Undergraduate Thesis Prospectus

Power Plant Design using Allam Cycle CCS

(technical research project in Chemical Engineering)

Agricultural Demand and Water Sustainability: Responsible Use of the Ogallala Aquifer

(sociotechnical research project)

by

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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General research problem

How may the sustainability of production processes be improved?

In the past 120 years alone, annual global GDP has grown from $3.4 trillion to more than $108 trillion, in international dollars and adjusted for inflation (OWID, 2020). Since 1990, growth has been particularly steep in Africa and Asia in recent years (Yuen & Jumssa, 2010). Coupled with this industrial explosion is the rise of carbon emissions from the burning of fossil fuels in industrial processes. In the US, carbon dioxide (CO_2) emissions have increased by 90 percent in the past half century (EPA, 2020). As much as one third of greenhouse gasses are produced in agriculture (Gilbert, 2012) and ammonia production emits more than 450 megatons of CO_2 equivalent greenhouse gasses annually (OSU, 2019). How companies and other public groups react to changing public policy or help facilitate its conception will largely determine whether the world sees improvements in the current environmental outlook.

Due to Jevons' Paradox however, this problem cannot be solved by simple improvements in technology efficiencies and economies (Jevons, 1865). Public initiatives such as recycling have also failed to produce lasting changes in public behavior that would assist in fighting the pollution problem. More sustainable processes are needed.

Power Plant Design using Allam Cycle CCS

How can carbon capture systems be implemented to improve power generation sustainability?

Overview of Carbon Capture Systems and the Allam Cycle

The technical research problem will be completed as a capstone project through the Department of Chemical Engineering with Professor Eric Anderson as technical advisor and alongside Michael Beekwilder, Ben Johnson, Conor Moran, and Alex Sims.

This project aims to develop a design for a 500 MW power plant based on a zero emissions, natural gas utilizing Allam Cycle. A 50 MW demonstration plant using this technology was built in 2018 and proved the validity of the model: this will serve as the basis for our scale up. The Allam cycle uses CO_2 as a working fluid to create a modified version of the Brayton cycle. It begins with a high pressure oxy-fuel combustor that combusts natural gas with pure O_2 and recycled CO_2 streams. The byproducts of the combustion are only CO_2 and water. The high-pressure outlet stream is then fed to a turbine that will generate power. The exhaust of this combustion gets separated, and then used to create a partially closed loop using the majority of the CO_2 for working fluid, and exporting all water.

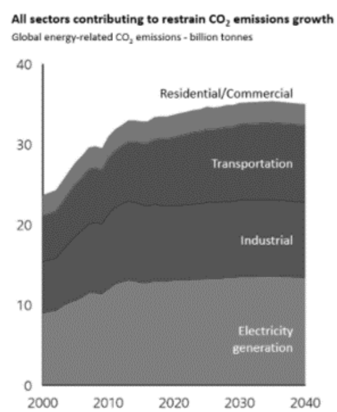

Figure 1: Timeline of Global CO_2 emissions broken down by sector

Tackling growing CO_2 emissions from the burning of fossil fuels has arguably become the biggest challenge of our generation. In 2015, the 197 parties to the United Nations Framework Convention on Climate Change (UNFCCC) developed the Paris Agreement to address growing concerns over global emissions and climate change. The Agreement requires countries to put forth their best efforts to reduce their impact on global temperatures through “nationally determined contributions (NDCs)”, with the ultimate goal of achieving a sustainable low carbon future and a global temperature rise of no more than 2°C from the pre-industrial era. The Paris agreement was developed to place an attainable limit on the detrimental impacts of global warming: a 2°C rise in temperatures will lead to severe heat waves, high risk of water and food scarcity, loss of biodiversity, increased flooding, and economic losses (an estimated $446 billion of U.S. GDP alone in 2017). Due to growing global populations and rises in living standards, yearly CO_2 emissions are projected to increase by 5% in 2040, despite breakthroughs in energy efficiency and a shift in the global energy mix towards renewables. It is estimated that CO_2 is currently emitted into the atmosphere at a rate of 36.6 gigatons per year (Figure 1), and to achieve a 2°C pathway, no more than 565 gigatons more of CO_2 may be released to the atmosphere over the coming years. Furthermore, Figure 1 shows that the electricity generation sector produces approximately 33% of global CO_2 emissions. The combination of rising emissions and an already large global emissions output has set the world off course from the 2°C pathway: projections show that this 2°C increase will likely be surpassed by 2035. Carbon capture technologies that eliminate emissions from the power plants have recently been developed to reduce the effect of the electricity generations sector on global emissions.

Carbon capture and sequestration (CCS) was first proposed and implemented in 1977 in Texas for enhanced oil recovery, but has since been applied to power generation and gas processing industries as well (IEAGHG, 2012). CCS processes employ three different methods, pre-combustion, post-combustion, and oxyfuel combustion. Pre-combustion capture refines the fuel of carbon elements before it is combusted, post-combustion separates out the CO_2 from the flue gas exhaust and Oxy-fuel combusts the fuel with pure O_2 with a gas shift reaction to form easily separable H_2O and CO_2. All three of these methods effectively capture the CO_2 from the process, but have heavy energy penalties, ranging from 5-40%. This major drawback makes CCS economically unattractive, which has limited CCS implementation - CCS may only see widespread use by severely reducing these associated energy penalties.

The Allam cycle, proposed in 2013 by Rodney Allam, offers a promising potential gain in economic viability for CCS (Allam et al., 2013). The process adapts well to the current U.S. energy industry through compatibility with the abundance of U.S. natural gas and coal reserves and the removal of emissions concerns. Additionally, an Allam cycle plant can output CO_2 directly to existing CO_2 pipelines with ease, taking advantage of existing infrastructure. The Allam cycle also provides an emission-free complement to renewable energies that can ensure energy demand is met under conditions where renewables cannot achieve their maximum outputs (lack of sun or wind). This novel power cycle can ease the transition between fossil fuels and renewables while simultaneously curbing fossil fuel emissions. Furthermore, the proven success of the 50 MW power plant serves as motivation for the scale up of the Allam cycle to a 500 MW plant for this design project.

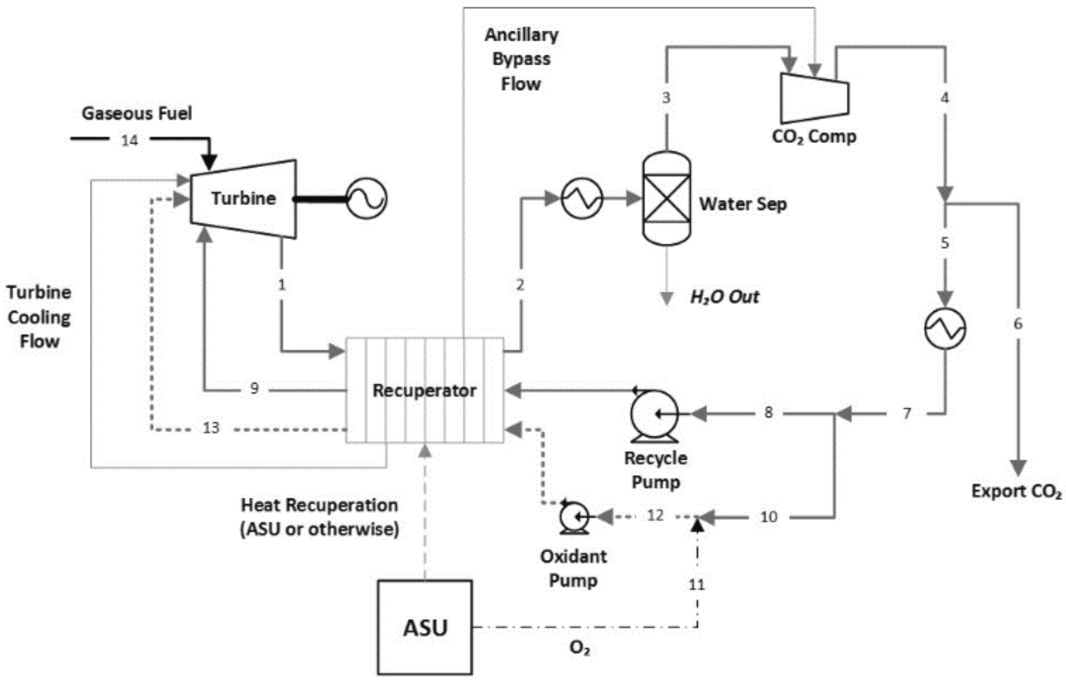

Figure 2: Simplified Process Diagram for Allam Power Cycle (taken from Allam (2017) without permission)

The Allam cycle operates similarly to previously established Oxy-Fuel Carbon Capture and Sequestration (CCS) units. Combustion is between a pressurized gaseous fuel and pure O_2 stream in order to turn a turbine and produce electricity. However, this cycle differs from normal Oxy-Fuel CCS units because the fuel stream and oxygen stream are fed in tandem with a hot CO_2 oxidant stream to the combustion chamber at approximately 300 bar. Combustion in the novel combustion chamber and turbine designed by Toshiba then occurs at an inlet temperature of 1150 C. Pure O_2 is obtained for this process from an on-site air separation unit (ASU) and fed directly through the recuperator to the combustion chamber, and into the recycled CO_2 stream to create the oxidant feed. In the context of this study, the ASU will be considered a black box. Upon expansion through the turbine, the exhaust stream consisting of CO_2 and water experiences a pressure and temperature reduction to 30 bar and 700 C. This exhaust stream also flows through the recuperating heat exchanger in order to transfer heat to the CO_2 recycle stream before moving to a separation unit (Allam 2017).

Table 1: Stream Data for 50 MW demonstration plant with stream numbers corresponding to numbers given in Figure 1 (taken from Allam 2017 without permission)

Stream	Temperature (°C)	Pressure (bar)	Mass Flow (kg/s)
1	727	30	923
2	43	29	564
3	17	29	563
4	23	100	909
5	23	100	881
6	23	100	28
7	16	100	881
8	16	100	689
9	717	312	586
10	16	100	191
11	16	100	41
12	2	99	233
13	717	310	233
14	266	330	10

After the exhaust stream from the turbine passes through the recuperator, the stream is further cooled to just above ambient air temperatures at 43 °C. The stream is then passed through a separator and condenses out the water produced from the combustion in the turbine. The water is high purity and can be disposed of with no processing. The remaining gaseous CO_2 stream, now slightly below ambient air temperature at 17 °C, passes through a CO_2 compressor and is compressed from the relatively low pressure exhaust stream (29 bar) up to high pressures (near 100 bar). Compressing the stream increases the temperature, and so it is sent through another heat exchanger to bring the temperature back down to post water separation temperatures. Before the CO_2 stream is cooled again, a portion of it is taken off as a product stream. This is a very high purity CO_2 stream and is pumped to a high pressure CO_2 pipeline where it can be sequestered or utilized. Overall, about 5% of the initial CO_2 stream out of the CO_2 compressor is taken out as a product. After cooling, the recycle stream is split into two separate streams. The first of these new streams is sent to the recycle compressor that compresses the recycle stream further to 310 bar. The other stream is mixed with pure oxygen from the ASU and then fed to an oxidant pump that also compresses it to 310 bar. Both of these streams are then fed to the recuperator and are used to help cool the product exhaust stream (Allam 2017).

This project will be completed as a team of five students over the course of two semesters in CHE 4438 and CHE 4476. The work on the computational analysis, economic estimates, and process design will be divided equally among the team members. Check-ins will occur regularly and frequently via routine meetings as a team, meetings with the capstone project advisor Professor Anderson, and continuous communication to ensure the schedule and Gantt chart are followed.

Design data will be obtained from sources such as the 50 MW demonstration plant currently operating in LaPorte, TX and articles about the theory and modeling of the Allam cycle in a natural gas power plant peer-authored by Rodney J. Allam. An example is given in Figure

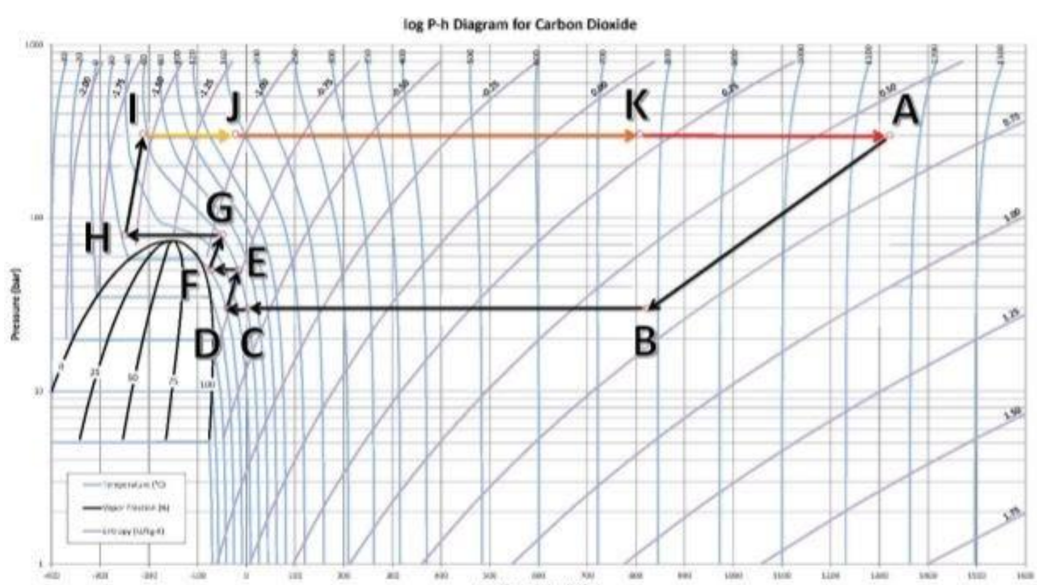

Figure 3. Pressure Enthalpy Diagram for the Allam Cycle (A→K) (Taken from Allam (2017) without permission)

3, where the pressure enthalpy diagram for CO_2 in the Allam cycle is given. This data will be incorporated into a thermodynamical model using Aspen Plus design software with RK-Soave and Peng-Robinson equation of state to best match the operational region of the Allam cycle. Aspen Plus was chosen as the process modeling software, because there is literature available describing how the demonstration plant was modeled under these conditions. Final deliverables will include material and energy balances for the process and unit operations, a PFD and simulation of the proposed Allam Cycle power generation system, analysis of safety and environmental issues, and an economic analysis.

Agricultural Demand and Water Sustainability: Responsible Use of the Ogallala Aquifer

How have U.S. agriculture enterprises, conservationists, and others competed to draw the line between responsible and irresponsible use of the Ogallala Aquifer?

Water Politics and the Aquifer

What is the limit of responsible water use? Water politics has shaped many U.S. policies, laws, and court cases for more than a century. The Ogallala Aquifer, residing under the Great Plains of the United States, offers an extraordinary case study for how water politics have affected the economic, environmental, and social health of the region and nation.

The aquifer lies under 174,000 square miles and holds 978 trillion gallons of water. But the supply has been declining by 325 billion (.03%) annually for almost 50 years (Brambila, 2014). Agricultural irrigation is depleting the aquifer; states above the aquifer account for 40 percent of irrigated acreage in the U.S. (USDA, 2020). In the U.S., crops and livestock are valued at $76 billion annually (Climate Hubs, 2017), providing a total of 22.8 million jobs (FB, 2019). At the present consumption rate, the aquifer may be depleted in 50 years (Bramibila, 2014). Experts in education, environmental policy, and agricultural innovation are striving to protect the aquifer.

Among high plains producers, the vast majority already recognize groundwater depletion as a serious threat (Lauer et al., 2020). Terrell and Hornbeck state that the discovery and subsequent depletion of one resource across a region creates economic hardship for the whole community (Terrell et al., 2002; Hornbeck et al., 2014).

Research on the Aquifer

Research on problems of resource conservation has been extensive. Cano et al. (2018) have proposed that measures to restore soil health and biology can reduce irrigation demand. Peterson et al. (2003) review the competing values governing aquifer conservation policy, finding that economic efficiency has prevailed over other values, including social equity and the duty of environmental preservation. Rad et al. (2020) showed that declining well levels result in lower average profits and increased downside risk to Midwest regional crops.

Edwards et al. (2012) developed municipal water conservation models for communities that depend on the aquifer, proposing that by adhering to them, communities can delay or prevent aquifer depletion. Economists have proposed that voluntary water conservation programs can significantly reduce total water demand (Lansford et al., 1983). Howe (2002) has examined similar groundwater management cases, reaching conclusions applicable to the conservation of the Ogallala Aquifer.

Participants of the Aquifer

Participants include agribusiness enterprises, large producers, agricultural associations (such as the Farm Bureau Federation), independent farmers, and conservation advocacies. Jeff Caldwell writes for AGCO, an agricultural company which urges farmers to “implement practical conservation measures" to "cut usage, while maintaining crop output (Caldwell, 2016). The Natural Resources Conservation Service, a nonprofit, "supports targeted, local efforts to conserve the quality and quantity of water" (Dostie, 2020).

Agricultural enterprises include Tyson Fresh Meats, which announced success in verifying "sustainable cattle production practices" in the Midwest region (Tyson, 2020). Benson Hill is also working with conservation experts and advocates "to establish best practice principles" in gene editing to improve crop sustainability (Benson Hill, 2018).

Some independent farmers strive to reconcile aquifer conservation and high farm productivity. The National Farmers Union desires to "advocate for family farmers… and their communities" and support more innovative solutions than shifting the market or reducing capacity (NFU, 2019). The news outlet Civil Eats seeks to inform and educate the American public through op-ed articles to "shift the conversation around sustainable agriculture" (Civil Eats, 2020).

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