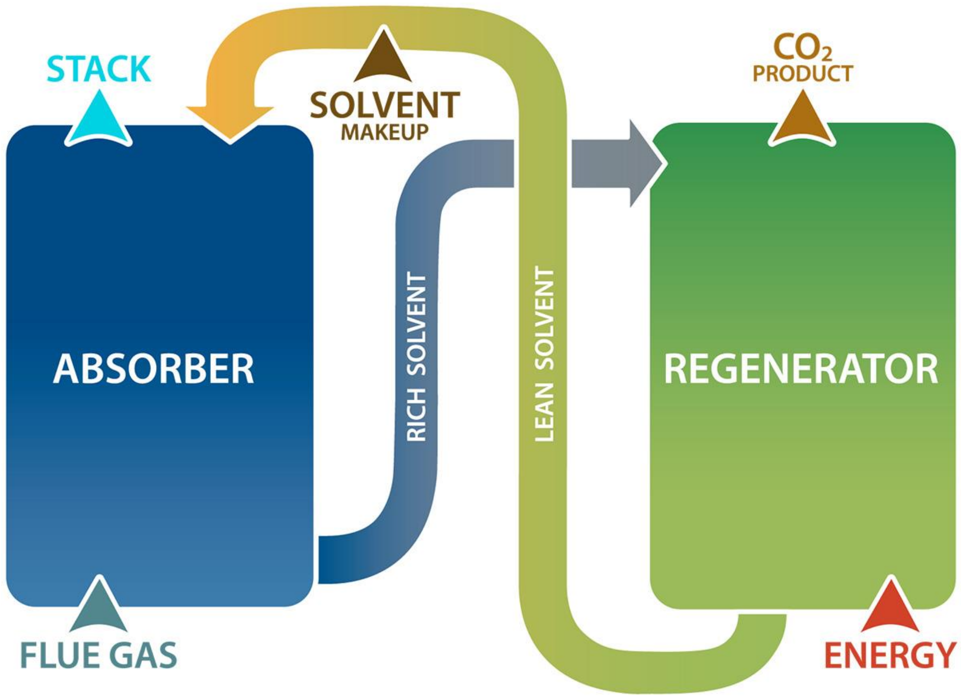
Post-Combustion Carbon Capture

- ☐ Four main methods for carbon capture:
  - Absorption
  - Adsorption
  - Membrane Separation
  - Cryogenic Processes
- ☐ Absorption with amine scrubbing is the most mature
  - Potentially has a 90% CO2 removal efficiency



Source: Rochelle, G. T. (2014). "From Lubbock, TX to Thompsons, TX: A technical review of the progress in amine scrubbing," plenary presentation at 12th Greenhouse Gas Control Technologies Conference, Austin, Texas.

- ☐ Monoethanolamine (MEA) is a widely used absorbent
  - Byproduct of antifreeze polyester production
  - Comparatively average rate of CO2 absorption
  - Most primary and secondary amines degrade at 100-130C while MEA degrades at 120C

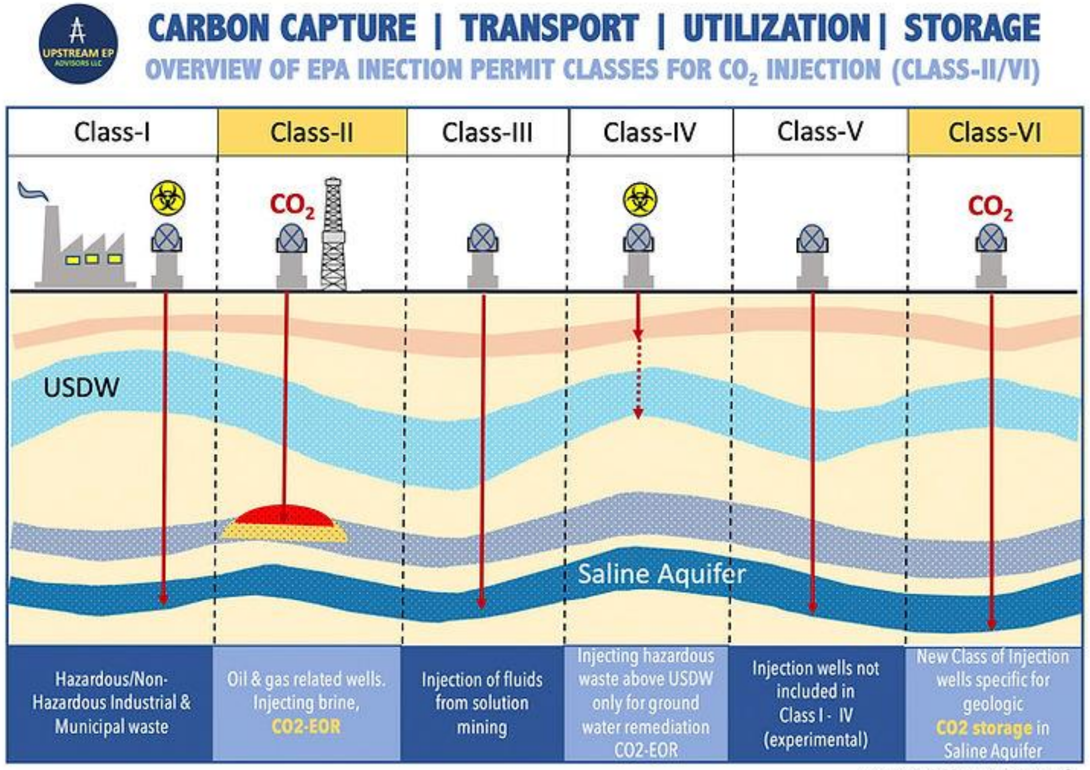


Post-Combustion Carbon Capture

- ❑ CO2 sequestration methods:
  - Class VI wells
  - Class II wells

- ❑ Class VI wells
  - Injection of pressurized CO2 for permanent geologic sequestration
  - Regulated by the Underground injection control program to protect drinking water sources

- ❑ Class II wells
  - Injection of pressurized CO2 underground to fluidize oil and gas reservoirs
  - The 2022 IRA offers $60/tonne CO2 injected when pressurized CO2 is produced ideally for $59.1/tonne



By: Tariq Siddiqui; MAR 2022 ©

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THANK YOU

Q&A

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