Building a Natural Gas Power Plant That is Environmentally Safe and Profitable
(Technical Topic)

Determining What Drives Local Communities to Support Clean Energy Technologies
(STS Topic)

A Thesis Project Prospectus Submitted to the

Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

Michael Beekwilder

Fall, 2020

Technical Project Team Members:
Benjamin Johnson, Alexander Sims, Conor Moran, 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

Signature ____

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

Approved ____ Date ________________________
Eric Anderson, Lecturer, Department of Chemical Engineering

Implementing Bridging Technologies to Create Clean, Fossil Fueled Power Generation

In 2018 the Intergovernmental Panel on Climate Change (IPCC) released a special report to the United Nations convention on climate change. In that report, the IPCC concluded that anthropogenic emissions were responsible for a 1 ^{o}C rise in the average global temperature from pre-industrial times (before the industrial revolution). Continued increase in global warming will cause irreversible damage to both human and non-human habitats. The IPCC summarized that "Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal times scales" (Masson-Delmotte, 2018 n.p.). Exxon Mobil's twenty-year energy outlook forecasts over 12 billion tons of carbon dioxide will be emitted annually in 2040 (Crane, 2019). Furthermore, Exxon also predicts that global energy consumption, and consequently fossil fuel consumption will also continue to rise through 2040. Renewable energies are one of the best ways to eliminate anthropogenic emissions, but large scale, renewable energy production is several decades away from being capable of meeting human needs.

Until renewables are developed to meet human needs, bridging technologies will be need to be implemented to meet the environmental needs of tomorrow with the technologies of today. One of the best technologies to accomplish this is Carbon Capture and Sequestration technologies (CCS), which enables the construction of a zero emissions, fossil fuel power plant. Unfortunately, this technology alone will not be able to solve the problem. If it does not receive the required support, CCS technologies may go unnoticed and loose public interest much like the Aramis technology studied by Bruno Latour in 1996. Being that the technical project of this prospectus is a bridging, zero carbon emissions, natural gas power plant, his work is very applicable to this topic. The same faults in the people working on the Aramis project are likely to exist for this power plant, especially because it is a bridging technology. Because of this, my STS research will focus on how community awareness and support can be effectively raised.

Zero Emissions Power Plant

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, described above, 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.

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 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.

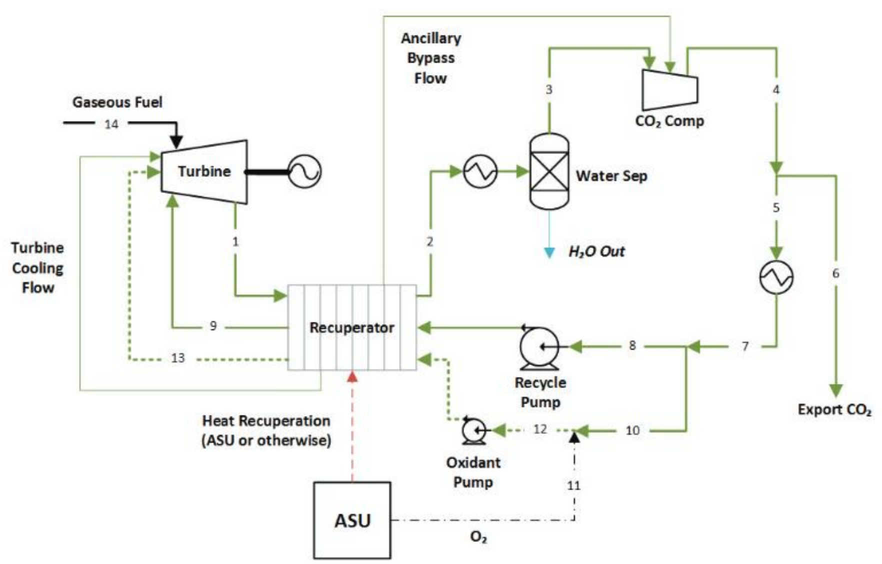

Figure 1: Simplified Process Diagram for Allam Power Cycle (taken from Allam, 2017)

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, stream numbers corresponding to numbers given in Figure 1

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 ^{o}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 ^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).

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

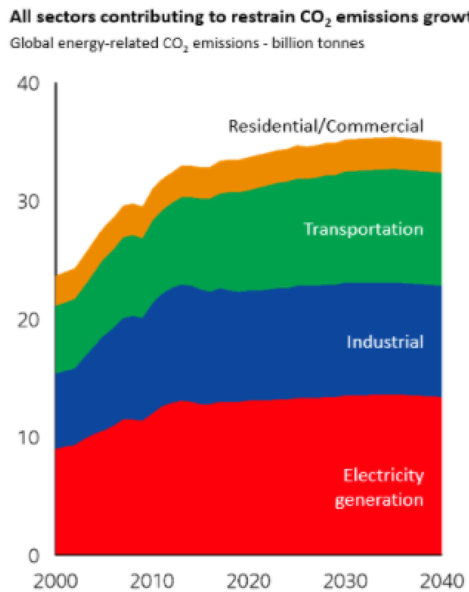

Figure 2: Timeline of global CO_2 emissions broken down by sector

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 more of CO_2 may be released to the atmosphere over the coming years. Furthermore, figure 2 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.

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

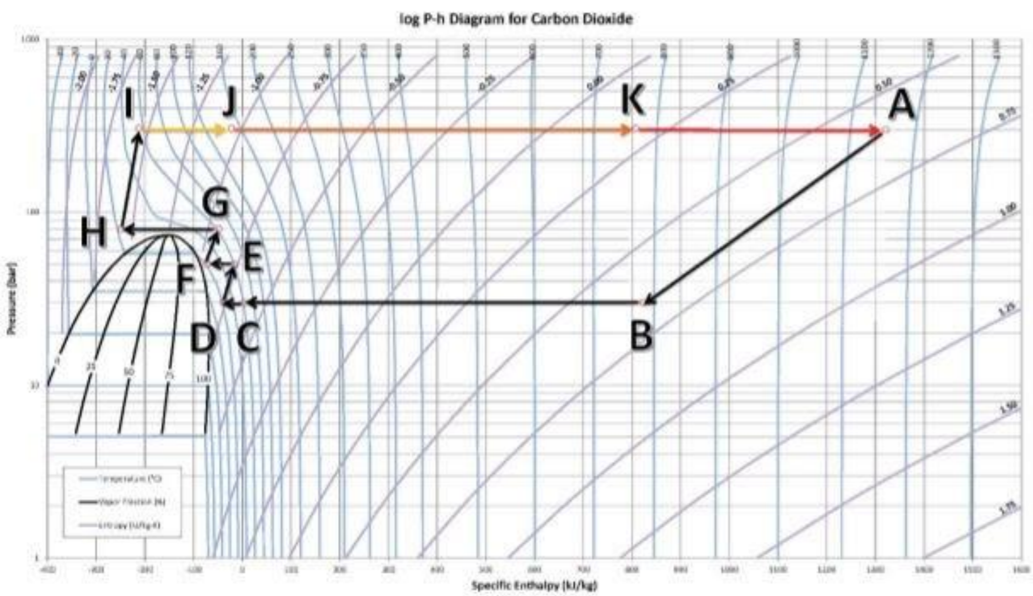

Figure 3. Pressure Enthalpy Diagram for the Allam Cycle (A→K) (Taken from Allam, 2017 pg. 4)

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.

Community Support for Bridging Technologies

As Latour concluded in his study on Aramis, technologies cannot be expected to win public support under their own steam. Latour writes that “If elected officials can kill Aramis, what should you do? Make them change their minds, or get other ones elected. You don't think you have the power? Then don't expect that Aramis will” (Latour, 1996 pg. 292). Actors who are engaged in the technical process need to seek out support for the emerging technology and make sure that the public has some degree of education on the technology of interest (Latour, 1996 pg. 292-3). The level of education an individual possesses on both climate issues and alternative energy technologies plays a significant role in determining support for any given energy issue (Moon, 2020). Because CCS technologies are a relatively new and are meant to be a bridging technology for future renewables, CCS suffers from having little public awareness of the benefits of using this technology. There is almost no policy or interest in pursuing policy on CCS which can cripple its path to becoming a useful tool to combat climate change. This presents a major conflict. How does our power plant fit into local community networks and what advantages or disadvantages does it seem to present to stakeholders in these communities? Won-Ki Moon emphasizes the importance of this question when he writes “As climate change mitigation technologies emerge, there is an increased need to understand public support for the technology and the policies that will shaper or thwart its evolution. Of particular importance are the communities directly impacted” (Moon, 2019 pg. 1). This answer to the aforementioned question will be found by completing a comprehensive literature review of what social, psychological factors predict CCS technology support. Among the factors studied for CCS support are, gender, age, and education, but will also include factors such as perceived knowledge of the subject, climate change awareness, and even the level of trust and perceived influence of community officials (Moon, 2020). In addition, these same factors will be expanded to show support for general clean energy policies.

Why will this knowledge be useful? In the attempt to gain support for clean energy technology, it is important to know what causes people to support it. For example, in a study done by Won-Ki Moon, it was found that not only did climate change awareness positively correlate to support for CCS technologies, but actor influence in a community, and the perceived benefit of CCS also correlated positively to CCS support. These three items had the strongest positive correlation to support. Actor influence in a community also correlated to high levels of social capital. If CCS technologies are to be supported, then it is of the utmost importance that these three things are maximized when attempting to win local community support for CCS. This could be done by holding advertising campaigns for climate change awareness that are hosted by local actors.

As outlined by the IPCC's report to the UN, there is an immediate need to introduce climate change mitigation technologies. If support for new and emerging technologies are not raised soon, there will be negative impacts on trying to implement the technology in the future. This is due to a number of reasons, the first being that if bridging technologies do not to start to gain support and interest domestically, then the USA cannot keep up with research abroad. If competitors to the US energy market are able to develop methods for cleaner power production, then it could hurt local economies in the USA (Myers, 2019 n.p.). This is mostly due to the fact that international government agencies, such as the UN, will hold the USA to lowering its CO_2 emissions, while energy demands continue to rise. Penalties for not meeting lower CO_2 emissions standards will likely be fines on the US government which will be passed down in the form of higher taxes/fines on local power facilities, which are ultimately passed on to local citizens (Myers, 2019 n.p.). If clean technologies cannot be developed domestically, then power will need to be purchased abroad, or hefty fines may be incurred from agencies such as the UN (Myers 2019 n.p.). Furthermore, the longer it takes to begin the process of raising awareness for clean technologies, the longer it will take for these technologies to gain public support and funding. This chain reaction can lead to long delays in clean technology development and implementation which will put local communities even further behind potential competitors (Moon, 2020 pg. 6).

To ensure that the USA, and local communities remain competitive in an energy intense world, the study done by Moon on what influences local actors will be used to analyze how the Allam cycle can help local communities. This will be done by utilizing actor network theory (ANT) and studying how individual actors connect to disseminate support for CCS technologies. The main challenges facing this study will be determining how to effectively disseminate information through community networks and potential barriers to that implementation (2012, Barriers to Implementation of CCS). In particular, the current pandemic will pose issues as it is much harder to not only form new connections and networks, but also to maintain current connections. However, it is expected that a clear, comprehensive study on what predictors are associated with CCS policy support will be delivered. This will be done by reviewing a case study by Won-Ki Moon and supported by a study done by Bart Terwel over the coming semester. This will require an in-depth analysis of their work and works cited by them. After reviewing relevant studies, the information will be synthesized to describe what advantages our power plant can provide to local actors and networks.

Deliverables for the Projects

A full-scale natural gas power plant will be modeled such that it is capable of meeting varying demands for power across a medium sized community as well as not emitting any harmful emissions. In combination with this power plant, an understanding will be developed of what predictors will help to increase community support for the new and potentially unknown technology. Upon completion of both of these objectives, a new method of power generation will be available. This plant will be able to generate power that meets the energy needs of today while also protecting the environment of tomorrow. It will also be a plant that can present clear advantages over traditional power plants at the local, community level.

Works Cited

Allam, R., Martin, S., Forrest, B., Fetvetd, J., Lu, X., Freed, D., . . . Manning, J. (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., Palmer, M. R., Brown, G. W., Fetvedt, J., Freed, D., Nomoto, H., . . . Jones, C. (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

Brad Page, C. (2019, March 22). *Why carbon capture could be the game-changer the world needs.* World Economic Forum. Retrieved October 05, 2020, from https://www.weforum.org/agenda/2019/03/why-carbon-capture-could-be-the-game-changer-the-world-needs/

Crane, Rob. “2019 Outlook for Energy: A Perspective to 2040.” ExxonMobil Outlook for Energy. 2020.

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

Latour, B. (1996). Preface, prologue, and epilogue. Aramis, or the love of technology. Catherine Porter, transl. Cambridge, MA: Harvard University Press.

Moon, W., Kahlor, L. A., & Olson, H. C. (2020, April 1). Understanding public support for carbon capture and storage policy: The roles of social capital, stakeholder perceptions, and perceived risk/benefit of technology. Energy Policy, 139.

Myers, M., & McDonald, T. (2019). *Bringing the US Environmental Technologies to Market* (pp. 1-10, Working paper). Dallas, Texas: EarthXCapital.

"Status of the Ratification of the Convention." *Unfccc.int*, The United Nations Framework Convention on Climate Change, unfccc.int/process-and-meetings/the-convention/status-of-ratification/status-of-ratification-of-the-convention.

"What Is the Paris Agreement?" *Unfccc.int*, The United Nations Framework Convention on Climate Change, unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement.

Terwel et al, 2011. Going beyond the properties of CO2 capture and storage (CCS) technology: how trust in stakeholders affects public acceptance of CCS, International Journal of Greenhouse Gas Control, 5 (2) (2011), pp. 181-188, 10.1016/j.ijggc.2010.10.001