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# Alternative Sourcing of CO<sub>2</sub> for Sustainable Power-to-Gas System Design

by

**Cameron Corbin Gallups**

An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

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5/5/2024

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## Abstract

Renewable energies are vital for sustainable energy and reducing greenhouse gas emissions. However, integrating them into the global energy grid faces challenges due to their unpredictable nature, particularly in regards to wind and solar energy. To address fluctuations, chemical energy storage systems, such as "power-to-gas" methods, can house excess electrical energy via chemical molecules, namely methane, enhancing grid stability and resource utilization. Due to its beneficial impact, the American Institute of Chemical Engineers' (AIChE) 2023 -2024 Student Design Statement challenges students to design a power-to-gas plant using renewable energy sources. A prioritized objective of the process design includes selecting a suitable CO<sub>2</sub> source that maximizes economic and environmental performance to achieve deliverable methane. Seeing how CO<sub>2</sub> makes up about 76 percent of total greenhouse gas emissions and is responsible for 80 percent of global warming [1], selecting a proper source for the process could have an enormous, beneficial impact on a reliable power grid and in lowering greenhouse gasses in the atmosphere. The current structure of the design challenge does not provide the proper time to rigorously look into diverse CO<sub>2</sub> options, limiting students to a time period of 60 days. The objective of this paper is to explore a potential source of CO<sub>2</sub>. The source can originate across different industries, including but not limited to, industrial, agricultural, and waste sites. Carbon capture from steel mill off gasses was chosen as the best source due to its high concentration of CO<sub>2</sub> and documented use with membrane separation. This source was then evaluated based on its economic and environmental viability to the power-to-gas process, considering factors like CO<sub>2</sub> concentration, feasibility, and implementation concerns. A combination of research from academic journals and cost analysis was used to justify the final selection.

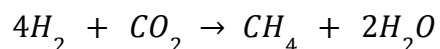
## Introduction & Basics

### Role of Power-to-Gas Technology

Factors such as industrialization, urban expansion, deforestation, and population growth have significantly contributed to the phenomenon of global warming. Of particular concern is the release of carbon dioxide (CO<sub>2</sub>), which constitutes approximately 80% of total greenhouse gas emissions [1]. By 2023, the concentration of CO<sub>2</sub> in the atmosphere had soared to nearly 420 parts per million [2]. The combustion of fossil fuels adds a substantial amount of greenhouse gasses to the Earth's atmosphere annually. Transitioning to dependable renewable energy sources presents a significant advantage, not only in curbing the adverse effects of fossil fuels on the environment, but also in addressing their finite nature. According to the Institute of Energy, humanity's dependence on fossil fuels as an energy source is approaching its end [2]. Current statistical analyses based on reserves and annual extraction rates indicate that there are approximately only 149 years of coal, 57 years of oil, and 49 years of gas left [3].

Carbon capture and utilization offers an alternative approach to reducing CO<sub>2</sub> emissions and moving towards cleaner, more sustainable energy sources. This involves capturing CO<sub>2</sub> released from various sources of pollution and transforming it into useful products that align with market demands [4]. Effective CO<sub>2</sub> utilization should, to some extent, offset the expenses associated with CO<sub>2</sub> capture. As the world transitions away from traditional fossil fuel consumption towards alternative fuels to preserve natural resources and address global warming concerns, significant attention has been placed on converting CO<sub>2</sub> into gaseous fuels. These processes are often referred to as 'power-to-gas' processes.

Methane (CH<sub>4</sub>) stands out as a highly valuable output of power-to-gas processes due to its significant environmental advantages. It yields more heat and light energy per unit mass compared to other hydrocarbons or fossil fuels, such as coal and gasoline derived from oil. Additionally, methane production generates substantially less carbon dioxide and other pollutants that contribute to smog and air pollution [5]. The exothermic Sabatier reaction plays a crucial role in methane production and is depicted below [6]. This reaction involves hydrogen (H<sub>2</sub>) and CO<sub>2</sub> as reactants, resulting in the production of CH<sub>4</sub> and water (H<sub>2</sub>O).



The remarkable aspect of the Sabatier reaction lies in its near-closed loop nature: the water produced can undergo further splitting and reintroduction into the reaction, facilitating the continuous generation of both oxygen (O<sub>2</sub>) and fuel via CO<sub>2</sub> methanation [6]. Industrially, the reaction operates by utilizing CO<sub>2</sub> separation to provide pure CO<sub>2</sub> and electrolysis to split water into hydrogen and oxygen. When these two reactants are combined under appropriate conditions, the desired products are obtained. The methane produced by the Sabatier reaction can be seamlessly integrated into an existing gas network.

### AICHE Design Competition

Given its significant potential and advantages, the American Society of Chemical Engineers' (AIChE) 2023-2024 Student Design Challenge involves the development of a methanation plant utilizing the Sabatier reaction. The objective of this project is to design a power-to-gas facility

that not only demonstrates economic feasibility but also maximizes environmental performance, thus enabling a cleaner methanation process. The project aims to select a carbon dioxide source based on considerations such as its economic viability, environmental impact, and supply reliability. Moreover, the plant must be powered by a renewable energy source (e.g. solar or wind), which will heavily influence its location. The choice of a CO<sub>2</sub> source is constrained to options that optimize both economic and environmental performance, meaning the selected source should contribute positively to the environment, be sourced from areas currently experiencing environmental degradation, and/or be carbon-neutral. Additionally, the process must ensure safety and generate sufficient CO<sub>2</sub> to adequately feed into the methanation unit. The H<sub>2</sub> source is required to be obtained through electrolysis, with the specific type of electrolysis chosen based on practical needs and economic viability. While the methanation process itself can be executed in various ways, it should prioritize economically and environmentally sound practices. The produced methane must undergo purification to meet specified criteria, ensuring its seamless integration into the existing energy grid. These purity standards are derived from the AIChE 2024 guidelines:

- A. The CH<sub>4</sub> produced should have an H<sub>2</sub>O composition of no more than 7 lbs of H<sub>2</sub>O per million cubic ft.
- B. The CH<sub>4</sub> produced should have less than 2 wt% H<sub>2</sub>
- C. The CH<sub>4</sub> should have 1-8 mol% CO<sub>2</sub>
- D. The CH<sub>4</sub> produced should be 90-95 mol% purity, overall

All the above criteria must be implemented in the design chosen to ensure the proper completion of deliverables.

As previously discussed, the methanation process can be broken down into four main stages: CO<sub>2</sub> sourcing, electrolysis, methanation, and purification/upgrading. This process is visually depicted in Figure 1.

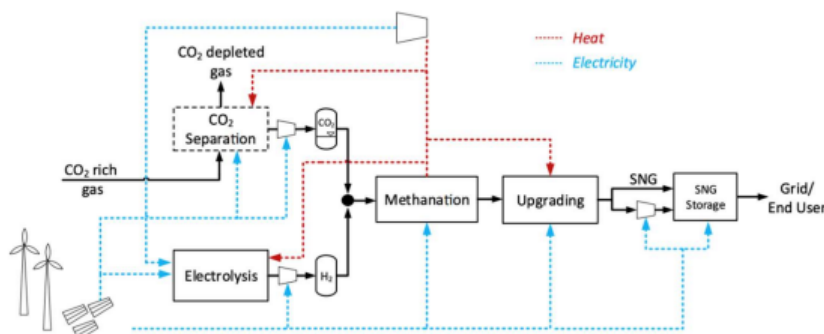


Figure 1: Power-to-Gas Process Courtesy of Gorre et al., 2009 as Given in the 2024 AIChE Student Design Competition Problem Statement [7]

### Objective of CO<sub>2</sub> Capture

Industry accounts for roughly a third of the world's total energy consumption and contributes to about 40% of the CO<sub>2</sub> emissions related to energy use [8]. Various research efforts emphasize the

need to tackle this issue by developing cost-effective technologies to capture CO<sub>2</sub> emissions from power plants and industrial processes. From there, the emissions are either used or safely stored underground. The advancement of Carbon Capture, Utilization, and Storage (CCUS) technology plays a vital role in enabling the transition to a sustainable energy future on a global scale.

Carbon capture technology is currently not utilized in industry, save for amine absorption, a specific type of scrubber commonly found in coal-based power plants [9]. This scrubber functions by introducing an amine solution and the contaminated gas into a distillation unit, where the amine solution absorbs dihydrogen sulfate (H<sub>2</sub>S) and CO<sub>2</sub> to produce a purified gas stream [10].

The primary challenge in expanding carbon capture technology lies in its high installation and operational costs, as well as concerns about accidental CO<sub>2</sub> release [10]. Efforts to reduce costs are anticipated to come from the adoption of membrane technologies for CO<sub>2</sub> capture and separation, along with incentives provided by the U.S. Department of Energy. Membrane technology offers several operational advantages, including a simple flow scheme, a smaller carbon footprint, handling/disposal issues, lower water usage, better turndown, and almost instant dynamic response. Additionally, the membrane process operates on electricity, eliminating the need for modifications to the power plant steam cycle unlike amine absorption [9]. The U.S. Department of Energy has allocated approximately \$2.5 billion in funding for carbon capture programs to accelerate investment in carbon capture, transportation, and storage technologies that have the potential to increase the implementation of carbon capture [11]. This funding aligns with President Biden's goal of achieving net-zero emissions in the U.S. within the next 26 years [12]. Apart from enhancing global competitiveness in clean energy, this funding is expected to generate manufacturing jobs and foster healthier communities [11].

The objectives for selecting a carbon capture source prioritize the two main concerns previously mentioned are limiting carbon capture from being so widely implemented: economic value and storage concerns. Choosing a CO<sub>2</sub> source that is both cheap to clean for methanation use and easy to store makes it more appealing to stakeholders who ultimately have final say on a process. Choosing a carbon source will start by identifying the most common CO<sub>2</sub> pollutants and then determining which of those has the most economical implementation. From there, carbon storage techniques to prevent leakage will be discussed to instill trust within the carbon storage system.

### Selection and Process Details

There are many sources of CO<sub>2</sub>, but the top three are due to electric power plants, cement production, and iron and steel plants. Table 1 below, taken from the American Chemical Society, details the largest CO<sub>2</sub> sources worldwide. Electric power plants account for the overwhelming majority of emissions, being 11x greater than the second greatest emission source. Carbon from cement production in itself still accounts for approximately 12% of CO<sub>2</sub> emissions, meaning that a large majority of CO<sub>2</sub> emissions can be mitigated and utilized to provide renewable energy if these three sources could be captured efficiently. Even though electric power creates the most emissions, cement production and steel plants release CO<sub>2</sub> at higher concentrations in their flue gasses. This higher concentration is beneficial for reducing the cost of capture, particularly for membrane processes in which separation efficiency is strongly dependent on CO<sub>2</sub> partial pressure, pressure being directly related to concentration [9]. Between cement production and



steel plants, steel plants have a higher average source size to source from making the CO<sub>2</sub> more accessible. Therefore, CO<sub>2</sub> produced from steel plants shall be selected and further analyzed.

*Table 1: Top CO<sub>2</sub> Sources Worldwide [9]*

Source	Number of Sources	Emissions 10 <sup>6</sup> tonnes/yr	Average Source size 10 <sup>6</sup> tonnes/yr	Average CO <sub>2</sub> Concentration (mol%)
Electric power plants	4940	10540	2.1	12-15%
Cement Production	1180	930	0.8	20-30%
Iron and Steel Plants	270	650	2.4	20-30%
Petrochemical	470	380	0.8	5-10%

Approximately 70% of integrated steel mills utilize blast furnace-blast oxygen furnace technology, which on average emits 1.7 tons of CO<sub>2</sub> per ton of steel produced. The off-gas from these furnaces contains approximately 20-28% CO, 17-25% CO<sub>2</sub>, 50-55% N<sub>2</sub>, and 1-5% H<sub>2</sub> [13]. More specific numbers are presented in Table 2 below. The presence of N<sub>2</sub> and Ar in the gas serves as inerting species within the fume. Extensive research on membrane technology for capturing CO<sub>2</sub> has shown promising results. Factors such as pressure ratio, membrane surface area, and stage cut during the operation are crucial in achieving both the quantity and purity of separated CO<sub>2</sub>.

*Table 2: Composition of Off Gas from Steel Blast Furnaces [8]*

Gas	Composition (% mol)
CO <sub>2</sub>	21.59
CO	23.45
H <sub>2</sub>	3.65
N <sub>2</sub>	46.51
H <sub>2</sub> O	4.2
Ar	0.6

Design simulations conducted by A. Ramirez indicate that separation costs can be as low as \$27 per ton of CO<sub>2</sub> for a two-stage membrane separation process with 95% CO<sub>2</sub> recovery [8]. The simulation parameters include 550,000 Nm<sup>3</sup>/h of off-gas, operating at 35 °C and a pressure of 1.05 bar.

While various materials are used for gas separation membranes, only a select few have been successfully implemented into large-scale production. Common materials include cellulose acetate, polysulfones, polycarbonates, polyimides, perfluoropolymers, and polydimethylsiloxanes [14]. However, obtaining comprehensive performance data for these membranes can be challenging; often, options are limited to specific gas combinations they are designed to accommodate [8]. This complicates the comparison of different membranes, especially when dealing with complex gas mixtures like blast furnace gas. Nevertheless, according to A. Ramirez's paper, MTR Polaris Membrane is considered best suited for CO<sub>2</sub> separation in the context of capturing it from steel off-gas, and thus, it will be the focus of this paper.

Another interesting observation about the composition of steel off gasses that's particularly beneficial to implementation in power-to-gas systems is the percentage of H<sub>2</sub> present. H<sub>2</sub> in the power-to-gas systems put forth from the AIChE guidelines is gathered from an electrolysis unit that is powered by renewable energy. The issue with using renewable energy to power an electrolysis unit is that it can be unreliable due to its dependence on weather conditions. This led the design team to create an electrolysis unit that produced more than the necessary amount of H<sub>2</sub> needed to run the methanation, storing it for periods when H<sub>2</sub> was unable to be produced. In short, a major setback in the hydrogen production process of the power-to-gas design was the unreliability of access to H<sub>2</sub>. Adding a H<sub>2</sub> permeable membrane could be of interest in order to not only recover CO<sub>2</sub>, but also H<sub>2</sub> to be utilized within the methanation process.

Due to the complex nature of the off gas and the rest of the power-to-gas subsystems for the project were created in Aspen Plus, the membrane process was attempted to be created in Aspen Plus for consistency. However, the Aspen package needed to simulate a membrane gas separation, MEMSIC, was not available for use at the time of report preparation. Instead, literature values were referenced for papers that were able to successfully model CO<sub>2</sub> capture via membrane separation. The key parameters, methods, and assumptions used to make the process are detailed in Table 3. A simplified block diagram not created in Aspen can be seen in Figure 2 to provide clarity to the structure of the carbon capture system. As seen in the figure, the furnace gas feeds into the membrane at a high pressure where the lower pressure gas is then removed at the permeate side. The retentate represents the clean gas created and the permeate represents the CO<sub>2</sub> extracted via the membrane. The multistage compressor and cooler used going into the membrane are to ensure that the high pressure needed on the top of the membrane is met and that it is sufficiently cooled as to not break down the membrane. The vacuum pump is used to remove air from the bottom of the membrane to promote a downward pull through the membrane itself. Without the vacuum, not enough transfer would occur. The cooler serves as a temperature regulator so that the CO<sub>2</sub> is at a reasonable temperature as it goes into the methanation unit.

Table 3: Process Parameters, Methods, and Assumptions Utilized in Aspen Model [15]

<b>General</b>
Peng-Robinson for energy calculations
Compressors and pumps are isentropic
Isentropic efficacy = 0.8
Mechanical efficiency = 0.9
<b>Multistage Constraints</b>
Max temp = 175 °C
Equal compression ratios across stages
<b>Heat Exchangers</b>
Shell and tube
Countercurrent flow
$U = 105 \text{ W/m}^2\text{-K}$
Cooling water in tube side
Inlet temp = 24 °C
Outlet temp = 34 °C
Gas outlet temp = 35 °C
<b>Membrane</b>
Ideal gas behavior
Crossflow
Perfect mixing

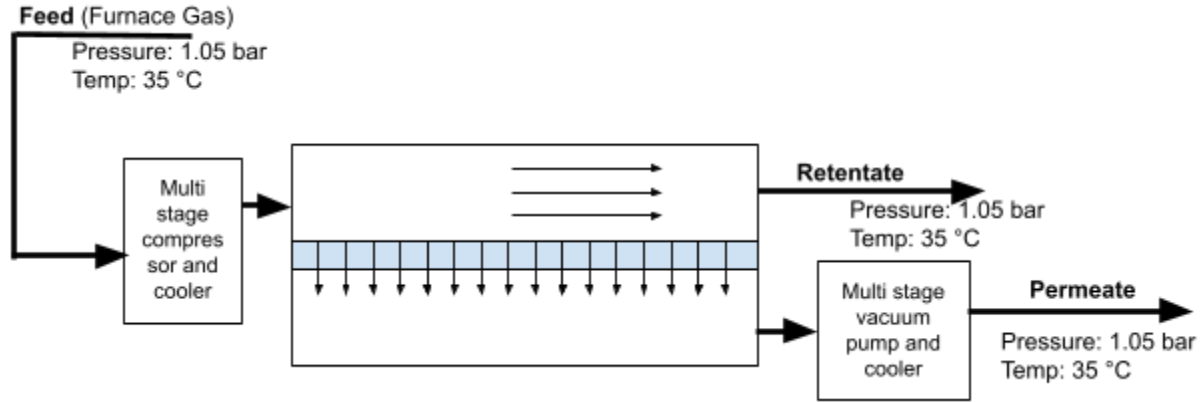


Figure 2: Cross-Flow Membrane with Single Stage Membrane

Since the MTR Polaris Membrane is a polymeric-dense membrane, calculations were done using a solution-diffusion mechanism. This process employs the use of key transport concepts and equations. The first is permeability across a membrane. This is typically defined as a passive diffusion rate of a species of interest across a membrane [16]. In this case,  $\text{CO}_2$  is applied. The equation for permeability can be seen in Equation 1.

$$P_i = D_i K_i \text{ (Equation 1)}$$

The second concept is pressure normalized flux across a membrane, which represents the flow of a substrate through a membrane's surface area [17]. The equation for flux can be seen in Equation 2. Notice that the flux can be simplified into permeability of species  $i$  over the length of the membrane.

$$J_i = \frac{D_i K_i (p_{i(0)} - p_{i(l)})}{l} = \frac{P_i}{l} \text{ (Equation 2)}$$

Since the off gas has multiple components, operations for multicomponent gas flow are required. Aspen has such capabilities to automate the calculations via its simulation database and is what was used for the economic analysis of this design.

## Economics

With cost being a key limitation of environmentally helpful CO<sub>2</sub> sourcing and capture, the process for carbon capture from steel mill off gasses will be analyzed to give an estimated cost calculation using the simulation reference in the selection section. This analysis only includes the operating and capital cost of the CO<sub>2</sub> sourcing and not the costs associated with the entire power-to-gas system design. Associated costs are described in a separate report.

Equipment costs, being a factor of the capital cost, include the membrane, membrane frame, compressor, vacuum pump, and heat exchangers. The equations for each can be seen below in Equations 3-7. Uncommon variable identification and units associated with them are provided in Tables 5 and 6 located at the end of this paper.

$$I_m = A_m K_m \text{ (Equation 3)}$$

$$I_{mf} = (A_m/2000)^{0.7} K_{mf} (P_{mf}/55)^{0.875} \text{ (Equation 4)}$$

$$I_C = C_o \left(\frac{P_{opr}}{6714}\right)^{0.8} MF_C MDF_C UF(ER) \text{ (Equation 5)}$$

$$I_{vp} = P_{vp} C_{vp} \text{ (Equation 6)}$$

$$I_{HE} = HX_0 \left(\frac{A_H}{139.4}\right)^{0.68} MF_{HE} MDF_{HE} (PF)(UF)(ER) \text{ (Equation 7)}$$

The capital cost equation can be seen in Equation 8. It sums all of the equipment factors and multiplies by an indirect cost factor to include equipment related costs that might have been neglected.

$$CAPEX = (\Sigma I_C + \Sigma I_{vp} + \Sigma I_{HE} + \Sigma I_{mf} + \Sigma I_m) ICF \text{ (Equation 8)}$$

Operation costs include the maintenance, energy, and cooling water costs, as well as the total operational expenditures. The equation for which can be seen in Equations 9-12.

$$C_{maint} = A_m v K_{mr} + 0.036(\Sigma I_C + \Sigma I_{vp} + \Sigma I_{HE}) + 0.01(I_m + I_{mf}) \text{ (Equation 9)}$$

$$C_{energy} = t_{op} P_{tot} K_{el} \text{ (Equation 10)}$$

$$C_{coolwater} = t_{op} W_{tot} K_{cw} \text{ (Equation 11)}$$

$$OPEX = C_{energy} + C_{coolwater} + C_{maint} \text{ (Equation 12)}$$

Finally, the specific separation cost can be calculated by obtaining the total annual costs and dividing it by the annual separated CO<sub>2</sub> predicted in tons per year. This can be seen in Equation 15. Key results of the economic analysis can be seen in Table 4 as presented in its original paper.

$$C_{cap} = [(\Sigma I_C + \Sigma I_{vp} + \Sigma I_{HE} + \Sigma I_{mf})ICF + (ICF - 1)a] + I_m a_m \text{ (Equation 13)}$$

$$C_{tot} = C_{cap} + C_{energy} + C_{maint} \text{ (Equation 14)}$$

$$C_{CO_2} = C_{tot}/M_{CO_2year} \text{ (Equation 15)}$$

Table 4: Key Elements from Cost Analysis for Capital and Operating Expenses for Steel Mill Carbon Capture [9]

System Item	Result
% CO <sub>2</sub> Capture	80%
Net Power Consumption (kW/CO <sub>2</sub> captured)	235
Membrane Area (m <sup>2</sup> / ton CO <sub>2</sub> captured)	2780
<u>Capital Expenses (\$1000/ton CO<sub>2</sub> captured/h)</u>	
Membrane	209
Compression & vacuum equipment	215
Refrigeration Equipment	20
Major Equipment Costs	624
Installation	624
Total Capital Expenses	1248
<u>Operating Expenses (\$/ton of CO<sub>2</sub> Captured)</u>	
Power @ \$0.05.kWh	11.8
Membrane Replacement (3 year life)	5.5
Operational Maintenance	3.7
Depreciation (12% of capital/year)	15
Total Capture Cost	36

The total capital expense (the expense to install such a system at an existing plant) is \$1.25 million. The membrane cost, which is unique to this carbon capture method, represents

approximately one-third of the overall expenditure on major equipment. Over a three-year period, replacing membrane modules accounts for merely ~10% of the total operational expenses. This is substantial as, depending on how well the membrane is taken care of, this life expectancy can increase, in turn causing this cost to go down in the operation section. Ideal operations would have to be studied for the exact life-extending conditions to be determined, however, and is beyond the scope of this paper. Continuing with operational expenses, energy is the largest contributor to cost. That is expected and typical for any plant. The cost of CO<sub>2</sub> capture within these facilities is approximately \$36 per ton, constituting approximately 10% of the total selling price of steel, being \$350 per ton of steel produced [9].

## Storage

As previously mentioned, despite the strong arguments in favor of adopting carbon capture technology, concerns about its increased cost and apprehensions regarding CO<sub>2</sub> storage impede its widespread implementation. The storage of any chemical component entails inherent risks, and CO<sub>2</sub> presents specific challenges, primarily carbon leakage. The initial step in addressing these risks, as recommended by the International Energy Agency, is to thoroughly comprehend their potential and formulate appropriate strategies through effective communication and consultation [22]. This approach forms the foundation for identifying any overlooked risks and enhancing public understanding of proper emergency protocols in the event of unexpected occurrences. By doing so, the overall safety of the operation is significantly enhanced.

The primary worry for stakeholders appears to be the possibility of leakage. When storing carbon in underground reservoirs, leakage could happen suddenly or gradually, creating potential environmental and social risks [23]. However, this risk is minimal and can be reduced through the implementation of appropriate safety measures along with ongoing research. Informing stakeholders and local communities about these risks to address their concerns could alleviate anxieties and foster the trust necessary for project approval. In industrial settings, CO<sub>2</sub> is typically stored in two main ways: mineral storage and deep geological storage [24].

Mineral storage involves the reaction of captured CO<sub>2</sub> with naturally occurring minerals, such as iron, calcium, and magnesium. This process occurs naturally over time through the weathering of rocks outside of industrial settings. The outcome produces minerals enriched with CO<sub>2</sub>, but stable, as they don't release carbon back into the atmosphere. However, since this natural process is typically slow under normal conditions, it demands significant energy input (largely due to maintaining temperature and pressure) to accelerate it. The Intergovernmental Panel on Climate Change suggests that facilities employing this method would require an additional energy increase of 60-180% compared to those not utilizing mineral storage [25]. Moreover, extracting CO<sub>2</sub> from these minerals demands an excess of energy, making it rarely employed and impractical both economically and logistically.

Utilizing geological storage (i.e. securely storing CO<sub>2</sub> underground in well-designed tanks) is considered the preferable alternative. In this approach, ensuring the safe operation of the storage site is crucial, with measures in place to detect and monitor any unintentional CO<sub>2</sub> leakage. Such leaks could pose hazards, as high concentrations of CO<sub>2</sub> can lead to suffocation [24]. Additionally, if CO<sub>2</sub> were to leak, it would negate the effectiveness of the process as a climate change mitigation method. However, according to the Intergovernmental Panel on Climate Change, the risks associated with well-selected, well-designed, and well-managed geological storage sites are generally low [25]. A specific concern with this method pertains to the potential outcome in the event of an earthquake that could damage the tanks or their transportation pipelines. Consequently, storage sites are typically situated in regions with minimal earthquake activity to mitigate this risk [24].

For optimal safety, it is recommended to utilize geological storage and select a storage site away from hazardous seismic zones. The team's proposed power-to-gas facility is planned to be situated in Iowa, alleviating concerns regarding this matter. Iowa lacks significant fault lines typically associated with earthquakes [26]. The state's seismic activity is minimal, with the two most recent earthquakes occurring in 2021 and 2004, both registering less than moderate on the



scale [26]. Aside location considerations, maintaining good industrial hygiene and implementing robust system monitoring practices will further enhance safety around storage operations.

## Conclusion

Globally, there is widespread consensus regarding the reality of climate change, predominantly attributed to excessive carbon dioxide emissions into the atmosphere. This pervasive issue necessitates prompt and concerted action. While numerous solutions have been proposed, many entail substantial financial investment. Thus, addressing this challenge is likely to require a multifaceted approach combining various strategies.

Currently the main method used for capturing CO<sub>2</sub> is through amine adsorption, primarily employed in coal power plants. Companies running these plants spend about \$60 for every ton of CO<sub>2</sub> they capture. According to R. Baker's estimates, this translates to roughly \$60 for every 1.25 MW of power produced [9]. However, when we consider other options like membrane separation in steel mills, the cost decreases. In steel mills, for every ton of CO<sub>2</sub> produced, about 0.55 tons of steel are generated, bringing in almost \$350 in profit per ton. Capturing CO<sub>2</sub> in these settings only costs about \$36 per ton, which is roughly 10% of the steel's total selling price. This represents a decrease of about \$20 per ton compared to the current method. One reason for this cost difference is that the off gasses in steel mills contain a higher concentration of CO<sub>2</sub> compared to those in coal power plants.

Because carbon capture from steel mill off gases is cost-effective and steel mills rank as the third-largest overall contributor to CO<sub>2</sub> emissions, there's a suggestion to incorporate it into the AIChE design challenge as the source of CO<sub>2</sub> for methanation. This approach keeps the overall plant cost low, fulfilling the requirement for an economical source, while also actively reducing harmful emissions and in turn meeting the environmental friendliness requirement. Unfortunately, the chosen carbon capture method could not be integrated into the available Aspen software without an additional add-on not provided by the university. Consequently, it was not utilized in the final power-to-gas system design selected by the design team. If Aspen had the necessary capabilities, it would have been implemented, enhancing the research behind the design. Instead, the team ultimately focused on fermenting corn, as researched by another teammate. Personal efforts were directed towards the electrolysis unit of the design, which is related to the other raw materials required for methane production with CO<sub>2</sub>. Despite its exclusion from the final report, combining CO<sub>2</sub> capture at steel mills with membrane technology shows significant promise for power-to-gas sourcing applications.

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## Nomenclature

Table 5: Cost Parameters for Equipment Cost, Capital Cost, and Operating Cost [18-21]

$K_m$	40	EUR/m <sup>3</sup>
$K_{mf}$	$286 \times 10^3$	EUR
$HX_0$	$3 \times 10^5$	USD <sub>1987</sub>
$MF_{HE}$	3.48	-
$MDF_{HE}$	3.2	-
PF	1.08	-
ICF	1.31	-
v	0.2	-
$K_{mr}$	10	EUR/m <sup>2</sup>
$t_{op}$	8000	h/year
$K_{el}$	0.05	EUR/kW
$K_{cw}$	0.1	EUUR/m <sup>3</sup>
a	0.071	-
$a_m$	0.231	-

Table 6: Symbol Identification

<b>Symbol</b>	<b>Units</b>	<b>Name</b>
$P_i$	$\text{mol}/(\text{m}^2\text{sPa})$	Permeability of membrane for species i
$D_i$	$\text{m}^2/\text{s}$	Diffusion coefficient of species i
$K_i$	$\text{mol}/\text{m}^3\text{Pa}$	Sorption coefficient of species i
$J_i$	$\text{mol}/(\text{m}^3\text{Pa})$	Pressure normalized molar flux of species i
$l$	$\text{m}$	Membrane thickness
$P_{i(0)}$	$\text{Pa}$	Partial pressure of species i at feed
$P_{i(l)}$	$\text{Pa}$	Partial pressure of species i at outlet