Design of a 500 MW, Zero Emissions Natural-Gas Power Plant Employing the Allam Cycle
(Technical Topic)

Cultural Opposition to Michael Mann's Climate Change Research on Temperature Modeling
(STS Topic)

A Thesis Project Prospectus Submitted to the

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Alexander Sims

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Technical Project Team Members:
Michael Beekwilder, Ben Johnson, Conor Moran, and Jay 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.

Signature: _________________*Alexander Sims*______________________________

Approved: ____ Date: ________________________
Kathryn A. Neeley, Associate Professor of STS, Department of Engineering and Society

Approved: ____ Date: ________________________
Eric W. Anderson, Professor of Chemical Engineering, Department of Chemical Engineering

Introduction

Recent human activity has caused a substantial increase in greenhouse gases, primarily carbon dioxide, which has led to faster rates of global warming. “Earth’s average temperature has increased about 2 ^{o}C during the 20^{th} century” and has continued to rise (NASA, 2020. Pg. 1). This has led to enormous changes in the environment, which poses threats to the environment, coastal communities, and agricultural industries. Carbon dioxide enters the atmosphere through multiple pathways including burning fossil fuels such as natural gas. Energy production accounts for a significant portion of the greenhouse gases produced by human activity, and 32.3% of total U.S. carbon dioxide emissions in 2018 (EPA. Overview of Greenhouse Gases, 2020). Alarmingly, these emissions have been growing as energy demand rises, since there is no zero-emission method for energy production that could slow the rate of global warming and the oncoming economic and environmental impacts. However, to effectively inspire climate action like the implementation of an emissions free power plant, the cultural dismissal of climate change needs to be addressed. For instance, Michael Mann, a climate scientist and professor, received criticism from politicians and industry groups trying to reduce the impact of and action stimulated by Mann’s research on global temperature trends over the past two millennium which showed the extent of global warming (Mann, 1998. Mann, 1999. Wright, 2013). If climate action continues to be stifled and belittled, more carbon dioxide will be released into the atmosphere accelerating global warming causing abnormal droughts and altered precipitation patterns to more intense frost seasons. Without action, consequences from global warming will cause significant humanitarian and economic ruin to millions of people by destroying industries through climate change and causing devastation by severe weather (NASA, 2020).

To address this problem, by decreasing carbon dioxide emissions, this technical project addresses aims to design a 500-megawatt, zero emission, natural gas power plant via the use of a novel process called the Allam Cycle. The Allam Cycle uses pure oxygen and excess carbon dioxide to ensure complete combustion of natural gas, making it physically and economically feasible to capture the carbon dioxide instead of venting it into the atmosphere (Allam, 2013. Eight Rivers, n.d.). This STS project will develop a better understanding of the cultural opposition towards climate action Mann experienced and why neither party involved fully attempted to understand the other's reasonings. The understanding gained from the STS project can be used to support future climate action research and technology.

Technical Topic: Design of a 500 MW, Zero-Emissions Natural-Gas Power Plant Employing the Allam Cycle

Tackling growing CO_2 emissions from the burning of fossil fuels has become a significant global challenge. 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 (United Nations, 2020). 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, 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 (EPA. Overview of Greenhouse Gases, 2020). 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.

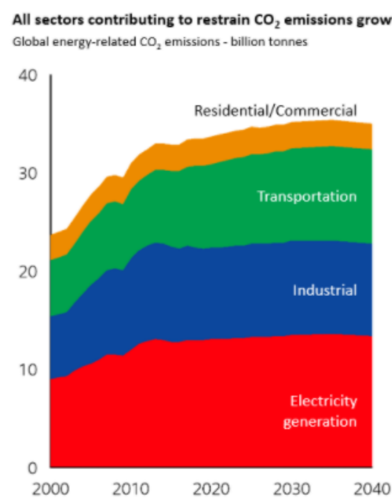

Figure 1. Timeline of Global CO2 emissions Broken Down by Sector (EPA. Overview of Greenhouse Gases, 2020)

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, 2013). The process, described below, 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 built in 2018 serves as motivation for the scale up of the Allam cycle to a 500 MW plant for this design project.

This project aims to develop a design for a 500 MW power plant based on zero emissions, natural gas utilizing Allam Cycle. A 50 MW demonstration plant using this technology 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.

The Allam cycle shown in Figure 2 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 further detailed in Table 2. Combustion in the novel combustion chamber and turbine designed by Toshiba then occurs at an inlet temperature of 1150 ^{o}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 ^{o}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).

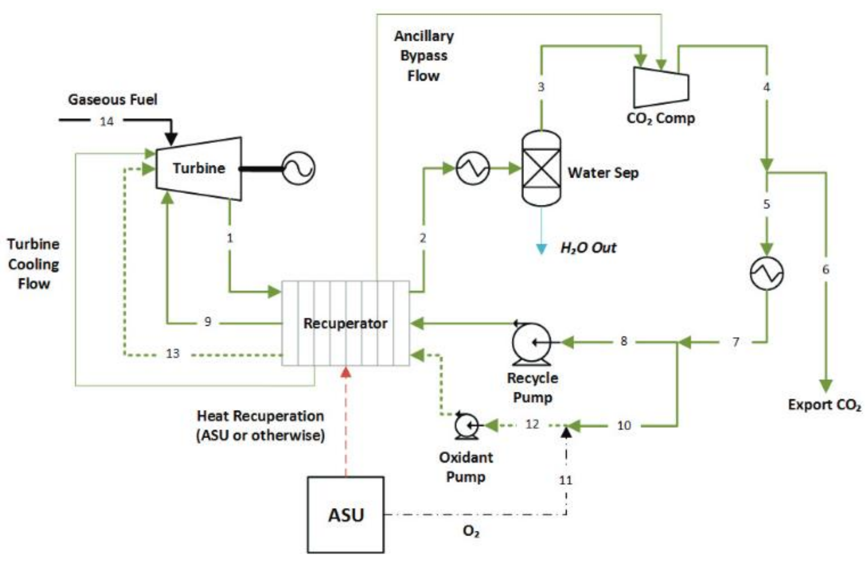

Figure 2. Simplified Process Diagram for Allam Power Cycle (Allam, 2017)

Table 1. Stream Data for 50 MW demonstration plant with stream numbers corresponding to numbers given in Figure 1 (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 ^oC. 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 ^oC, 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 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.

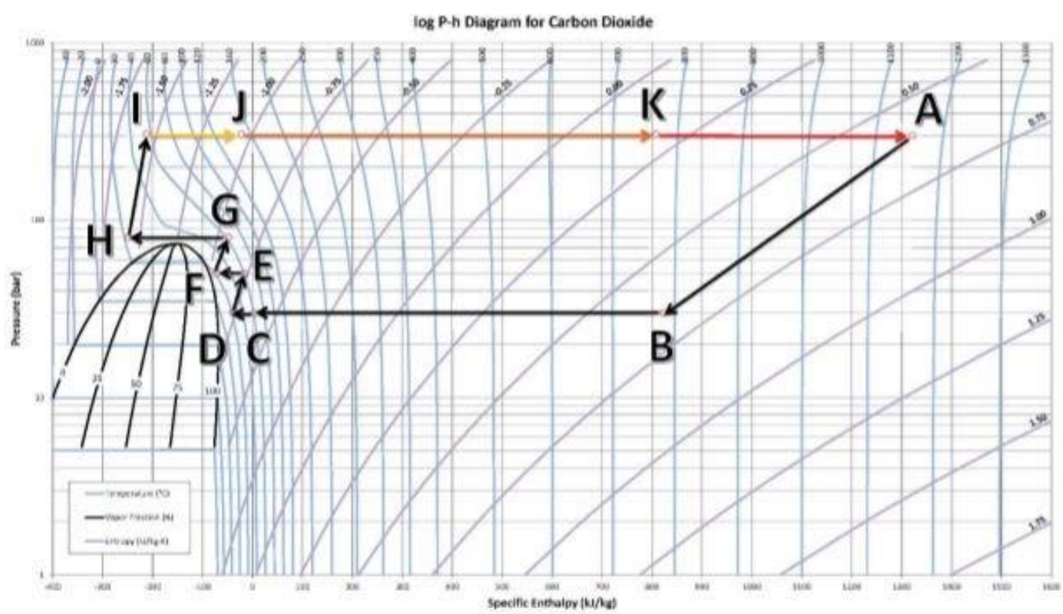

Figure 1. Pressure Enthalpy Diagram for the Allam Cycle (A→K) (Allam, 2017)

STS Topic: Cultural Opposition to Michael Mann's Climate Change Research on Temperature Modeling

Understanding the technical and scientific factors that go into this project provides only a partial view of its effect on lowering greenhouse gas emissions. A fuller understanding can be grasped by analyzing the cultural challenges, such as climate change denial, that need to be overcome to implement technology such as the Allam cycle. People who are opposed to climate action, are generally opposed because they deny climate change is occurring or is caused by humans due to ideological, scientific, or political reasons (Bjornberg, 2017). Research shows that in the last 25 years climate change "denial indeed had a significant negative impact on societal debates and decision-making, [and that] despite huge advances in environmental sciences over this time period, denial prevails in some cases" (Bjornberg, 2017. Pg. 239). This denial is clearly evident when legislators use their position to inhibit climate action such as when in 2005 Senator Joe Barton asked three climate researchers for information on certain paleoclimate research in an attempt to discredit it. This research included the 1998 and 1999 papers Mann co-published on research that reconstructed the global average temperature in the 20th century shown in Figure 4 (Climate of Distrust, 2005). Barton asked for the background information to investigate the 'significance of methodological flaws and data errors' Barton suggested were in the

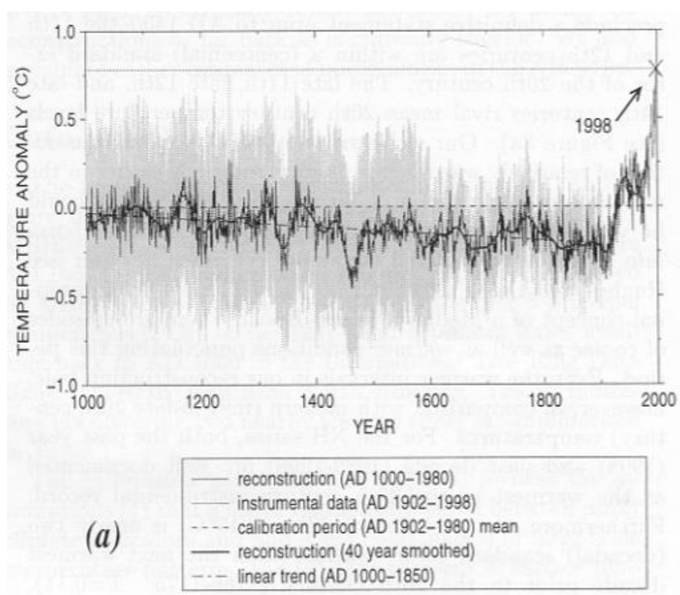

Figure 2. Millennial Temperature Reconstruction (Mann, 1999)

study. Despite subsequent studies supporting Mann's observation, Barton continued to "use his political influence to put pressure on the scientific process" (Climate of Distrust, 2005. Pg. 1). Similarly, in 2007 Senator James Inhofe discredited the science of climate change and attacked Mann's work on the Senate floor days before the vote on the Climate Stewardship Act (Wright, 2013). Ultimately the bill was rejected, stifling a program to decelerate the production of greenhouse gases. Continued failure to address climate change, like such described in this case study, and reduce the impact of climate denial could result in Mann's research and future attempts for climate action to be ineffective. This would result in a failure to slow global warming and therefore a failure to slow the change in climate patterns that can destroy lives and businesses (NASA, 2020).

This STS project will first aim to understand why industry groups and politicians including Inhofe and Barton aggressively targeted Mann to discredit his research. Additional research will be done to create a framework of conflict management techniques and climate action benefits to apply to future situations in order to mitigate the impact of climate change denial. Constructing this framework depends appreciably on the feasibility of encouraging and implementing international change towards a common goal. Therefore, it is vitally important to build upon sociotechnical concepts such as Eisenhardt's approach to facilitate arguments like that between Mann and his criticizers to ensure this main challenge can be overcome. Eisenhardt proposed an approach to "encourage members of a team to argue without destroying their ability to work together", and this framework about "sticking to the facts" and "creating common goals" is important to working through the barriers of compromising (Eisenhardt, 1997. Pg. 78). This will help provide a better framework for understanding the relationships between the actors and how international agreements can be reached that satisfy everyone's needs.

Second, this STS project will analyze the inability for the various parties to understand each other's prospective including how factors such as industry contributions and job growth influenced each party to promote or discourage global climate action. Neeley's Technical, Organizational, and Cultural framework will be applied to analyze these non-technical factors to provide a deeper understanding for why Mann's work failed to be implemented despite the promising technical aspects (Neeley, 2010). Finance serves as a significant actor both to promote climate change denial and climate action. Mann argued that the main reason Inhofe "declared human-caused climate change was the single greatest hoax" was because "he's the single greatest recipient of fossil fuel money in the US Senate" (Wright, 2013. Pg. 751-752). By that statement, Mann assumed that financial gain was the most significant factor in Barton's choice to denounce environmental bills in the senate and climate change research. This project will attempt to analyze the relationships between different actors and climate change to find ways to end disputes between climate change deniers and advocates. For example, if Barton was truly discouraged by economic interests, he could have been convinced to support climate action on the basis that climate action, such as the Paris Agreement, is a huge stimulus to countries' economies as action to fight climate change could produce $26 trillion in economic investments into the energy, food, industry, and water sectors as well as twenty-four million new jobs. In addition, over the past two decades, climate related disasters costed nearly $2.3 trillion, and worsening disasters and air pollution pose huge financial burdens and curbing climate change now would save money in the future (Green, 2019). Employing STS research including Eisenhardt's management techniques and Neeley's integrated view of technology in these ways will allow for a better understanding to better inspire climate action.

Conclusion

The technical project will culminate in the design of a 500 MW natural gas power plant that releases zero emissions into the atmosphere because of an economically viable method for carbon sequestration. The STS project will provide an improved understanding of the why Mann's research received pushback and how an agreement could have been reached that addressed all parties' concerns. By completing these deliverables, this technical design could be effectively implemented, with the aid of the knowledge gained from the STS research, in natural gas power plants globally, partially stopping future carbon dioxide emissions from energy production. This would have a significant impact in slowing the rate of global warming and reduce the climate changes associated with global warming including: improving air quality, saving land from rising sea levels, and protecting businesses such as farms from changing weather patterns that could destroy crops.

References

Allam, R. et al. (2017). Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture. *Energy Procedia, 114*, 5948-5966. doi:10.1016/j.egypro.2017.03.1731

Allam, R., et al. (2013). High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating Atmospheric Emissions, Including Carbon Dioxide. *Energy Procedia, 37*, 1135-1149. doi:10.1016/j.egypro.2013.05.211

Bjorberg, K., Karlsson, M., Gilek, M., and Hansson, S., (2017) Climate and environmental science denial: A review of the scientific literature published in 1990–2015. *Journal of Cleaner Production*, Vol. 167, 229-241. https://doi.org/10.1016/j.jclepro.2017.08.066

Climate of distrust. *Nature* 436, 1 (2005). https://doi.org/10.1038/436001a

Eight Rivers. The Allam-Fetvedt Cycle and NET Power. (n.d.). Retrieved from https://8rivers.com/portfolio/allam-cycle/

Eisenhardt, K.M., Kahwajy, J.L., & Bourgeois, L.J. III (1997). How management teams can have a good fight. Harvard Business Review, 75, 77-85.

EPA. Overview of Greenhouse Gases. (2020, September 08). Retrieved from https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Green, C. (2019, November 4) 6 Reasons Why the Paris Agreement is Good for Economies. Retrieved from https://unfoundation.org/blog/post/6-reasons-why-paris-agreement-is-good-for-economies/

IEAGHG. (2012). A Brief History of CCS and Current Status [Pamphlet]. International Energy Agency, Greenhouse Gas R&D.

Mann, M.E., Bradley, R.S., and Hughes, M.K. (1998). Global-Scale Temperature Patterns and Climate Forcing Over the Past Six Centuries. *Nature*, 392, 779-787.

Mann, M.E., Bradley, R.S. and Hughes, M.K. (1999). Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations. *Geophysical Research Letters*, 26, 759-762.

NASA. The Effects of Climate Change. (2020, August 21). Retrieved from https://climate.nasa.gov/effects/

Neeley, K.A. (2010). Toward an integrated view of technology. In K.A. Neeley, Ed. Technology and democracy: A sociotechnical systems approach. San Diego, CA: Cognella, pp. 37-45.

United Nations. What is the Paris Agreement? (2020). Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

Wright, C., & Mann, M. (2013). Future imaginings and the battle over climate science: An interview with Michael Mann. *Organization, 20*(5), 748-756. doi:10.1177/1350508413489818