Power Plant Design Using Allam Cycle CCS

(Technical Paper)

Black to Green: How and Why Power Groups Have and Have Not made the Switch to Alternative Energy

(STS Topic)

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Benjamin Johnson

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Technical Project Team Members

Michael Beekwilder

Conor Moran

James Perry

Alexander Sims

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 ____ Date __________

Benjamin Johnson

Approved ____ Date __________

Eric W. Anderson, Department of Choose Department

Approved ____ Date __________

Kathryn A. Neeley, Associate Professor of STS, Department of Engineering and Society

Introduction

The middle class continually rises each year around the globe, and with it energy demand. In consequence of this rising need, output emissions, including greenhouse gases (GHG) congruously rise as well. GHGs are identified to be a source of global climate change, which threatens human life with long term environmental changes. (Masson-Delmotte et al., 2018). In order to reconcile the world's need between rising energy demands and the need to protect the environment, massive amounts of time and money are spent on researching renewable/alternative energy sources that produce reduced/zero emissions. Carbon Capture and Storage/Sequestration (CCS) is in the spotlight as viable technology to fit this need as it can be retrofitted or incorporated into new power plant facilities (Cloete, 2014). To understand the gravity of investment in CCS, 37 % of the US energy consumption in 2019 was derived from petroleum, 11% from coal, and 32% from natural gas (EIA, 2020). These three fields make up 80% of energy consumption in the US can all have various forms of CCS deployed for use which means massive amounts of reduced emissions. The approach of focusing efforts on the major emitting sectors with technology, namely CCS, is crucial in worldwide effort to prevent irreversible climate change (Masson-Delmotte et al., 2018). In the technical portion of this project, a 500 MW power facility that generates electricity from natural gas using the Allam Power Cycle while producing zero emissions is designed and evaluated for viability of implementation. The design created and demonstrated to work as expected at the 50 MW level will be scaled up and modeled to the 500 MW level and evaluated for efficiency, cost, energy output, and ability to manage emissions (Allam, 2017). Additionally, a detailed examination of stakeholders such as energy conglomerates, political groups, and municipalities that were previously resistant to alternative energy sources, will be performed to understand how/why they have adopted new methods. This STS project will be aimed at developing a framework to explain the hesitancies of stakeholders in adopting alternative technology, how and why those hesitancies have been overcome, and how that can be applied to other groups.

Tech Prospectus: Power Plant Design Using Allam Cycle CCS

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.

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.

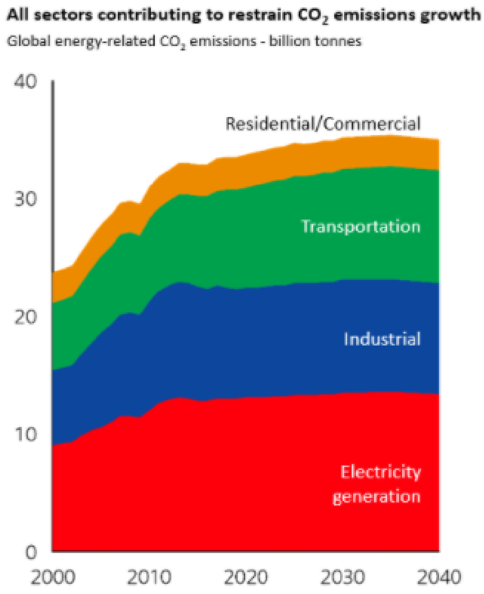


Figure 1: Timeline of global CO_2 emissions broken down by sector

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 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.

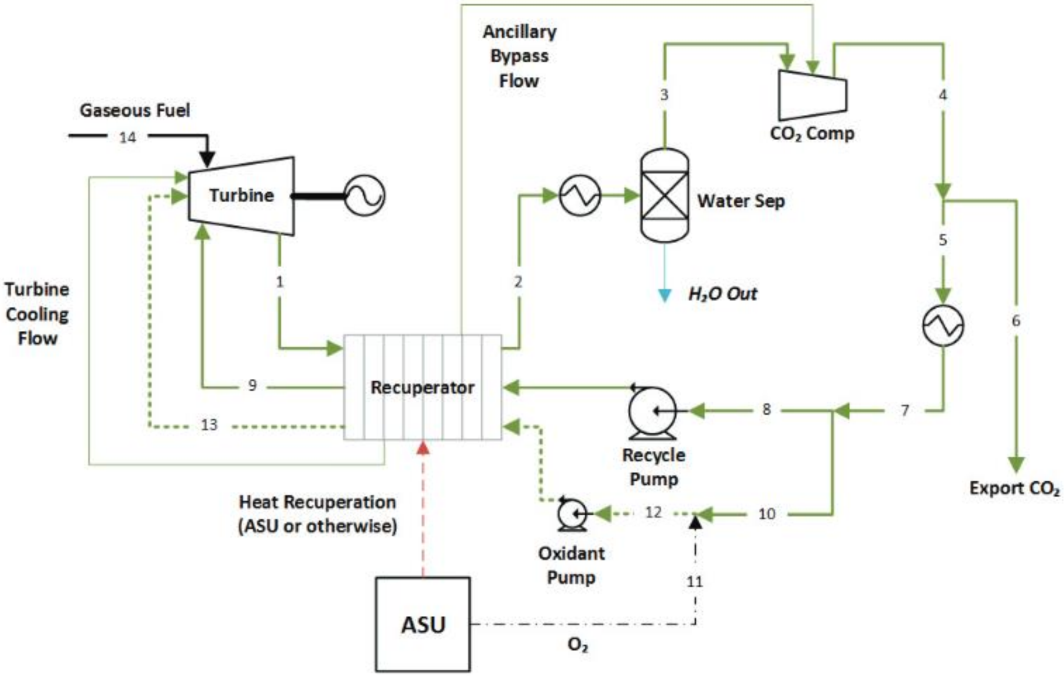
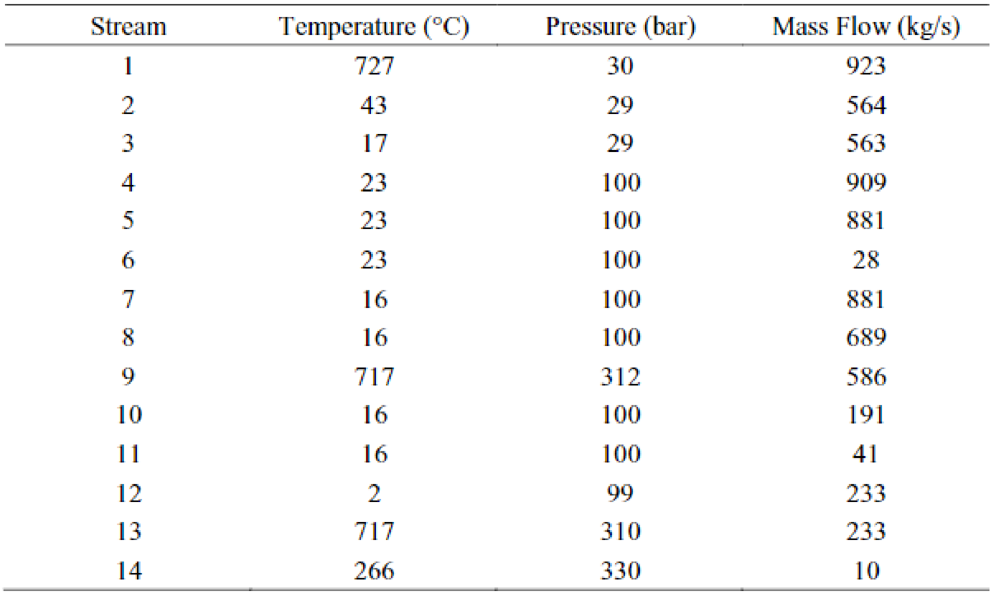


Figure 2: Simplified Process Diagram for Allam Power Cycle (taken from Allam (2017) without permission)

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 2 (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

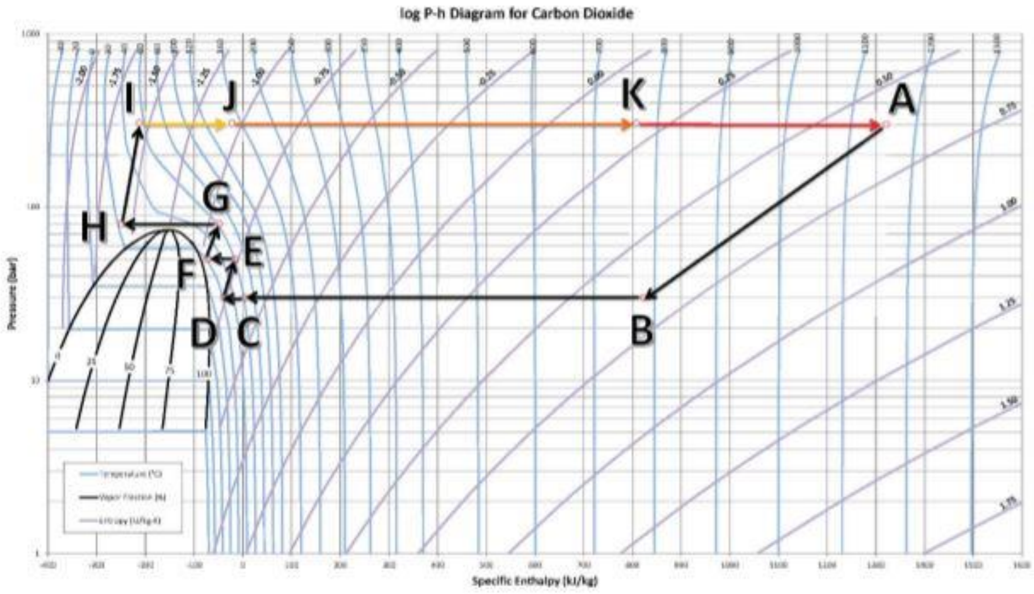


Figure 3: Pressure Enthalpy Diagram for the Allam Cycle (A→K) (Taken from Allam (2017) without permission)

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.

STS Prospectus: Black to Green: How and Why Power Groups Have and Have Not Made the Switch to Alternative Energy

Even with the evidence available of rising global temperatures and long-term negative climate change occurrences, there is still resistance in the power sector to convert to alternative (a term encompassing renewables, green, and CCS energy techniques) energy. In order to find the root of this resistance, and understand modern trends in the power sector, the motivations and histories of stakeholders in the sector need to be understood and mapped.

In previous research such as that completed by Tidewell on PV solar installation distribution in Georgia, Tidewell found that there is just as much weight associated with, "social, political, and ecological factors," preventing alternative energy adoption as there is associated with, "[econometric] and technical feasibility" (Tidewell et. al, 2018). Traditionally, the sociotechnical explanation for resistance to alternative energy sources, also called Renewable Energy Technologies (RET), has leaned on the Not-In-My-Backyard, or NIMBY, argument. NIMBY is a general encapsulation of the social resistance to having power infrastructure, regardless of how safe/efficient, newly developed in communities on the basis of individual's desire for non-impedance from outside groups. While there is truth to the NIMBY argument, many studies on this intersection of RET and communities have been done, all finding increasingly complex factors that can contribute to this difficulty of integration (Batel, 2020). NIMBY does not adequately explain the reasons that stakeholders do not adopt alternative energy sources. Over time however, some groups resistant to new alternative tech have adopted it, and this STS study is aimed at understanding what made that change take place, so that it can be applied as a framework for other groups.

Investigating the reasons stakeholders are hesitant to adopt alternatives to fossil fuel derived energy has led to the discovery that there are as many reasons as there are individuals/groups involved. These reasons range from solely economic investment bases to climate change denial (State of California, 2020). When investigating stakeholders who have monetary investments in power conglomerates specifically, a large reason for their hesitation in conversion of power production investments is stranded assets and sunken costs, like large reserves and investments in fossil fuels that would become unused (Sen & Von Schickfus, 2020). Additionally, currently developed alternative energy has a largely varying level of efficiency and investment cost. Some technologies have large upfront capital that turns stakeholders off to investment, and others simply do not produce as much energy per area/dollar as current methods. The cost of this hesitancy has already been seen. Energy portfolios in the US are on track to pass the 2°C mark defined by the Paris agreement and set for the year 2035. Sea levels continue to rise, and previously thriving ecosystems are struggling to remain intact with the advent of new temperatures. As long as communities, policy makers, and energy conglomerates continue to resist alternative energy, it will remain non-mainstream, emissions continue to rise, and global environmental damage will worsen (Lancaster & Berndt, 1984; Cloete, 2014).

In this STS study, instances where energy stakeholders have been resistant to alternative energy technologies will be compared with instances where similar (or even the same) stakeholders, have adopted alternative energy technologies. The aim of this comparison will be the quantifications of how resistance has impacted the US energy portfolio and emissions, a detailed definition of the most common reasons resistance occurs, when these instances of resistance have been overcome, how were they overcome, and developing directives on how to overcome problems for other groups that have not yet switched to alternative sources of power generations

(Muhumuza et al., 2018). This pursuit of definition will be challenging for a number of reasons, the largest being that there is no definitive answer to this question that will work for all stakeholders, and there is a very limited amount of study already performed on this topic. I anticipate at the end of this project having a much better understanding of this challenge, but not a comprehensive answer.

Conclusion

It is anticipated that this project will result in a functional model of a 500 MW natural gas power plant using the Allam Cycle, and a more rigorously mapped understanding of the reasons power conglomerates have, based on the actor-network and technology available to them, that drive change either towards or away from alternative energy in the sector. The designed Allam facility should be a legitimate answer to the actors resisting change in the energy sector because it will be economically, environmentally, and socially more acceptable than other options, thus a good investment from the perspective of a power conglomerate. Should the technical project succeed, there will be a new answer to the continuously growing global power demands, and the necessity to reduce emissions for the health of humanity and the earth. Better understanding motivations behind changes in the energy sector regarding alternative energy will assist in pushing alternative/green energy into the mainstream methods of energy production. This spotlight will assist in the technical goal of driving down emissions projections, and meeting the continuously growing energy demands of the US.

References

Allam, R., Martin, S., Forrest, B., Fetvedt, 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

Cloete, S. (2014, February 18). Why We Need CCS, Part 1: The Basics. Retrieved October 05, 2020, from https://energycentral.com/c/ec/why-we-need-ccs-part-1-basics

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

EIA. (2020, May 7). US Energy Facts Explained. Retrieved October, from https://www.eia.gov/energyexplained/us-energy-facts/

"Emissions Sources (2020)." *Climate Central*, 19 Feb. 2020, www.climatecentral.org/gallery/graphics/emissions-sources-2020.

Governor's Office of Planning and Research, State of California (2020). Common Denier Arguments. Retrieved October 05, 2020, from https://opr.ca.gov/facts/common-denier-arguments.html

.

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

Lancaster, R. R., Berndt, M. J. (1984). Alternative energy development in the USA The effectiveness of state government incentives. *Energy Policy*, *12*(2), 170-179. doi:10.1016/0301-4215(84)90167-8

Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp.

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *World Meteorological Organization, Geneva, Switzerland, 32 pp.*

Muhumuza, R., Zacharopoulos, A., Mondol, J. D., Smyth, M., & Pugsley, A. (2018, December 1). Energy consumption levels and technical approaches for supporting development of alternative energy technologies for rural sectors of developing countries. *Renewable and Sustainable Energy Reviews*, 97, 90 - 102.

NASA. “A Degree of Concern: Why Global Temperatures Matter – Climate Change: Vital Signs of the Planet.” *NASA*, 25 June 2019, climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/.

Pilorgé, H., Mcqueen, N., Maynard, D., Psarras, P., He, J., Rufael, T., & Wilcox, J. (2020). Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector. *Environmental Science & Technology, 54*(12), 7524-7532. doi:10.1021/acs.est.9b07930

Sen, S., & Von Schickfus, M. (2020, March 1). Climate policy, stranded assets, and investors' expectations. Journal of Environmental Economics and Management, 100.

Susana Batel, Research on the social acceptance of renewable energy technologies: Past, presen, and future, *Energy Research & Social Science*, Volume 68, 2020, 101544, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2020.101544.

Tidwell, J. H., Tidwell, A., & Nelson, S. (2018). Surveying the Solar Power Gap: Assessing the Spatial Distribution of Emerging Photovoltaic Solar Adoption in the State of Georgia, U.S.A. *Sustainability (Basel, Switzerland)*. doi:10.20944/preprints201810.0184.v1

UNFCCC. "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.

UNFCCC. "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.