Prospectus

Design of a 500 MW Natural Gas Allam Cycle Power Plant

(Technical Topic)

Analysis of the Failure of the Largest Clean Coal Power Plant in Kemper County, MS

(STS Topic)

By

Conor Moran

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Technical Project Team Members: Benjamin Johnson, Michael Beekwilder, Alexander Sims, James Perry

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.

Signed: *Conor James Moran*

Approved: _______________________________________ Date ________________________
Benjamin Laugelli, Department of Engineering and Society

Approved: _______________________________________ Date ________________________
Eric Anderson, Department of Chemical Engineering

Introduction

Tackling carbon emissions is arguably the biggest challenge of the 21st century – a challenge formally addressed by the Paris Agreement of 2015. The 197 parties to the agreement have promised to actively create "nationally determined contributions" (NDCs) towards carbon neutrality through the combination of energy efficiency improvements and the use of renewable energy technologies (*Status of Ratification of the Convention*, n.d.; *What Is the Paris Agreement?*, n.d.). Due to a heavy reliance on cheap, abundant, and carbon-intensive fossil fuels, the world is on track to pass the 2°C limit set forth by the Paris agreement by 2035 – which will have disastrous consequences globally (*Emissions Sources*, 2020).

Massive research and development efforts have been made for carbon capture and sequestration (CCS) technologies that address emissions head-on, with a heavy emphasis on solutions for the electricity generation sector. Pre-combustion, post-combustion, and oxyfuel combustion CCS techniques remove sources of CO_2 at different points during fuel to electricity conversion processes (Budinis et al., 2018). While pre-combustion capture and oxyfuel combustion are not yet commercially viable, more mature post-combustion capture techniques have begun to permeate into the energy sector. The problem with these CCS technologies is that their use requires large capital investments and introduces severe energy penalties to a power plant, limiting their widespread adoption (Budinis et al., 2018). To address the downfalls of CCS technologies, I will propose the development of a large scale Allam cycle-based power plant – a breakthrough technology that enables competitive electricity generation from fossil fuels while actively sequestering all emissions.

While technical improvements to the efficiency and cost of CCS methods remain a primary driver for increasing their viability, there are important economic and political factors that shape their development and implementation. These non-technical factors include CCS incentives, public opinion and perception of CCS, energy policy, and fuel markets (Budinis et al., 2018). A lack of understanding regarding these social factors will invariably hinder their implementation and the achievement of the Paris Agreement goals, making way for a grim future of global food and water insecurity, flooding, losses of biodiversity, and economic losses (Buis, 2019).

To effectively mitigate carbon emissions using CCS, the technical and social aspects of the issue must be addressed simultaneously. Using chemical process modeling and simulation, I will address the issue by developing the technical specifications for the construction of a large-scale (500 MW) Allam cycle based power plant that will prove the technology's commercial feasibility. Furthermore, I will apply actor-network theory to a failed large-scale integrated gasification combined cycle (IGCC) power plant in Kemper County, MS to determine what human and non-human actors impede the success of breakthrough CCS technologies.

Technical Problem

Reducing 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 (*Status of Ratification of the Convention*, n.d.). 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 (*What Is the Paris Agreement?*, n.d.). The Paris agreement was developed to place an attainable limit on the detrimental impacts of global warming: a greaterthan 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) (Buis, 2019). Due to growing global populations and rising 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 (Crane, 2020). It is estimated that CO_2 is currently emitted into the atmosphere at a rate of 36.6 gigatons per year (figure 2), and to achieve a 2°C pathway, no more than 565 gigatons of CO_2 may be released to the atmosphere over the coming years (*Emissions Sources*, 2020). Furthermore, figure 2 shows that the electricity generation sector produces approximately 33% of global CO_2 emissions (Crane, 2020). 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 (*Emissions Sources*, 2020). Carbon capture technologies that eliminate emissions from power plants have recently been developed to reduce the effect of the electricity generation sector on global emissions.

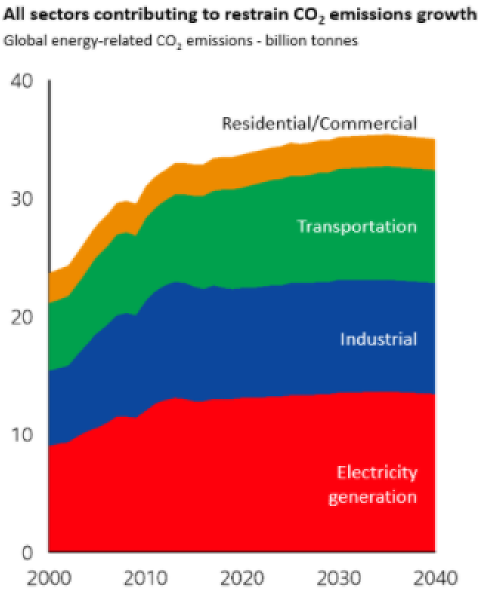


Figure 2: Timeline of global CO_2 emissions broken down by sector

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 (*A Brief History of CCS and Current Status*, n.d.). CCS processes typically employ one of three different methods, pre-combustion, post-combustion, and oxyfuel combustion (Budinis et al., 2018). According to Budinis et al., pre-combustion capture purifies the fuel of carbon elements before it is combusted, post-combustion separates out CO_2 from flue gas exhaust, and oxyfuel combustion techniques combust fuel with pure O_2 to form readily separable H_2O and CO_2. All three of these methods effectively capture CO_2 emissions, but have large energy penalties, ranging from roughly 5-30% (Budinis et al., 2018). This major drawback can make CCS economically unattractive, which has limited CCS implementation (Budinis et al., 2018).

The Allam cycle, proposed in 2013 by Rodney Allam, offers a promising potential gain in economic viability for CCS (R. J. 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 pipeline infrastructure (R. Allam et al., 2017). The Allam cycle could also serve as an emissions-free complement to renewable energy technologies that can help ensure energy demand is met in spite of renewables intermittency (lack of sun or wind) (R. Allam et al., 2017). 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 (R. Allam et al., 2017; Goff, 2019) serves as motivation for the scale up of the Allam cycle to a 500 MW plant for this design project.

This technical project aims to design a 500 MW zero-emissions Allam cycle power plant that utilizes natural gas. A 50 MW Allam cycle demonstration plant was built in 2018 and proved the validity of the technology, which will serve as the basis for our scale up (R. Allam et al., 2017; Goff, 2019). The Allam cycle uses CO_2 as a working fluid to create a modified version of the Brayton cycle (R. J. Allam et al., 2013). According to Allam, the process begins in a high pressure oxyfuel combustor that combusts natural gas with pure O_2 and recycled CO_2 streams. The combustion products of the reaction are solely CO_2 and water. The high-pressure outlet stream is then fed to a turbine in order to generate power. Next, the combustion exhaust gases are separated; the resulting CO_2 is used as the working flood to create a partially closed loop, while the water can be removed as waste.

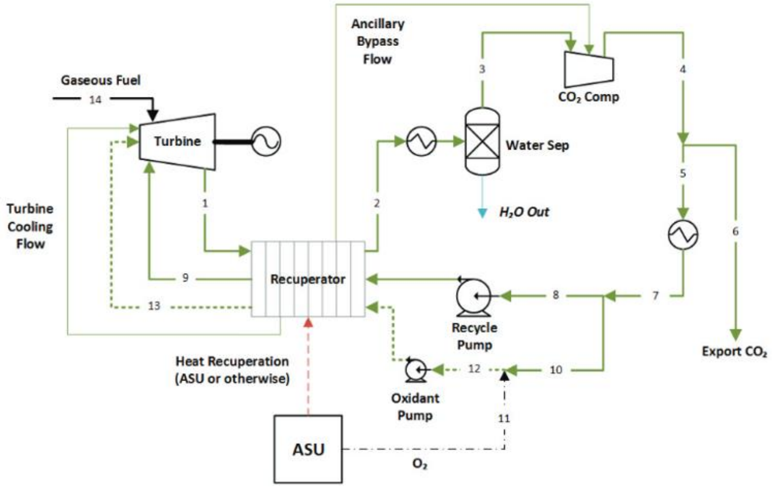
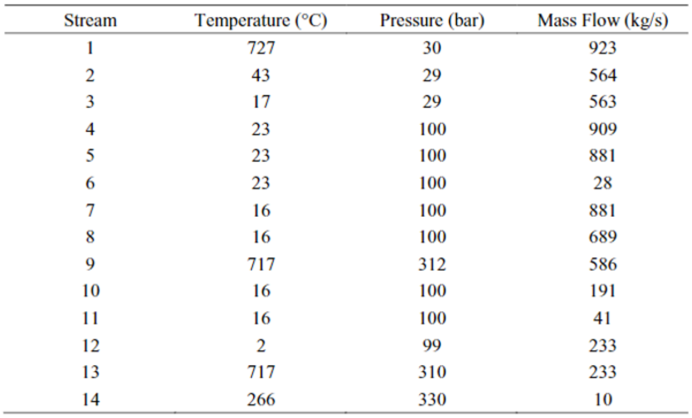


Figure 1: Simplified Process Diagram for Allam Power Cycle (Allam 2017)

The Allam cycle operates similarly to simple oxyfuel carbon capture and sequestration (CCS) units – combustion occurs between a pressurized gaseous fuel and a pure O_2 stream in order to turn a turbine and produce electricity (R. J. Allam et al., 2013). However, this cycle differs from normal oxyfuel CCS units because the fuel stream and oxygen stream are fed in tandem with a hot CO_2 oxidant stream to the combustion chamber. Combustion in a novel combustion chamber and turbine designed by Toshiba then occurs at an inlet temperature of

1150 °C (R. J. Allam et al., 2013). Allam et al. specifies that pure O_2 is obtained for this process from an on-site air separation unit (ASU), and is fed directly through a heat recuperator to the combustion chamber, mixing with the recycled CO_2 stream to create an oxidant feed. In the context of this study, the ASU will be considered as 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 (R. J. Allam et al., 2013). Allam et al. goes on to mention that 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.

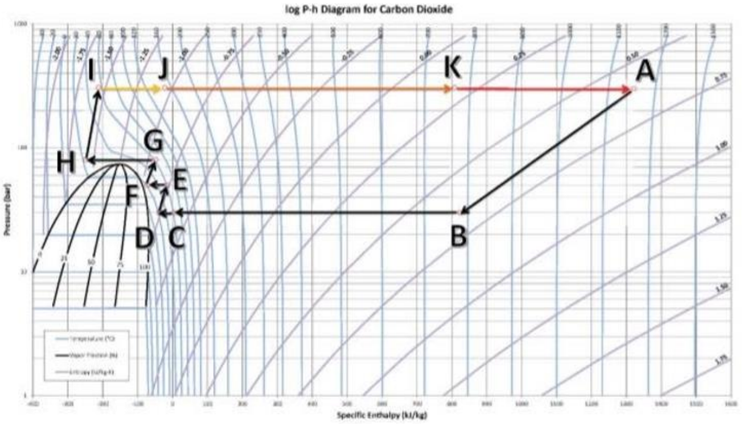
Table 1: Stream Data for 50 MW demonstration plant (Allam 2017)



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 flash separator, which condenses out the water combustion product. The water is of high purity and can be disposed of with no additional 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 low pressure (29 bar) up to high pressure (near 100 bar) (R. J. Allam et al., 2013). Allam et al. mentions that compressing the stream increases the temperature, requiring an additional heat exchange step to bring the temperature 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, resulting in a very high purity CO_2 stream capable of achieving proper CO_2 pipeline pressures for sequestration or utilization. Overall, about 5% of the initial CO_2 stream out of the CO_2 compressor is removed as product. After cooling, the recycle CO_2 stream is split into two separate streams. The first of these new streams is sent to a recycle compressor that compresses the recycle stream to a pressure of 310 bar. The other stream is mixed with pure oxygen from the ASU and is subsequently 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 (R. J. Allam et al., 2013).

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 (R. Allam et al., 2017). An example of design data is given in Figure 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 the RK-Soave and Peng-Robinson equations of state to best match the characteristics of supercritical CO_2 utilized in the Allam cycle. Aspen Plus was chosen as process modeling software because there is existing literature describing how the demonstration plant was modeled under these conditions (R. Allam et al., 2017).



Pressure Enthalpy Diagram for the Allam Cycle (A→K) 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 that deliverables are finished promptly.

STS Problem

In February of 2006, the U.S. Department of Energy and Southern Company Services entered a cooperative agreement under the Clean Coal Power Initiative to produce the largest Integrated Gasification Combine Cycle (IGCC) power plant in the world, which was set for development in Kemper County, MS (Newsome et al., 2018). The plant was meant to operate using new Transport Integration Gasification (TRIG) technology to produce syngas from locally mined lignite coal in a process known as gasification (pre-combustion capture) (Newsome et al., 2018). The produced syngas, a mixture of primarily hydrogen, CO, and CO_2 could be “cleaned” with emissions control equipment to capture over 65% of the CO_2 for use in enhanced oil recovery (EOR), achieving emissions levels comparable to widely used natural gas-fired power plants (*Southern Company - Kemper County, Mississippi*, n.d.). While the project was planned to be completed by 2014 at a total cost of roughly $3 Billion, problems relating to the gasification technology severely delayed the project and pushed the final project cost to roughly $7.5 Billion (Swartz, 2017). in June of 2017, the Kemper plant announced the indefinite suspension of the coal gasification technology in favor of running on cheap natural gas that could help manage the poor economics of the project (Guess, 2017).

While the failure of the project is often attributed to flaws in the construction and design of the gasification technology as well as influence from the natural gas market, this fails to account for mounting pressures to prove the technology and underscores the importance of the role played by organizational actors such as the government, Southern Company Services, and environmentalists (Kelly, 2018). As an example, power generation regulations developed by the government incentivized further development of the Kemper plant in spite of poor design by allowing Southern Company Services to profit off of the project before finishing installation (Kelly, 2018). If we continue to base root cause analyses on the technical shortcomings of CCS projects, we will fail to gain an understanding of how these non-technical actors can influence project outcomes, and similar CCS failures may happen in the future that are entirely unrelated to the feasibility of the technology itself.

I argue that poor construction and design of the Kemper project in conjunction with falling natural gas prices, exploitable government regulations, societal pressures, internal conflict among project stakeholders, and influence from anti-project environmentalists led to the failure of the Kemper County Energy Facility’s use of coal gasification. Actor-Network theory seeks to identify and characterize a network builder who recruits both non-human and human actors to accomplish a specific goal. The process by which these actors are assembled to form and stabilize a network is known as translation. Applying this concept, I will describe the process by which the Kemper project network was created and the process by which the network dissolved to gain an understanding of the human and non-human actors that must be accounted for when developing future CCS projects. To undertake this analysis, I will utilize evidence from exclusive interviews with parties involved in the development of the project, press releases and public reports from Southern Company Services, and reports from the Department of Energy.

Conclusion

The deliverable for the technical problem discussed in this paper will be a full design of a 500 MW Allam cycle-based power plant capable of achieving high efficiencies with no emissions, with detailed modeling and simulation work to support this goal. The STS research paper will strive to determine why the largest Integrated Gasification Combined Cycle (IGCC) project in the world failed to deliver upon its promise. This will be accomplished by applying Actor-Network theory to characterize how relevant human and non-human actors play a role in shaping the development of CCS plants. The combined results of this technical report will serve to address the issue regarding implementation of breakthrough CCS technologies from a socio-technical lens, highlighting key considerations for the success of CCS projects and proposing the adoption of a particularly promising CCS technology.

Word Count: 2,609

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