CAPACITY PLANNING AND INVESTMENT FOR ELECTRIFICATION OF MARITIME CONTAINER PORTS

IMPACT OF ELECTRIFICATION ON THE ECONOMY AND ENVIRONMENT

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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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Introduction

A looming threat to humanity's continued existence is the ongoing climate change crisis and the role that greenhouse gas emissions play in the crisis. Global warming is currently exacerbated by ongoing pollution that is a byproduct of our functioning, materialistic society. This serious environmental issue has led to research into non-traditional, renewable sources of energy, many of which have exploded in popularity over the last ten years (*Why the Future Involves E-Mobility | McKinsey*, 2021). These sources, commonly known as green-energy sources, could completely change the outlook of our energy infrastructure if properly implemented, bringing society to an age of sustainability that could extend long into the foreseeable future. Due to the novelty and expensive nature of installation for these energy sources, including wind, solar, and hydroelectric, many companies are yet to adopt green energy, remaining reliant on fossil fuel sources, such as coal, oil, or natural gas. It is now common knowledge that green energy power is more environmentally sustainable, but many remain staunch supporters of fossil fuel use, dismissing the idea of a future without oil and gas. A complex sociotechnical problem arises, as electricity sourced from green-energy is significantly less harmful to the environment than burning natural gas or fossil fuels, but extremely difficult to implement on a broad scale in the current state of the global economy. Electrification, which is defined as the process of transitioning from gas-powered equipment to equipment powered by electricity, has one of its largest applications in reducing emissions from a massive swathe of industries and organizations, specifically in powerful industrial equipment and large-scale infrastructure.

The research discussed in this thesis focuses around the economic feasibility of transitioning to electric-powered machinery, including quantifying the benefits of electrification

on overall emissions, diving into the social costs of emissions, and considering arguments on the value we should place on the sustainability of our environment. Actor-network theory is used as the theoretical framework throughout the paper, as many non-human factors are crucial to consider in a holistic view of the electrification process. Using additional research from the technical topic on the current electrification process at the Port of Virginia as a case study to support my findings, the long-term feasibility of many of these technologies is determined, providing a broad electrification solution to help curb this impending crisis. This recommendation is created with the perspectives of various stakeholders in mind, ideally finding a scenario that maximizes general public welfare.

While the scope of this research is limited to the United States, the effects of recently employed mitigation strategies from other environmentally conscious nations are considered, providing a broad array of real-life experiments that have already been conducted, allowing their effectiveness to be judged for potential use in the United States. These outside perspectives help guide potential recommendations for the current state of energy production and usage in the US, as many economically feasible options have been used across the globe. As the largest contributor to this environmental catastrophe, producing 20% of global carbon dioxide emissions since 1850 and the second most per capita over that time period (Evans, 2021), so the United States must be a leading force in correcting the damage we have caused to our planet's atmosphere. This paper explores the sociotechnical aspects related to the costs of electrification and the potential for its widespread implementation across various industries. It specifically examines the impact of electrification on greenhouse gas and carbon dioxide emissions, with a focus on the transportation and automobile sectors.

Analysis

While the electrification of gas-powered vehicles and machinery may seem like an easy choice for long-term sustainability, the current costs of generating clean energy to power electrified vehicles complicates the issue. Since the vast majority of national electricity production currently comes from fossil-fuel sources, mass electrification may actually increase overall carbon production in the short-term (Zhang & Fujimori, 2020), mostly due to emissions during manufacturing, as well as electricity generated by fossil fuels. They show that future widespread adoption of green energy production is vital in the effectiveness of the electrification movement. While the prevalence of short-term disadvantages discussed in Zhang and Fujimori's research are certainly concerning, the long-term consequences of climate change are potentially monumental and irreversible, so any reasonable steps towards adopting mitigation strategies should be taken as soon as possible, achieving maximum effectiveness going forward. Emissions would be vastly reduced if we eventually reach the green energy capacity to support the power grid and end our reliance on fossil fuels for electricity, however a full grid transformation would require even more investment and up-front fixed costs to support the magnitude of green energy production needed. A complex economic issue arises, where the trade-off between short-term and long-term wealth is unknown, leading to controversy and several varying opinions among scholars, scientists, and legislators.

A 2009 New York study showed that full lifecycle electric vehicle usage reduced greenhouse gas emissions by 40-80%, depending on the type of vehicle used, including hybrid, fully electric, and a baseline of standard ethanol gasoline. (Elgowainy et al., 2009). This finding demonstrates the effectiveness of electric vehicles in reducing emissions, despite numerous criticisms that their manufacturing offsets the environmental benefits of their usage. Other studies support these findings, such as one 2019 study which quantitatively determined that

electric vehicles will be economically competitive with gas vehicles by across global markets by 2035 (Chen & Melaina, 2019). One could argue there are several assumptions in their model that could fail to hold over the next 15 years, however the comprehensive argument of the paper is extremely convincing, providing a valuable perspective on the future of the electric vehicle market.

The National Renewable Energy Laboratory (NREL) performed a study where the choice to electrify is viewed as a trade-off between the electric-powered system of the future and the status quo of our current system from an economics standpoint, taking into account cost estimates for future natural disasters and other climate change related events (Zhou & Mai, 2021). As the sixth edition of this grid simulation study, Zhou & Mai's research effectively provides data-driven analyses on US power systems under different models of electrification, drawing some unexpected conclusions. They showed that mass electrification would lead to a massive overall increase in electricity demand, causing some of their scenarios with minimal renewable energy implementation to show an increase in overall emissions by the year 2050. The general expansion of our grid is a known roadblock in mass electrification, especially due to the potential for expanded fossil fuel usage which could be necessary to fill the gap in national energy requirements.

Supporting these results, a 2017 study of five different vehicle types compared diesel versus electric vehicles finding that electric vehicles are cheaper in the long run in all five scenarios. (Falcão et al., 2017). This insight provides further support for the urgent need to electrify, showing that even in a worst-case efficiency scenario, a positive outcome arises. While this study could be considered outdated, it is unlikely the results would significantly differ today. The Falcão et al. study shows yet another convincing argument in support of future

electrification of vehicles. The multitude of credible sources using quantitative research that show feasibility of electrification expresses a strong argument for a societal transition that many scholars previously believed to be impossible, the complete obsoletion of non-renewable energy sources.

The up-front, fixed investment required for green energy and electrification is daunting, but the state of our climate should be valuable enough to society as a whole in the long-run to consider drastic measures. Future unseen economic consequences such as stronger and more frequent natural disasters increase the urgency of action. Despite the short-term difficulties of mandating cleaner emissions standards, the social value of the environment to society should play a large part in any policy decision on electrification. There are currently few incentives for individual corporations to make costly investments into electrified equipment, so economically reasonable policy measures are needed to bring down the price of electrification and force lingering companies into compliance. Despite this, over $400 billion has already been invested into electrified mobility equipment alone, with around $100 billion of that coming since the beginning of 2020 (*Why the Future Involves E-Mobility | McKinsey*, 2021), and that trend is expected to continue going forward, leading to faster future growth. Investments in the electrification movement indicate a significant trend towards electrification and away from gas-powered equipment. As technology matures and costs continue decreasing, one could say it seems it is inevitable that electrification will become increasingly widespread across a broad array of industries.

Looking at fuel cell durability, longevity, and fuel economy in electric vehicles to determine economic feasibility of large-scale electric vehicle usage (Song et al., 2018), Song et al. effectively show the positive economic impacts of their improved electric vehicle design.

They convey that continual increases in efficiency come as technology advances, meaning the economic feasibility of these technologies will continue developing with it. Future designs and advances in technology will be instrumental to widespread electrification, so investment in the field should continue to grow if we hope to make a significant difference in mitigation. The dilemma can be looked at in terms of the actor-network theoretical framework, where each group of stakeholders prioritizes their own goals and incentives, however the entirety of the global population has only one collective common interest, which is to mitigate the effects of climate change. Wei et al. take a different perspective on the issue, arguing that the up-front costs of green energy are currently too high to make it worthwhile for the majority of industries in the short-run, meaning new regulations would have to be implemented in hopes of collectively reaching net-zero carbon emissions (Wei et al., 2019). Once widespread electrification becomes more affordable, corporations will likely be willing to adopt it, working towards humanity's collective goal of a healthy and safe environment.

When looking at the efficiency of green energy sources for on-terminal usage at the Port of Virginia, the Capstone team found very insightful and unexpected trends in the industry. To begin, the electric grid capacity needed for full electrification is between two or three times larger than our current grid infrastructure (*The Rewiring America Newsletter*, 2022). Expanding our electric grid in a sustainable way should be the priority, using a combination of clean energy sources while tapering off fossil fuel usage, as this could be considered a valid prerequisite to mass electrification. Different energy sources have a broad array of fixed costs and inefficiencies that are sometimes unaccounted for, meaning careful consideration is crucial in any decision to invest in clean energy.

Despite its widespread usage, solar energy is currently the most costly and inconsistent in many regions due to the periodical lack of sunshine. Looking into the future, costs of all types of green energy sources are expected to fall, making mass electrification more economically feasible. 2027 estimates have geothermal energy as the cheapest renewable energy source at that time, with price decreasing to around $22.04/MWh (*U.S. Levelized Capital Costs by Energy Source 2027*, 2021). Currently, geothermal energy costs between $56-$93/MWh (*U.S. Levelized Energy Costs by Source 2021*, 2021), so costs are decreasing quickly across the green-energy industry. The cheapest clean energy source at the present time is wind, with a cost of $26-$50/MWh, however this is only expected to decrease to an average of $29.90/MWh for onshore wind by 2027, while offshore wind platforms are predicted to be about four times more expensive than onshore. (*U.S. Levelized Capital Costs by Energy Source 2027*, 2021). Broader adoption of offshore wind in the short-term, such recent investments at the Port of Virginia, could allow electrification to become more viable in the near future.

Discussion

While the focus of this research is quantitative, objective, and generally apolitical, currently enacted laws and other geopolitical factors surrounding energy are worthy of consideration in a holistic recommendation. Current political situations abroad, such as the Russia-Ukraine conflict, have greatly impacted the global supply of fossil fuel energy, but it will be assumed for this research that the United States will become energy independent in the future, using internal natural resources to fill in any gaps left by new green energy infrastructure. While the sustained future of our planet should outweigh any other rationale in a social setting, this typically gets thrown to the wayside when finances come into play. Studying more trends in the green energy industry is useful in determining whether electrification could be optimal some

number of years in the future rather than immediately as technology continues to advance is strongly deserving of heavy consideration as a feasible option. Analyzing these sources using actor-network theory, taking all parties into account, and providing a comprehensive view of the situation are crucial when recommending a proper course of action. The true value of the environment is difficult to gauge, so a holistic recommendation takes into account our social optimum of a cleaner environment, while looking at the monetary trade-offs from an objective perspective.

Many of the stakeholders involved have very different views on the current outlook of our climate situation. Beginning with the citizens of the United States, a solid majority of Americans support federal action to move towards a clean energy power grid by 2035, with just six very rural congressional districts having minority support for this action (*Americans Support Federal Action to Reach a 100% Clean Energy Grid – Third Way*, 2021). As an organization that represents the will of the people, overwhelming national support should allow the government to take action, ideally before 2035, although the type of policies implemented come down to election choices. While current President Joe Biden is from the Democratic Party, Congress is under split control, with Republicans possessing control the House of Representatives. While many policies remain unlikely to pass in the foreseeable future, Democratic representatives have gone as far as legislation such as the Green New Deal to advance their agenda of building a "thriving, equitable, and globally competitive clean energy economy" (*COMBATING THE CLIMATE CRISIS AND PURSUING ENVIRONMENTAL JUSTICE*, 2023). There are many Republicans against electrification for various reasons, so ideally a government compromise can come soon to address the issue. This remains unlikely due to difficulty of passing legislation that some would consider controversial in a split Congress, especially when lobbying is involved. As

for corporations, many large oil and gas companies are against any legislation that will hurt their potential future profits and the profits of their shareholders. By using lobbyists, they persuade Republicans to look out for their economic interests, keeping fossil fuels relevant for as long as possible. On the contrary, many other corporations are extremely environmentally conscious, leading them to lobby the Democrats. The ensuing situation is a bureaucratic nightmare that pops up frequently in our political system. To realistically take meaningful action, incentives for corporations will be necessary to smooth the economic fallout of this type of policy. These incentives should include tax breaks from green energy usage, extra funding for green energy research and technological advances, and even potential paths for oil and natural gas companies to invest in the green-energy industry.

Regarding the future impacts of climate change, if our current trajectory remains unmitigated by any strategies that we deploy, the Stanford Institute for Economic Policy research estimated that global gross domestic product (GDP) would drop by around 20% by 2100 compared to projections, strictly due to natural disasters worsened by the climate change crisis (*Calculating the Costs of Climate Change | Stanford Institute for Economic Policy Research (SIEPR)*, 2016). This prediction is 10x higher than the predictions used in policy debates around 2016 and the environment has continued to deteriorate since this publication. Although this is just one of many predictions, the impact of such a decrease in GDP would be catastrophic for global welfare, undoing decades of progress and disproportionately affecting countries most vulnerable to climate-related disasters. In this scenario, the severity of the climate situation would continue to worsen over time, causing increasingly devastating economic damage the longer the greenhouse gas problem remains unaddressed. The quantitative economic impact does not include the social impact, as increased intensity of natural disasters will significantly harm

quality of life for people all around the world, leading to higher mortality rates from climate-related disasters and even a lower life expectancy (*Climate Change Could Become Leading Global Risk Factor For Health - Health Policy Watch*, 2021). The dangers of inaction are clear, yet it appears that many around the globe are still unaware of imminent widespread impacts, or unwilling to change, as damage gas already begun in certain areas prone to natural disasters and rising sea levels.

Considering the research and current climate state, I believe the optimal recommendation for the present situation is to increase green energy capacity quickly in the short-term, providing regulations with feasible economic incentives to American corporations, such as tax breaks. Only after we have sufficient clean-energy grid capacity would it make sense to move towards widespread electrification of machinery. 2022 was the most significant investment into green energy in human history and these investments are only expected to grow over the next few years (*2023 Energy Predictions: IRA Spurs Clean Energy Boom, Electric Trucks Accelerate, Battery Demand Surges, EPA Cuts Power Sector Pollution*, 2023), making this recommendation feasible. As a continuation of current progress, this recommendation would still require robust investment due to the extreme scale of the current problem. Due to expensive technology and a lack of infrastructure, the current situation is too premature for effective widespread electrification of vehicles and machinery, but this is still something that we should strive for in the near future. Immediate electric vehicle adaption is marginally helpful but should not be immediately mandated, mainly due to imminent technology improvements, the timeframe that full-scale adoption would require, and future expected growth of green energy usage.

To realistically implement this policy before the next election cycle, a bill will have to pass the Republican-held House of Representatives, meaning compromises must be made to

appease oil and natural gas lobbyists. Sweeping policy likely will not make it out of the legislature in this cycle, however smaller policy measures could be achieved, kickstarting these processes. More economic incentives for companies to transition to green energy is likely the best course of action at the moment, followed by legislation surrounding ways to increase the speed of widespread electrification, although this may have to wait until after the 2024 election cycle.

It is impossible to quantitatively determine the optimal rate of adoption for green-energy and electrification, however it is clear that progress must continue to accelerate over the coming decades to avoid dire consequences. Eventually, there must be an intense worldwide focus on the issue, but taking advantage of known popular support at home is necessary in the current geopolitical state. While global agreements can help, there are few incentives to follow international guidelines due to the loafing effect. This could be eliminated through legitimate consequences towards neglecting these agreements, such as economic sanctions, however this is not an ideal scenario. While the easiest course of action for our societal needs is to slowly phase in green energy and electric vehicles, the current state of our environment demands immediate action. As a global superpower the United States has a chance to lead by example, first transforming its power grid and eventually making fossil fuels obsolete through the process of widespread electrification. While global cooperation is necessary to successfully mitigate the crisis, our allies and potentially some of our adversaries would be more likely to follow suit if we decisively act now.

Conclusion

Climate change is certainly sociotechnical in nature, as the dilemma meets at the intersection of science, technology, and society. This impending crisis is especially difficult to

comprehend due to the complexity of monetarily quantifying the effects. Accurate predictions of future conditions are impossible to create, so the general best course of action is to effectively mitigate known effects where feasibly possible, especially due to the dire outlook of many predictions. These findings will not solve the crisis holistically, but they dive into one popular mitigation strategy, electrification. Despite the difficult nature of the subject, this research-backed strategy for maximizing expected future welfare is effective in mitigating the long-term effects of climate change, while accounting for society's current needs and the limiting short-term consequences impacting our way of life. New knowledge of electrification and green energy was presented to the Port of Virginia, providing new ideas in their journey towards net-zero emissions, while minimizing financial costs in the process. This research has supported our presentations to the Port, leading to the consideration of on-site green energy infrastructure to further improve their environmental impact. Creating a comprehensive argument and a goal-directed mindset is especially important when presenting to a large-scale client, such as the Port of Virginia.

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