Upholding Social Justice Principles in Carbon Capture and Sequestration: Case of Southeastern Michigan

by

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Final Report

A research conducted in partial fulfillment of the requirements
for the degree of Master of Science
School for Environment and Sustainability
University of Michigan
April 2024

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Executive Summary

As the world is grappling with a worsening climate change crisis, there is a growing consensus that the world might need to scale up carbon dioxide removal activities to complement mitigation and adaptation efforts. Climate change and decarbonization can cause disproportionate impacts on disadvantaged communities, such as increased energy burden and job displacement, especially in regions such as Southeastern Michigan. Thus, it is important to prioritize the needs and concerns of these communities by implementing targeted policies and investments, increasing awareness, and empowering them to participate in decision-making processes. In particular, the Justice40 Initiative can be a momentum to support this transition process. The Justice40 Initiative's goal is to ensure that 40% of the overall benefits of certain Federal investments flow to disadvantaged communities. In this context, this project aims to study the feasibility of Carbon Capture and Sequestration (CCS) in the Southeastern Michigan region while promoting a sustainable environment and transition through the Justice40 Initiative. While there are several research projects that focus on the technological aspect of CCS, studies to understand the policy, socioeconomic, and social justice aspects of CCS deployment are still lagging. As societal consideration is a key component of success for any CCS initiative, it is imperative to advance the social aspect in addition to providing economic and policy incentives that can catalyze deployment at scale. With the geographical focus on Southeastern Michigan, our study utilizes three research approaches: (1) geospatial analysis, (2) social life cycle assessment (S-LCA), and (3) stakeholder engagement. This report presented our results of literature review, analysis and the recommendations for policymakers and project developers. The geospatial analysis presents the reclassification of pollution burden based on the burden indicators such as energy and housing from the Climate and Economic Justice Screening Tool. Further, the cluster analysis exhibited spatial distribution patterns and the relationships with the emitter location and disadvantaged communities. The social life cycle assessment presented a framework for analysis focusing on potential social issues and opportunities from the lens of sustainable development's three pillars: People, Planet, and Prosperity. The societal aspect of the development of a CCS facility includes key stakeholder categories, such as workers, society, and local communities. Finally, the stakeholder engagement part presented key insights from diverse stakeholders including public, private, and civil representatives. Participation in conferences and workshops allowed us to interact with several stakeholders and provided valuable insights into

conducting social studies while establishing connections with fellow scholars. Overall, our study highlights the importance of engaging with local social groups and the need for ensuring transparency, building credibility, and upholding aspects of recognitional, procedural, and distributional justice. Effective Greenhouse Gas (GHG) emissions control, especially from major sources like power plants, combined with targeted social justice interventions in heavily burdened clusters, is crucial. Addressing labor rights, community engagement, and indigenous rights within the context of CCS projects is paramount to ensuring an equitable and just transition to net-zero emissions. Transparent communication, thoughtful implementation, and genuine stakeholder engagement are essential to ensure equity and leveraging Michigan's geological potential for CCS. This holistic approach will enable the region to navigate the complex interplay between technological advancement, environmental sustainability, and social equity.

Acknowledgment

To fulfill the capstone requirement for the University of Michigan School for Environment and Sustainability (SEAS) Master of Science program, students Hejing Hu, Michael Somantri, Zirui Peng, and Ziwen Tan, partnered with our client, DTE Energy, and our faculty advisor Dr. Rajiv Ghimire on this Master's Project. We wish to thank Dr. Ghimire and Anthony Muzzin for their constant support throughout the process of this research project. We also want to thank our many interviewees and informants for their time and effort in our research as well.

We acknowledge that the University of Michigan resides on the traditional lands of the Anishinaabeg – the Ojibwe, Odawa, and Bodewadmi. As we continue to work, play, and live on these territories, we encourage everyone to reflect on the ongoing effects of colonization on indigenous people and tribal sovereignty. With this statement, we affirm that acknowledgement is the first of many steps and that in order to support indigenous people and be good neighbors and stewards of their homelands, we should take meaningful action toward decolonization.

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Chapter 1. Introduction

High dependency on fossil fuel resources has caused the atmospheric and oceanic carbon dioxide concentrations to be at an all-time high and causing well-documented damage to climate, habitats, and communities. There is no doubt that human activities, principally through greenhouse gasses emission, have caused the current global warming, with global surface temperature reaching 1.1 degrees Celsius above pre-industrial period (IPCC, 2023). Stabilizing the climate, and providing equitable access to electricity, energy, water, and other supporting infrastructures is an urgent societal challenge. While the past attempts have concentrated on reducing future emissions, the pace of mitigation has been slow and there already is a substantial amount of greenhouse gasses in the atmosphere. We have to acknowledge the impacts of climate change will be distributed unequally with disadvantaged communities, who contributed least to climate change, bearing the greatest burden such as the ability to mitigate damages, increased energy cost, and job displacement. Many climate-related efforts are pursued by various stakeholders and sectors in the form of climate mitigation and adaptation. However, an abrupt shift in the name of decarbonization potentially risks marginalizing disadvantaged communities and reproducing harms of the past. Thus, tackling climate change and ensuring social justice requires the balance of social, economic, and environmental well-being or sustainable development which has become one of the main pursuits of today's societies (Neugebauer et al., 2017). Sustainable development offers a relevant alternative to conventional development, as it also encompasses environmental protection and social equality. This includes ensuring that all communities, particularly those historically disadvantaged, have access to low-carbon & clean energy, healthcare, education, and economic opportunities.

The United States and the State of Michigan require a comprehensive climate action plan to ensure a sustainable environment and a just energy transition. The recent progress at the state and the national level has been encouraging. For example, in 2020, Governor Whitmer enacted an Executive Order to establish the Council on Climate Solutions (Exec. Order No.182, 2020). The council's objectives are to identify opportunities for the development of emission reduction strategies and resolve impact disparities across Michigan for communities disproportionately impacted by climate change. At the federal level, the Federal Inflation Reduction Act has focused on several approaches for rapid decarbonization. While the focus has been more on emission reduction and renewable energy there is a realization that these efforts might not be enough and we might need some level of carbon dioxide removal.

Reaching net zero primarily requires deep and rapid reductions in gross emissions of CO_2. For some hard-to-abate sectors (aviation, shipping, and industrial processes), the past and current emissions would need to be counterbalanced by deployment of carbon dioxide removal to achieve net zero (IPCC, 2023). Numerous technologies and practices are promising in the carbon dioxide removal realm such as bio-energy with carbon capture sequestration (BECCS), utilization of carbon-enhanced minerals, ocean-based storage, afforestation/reforestation and geological sequestration. These technologies have the ability of removing legacy emissions that have been building in the atmosphere since the industrial revolution. However, studies to understand the policy, socioeconomic, environmental, and social justice aspects of CDR deployment are still lagging. As societal consideration is a key component of success for any CDR initiatives, it is imperative to advance social and political aspects in addition to providing economic and policy incentives that can catalyze deployment at scale. Finally, each carbon dioxide removal project will have unique impacts, benefits, trade-offs, risks, and opportunities for communities and for the global effort to address climate change (Batres et al., 2021).

The deployment of large scale CDR requires massive support and collaboration from multiple parties. As mentioned above, the Federal Inflation Reduction Act is a huge milestone indicating support from the federal government to accelerate the decarbonization agenda. In order to ensure equitable transition, during his first week in office, US President Joe Biden issued Executive Order 14008, Tackling the Climate Crisis at Home and Abroad. Section 223 of EO14008 established the Justice40 initiative, which directs 40% of the overall benefits of certain Federal investments to flow to disadvantaged communities (Exec. Order No. 14008, 2021). The program's goal is to ensure improved quality of disadvantaged communities that are marginalized, underserved, and overburdened by pollution. DOE's working definition of ‘disadvantaged communities’ is based on cumulative burden and includes data for 36 burden indicators collected at the census tract level. At this point, there is still a lack of clarity on how this initiative should be implemented to ensure a sustainable environment and just transition.

In 2022, DTE Energy, a diversified energy company based in Detroit, and Battelle Memorial Institute initiated the CarbonSAFE Phase II Project. The project's overall objective is to advance the commerciality of carbon capture sequestration (CCS) in Southeastern Michigan while supporting, promoting, and protecting Diversity, Equity, Inclusion, and Accessibility (DEIA) and enhancing the benefits to the disadvantaged communities. The CarbonSAFE project aligns with both Michigan's MI Healthy Climate Plan and the country's goals for reducing GHG emissions by both decarbonizing electricity and scaling up carbon dioxide removal. DTE is engaged with community partners who may be interested in collaborating on, learning about, and assisting with the creation and execution of the Justice40 Initiative Plan. As part of the initiative, this project led by a team of graduate students from the University of Michigan's School for Environment and Sustainability (SEAS) assists DTE with the evaluation of societal considerations and impacts of the Southeastern Michigan Carbon Capture Sequestration project.

The study focuses on three research questions. (1) What is the relationship between social burdens and GHG emission, and how is that relationship changing in the region of disadvantaged communities? In answering this question, we utilize spatial tools and analysis with data specific to Southeastern Michigan. Geospatial analysis is often used to identify and understand spatial patterns in data and explore relationships between different geographical features or attributes of geographical features. First, we performed reclassification based on the eight burden indicators, such as energy, housing, etc., from the Climate and Economic Justice Screening Tool (CEJST). Subsequently, we performed spatial analysis, such as cluster analysis, to explore their spatial distribution patterns. The last step was finding relationships between the emitter location and DAC.

The second research question is (2) what would be the societal impacts and benefits of deploying the carbon capture sequestration project? In exploring sustainable technologies, the life cycle assessment (LCA) offers vital insights from the lens of sustainable development's three pillars: people, planet, and prosperity. For this specific research question, we focused on the societal (people) aspect of the development of a CCS facility. We selected the social life cycle Assessment (S-LCA) as our primary framework to analyze the societal impacts throughout the entire project life cycle. Key stakeholder categories, including workers, local communities, and society play pivotal roles in the process, fostering credibility and trust in the pursuit of sustainable development.

The third research question is (3) how do we ensure that the benefits of the carbon capture sequestration investment flow to disadvantaged communities? The last question needs to be answered to connect the first two questions. In particular, this question addresses the implementation of the Justice40 Initiative in the context of the deployment of emerging technologies. The team drafts an implementation plan to maximize the benefits, identify barriers, opportunities, and resources needed for achieving the milestones identified in the implementation plan. The result of this analysis aims to be a foundation for future Justice40 Initiative plans.

This report presents the literature review, research methods, results and the discussion of policy relevance of our research and is divided into seven chapters. *Chapter 2* presents a literature review focused on the grand challenges of climate change, the main drivers of CCS deployment, along Environmental Justice (EJ) issues, specifically in the context of Southeastern Michigan. *Chapter 3* elaborates on the research methodologies for geospatial analysis, S-LCA, and communities & stakeholders engagement. Methods for quantitative analysis included spatial data modeling and some parts of the social life cycle assessment, particularly the inventory and impact assessment. Methods for qualitative analysis included outreach to several stakeholders from private and public institutions and scholars' knowledge about the issue. The team performed semi-structured interviews to engage with the identified key stakeholders. *Chapter 4, 5 and 6* present the results of geospatial analysis, social life cycle assessment, and stakeholders engagement. Finally, *Chapter 7* presents the discussion and conclusions

Chapter 2. Literature Review

This literature review focuses on the three main aspects: the grand challenges of climate change (climate mitigation and adaptation), carbon removal technologies, and environmental justice (EJ). We expect to see many intersections of these aspects as we move forward to mitigate and adapt to the climate change phenomenon.

2.1 Grand Challenges of Climate Change

The burden of climate change is profound, which underscores the urgent need for climate mitigation and adaptation strategies. In addressing the critical issue of climate change, a comprehensive strategy that encompasses both mitigation and adaptation is essential. A study by Lawler et al., 2013, illuminates the necessity of this dual approach. Mitigation, which targets the reduction of GHG emissions, is pivotal in confronting the root causes of climate change. The paper's projections, such as the anticipated rise in average temperatures across the United States, underscore the urgency of mitigation. By implementing strategies like sustainable transportation, clean energy, and carbon dioxide removal, we aim to curb the increasing trend of temperatures, which, under various scenarios, could see significant rises by the end of the century. Mitigation is, therefore, crucial in our endeavor to limit the extent of climate change and its far-reaching impacts. Parallel to mitigation, adaptation plays a complementary role in preparing for the inevitable consequences of climate change. As the report details, significant warming across different regions of the United States necessitates adaptive measures. These include enhanced disaster management and robust flood protection infrastructure, particularly crucial in areas expecting the greatest temperature increases, such as northern regions and Alaska. Adaptation is about building resilience and reducing the vulnerability of communities to altered climatic conditions, which are already manifesting in the form of extreme temperature days and shifting seasonal patterns.

The interplay of mitigation and adaptation forms the cornerstone of a sustainable response to climate change. Given the critical importance of limiting global temperature increase to 1.5 degrees Celsius, carbon dioxide removal technologies are highlighted as a key part of mitigation measures, as reducing emissions through mitigation alone is not enough. Nonetheless, the integration of adaptation strategies remains an important part of the overall approach. This dual strategy not only addresses the immediate challenges posed by climate change but also prepares us for a future in which the impacts of climate change are managed effectively and sustainably. At their core, both mitigation and adaptation are key to a sustainable future, and our projects' emphasis on technological climate mitigation, particularly in the application of carbon capture sequestration, reflects our commitment to solving the root causes of this global problem. Aside from removing emissions, most impacts from this project are necessarily local. Therefore, we must go beyond technology-level analyses (Morrow et al., 2020). Key social aspects appear underrepresented, even though social factors have proven critical to carbon removal deployment (Storrs, Lyhne, & Drustrup, 2023).

2.2 Carbon Removal Technologies

In the field of climate change mitigation, carbon removal technologies have emerged as a pathway strategy due to its potential to offset the adverse effects of excessive carbon emissions caused by human activities. Figure 1 shows observed and projected changes in carbon emissions and temperature with three potential climate scenarios for humanity underscoring the urgency of such measures. Assuming that carbon emissions from fossil fuels have peaked, this represents a lower scenario. Conversely, the red and green lines depict the higher and even lower scenarios, with projected global warming of 2.7° - 5.2 °C and 0.3° - 1.8 °C by the end of the 21st century, respectively (Hayhoe et al, 2018). The Paris Agreement establishes the overarching goal of limiting global warming to 1.5°C above pre-industrial levels, as shown by the green line. Immediate and substantial reductions in carbon emissions are imperative to adapt to the lower scenario and meet global temperature targets.

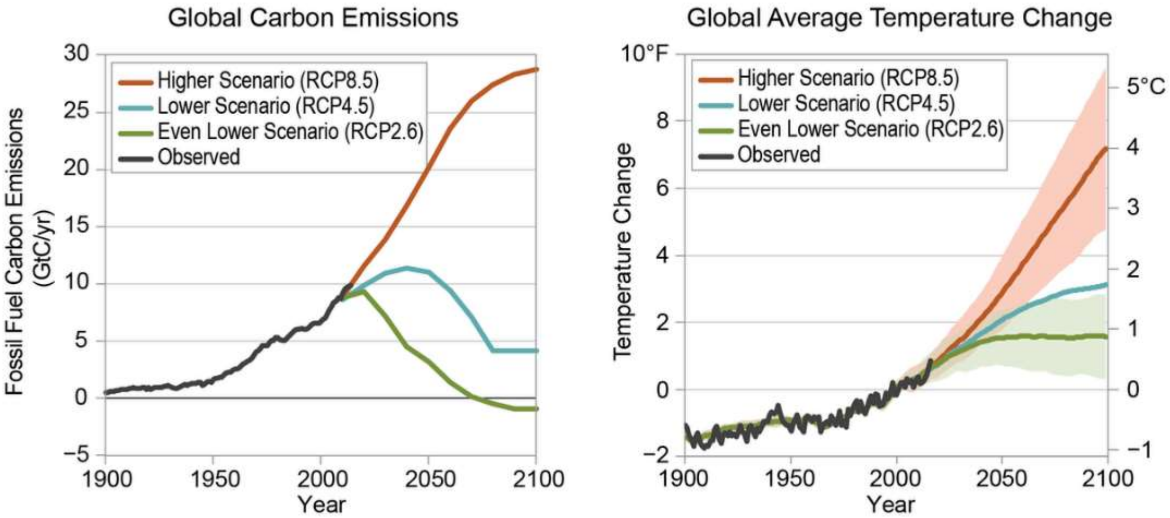


Figure 1. Observed and Projected Changes in Carbon Emissions and Temperature (Hayhoe et al, 2018)

The need for rapid carbon removal action to follow the 1.5°C trajectory is demonstrated by Figure 2 (IPCC, 2023). It argues that relying solely on traditional mitigation technologies, such as renewable energy or energy-saving practices, is not enough. Identifying the main sources of carbon emissions is critical, with electricity, transport, manufacturing, buildings and agriculture being the five major challenges. The most effective decarbonization pathways involve multiple strategies and will vary by sector and region, but in the electricity and industrial sector, carbon capture sequestration (CCS) stands out because it directly addresses key challenges related to process emissions, the combustion from high temperature heat, and the lock-in of existing infrastructure.

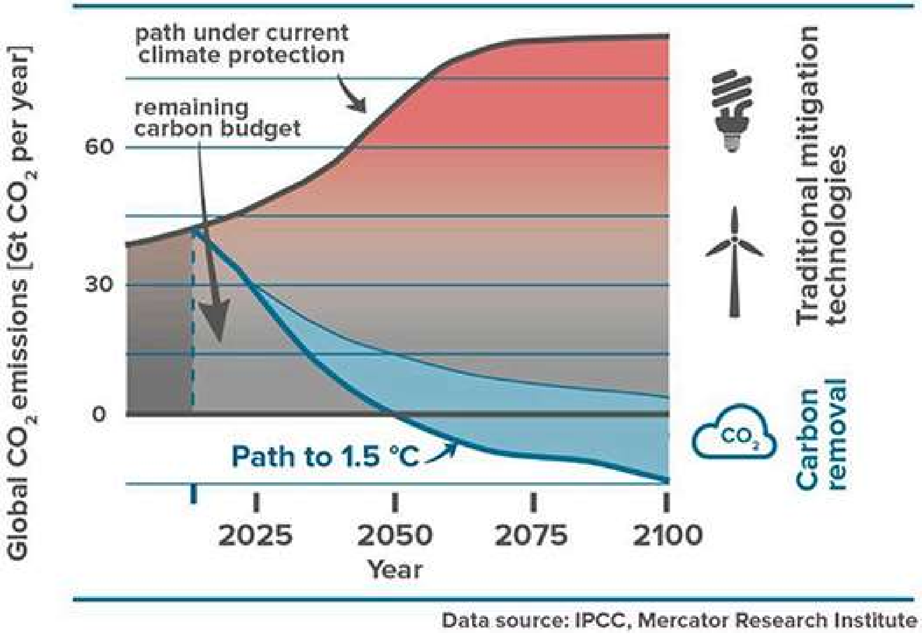


Figure 2. Global CO_2 Emissions Reduction Scenarios (IPCC, 2023)

In considering carbon removal technologies, it is important to understand the features of carbon capture, carbon sequestration, and carbon utilization. That being said, the scope of this study only focuses on the carbon capture sequestration technology which involves isolating CO_2 from industrial processes and energy-related point sources such as power plants to a geological formation:

- Carbon capture: a process by which carbon oxides (CO and CO_2) are isolated from dilute mixtures, such as air, water, or flue gas (Wilcox, 2012,). Direct Air Capture isolates CO_2 from ambient air and flue gas capture removes CO_2 from a point source emitter in a place such as a steel and cement manufacturing plant, natural gas plant, or ethanol plant.
- Carbon sequestration: this process involves storage in geological, mostly underground reservoirs with or without mineralization to carbonates. Key features of carbon sequestration include carbon removal at geological time scales and potential volume exceeding 100,000 gigatonnes of CO_2 (Mason et al., 2023).
- Carbon utilization: this process takes the carbon dioxides as a raw material to convert them to products. This conversion into useful products such as construction aggregates, fuels, polymers, and chemicals (Mason et al., 2023).

2.2.1 Carbon Capture

Separating CO_2 requires energy, and often modifications to existing processes. After the separation process, the CO_2 stream can be further purified and compressed to make it ready for transport. There are four main carbon capture approaches, and in certain cases they can be combined to create hybrid capture methods (International Energy Agency, 2019).

- *Post-combustion capture*: CO_2 is separated from a mixture of gasses at the end of an industrial or energy process, for example from combustion flue gasses using an absorptive or adsorptive substance or a membrane.
- *Oxy-fuel combustion*: Instead of air, nearly pure oxygen is used to combust fuel, producing flue gas composed almost solely of CO_2 and water vapor. Part of the flue gas is recycled to the combustion chamber to control the combustion temperature, while the remainder is dehydrated to obtain a high-purity CO_2 stream.
- *Pre-combustion capture*: In a reforming/gasification process, fossil fuels or bioenergy can be processed with steam and/or oxygen to produce a gaseous mixture called syngas, consisting of carbon monoxide and hydrogen. The carbon monoxide is reacted with more steam to yield additional hydrogen and convert the carbon monoxide to CO_2. The CO_2 can then be separated from the high pressure gas mixture, yielding raw syngas for combustion or chemical production.
- *Inherent separation*: Certain processes in industry and fuel production generate high-purity CO_2 streams as an intrinsic part of the process (e.g. gas processing and ethanol production). Without CO_2 capture, the CO_2 produced is vented to the atmosphere.

2.2.2 Carbon Sequestration

There are two types of carbon sequestration: biological and geological sequestrations. Reservoirs that store carbon over long periods of time are called “carbon sinks.” Biological sequestration is the storage of carbon dioxide in vegetation such as grasslands or forests, as well as in soils and oceans. Carbon goes in both directions in the ocean. When carbon dioxide is released into the atmosphere from the ocean, it creates what is called a positive atmospheric flux. A negative flux refers to the ocean absorbing carbon dioxide. Think of these fluxes as an inhale and an exhale, where the net effect of these opposing directions determines the overall effect.

Oceans absorb roughly 25 percent of carbon dioxide emitted from human activities annually (Kerlin, 2019a).

Other forms of biological sequestration are through soil and forests. Carbon is sequestered in soil by plants through photosynthesis and can be stored as soil organic carbon . Soil can also store carbon as carbonates. Such carbonates are created over thousands of years when carbon dioxide dissolves in water and percolates the soil, combining with calcium and magnesium minerals, forming "caliche" in desert and arid soil (Kerlin, 2019b). Carbonates are inorganic and have the ability to store carbon for more than 70,000 years, while soil organic matter typically stores carbon for several decades. About 25 percent of global carbon emissions are captured by plant-rich landscapes such as forests, grasslands and rangelands (Kerlin, 2018).

In recent years, much research has focused on the geological carbon sequestration to assess the feasibility of CO_2 storage on a commercial scale. Sequestration processes involve different trapping mechanisms according to the hydrodynamic, physical, and chemical conditions in the formation (Zhang & Song, 2014). Three classes of target reservoirs are capable of sequestering large volume of CO_2 (Friedmann, 2007):

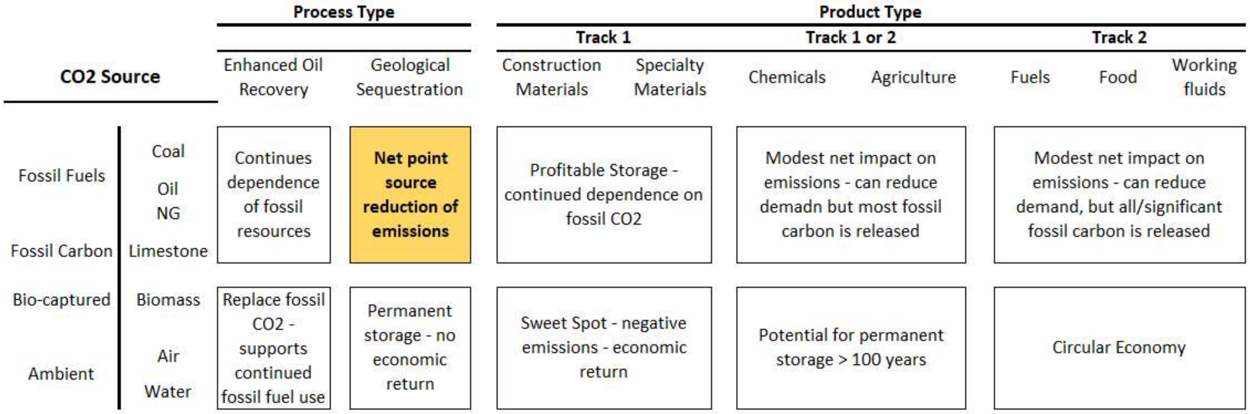
- Saline formations: These contain brine in their volumes, commonly with a salinity greater than 10,000 ppm
- Depleted oil and gas fields: A combination of water and hydrocarbon fills their pore volumes, and in some cases, economic gains can be achieved through enhanced oil recovery or gas recovery
- Deep coal seams: Often called unmineable coal seams, these are composed of organic materials and contain brines and gasses in their pore and fracture volumes.

2.2.3 Carbon Utilization

Conversions of CO_2 create products that generate revenue from their sales to help cover the increased cost of production from capturing and using CO_2. While of lower CO_2 storage capacity than sequestration overall, the annual utilization potential is sufficient in the long term to more than adequately handle inevitable CO_2 emissions from hard-to-abate industrial sectors and the use or decomposition of short-lived CO_2 products at the several gigatonnes/year level (Sick, 2021). Some technologies for CO_2 capture and utilization are ready for deployment, while others will require substantial R&D investments (Mason et al., 2023).

Understanding the potential climate impacts of CO_2-based products is aided by the concept of Track 1 and Track 2 products (Sick et al., 2022). The distinction between these two tracks is in the anticipated product lifetime and associated time during which underlying CO_2 is removed from the environment. Track 1 products have lifetimes of at least 100 years, with potential lifetime of thousands of years for some polymer materials and some construction materials. In contrast, Track 2 products are consumed or decomposed in less than 100 years. They re-release CO_2 on a time scale that has different climate implications (Sick et al., 2022).

This study focuses on carbon capture sequestration using geological formation, which acts as a net point source reduction of emissions. Figure 3 illustrates the variety of CCUS (Carbon Capture, Utilization, and Storage) sources and sinks. The row exhibits the CO_2 sources while the column shows the CO_2 sinks. It presents a challenging and intricate landscape for professionals and policymakers. Essential instruments like Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) play a crucial role in assessing the environmental effects, technical practicality, economic viability, and impacts on society (Mason et al., 2023). Efforts are being made to improve these tools, which will enable thorough evaluations for gaining public acceptance.



		Process Type		**Product Type**						
				Track 1		**Track 1 or 2**		**Track 2**		
CO2 Source		Enhanced Oil Recovery	Geological Sequestration	Construction Materials	Specialty Materials	Chemicals	Agriculture	Fuels	Food	Working fluids
Fossil Fuels	Coal Oil NG	Continues dependence of fossil resources	**Net point source reduction of emissions**	Profitable Storage - continued dependence on fossil CO2		Modest net impact on emissions - can reduce demadn but most fossil carbon is released		Modest net impact on emissions - can reduce demand, but all/significant fossil carbon is released		
Fossil Carbon	Limestone									
Bio-captured	Biomass	Replace fossil CO2 - supports continued fossil fuel use	Permanent storage - no economic return	Sweet Spot - negative emissions - economic return		Potential for permanent storage > 100 years		Circular Economy		
Ambient	Air Water									

Figure 3. CO_2 Sources and Sinks Matrix (Mason et al., 2023)

2.2.4 Policy Regulatory and Incentives for Carbon Removal Technologies

Federal and state policies, along with private sector investments, can help to develop and deploy carbon removal technologies. The Bipartisan Infrastructure Law and Inflation Reduction Act creates a strong foundation for scaling up the required infrastructure. At the same time, policies and regulations are needed to ensure carbon removal is deployed responsibly, incorporating robust community engagement, consistent measurement, reporting, and attention to environmental and societal impacts of projects.

1. 45Q Tax Credit - IRA Extension

Section 45Q of the United States Internal Revenue Code provides a tax credit for CO_2 storage that was first introduced in 2008. The intention of this policy is to incentivize deployment of carbon capture, utilization and storage (CCUS), and a variety of project types that are eligible. In order to claim a tax credit, the emissions must be measured at the point of capture as well as the point of disposal, injection, or other use. The Bipartisan Budget Act of 2018 (P.L. 115-123) expanded and extended the 45Q tax credit. Changes included: largest credit amount, a start-of-construction deadline and a 12-year claim period instead of the 75 million metric ton cap, allowing the credit for CO_2 utilization, allowing smaller facilities to claim credit, and allowing owners of carbon capture equipment to claim tax credits, which creates flexibility in ownership structures facilitating tax equity investment (Jones & Marples, 2021).

The introduction of the Inflation Reduction Act (IRA) created a significant stimulus for investments by expanding and extending the 45Q tax credit. This update increases the incentive from $17 to $85/metric ton for geologically sequestered CO_2. In addition, IRA extended the commence-construction window for qualifying projects up to seven years until January 1, 2033. Recipients of the 45Q tax credit are able to transfer some portion or all of the credit value to any third-party, tax-paying entity in exchange for a cash payment during any portion of the 12-year credit window (Inflation Reduction Act Sec. 13104, 2022).

In addition, IRA expands the tax credits into a two-tier regime consisting of a base credit and an additional bonus credit. The bonus credit is available for eligible projects that satisfy certain prevailing wage and apprenticeship requirements. Taxpayers must ensure that any laborers, mechanics, or contractors employed are paid prevailing wages in the geographic area where the project is located. The minimum prevailing wages are determined by the US Department of Labor. In terms of apprenticeship, no fewer than the “applicable percentage” of total labor hours are performed by qualified apprentices (Jones & Marples, 2021).

2. Cap and Trade

The US currently does not have a carbon tax on a national level. However, there are 12 Eastern states that together make up the Regional Greenhouse Gas Initiative (RGGI), as well as California and Washington, have cap and trade programs. The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory cap and trade program in the US to reduce CO_2 emissions from the power sector. Within RGGI states, regulated power plants must acquire one RGGI CO_2 allowance for every short ton of CO_2 they emit. There will be quarterly auctions to distribute allowances that can be purchased by power plants and other entities. Fossil fuel-fired power plants sized 25 MW or greater must acquire enough RGGI allowances to cover their emissions (Regional Greenhouse Gas Initiative, 2023).

The California Cap and Trade Initiative is a vast emissions trading system that spans various sectors and is one of the largest in the world. It plays a crucial role in California's efforts to meet its climate objectives of lowering emissions by 80 percent below 1990 levels by 2050. The program covers entities such as electricity generators, large industries, and fuel supply industries that emit 25,000 metric tons of CO2 or more annually. The California Air Resources Board (CARB) oversees the program and conducts quarterly auctions where polluters can purchase credits. The revenue generated from the auctions goes back to utility ratepayers through the California Climate Credit, as well as the Greenhouse Gas Reduction Fund and California Climate Investments program, which finance various projects aimed at reducing greenhouse gas emissions, such as energy efficiency, clean transportation, and solar energy (Center for Law, Energy, and Environment, UC Berkeley, 2021).

3. Voluntary Carbon Market

In contrast with above policies, Voluntary Carbon Market (VCM) is a decentralized market where private actors voluntarily buy and sell carbon credits that certify removals or reduction of GHG emissions in the atmosphere (Dyck et al., 2022). Companies can make investments for projects or programs that generate tradable GHG credits, to acquire credits to voluntarily offset GHG emissions or to otherwise support other climate action initiatives through financing. Overall, the market for carbon credits could be worth upward of $50 billion in 2030 (McKinsey, 2021). The combination of industrial process emissions and CCS supports 31% of the US voluntary carbon market (VCM) with up to 125 million credits registered until 2022 (Haya et al., 2022).

According to the above overview, none of these policies and initiatives directly address the social, equity, and justice aspects of carbon removal deployment. The extension of IRA on 45Q tax credit only specifies the minimum requirement, such as prevailing wages and apprenticeship, for a project to be eligible for the additional tax credit. There is no single provision mentioned to actively include communities in the decision-making process. Since we are still in the early stages of development, advocating targeted policies and stakeholder engagement are imperative to ensure sustainable and equitable ways to scale up carbon removal technologies.

2.3 Environmental Justice (EJ)

As mentioned above, the necessity of carbon removal technologies is clear to help the planet maintain a temperature trajectory below 1.5 degrees above the pre-industrial era. Since the industrial era, disadvantaged communities have been neglected and disproportionately impacted across industries. Leaving them without a voice in the decision-making process regarding siting and the overall direction of the project will put us into the same pit again. In this case, environmental justice (EJ) will be an essential component to deploy the technology at a larger scale. For example, decarbonization efforts, while essential for reducing GHG emissions, can have unintended consequences on vulnerable communities. Transitioning to cleaner energy sources might lead to job displacement in fossil fuel-dependent sectors and increase energy bills due to the initial higher costs of renewable energy technologies. These shifts could disproportionately affect disadvantaged communities, highlighting the importance of incorporating EJ principles into climate action plans. This approach ensures that the benefits of decarbonization, particularly carbon removal technologies are equitably distributed, preventing further marginalization of these communities. Carbon removal technologies don’t scale up in a vacuum but should recognize the interconnectedness with prosperity, planet and the people (Friedmann, 2019).

2.3.1 History of Environmental Justice

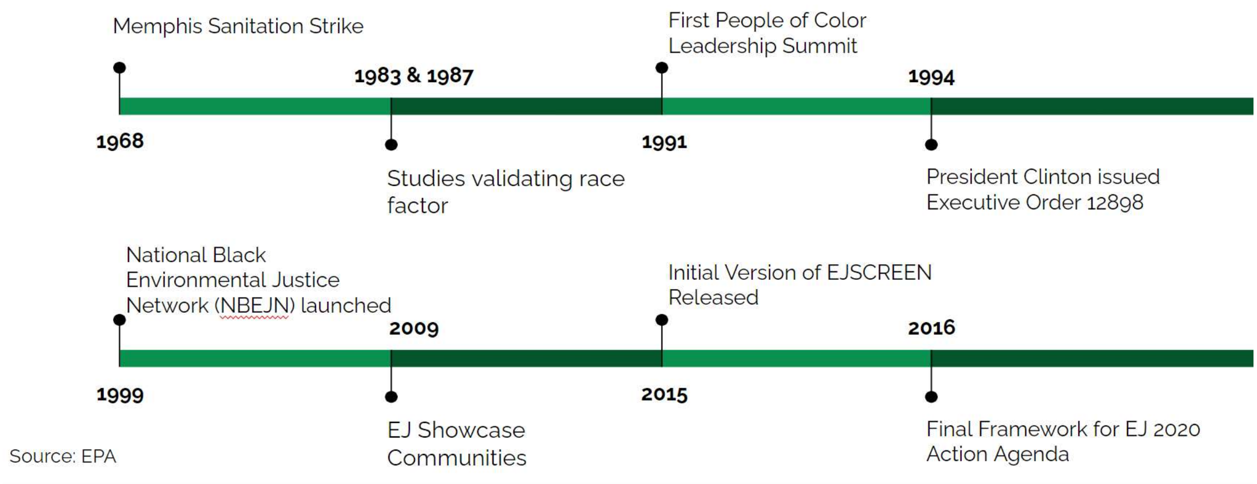
Environmental Justice (EJ) is a movement and a field of study that addresses the disproportionate environmental burdens faced by marginalized communities. These burdens include but are not limited to, greater exposure to pollution and limited access to natural resources. The Environmental Protection Agency (EPA) defines EJ as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (*Environmental Justice | US EPA*, 2023). This principle is grounded in the pursuit of equitable protection from environmental and health hazards and equal participation in decision-making processes affecting the environment.

The origins of the Environmental Justice movement can be traced back to various grassroots and national movements, often led by communities of color. A notable early event was the Memphis Sanitation Strike in 1968, where African Americans mobilized against environmental injustices on a national scale for the first time. Further momentum was gained in the 1980s, particularly with the Warren County PCB landfill protest in 1982, which brought to light the issue of environmental racism. This period also saw critical academic contributions, like the 1983 and 1987 studies confirming the racial bias in the siting of hazardous waste facilities (Steady, 2009).

The movement continued to grow in the 1990s, marked by significant events and policy developments. In 1991, the first National People of Color Environmental Leadership Summit was convened in Washington D.C., laying down principles that would guide the EJ movement. Following this, in 1994, President Bill Clinton signed Executive Order 12898, focusing federal attention on environmental and health effects in minority and low-income populations. This order was a crucial step in recognizing EJ in federal policy (*Environmental Justice | US EPA*, 2023).

In the subsequent decades, the movement and its influence expanded. The National Black Environmental Justice Network (NBJEN) was established in 1999, focusing on environmental and health disparities in Black communities. By the 2000s, EJ had become an integral part of environmental policymaking. In 2009, the EPA announced a national initiative to address EJ challenges in 10 designated communities. This period also saw the development of tools like EJSCREEN, released in 2015, which provided a web-based screening and mapping tool for identifying areas affected by environmental injustices (Bowen, 2002).

The EJ 2020 Action Agenda, created by the EPA in 2016, marked another significant advancement, laying out a strategic plan for addressing EJ issues. This agenda aimed to integrate EJ considerations into all EPA decisions, emphasizing the importance of community-based approaches and improving the EPA's ability to address complex environmental issues in diverse communities.



Source: EPA

Figure 4. Environmental Justice History

2.3.2 Principles of Environmental Justice

Environmental justice (EJ) encompasses several core principles aimed at ensuring equitable treatment and involvement of all people regardless of their race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This section outlines four fundamental principles of EJ: procedural justice, distributive justice, restorative justice, and retributive justice, and their significance in the context of environmental management and policy-making.

1. Procedural Justice

   Procedural justice focuses on fairness in the processes that resolve disputes and allocate resources. It emphasizes the right of communities to be involved in decisions that affect their environment and health. This principle seeks to ensure that decision-making processes are transparent, inclusive, and account for the needs and voices of all stakeholders, particularly marginalized communities that have historically been excluded from such processes (Albin, 2017).

2. Distributive Justice

   Distributive justice pertains to the equitable distribution of environmental benefits and burdens. It challenges the disproportionate impact of environmental harm on low-income populations and communities of color and advocates for a fair sharing of the benefits derived from environmental resources and policies. This principle addresses inequalities in environmental quality and access to natural resources, aiming to rectify the imbalance in environmental protection and enhancement across different communities (Aragao, 2016; Chang, 2018).

3. Restorative Justice

   Restorative justice emphasizes healing and making amends for injustices. In the environmental context, it focuses on repairing the harm caused by environmental degradation and pollution, restoring ecosystems, and reconciling the relationship between humans and nature. This principle involves acknowledging the damage, taking responsibility for it, and involving all affected parties in the restoration process. It represents a shift from punitive approaches towards healing and sustainable solutions (Wallsgrove, 2022; Hazrati & Heffron, 2021).

4. Retributive Justice

   Retributive justice is concerned with punishment of offenders as a means of achieving justice. It seeks to hold individuals or entities accountable for their actions that cause environmental harm, through penalties that are proportionate to the offense. This principle is based on the notion that punishment can deter future violations and vindicate the rights of victims. However, it also raises questions about the effectiveness of punitive measures in addressing the root causes of environmental problems and promoting long-term sustainability (Caruso, 2020; Willigenburg & Van der Borght, 2021).

The principles of environmental justice—procedural, distributive, restorative, and retributive—offer a comprehensive framework for addressing and mitigating environmental inequities. By integrating these principles into environmental policy and practice, we can work towards a more just and sustainable future for all communities.

2.3.3 Environmental Justice and Carbon Dioxide Removal

In recent years, the relationship between EJ and technological advancements, particularly in the realm of Carbon Dioxide Removal (CDR), has become a focal point of discussion. Batres et al. (2021) explore how large-scale CDR technologies, such as Bioenergy with Carbon Capture and Storage (BECCS), could impact marginalized communities. They caution that these technologies, if not implemented with EJ principles in mind, could exacerbate existing inequalities. For instance, land-intensive CDR strategies might lead to land dispossession or degradation, disproportionately affecting marginalized groups. The authors advocate for inclusive governance frameworks that embed EJ principles in the deployment of these emerging technologies.

Transitioning to the public's viewpoint, Cox, Spence, and Pidgeon (2020) offer insights into how CDR technologies are perceived in the United States and the United Kingdom. Their study presents a nuanced understanding of public attitudes towards CDR, revealing a significant influence of climate urgency on perceptions. It is evident from their findings that CDR is often seen as a slow response to the immediate climate crisis, raising concerns about its ability to address the fundamental causes of climate change. This research suggests that the social license for CDR technologies may depend heavily on how these temporal and ethical concerns are addressed and resolved (Cox et al., 2020).

Further expanding this discourse, the Carbon Removal Justice Fellowship, established by the National Wildlife Federation in partnership with American University’s Institute for Carbon Removal Law & Policy, aims to center equity and justice in carbon removal policy. This fellowship brings together professionals from diverse backgrounds, including environmental law and community advocacy, to address the intersection of EJ and CDR. The program emphasizes the need for the carbon removal industry to incorporate EJ considerations from the outset, recognizing the intertwined nature of projects and communities economically and environmentally (Ferrell, 2023). With the increasing necessity for large-scale deployment of CDR to achieve climate goals, the integration of EJ principles—particularly procedural justice, distributive justice, and restorative justice—into CDR practices has become imperative.

Incorporating procedural justice into CDR initiatives involves fostering transparent and inclusive dialogues between developers, stakeholders, and especially disadvantaged communities throughout the project’s life cycle. This ensures that all parties have meaningful participation in decision-making processes, thereby building trust and securing the social license necessary for the implementation of CDR technologies. Terlouw et al. (2021) emphasize the significance of considering the life-cycle environmental impacts of CDR technologies, recommending rigorous assessment and transparent reporting to avoid misinterpretation of data and to ensure environmental integrity and public accountability. Maher, and Symons, in their 2022 study, delve into the intricacies of the international politics surrounding CDR. They address the need for cooperative global governance in this domain, focusing on the development of international cooperative efforts in areas like CDR accounting, technology development, and governance mechanisms. Their research is pivotal in highlighting the importance of social justice impacts and the acquisition of social license in the realm of CDR (Maher & Symons, 2022,).

Furthermore, distributive justice mandates that the benefits and burdens associated with CDR technologies are equitably shared. This entails not only the creation of high-quality jobs in disadvantaged communities but also the mitigation of potential environmental harms, ensuring that these projects do not add to the historical burden of pollution and degradation borne by these communities. For example, a CDR facility's establishment in a disadvantaged region should prioritize hiring local residents, providing them with fair wages and skill development opportunities, while also implementing stringent measures to protect local air and water quality. This approach aligns with the broader goals of climate justice, recognizing that climate change and its mitigation efforts can have disproportionately harmful social, economic, and public health impacts on disinvested populations (Sabbagh & Schmitt, 2018).

Restorative justice offers a pathway to repair harms and restore both ecological and community health. Utilizing degraded lands for afforestation projects without displacing current uses, or repurposing legacy industrial sites for carbon capture, presents opportunities to remediate contaminated environments while contributing to global carbon dioxide removal goals. Such efforts, as highlighted by Batres et al. (2021) and Terlouw et al. (2021), not only sequester carbon but also contribute to the healing of landscapes and communities historically marred by industrial activities.

The CDR industry, while offering solutions like addressing legacy emissions and facilitating self-determined development in certain regions, faces challenges related to energy demands, water use, and the economic costs of CO_2 transportation. There is an increasing recognition within the industry of the need to address the country's history of racist pollution, siting injustices, and undelivered promises. EJ principles such as self-determination, informed consent, and mutual respect are being advocated for inclusion in early project planning stages. Active EJ organizations have been critical of CDR conversations that overlook social implications and the historical legacies of adding more industrial projects in communities. This skepticism is rooted in concerns that CDR might serve as an excuse for mitigation deterrence, thereby postponing the necessary transition away from fossil fuels (McLaren & Táíwò, 2020).

These discussions and initiatives reflect a growing awareness within the field of CDR technology of the need to integrate EJ principles. The focus is on ensuring that technological advancements in carbon removal do not perpetuate environmental inequities but rather contribute to sustainable and just climate solutions.

2.3.4 Justice40 Initiative

Another significant development in the realm of EJ is the Justice40 Initiative, spearheaded by President Biden's administration in 2021, which exemplifies a landmark commitment toward weaving environmental justice (EJ) into the fabric of federal climate and environmental policies. This initiative mandates that 40% of the overall benefits from federal investments in critical areas such as climate action, clean energy transition, and infrastructure improvements directly support disadvantaged communities that have historically borne the brunt of environmental neglect and degradation (Conley, Konisky, & Mullin, 2023). This move marks a significant stride in rectifying historical injustices by promoting equitable distribution of resources and ensuring that vulnerable populations are not left behind in the nation's progress toward sustainability and resilience against climate change.

The Justice40 Initiative is vital because it recognizes and addresses the disproportionate impact of environmental and climate-related issues on marginalized communities. By earmarking a significant portion of federal benefits for these communities, the initiative seeks to ensure that they receive their fair share of support in climate resilience, access to clean energy, and environmental restoration efforts. This approach not only aims to reduce existing disparities but also to foster inclusive growth and development that benefits all sectors of society (Conley, 2023).

Applying the Justice40 Initiative involves a meticulous process where federal agencies are tasked with identifying and channeling benefits to disadvantaged communities. This involves collaborative efforts with state and local governments, as highlighted in early state implementations of the initiative within the transportation sector, where efforts are made to align with Justice40's objectives through the federal highway program and the National Electric Vehicle Infrastructure (NEVI) program (Conley, Konisky, & Mullin, 2023). These collaborative endeavors underscore the initiative's comprehensive approach, emphasizing the importance of integrating EJ principles across various levels of governance and sectors of the economy.

The Justice40 Initiative represents a proactive and substantial effort to embed EJ principles deeply within the United States environmental and climate policies. By ensuring that a significant portion of federal investments benefits disadvantaged communities, the initiative lays a foundation for a more just and equitable approach to addressing climate change and environmental issues. It stands as a testament to the commitment of the Biden Administration to not only tackle environmental challenges but also to ensure that the nation's progress toward a sustainable future is inclusive and equitable for all its citizens.

2.3.5 Environmental Justice in Southeastern Michigan

The state of Michigan has 85 counties and the focus of this study is on nine counties in Southeastern Michigan. This region includes the Detroit metropolitan area and is the most populous and economically significant area in the state. According to the census, the total population of Michigan is 10.05 million and more than half of the total population lives in this region (Census, 2020). Among the total population of Michigan, the non-white population accounts for 25%. Southeastern Michigan has 35% of the non-white population compared to the total population (Census, 2020). The area near Detroit has an even higher percentage of non-white population. The wealth gap between minorities and White Americans is an enduring social problem (Bonaparte, 2023). A larger non-white population means more economically and socially vulnerable in that region.

Southeastern Michigan also has serious environmental problems. A growing number of reports and studies point to numerous environmental injustices in Southeastern Michigan. 48217 is a zip code area that is only a few kilometers away from downtown Detroit. It is the most polluted place in Michigan. There are currently 52 heavy industry sites within a 3-mile radius of this zip code, and almost half of them handle toxic chemical waste (Schlanger, 2016; Benz, 2019). In addition to affecting physical health, the pollution can also affect other aspects, such as school attendance, which is extremely low near this site (Mohai et al., 2011). So, the impact of environmental problems is multifaceted in southeastern Michigan.

Environmental health disparities in Southeastern Michigan are further exemplified by the initiatives of the Detroit Environmental Justice Coalition to address the cumulative impacts of pollution. Their efforts underscore the critical need for a concerted response to the intertwined issues of air and water quality, waste management, and land use that disproportionately affect the region's non-white population. For instance, the Marathon Petroleum Refinery, a significant source of sulfur dioxide emissions, has been a focal point of community advocacy for stricter pollution controls to protect the health of nearby residents (*About Us - Detroit Environmental Justice Coalition*, 2024).

Moreover, campaigns by Michigan United for clean air and water spotlight the broader social inequities faced by communities in Southeastern Michigan (*Environmental Justice - Michigan United*, 2024). Their work sheds light on the systemic nature of environmental injustice, where economically and socially disadvantaged groups bear the brunt of industrial pollution and its associated health risks. These disparities are indicative of a broader pattern of environmental racism, where minority communities experience higher incidences of sickness and disease linked to their living conditions.

At the same time, the Justice40 Initiative also calls on people to pay attention to the vulnerable groups. To meet the goal of the Justice40 Initiative, the Administration is transforming hundreds of Federal programs across the government to ensure that disadvantaged communities receive the benefits of new and existing Federal investments in these categories (*The White House*, 2023). Thus, it is extremely important to focus on minorities or disadvantaged communities in Southeastern Michigan.

Chapter 3. Research Methodologies

This chapter describes the methodologies the team used for quantitative and qualitative data collection and analysis. The quantitative portion of this study comes from the geospatial analysis and some parts of the Social Life Cycle Assessment (S-LCA) and the qualitative part consists of stakeholder engagement.

3.1 Geospatial Analysis

3.1.1 Goal overview

Geospatial analysis is often used for identifying and understanding spatial patterns in data and to explore relationships between different geographical features or between attributes of geographical features. In this case, geospatial analysis is used to identify the spatial pattern of social impact in CCS projects with a focus on Justice 40 guidelines. We collected the data of disadvantaged communities (DAC) from the Climate and Economic Justice Screening Tool (CEJST). In terms of GHG point sources, we obtained it from the Facility Level Information on GreenHouse Gasses Tool (FLIGHT). Here are goals:

1. Understanding the spatial distribution of burdens and GHG emissions in Southeastern Michigan.
2. Classify the area based on its characteristic (burden and GHG)
3. Figuring out how DAC is impacted by GHG emissions.
4. Understanding yearly GHG change and main usage of GHG.

3.1.2 Study area

Our study area is Southeastern Michigan, which includes 9 counties. We used the data from all counties of cumulative burden mapping. For the purpose of detailed analysis, we have used 7 counties with sufficient sample size for calculating interpolation of GHG emission. These counties are Livingston, Washtenaw, Monroe, Wayne, Oakland, Macomb, and St.Clair. The other counties Lenawee and Lapeer in our study area only have one GHG emission facility in the FLIGHT dataset so they were not included as the result of interpolation will be rough. An important point in the use of interpolation is the continuity of point source data and sufficient sample size. When the sample size is small, the results of interpolation will not be referential, which is why we did not choose these two counties.

After determining the research scope, we chose Census Tract as our research unit. Finally, all the results are presented with Census Tract as the minimum mapping unit.

3.1.3 Data and overall workflow

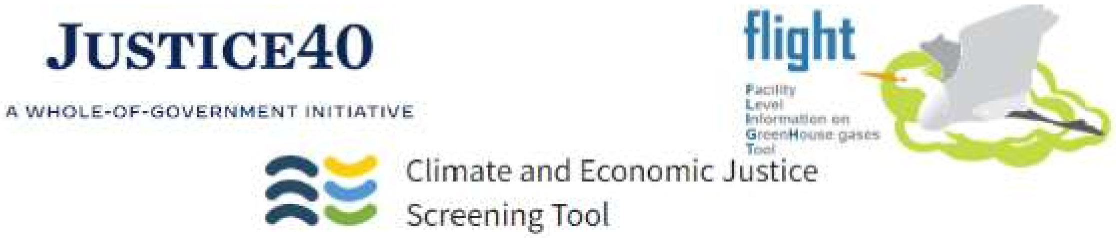


Figure 5. Geospatial data analysis guidelines and data

Climate and Economic Justice Screening Tool, CEJST: In January 2021, an executive mandate from President Biden, under Executive Order 14008, instructed the Council on Environmental Quality (CEQ) to craft a novel instrument, known as the Climate and Economic Justice Screening Tool (CEJST). This sophisticated tool incorporates an interactive map and harnesses datasets acting as proxies for challenges across eight pivotal sectors: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. It meticulously analyzes this data to pinpoint communities burdened by these challenges, specifically those that are disproportionately impacted and underserved. Such identification is pivotal for federal agencies, enabling them to target disadvantaged communities for the benefits of programs under the Justice40 Initiative. This initiative ambitiously aims to allocate 40% of the cumulative benefits from investments in climate, clean energy, and associated fields to these marginalized communities, thereby addressing systemic inequities (CEJST, 2022).

The dataset we utilized is version 1.0, which was launched on November 22, 2022. As an open-source dataset, it undergoes frequent updates. This dataset operates on a census tract scale, assigning rankings to each tract based on specific burdens, with rankings ranging from 0% to 100%. A higher ranking indicates a greater burden within the census tract. Beyond merely displaying burdens, the dataset also provides a definition for Disadvantaged Communities

(DAC). Typically, a census tract is designated as DAC if it meets two key criteria: firstly, it exhibits one or more burdens surpassing the 90% threshold; secondly, it exceeds the socioeconomic threshold, defined as 65% of the low-income population. The CEJST originally had 32 burdens with 8 categories in total. However, 4 burdens are binary data, so we decided to exclude these burdens because we need to calculate averages. A table of definitions of burdens is in Appendix 1.

Facility Level Information on GreenHouse Gasses Tool (FLIGHT) constitutes a facility-level point data source, serving as an interactive explorer that grants access to the EPA's comprehensive annual inventory of U.S. Greenhouse Gas Emissions and Sinks, alongside its state-specific counterpart. This tool sheds light on the greenhouse gas (GHG) emissions originating from significant facilities within the United States Additionally, FLIGHT enables the visualization of data across various formats, such as maps, tables, charts, and graphs, applicable to both individual facilities and collective groups. Users have the capability to peruse the dataset for specific facilities by employing criteria like name or location, or to refine the dataset through filters for state or county, fuel type, industry sectors and sub-sectors, annual facility emission thresholds, and types of greenhouse gasses. Furthermore, it facilitates the comparison of emission trends over time and the downloading of data generated through analytical processes. For this study, adhering to the principle of maximizing observational data, we selected all emissions data from all types of plants across Southeastern Michigan in 2022.

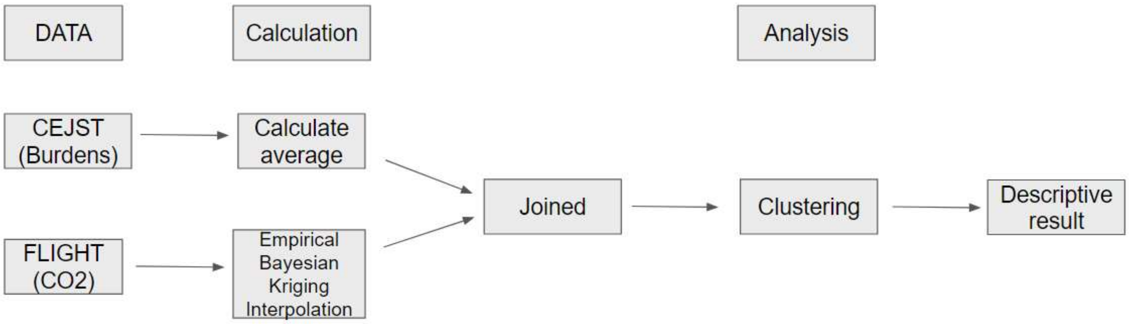


Figure 6. Overarching Workflow for Geospatial Analysis

3.1.4 Burdens cumulative status

Before conducting cluster analysis, we calculated the burden cumulative map first. According to the CEJST definition, any burden category in a region that exceeds the threshold defines the region as a DAC. However, the number of burden categories that exceed the threshold is different in each region, for example, we have eight categories, so there will be one to eight cumulative states. Using only the DAC may overlook this bias, so our first step is to calculate the number of burden categories that exceed the threshold in each census tract, and then make a burden cumulative map.

3.1.5 Cluster analysis

Our initial step involved computing the mean values for various burdens. This process entailed calculating two distinct averages for subsequent analysis: one for each category of burden to facilitate clustering analysis, and another for all burdens to aid in the creation of a bivariate choropleth map.

Given that GHG data is derived from point sources, while burden data pertain to census tracts, it was imperative to align these datasets at a uniform data level. To achieve this, we employed interpolation techniques, which are instrumental in predicting the geographical distribution of phenomena at unsampled locations based on existing data points. Researchers need to consider its accuracy since it is a technology of prediction. Besides, the selection of interpolation methods is subjective, no interpolation methods are applicable to all situations (Uddin & Czajkowski, 2022). Therefore, comparing different interpolation methods is what researchers usually do before further analysis. When interpolating the CO2, we need to create a gradual and smooth surface to satisfy its physical properties (Uddin & Czajkowski, 2022). For this purpose, we explored two interpolation methods commonly utilized in carbon-related studies: Inverse Distance Weighting (IDW) and Kriging, both known for their ability to produce gradual and smooth surfaces.

Inverse Distance Weighting (IDW) is a sample and widely used interpolation method. The value of each prediction point is predicted based on the average of its adjacent data points and inverse distance criteria (Kane et al., 1982). On the other hand, Kriging is a more sophisticated geostatistical approach that takes into account not only the spatial distance between sample points but also the variance among them. It involves calculating the distances and orientations among all pairs of data points to assess the spatial autocorrelation across a specified surface (ArcGIS Help). Kriging is differentiated into four primary variants: Simple Kriging, Universal Kriging, Ordinary Kriging, and Empirical Bayesian Kriging. This study encompasses an examination of all four Kriging methodologies.

In assessing the efficacy of interpolation methods, cross-validation is indispensable, also referred to as the leave-one-out resampling technique (ArcGIS Help). This approach entails initially running the interpolation model, subsequently removing a single data point, predicting its value with the remaining dataset, and iterating this process for each point once (Davis, 1987). During these iterations, the residuals between the estimated and actual values of the omitted point are calculated to gauge the precision of the interpolation (Bezyk et al., 2021). The accuracy of each interpolation method within the cross-validation framework is quantitatively assessed using statistical metrics, such as the root mean square error (RMSE), a common measure of prediction error (Peckham & Jordán, 2007). Prior to executing each model, data normalization is performed to ensure a consistent basis for comparing the RMSE values across different interpolation methods. Table 1 lists the RMSE results (from the lowest to the highest) of IDW and the above four Kriging methodologies.

Table 1. RMSE of Interpolation Method

Interpolation Method	**RMSE**
Empirical Bayesian Kriging	0.138
Ordinary Kriging	0.147
Inverse Distance Weighted	0.177
Universal Kriging	0.181
Simple Kriging	0.192

Typically, a lower RMSE signifies a superior model performance. Furthermore, given That GHG data are not uniformly distributed, the Kriging method is posited to yield more precise and reliable outcomes compared to IDW, which is based on the Kriging method's consideration of the spatial relationships among sampling points, rather than merely their proximities to the points of interpolation (Falivene et al., 2010). Consequently, Empirical Bayesian Kriging emerges as our selected approach, underpinned by its demonstrated effectiveness in our analysis.

Upon aggregating the interpolated raster data, we computed the average GHG data for each census tract and integrated them into the burden dataset. To explore the spatial patterns of GHG and burden data across regions, we employed clustering analysis. Many researchers compare k means to k medoids when using clustering algorithms, as these are the two most widely used clustering methods (Ushakov & Vasilyev, 2021). These techniques categorize data based on their mutual proximity, striving to minimize intra-group variances while amplifying inter-group disparities (Farber & Xiao, 2013). Nonetheless, k-medoids demonstrates a lower sensitivity to outliers compared to k-means (Arora & Varshney, 2016). Given the significant presence of outliers and the non-normal distribution of our GHG data, alongside the importance of incorporating outliers' effects into our analysis, the k-means algorithm aligns more closely with the requirements of our study.

In unsupervised classification, determining the requisite number of clusters prior to executing the algorithm is pivotal. Common methodologies for ascertaining the optimal number of clusters include the Silhouette Index, the Elbow Method, and the Pseudo F-statistic, which are widely acknowledged for their efficacy (Liu et al., 2018; Kumar et al., 2024). The above method applies when the number of clusters is unknown. If the number of clusters is predetermined, we can run the cluster directly (Liu et al., 2018). Given our focus on two primary variables, GHG levels and burden data across eight categories, we categorized them into four distinct classes as follows:

Table 2. Characteristics of four classes

High CO_2, High Burdens	High CO_2, Low Burdens
Low CO_2, High Burdens	Low CO_2, Low Burdens

3.2 Social Life Cycle Assessment (S-LCA)

When considering the sustainability of products, services, and technologies, a life cycle perspective brings powerful insights into the impacts from the extraction of raw materials to the end of life. Social life cycle assessment (S-LCA) is one of the methodologies that have been developed to assess the sustainability of the three Pillars (People, Planet, and Prosperity), focusing on the People Pillar. Originating from the discussion on how to deal with social and socio-economic criteria in E-LCA, S-LCA emerged as a study dedicated to assessing the impacts on social welfare. It offers a systematic approach framework that combines quantitative and qualitative data. This assessment aims to inform better and improve an organization's social performance and, ultimately, the well-being of stakeholders.

S-LCA is based on the ISO 14040 framework for E-LCA. It includes four phases: goal and scope, inventory analysis, impact assessment, and interpretation as demonstrated in Figure 7. The entire process will be iterative, which means that we can improve the assessment over time, going through several assessment loops and moving from generic results to more site- and case-specific ones (UNEP, 2020).

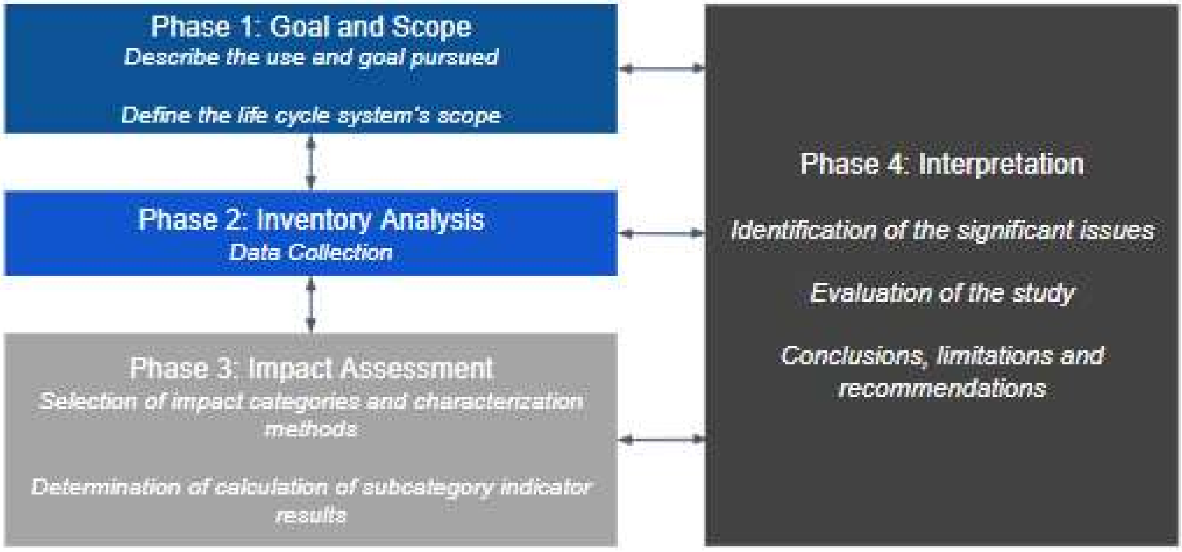


Figure 7. Four Phases of Life Cycle Assessment

3.2.1 Goal and Scope

The goal is the first step of S-LCA, which defines the study. In this stage, the team needs to define the intended use of the study, audience target, study subject, and affected stakeholders. The goal(s) should be clearly defined to ensure successful outcomes. Ideally, the goal should align with the subsequent phases' impact pathway assessment.

The scope specifies the study object and determines the methodological framework. The system is defined to a certain extent when setting the scope, and the scope itself might be based on the availability of data, study limitations, or other influencing factors. This scope should be clearly defined before proceeding to the subsequent phase. Below are several aspects that need to be considered in the scoping phase:

1. System Function
2. Functional Unit
3. Product System
4. System Boundaries

3.2.2 Inventory Analysis

Life cycle inventory consists of the inventory of all flows of the studied system normalized per functional unit (if a quantitative approach is implemented). To obtain this inventory, the following steps are taken:

A. The studied system is subdivided into interlinked processes that provide products or services to each other
B. Flow amounts are obtained for each process, commonly normalized to a process output
C. The total amounts of the processes and their flows are quantified for the reference flow, which is commonly done based on a linear relationship
D. Data on the social inventory data related to the main stakeholders defined in the G&S must be collected for all processes and flows before defined

Only step A needs to be applied if collecting solely qualitative or semi-quantitative data. In this study, we only collected semi-quantitative data using Social Hotspot Database (SHDB).

3.2.2.1 Social Hotspot Database (SHDB)

In performing the life cycle assessment, we utilized Social Hotspot Database (SHDB) v5 as the main database. This database was accessed through openLCA, an open-source tool that allows us to use any type of database for environmental and social impact modeling. SHDB uses the Global Trade Analysis Project (GTAP) global economic equilibrium model version 9, using 2011 as the primary reference year. This version of the GTAP model contains trade data for 57 economic sectors for each 140 countries and regions. Wage payment provided by the GTAP model (Input/Output model) combined with estimates of sector and country-specific wage rates ($/hr) allows an estimate of labor intensity represented by working hours.

In addition to the above data, SHDB also includes publicly available information on over 160 social impact indicators for 244 countries and territories and 57 sectors. Data sources include intergovernmental databases, country statistics, NGO reports, Trade Unions, and academic papers. Quantitative statistics and qualitative information by country and sector are used to develop characterization models (Norris et al., 2015). These models assign a risk or opportunity level to the data to help identify target areas in the value chain to verify or improve social conditions.

The SHDB provides contextual information that represents the typical situation in a country and sector/industry. In this study, we use SHDB as the primary inventory data to assess the impacts of a carbon capture sequestration. There are several reasons in choosing SHDB as the primary data source. First, the CCS project is still in the feasibility phase, which there is no dedicated companies across the value chain that can provide primary data or assess the actual performance of the project. Second is the limited resources and time in performing comprehensive data collection from multiple sources. According to the mentioned reasons, the team decided to use SHDB to make an initial impact assessment. Then, the future projects might leverage the result of this study to perform more in-depth and targeted studies. We acknowledge the actual performance of the supply chain can vary from the average, so it is possible that this generic data needs to be replaced by specific primary data.

3.2.2.2 Activity Variable and Hotspot Assessment

Activity variable information and social hotspot assessment provide information that can guide the decision process concerning if and where to conduct case-specific assessments. The use of the activity variable provides a first set of information on the relative importance of the unit process. A hotspot assessment provides additional information on where the issues of concern may be the most significant in the product's life cycle. This step is essential for prioritization in conducting an S-LCA is very costly, time-consuming, and often not relevant to collect data on-site at every organization involved in the entire value chain.

3.2.2.3 Stakeholder Categories, Impact Categories, and Impact Subcategories

UNEP-SETAC (UN Environment Programme - Society of Environmental Toxicology and Chemistry) guideline is the main framework to perform social life cycle assessment. Many social impact assessment tools refer to this guideline to build their platform, including SHDB. According to the UNEP-SETAC guidelines, there are five main stakeholder categories: workers, local communities, value chain actors, consumers, and society. However, SHDB v5 merges value chain actors and consumers into the same category, leaving four stakeholder categories. Stakeholder categories are the basis of an S-LCA because they are the items on which the justification of inclusion or exclusion in the study scope needs to be provided. Figure 8 shows the classification of impact categories and subcategories. These impact subcategories will be linked to the impact indicators, which are the main data collected in the inventory analysis. We also group the impact subcategories into larger impact categories besides stakeholder categories, so it will be easier and support the impact assessment and interpretation processes.

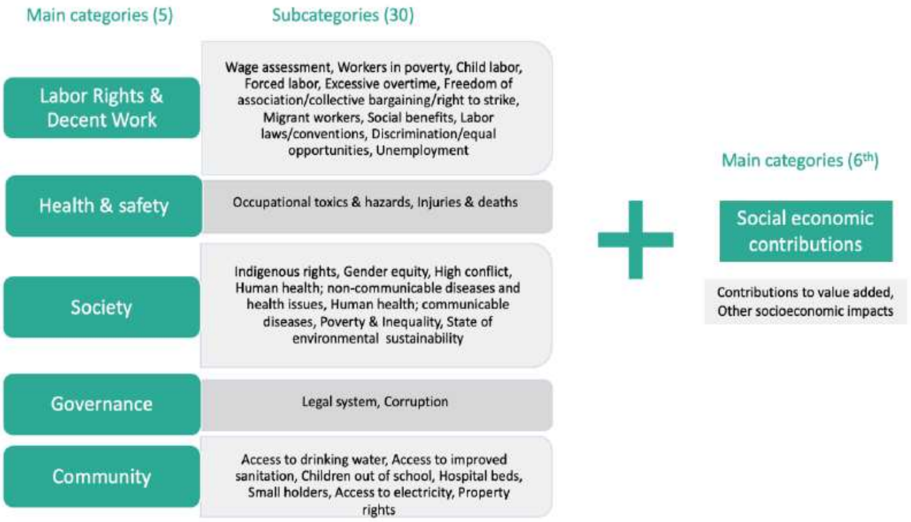


Figure 8. Categories classifications (SHDB, 2023)

Further materiality assessment of each stakeholder category and impact subcategory will be performed in the following chapter to determine whether the category is relevant to this specific study. It also ensures that all stakeholders and impact subcategories are within the scope of the study and efficiently allocates resources to perform the study.

3.2.2.4 Data Quality

It is important to address data quality and integrity, as this is fundamental to ensure the findings' reliability and validity and reach useful conclusions. Depending on the type of indicator and data needed (quantitative or qualitative, generic or specific), appropriate measurement methods, sources and instruments must be defined. Both the measuring methods and instruments, but also the indicators themselves, should be measured on the following minimum criteria:

- Reliability: The extent to which an instrument produces reliable and consistent results;
- Validity: The extent to which an indicator and instrument are measuring an intended concept (e.g. a social issue or sub-category), based on soundness and empirical analysis (if possible)
- Objectivity: The extent to which an investigator/data source is separated from the object of investigation and without bias.

3.2.3 Impact Assessment

The purpose of impact assessment is to assess a product system’s life cycle inventory results to better understand their significance. In other words, impact assessment translates what we measure (cost, working hours) into what we care about (fair wage, gender equality). Prior to performing the S-LCA, the team must decide if the assessment will focus on the product or organization. This decision leads to the type of assessment method to be used for the impact assessment. According to the UNEP/SETAC S-LCA Guideline, there are two main approaches in S-LCA. Type 1 is the reference scale, which aims to describe a system with a focus on its social performance or social risk. On the other hand, Type 2 predicts the product system's consequences, emphasizing characterizing potential social impacts (Osorio-Tejada et al., 2020). This method is called the Impact Pathway Approach.

Reference Scale Approach (Type 1) specifically assesses the social performance of activities of organizations in the product system based on specific reference points or standard requirements. Therefore, this assessment relies on data, information, and judgment on the activities of companies. Commonly, no further effect evaluation will be performed. In contrast, the Impact Pathway Approach (Type 2) will focus on the causal relationships between product systems and possible social impacts along the pathway (short, medium, and long-term impacts). This approach is more in line with the E-LCA, where inputs (e.g., CO2 emissions) are linked to environmental/societal problems (e.g., global warming) and with the endpoint (e.g., impacts on human health).

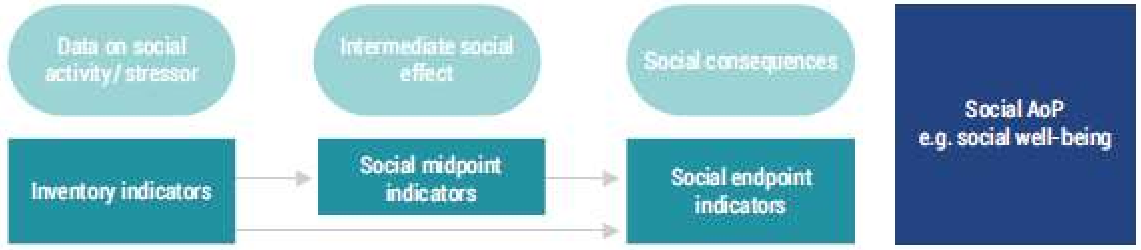


Figure 9. Illustration of the social impact pathway approach (UNEP, 2020)

In this study, we use a specific impact assessment embedded in the SHDB tool. The SHDB impact assessment method is called the Social Hotspot Index (SHI). This method is similar to the type 1 approach (reference scale). The information on the labor intensity that we collected from the inventory process is used together with the social risk level to express social risks and opportunities in terms of medium risk hours equivalent (mrheq), by sector and country for 5 social impact categories. The expression of social impact in medium risk hours equivalent (mrheq) provides the possibility to calculate a social footprint and identify target areas across CCS value chain to verify and improve social conditions. Below are the weighting factors that represent the relative probability of an adverse situation. Relative probabilities are expressed in relation to the medium risk level.

Table 3. Social Hotspot Index (SHI)

Very High Risk	10
High Risk	5
Medium Risk	1
Low Risk	0.1

The weighting of risk level will increase or lower the mrheq. For example, if fair wage in sector X and country Y has been assessed as potentially very high risk and the working hours to produce $1,000 of final product has been estimated to be 500 hours. The medium risk hours equivalent will be 500 hours x 10 = 5,000 mrheq.

3.2.4 Interpretation

Interpretation is the final phase of S-LCA, in which the results of the assessment are checked and discussed in depth. The discussion forms a basis for conclusions, recommendations, and decision-making in accordance with the Goal and Scope definition. The Interpretation phase is built upon the requirements of ISO 14044 (2006), and it consists of the following steps:

1. Identification of the significant issues
2. Evaluation of the study (which may include completeness and consistency)
3. Conclusions, limitations, and reporting

3.3 Communities and Stakeholders Engagement

The project emphasizes the critical role of diverse stakeholder engagement in addressing climate change, outlining the need for a multi-dimensional approach that involves continuous dialogue between the research community and various stakeholders. This approach is based on a robust knowledge foundation, which is essential for understanding project intricacies and ensuring stakeholder ownership. It recognizes the importance of stakeholders, including policymakers, business leaders, academics, NGOs, and community members, and prioritizes their active involvement through a careful selection process. The strategy for expanding on stakeholders engagement involves four key stages: Introduction and Awareness, In-Depth Discussions, Structured Feedback, and Continuous Reflection. This early engagement is a guiding principle, enhancing the effectiveness and impact of collaborative efforts, ensuring a comprehensive and inclusive approach to stakeholder engagement, vital for the project's success in fostering sustainable and impactful change in climate action.

Building upon these principles, we aim to analyze the challenges and strategies for engaging stakeholders in the development of decarbonization pathways. This approach underscores the importance of collaborative dialogue between researchers and stakeholders from various sectors, including governments, NGOs, industry, and financial institutions, to address the complexities of climate change. Based on the above public engagement guidelines, the team plans to have a stakeholder interview with a particular focus on CCS in the Southeastern Michigan region. The aim is to gather the perspectives of various stakeholders to provide insights into the challenges, barriers, and considerations affecting the fairness and unfairness of CO_2 technology removal. This data will validate preceding studies, such as Geospatial Analysis and S-LCA.

To accommodate the preferences of our stakeholders, we conducted semi-structured interviews via a virtual meeting platform. The estimated time for each interview is 30 minutes. We recorded these interviews with the consent of the interviewee to ensure accurate transcription for analysis. Our interview guide is pre-tested and validated by program consultants and contains a combination of open ended questions. Each of us took Human Subject Research training and secured permission from the Institutional Review Board at the University of Michigan before beginning interviews with our respondents.

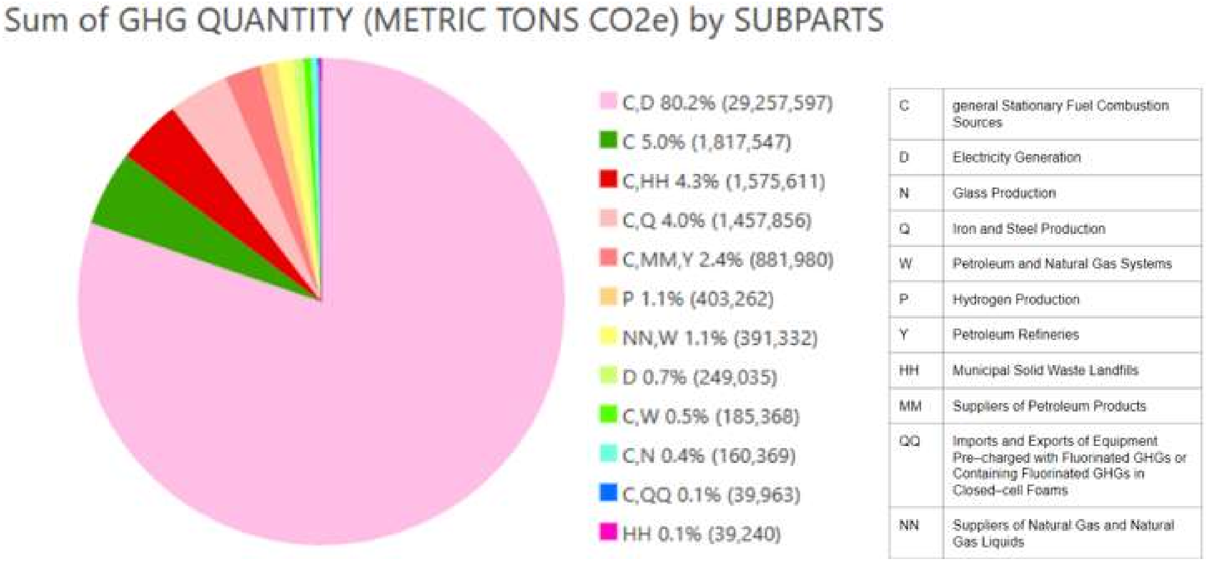
To understand decision-making at the government level, we conducted interviews with state, federal, and local agencies, including the Michigan Department of Environment, Great Lakes, and Energy (EGLE) and the U.S. Department of Energy. We also sought insights from the private sector and industrial emitters by arranging discussions with representatives from the Michigan Chambers of Commerce and the University of Michigan Central Campus Power Plant. Additionally, we engaged with academic experts from institutions like the Global CO2 Initiative, the Kleinman Center for Energy Policy at the University of Pennsylvania, and the Center for Sustainable Systems at the University of Michigan. This comprehensive approach not only broadens our understanding across multiple sectors but also reinforces our analysis, ensuring our solutions to climate change are grounded in a diverse array of perspectives and are both effective and sustainable.

The stakeholders' engagement also includes our participation in regional, national and international conferences and workshops. In order to present the preliminary results, we participated in the 4S (Society of Social Studies of Science) Conference in Honolulu, Hawaii, from Nov 8-11, 2023. The experience of interacting with other participants provided valuable insights into conducting social studies and establishing connections with fellow scholars. To understand the local context and the role of carbon capture on climate action, we participated in Midwest Climate Summit Apr 3-5, Indianapolis, Indiana. Following that we presented our poster and interacted with stakeholders at the Innovations in Climate Resilience Conference from April 22-24 in Washington DC organized by Battelle Memorial Institute. The conference focuses on adaptation, mitigation and sustainability and has a theme on “Carbon Capture & Storage: From Concept to Implementation”.

Following interviews, we proceeded to anonymize the collected data to ensure confidentiality before undertaking a thematic analysis of the interview transcripts. Thematic analysis, a widely used qualitative data analysis method, was employed to extract key themes and patterns from the interview data. (Braun & Clarke, 2012) Thematic analysis involves systematically organizing and interpreting qualitative data to identify recurring patterns of meaning, which can provide valuable insights into stakeholders' perspectives, experiences, and attitudes regarding CCS technology and its implications for climate action.

Chapter 4. Geospatial Analysis

4.1 Annual Variations in Greenhouse Gas Emissions (GHG) by Usage Type



C	general Stationary Fuel Combustion Sources
D	Electricity Generation
N	Glass Production
Q	Iron and Steel Production
W	Petroleum and Natural Gas Systems
P	Hydrogen Production
Y	Petroleum Refineries
HH	Municipal Solid Waste Landfills
MM	Suppliers of Petroleum Products
QQ	Imports and Exports of Equipment Pre–charged with Fluorinated GHGs or Containing Fluorinated GHGs in Closed–cell Foams
NN	Suppliers of Natural Gas and Natural Gas Liquids

Figure 10. Pie chart of emission amount by subparts [The Pink is dominant by electricity generation]

Most factories in Southeastern Michigan were hybrid plants. They had a combination of different sources. GHG emissions from electricity generation were the main emissions. Figure 10 showed that the largest emitter was a combination of general stationary fuel combustion sources and electricity generation, with emissions equaling about 80% of Southeastern Michigan's total GHG emission. According to the EPA 2021, Electricity generation accounted for 25% of the country's total GHG emissions. The total GHG emissions from all other industries were not as high as those from electricity production. Taking the facility (located in Monroe City), which had the largest GHG emissions in Southeastern Michigan as an example, total emissions from that facility in 2022 were 14,908,126 tons of CO_2e; electricity generation accounted for 99.9% (14,894,825 tons of CO_2e) of the total emission. The proportion of General stationary fuel combustion sources was 0.01% (13301 CO_2e).

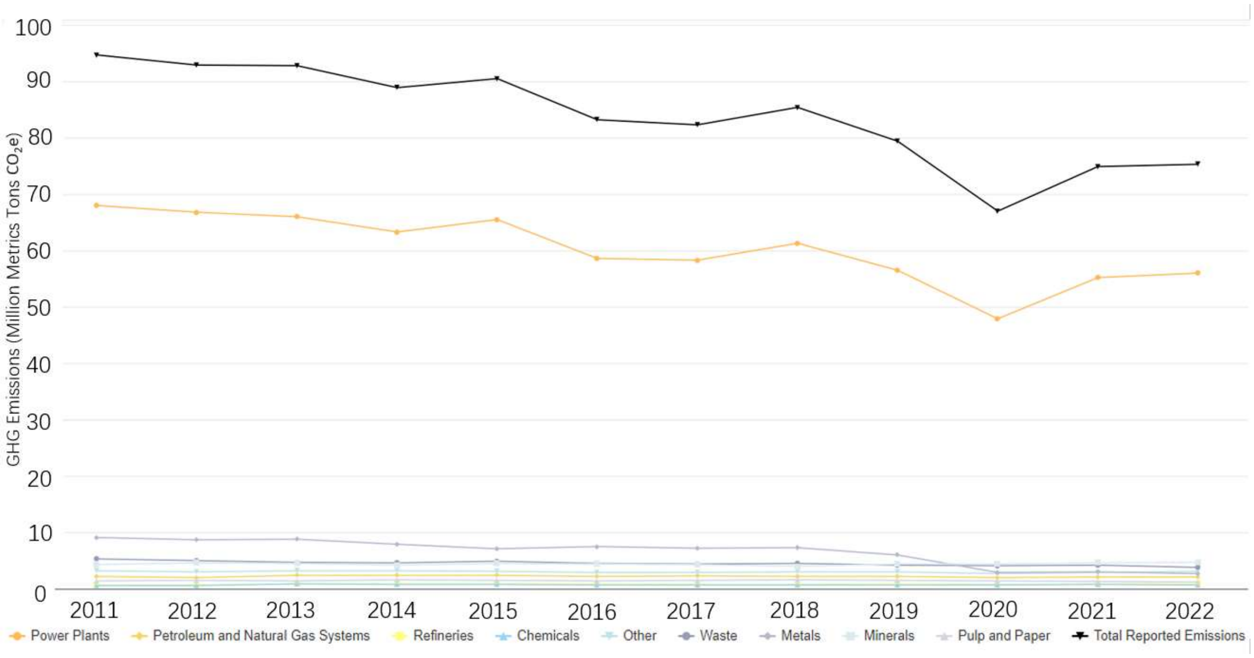


Figure 11. Line chart of emission amount by types from 2011 to 2022 (FLIGHT, 2022)

According to Figure 11, power plants account for about 60 percent of total emissions. From a historical perspective, Michigan's GHG emissions had shown a downward trend. This indicated the effective control of GHG emissions by the large facility in Southeastern Michigan. Southeastern Michigan also contributed to reducing carbon emissions after the United States rejoined the Paris Agreement in 2021.

In 2020, GHG emissions from both power plants and plants used to smelt metals saw a strong decline. There was then a rebound in 2021. The reason for this phenomenon was the Covid-19 pandemic. On a global scale, GHG emissions fell by 8.8% in the first half of 2020, which was the largest decline in any period in history (Liu et al., 2020).

The significant reduction in human activity during the pandemic reduced the demand for energy and materials such as electricity and steel, so the reduction in the capacity of large facilities led to a sharp drop in GHG emissions (Ukhurebor et al., 2022). Since this was a decline in GHG emissions due to disease disasters, we cannot attribute it to policies or people's efforts.

4.2 Cumulative Burdens and GHG in Disadvantaged Communities (DAC)

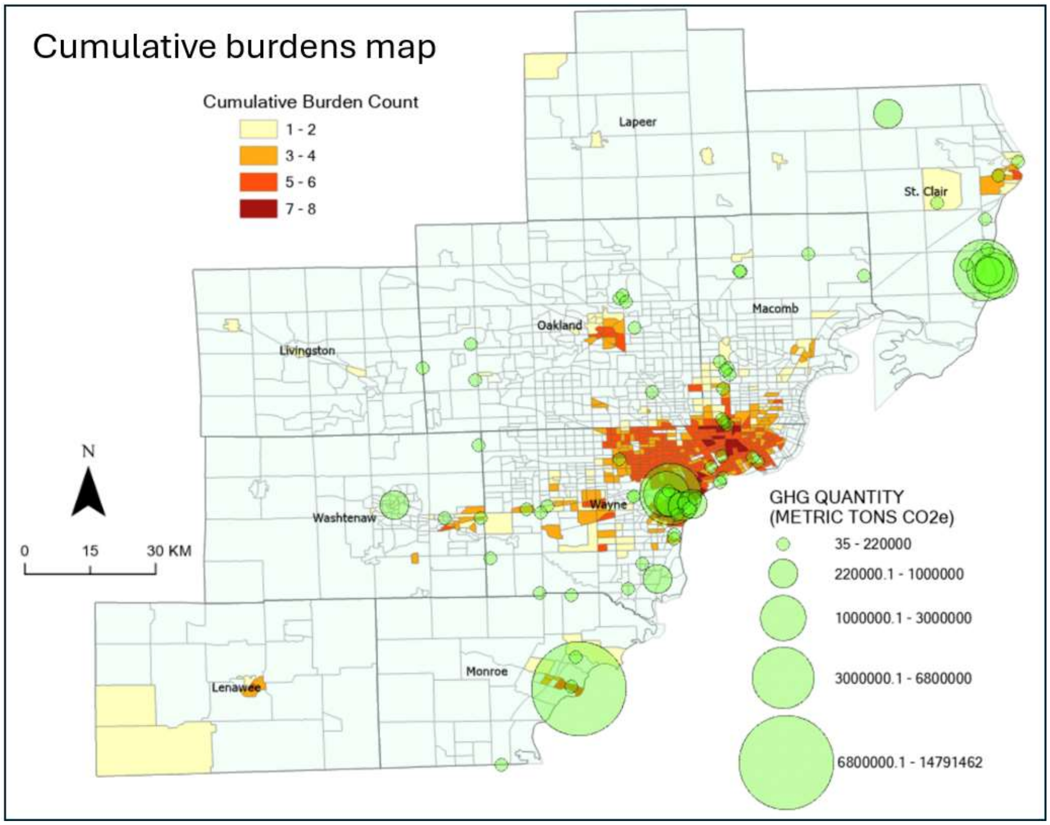


Figure 12. Cumulative burdens categories within DAC region and GHG emission

In Figure 12, Disadvantaged Communities (DACs) were predominantly clustered around Detroit, with most census tracts in Detroit and Pontiac experiencing higher cumulative burdens. Conversely, Livingston, Lapeer, and Lenawee counties exhibited the lowest concentration of DACs. This map revealed that cumulative burdens did not always align with GHG emissions. For instance, Monroe City displayed both higher cumulative burdens and emissions, while Marine City, despite not being categorized as a DAC, also recorded high GHG emissions. Additionally, the distribution of DACs did not mirror the spatial pattern of facility GHG emissions, suggesting a lack of strong spatial correlation between these factors.

4.3 Overview of GHG and Burdens in Southeastern Michigan

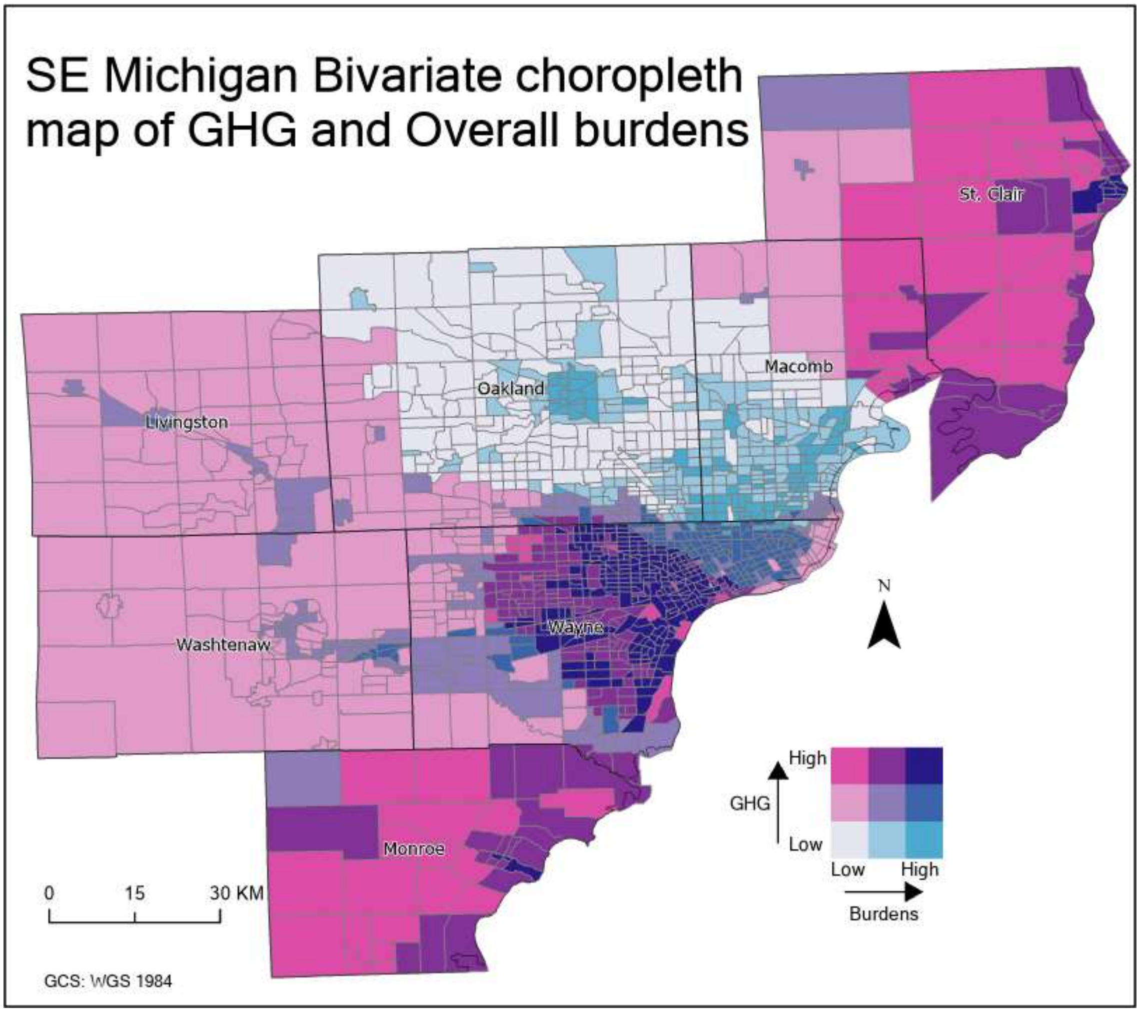


Figure 13. Bivariate choropleth map of GHG and overall Burdens

We found that the relationship between GHG and burdens in Southeastern Michigan was strongly clustered. High GHG emissions were concentrated in Monroe and St. Clair Counties. This was because the two counties had two large facilities and were major sources (80%) of GHG emissions in Southeastern Michigan. Southwest Detroit also had a high carbon emission cluster, as there were several sources of different types of emissions in that area. On the contrary, Northeast Detroit had lower GHG emissions although the burdens were still high. It was because Northeast Detroit did not have a major emission source.

Livingston and Washtenaw were two counties that had lower burdens with median GHG emissions. The area was characterized by low population density. However, due to the diffusion of large amounts of GHG emissions from Monroe's facilities, the region also experienced moderate impacts. An interesting phenomenon was emerging in these two counties. Major cities in both counties, Ann Arbor, Brighton, and Howell, had seen burdens rise compared to suburban regions, but the GHG emissions remained stable. This meant that urban residents in the region generally had more living burdens than suburban residents. According to the 2020 census, the median household income of major cities in these counties was about 70k, but the median household income of suburban residents was about 80k-90k.

The low-emission areas were mainly in Oakland and Macomb counties. Even though the two counties performed well as a whole, the details varied from place to place. For example, Troy was a city located in Southeast Oakland which showed very low level in the burdens and GHG emissions. According to the 2020 census, the median household income of Troy was 104100 US dollars per year. However, Pontiac, a city located in the center of Oakland, had a higher burden. According to the 2020 census, the median household income at this place was about 34670 US dollars per year, which was one-third of Troy. There was significant stratification in the average income of different racial/ethnic groups (Akee et al., 2019). According to the DATA USA 2020, Pontiac’s largest racial group was black, which was about 50%. However, Troy’s population was more than 70% white. Two cities, only 8 miles from each other, were completely different from each other. The Detroit metro area was notoriously segregated. Studies had also shown that suburban blacks were more segregated and isolated than urban blacks (Darden & Kamel, 2000). From a livability standpoint, parts of Oakland and Macomb, which were shown in white in Figure 13, were some of the most livable areas in Southeastern Michigan. Other regions would either be affected by GHG emissions or would have a higher burden index.

The burden index was diffused from the center to the surroundings. The central area (Detroit) had the highest-burden index, while the surrounding area showed a decreasing burden index. The specific reasons needed to be explained in the context of Detroit's history. Detroit had become a model for urban industrial decline around the world (Reese et al., 2017). The main reason for its declination could be attributed to the large-scale urban sprawl that began in the 1960s. In other words, Detroit experienced severe low-density spreading development. After World War II, the once-popular Detroit auto factories began to move to the suburbs and even further places like Canada (Burnham & Sugrue, 1998). The loss of many jobs in the urban areas also caused whites to move to the suburbs. Detroit was consistently ranked among the top 10 most segregated cities (Data Driven Detroit, 2024). According to the census, eighty percent of the residents of downtown Detroit were black. Due to policy pressure and massive loss of resources, the Detroit government could not afford its expenses and declared bankruptcy in 2013. Although Detroit had tried to revive itself since 2013, for example with grants from the state of New York and the federal government, or with foreign investment (especially from China), Detroit could hardly be called a living city (Brecher, 2014; Reese et al, 2017; Eisinger, 2014). The result of more than half a century of strict urban sprawl had become evident, and it was difficult to change in a short time period. This also explained why the burden index for residents of Southeastern Michigan showed a decreasing pattern from Detroit as the center to surrounding regions.

4.4 Cluster Analysis Results

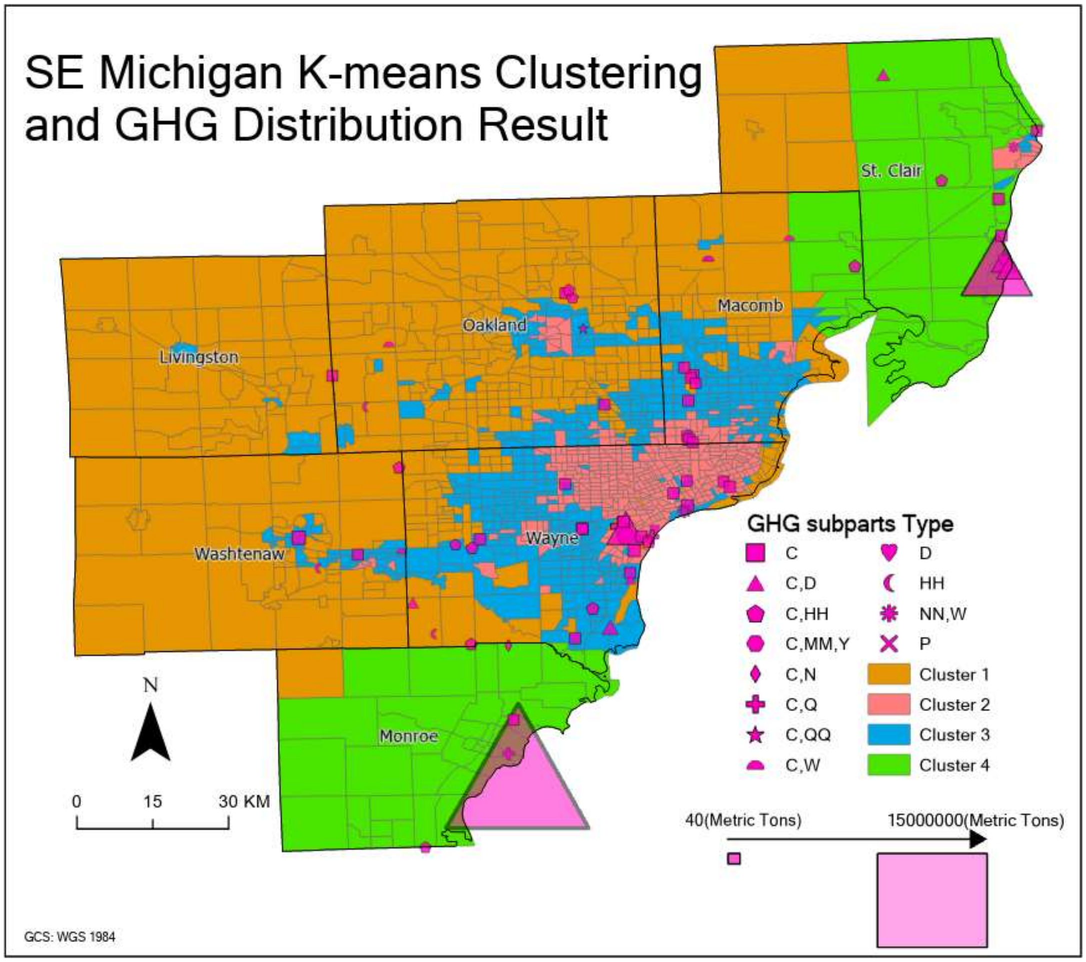


Figure 14. Clustering result with GHG subparts by type (Note: C=General Stationary Fuel Combustion Sources, D=Electricity Generation, N=Glass Production, Q=Iron and Steel Production, W=Petroleum and Natural Gas Systems, P=Hydrogen Production, Y=Petroleum Refineries, HH=Municipal Solid Waste Landfills, MM=Suppliers of Petroleum Products, QQ=Import and Exports of Equipment Pre-charged with Fluorinated GHGs or Containing Fluorinated GHGs in Closed-cell Foams, NN= Suppliers of Natural Gas and Natural Gas Liquids)

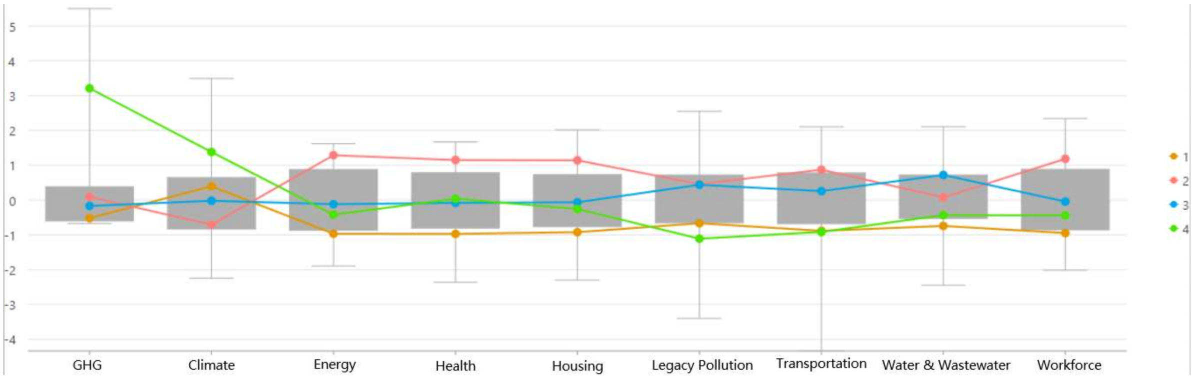


Figure 15. Boxplot of clustering result by GHG and burden categories

K means clustering showed more detail than the bivariate choropleth map. Based on Figure 15, we could not only focus on the spatial pattern of the cluster but also look at the mean of each variable in each cluster. The audience could recognize what were the similar variables that made these census tracts a cluster.

Spatially, clustering and bivariate maps had similar characteristics. For example, Cluster four (green) distribution contained Monroe county and St. Clair county. The bivariate map told us that the region had high GHG emissions. A line chart looking at clustering results confirmed this view, with GHG emissions in the region being several times higher than elsewhere. The reason was that the area had the two largest power plants in Southeastern Michigan. They were located in Monroe City and Saint Clair Haven city, and GHG was spread across the county. The climate burdens were also much higher than what clusters did. The reasons were attributed to five components of Climate: Expected agriculture loss rate, Expected building loss rate, Expected population loss rate, Projected flood risk, Projected wildfire risk. These climate burdens meant the probability of these events occurring due to climate change. In other words, the higher GHG emissions led to more frequent climate changes and resulted in a higher level of the 5 burdens above. Energy, health, and housing were moderate, while legacy pollution, transportation, water & wastewater, and workforce burdens were at a lower level. In general, cluster 4 belonged to the region with high GHG emissions and low burden.

Cluster 2 (pink) was primarily located in and around Detroit. The cluster was also notable for its characteristics, with high levels of GHG emissions (A large number of medium-sized GHG emission sources were clustered south of Detroit) and high levels of

Burden value. But climate burdens showed the lowest value of all clusters, and the reason was that Detroit was a well-urbanized place and there was no possibility of Detroit having a higher agriculture loss and wildfire cost by climate change. However, the remaining three low values of the climate burden were reasonable, which reflected Detroit's high resilience in the face of climate change-induced disasters. Energy, health, and housing showed the highest levels across clusters. This meant that Detroit was not a habitable area. This cluster was characterized by high GHG emissions accompanied by a high burden index except the Climate.

Cluster 3 (blue) geographically wrapped Cluster 2. The cluster had lower GHG emissions and fewer plants had been built on the cluster. The climate, energy, health, housing, and workforce burdens were on moderate levels across Southeastern Michigan. However, legacy pollution and water & wastewater had the highest-burden indices. In conclusion, this cluster belonged to a region with low GHG emissions and relatively high burdens.

Cluster 1 (orange) covered the suburban portion of Southeastern Michigan. Cluster 1 was the opposite of Cluster 2, with a low level of all burdens except for the climate burden. Even with low GHG emissions, the region was vulnerable to losses from climate change. This was due to the difference in urban form and infrastructure construction between cities and suburbs. Cities had better facilities and resources to cope with the effects of climate change. Another reason was that differences in Land Use and Land Cover (LULC) led to differences in climate impacts. For example, suburban areas had a larger area of farmland, so farmland was naturally more likely to be affected than urban areas. In conclusion, this cluster was characterized by low GHG emissions and a low burden index except for the Climate.

4.5 DAC Distribution Analysis Results

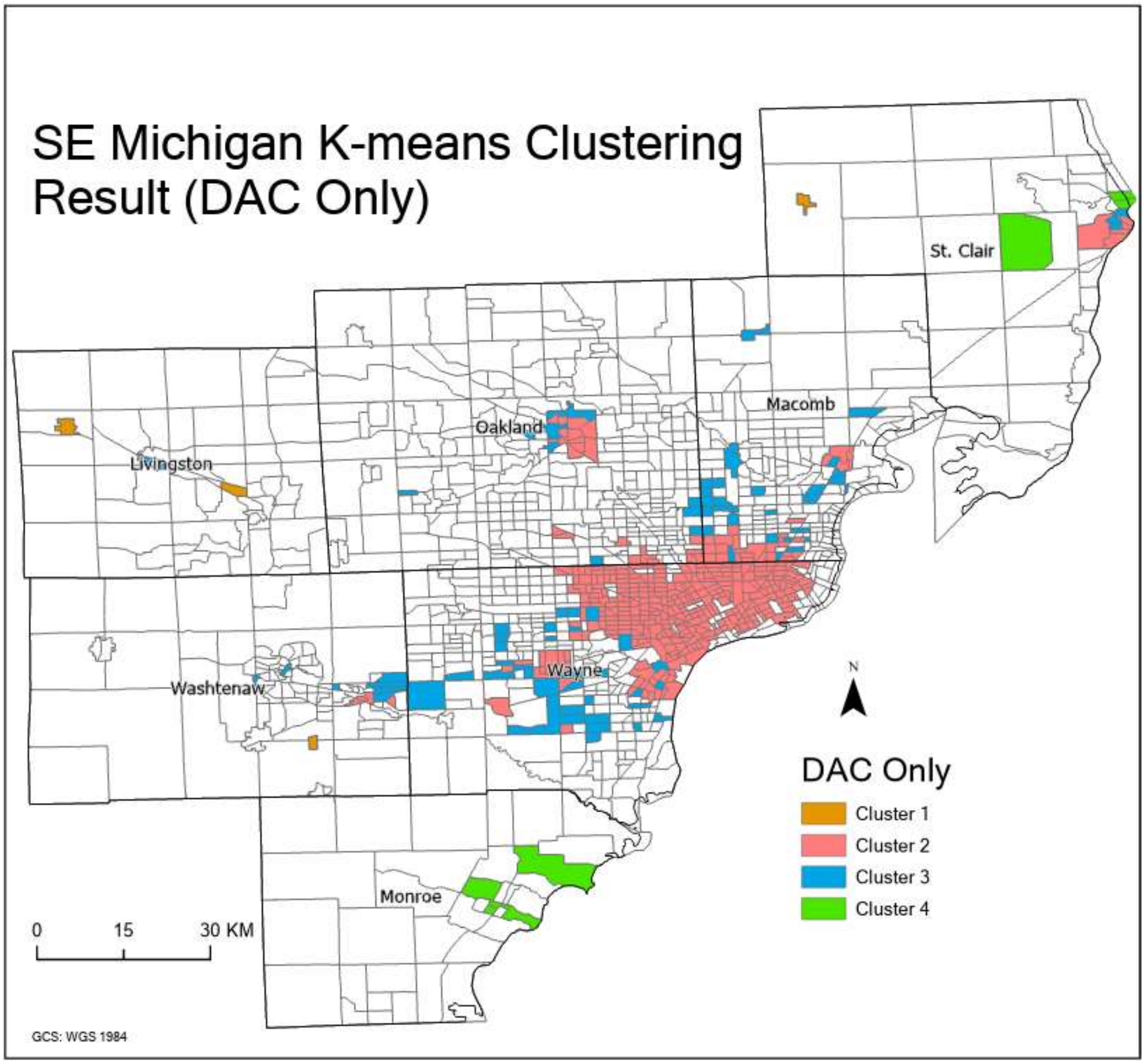


Figure 16. Clustering result (DAC Only)

In conjunction with Justice 40, it was important to focus on where the disadvantaged community (DAC) stood in terms of carbon emissions and burdens, particularly in the case of Southeastern Michigan. Based on Figure 17, we chose to continue with the result of K-means clustering, and then calculated the proportion of DAC (as defined by CEJST) in each cluster.

Table 4. The proportion of each cluster falls within the DAC

Cluster 2: 386/407=0.948	Cluster 3: 87/469=0.186
Cluster 4: 9/85=0.106	Cluster 1: 4/449=0.009

In line with Table 4, about 95% of Cluster 2 was defined as a Disadvantaged Community (DAC). Most of them were located in Detroit and Pontiac City. According to the results of the cluster analysis, Cluster 2 was a region with high GHG emissions and high burdens. It was also the most segregated area in Southeastern Michigan. Justice 40 aimed to ensure that 40% of the overall benefits of certain federal investments flowed to disadvantaged communities. For policymakers and related organizations, we advocated using Cluster 2 (pink) as the primary goal for addressing social justice issues in Southeastern Michigan.

Chapter 5. Social Life Cycle Assessment

5.1 Goal and Scope

5.1.1 Study context

This study was part of a capstone project focusing on justice principles in carbon capture sequestration in Southeastern Michigan. S-LCA is an insightful tool that systematically evaluates the social impacts of emerging climate technologies. It is imperative to incorporate social aspects in addition to technological, environmental, and financial considerations to ensure sustainable environmental and just transition.

5.1.2 Study objective

The primary objective of this study was to identify potential social issues through hotspot analysis of a carbon capture sequestration project. The focus was on the product systems, including specifically contributing sectors to each unit process.

5.1.3 System function and functional unit

The function of the system in this study was to capture, transport, and sequester (storage) the CO_2 emission from industry-scale emitters to the sequestration location. As stated in ISO 14044 (2006): “The scope shall clearly specify the functions (performance characteristics) of the system being studied.” In agreement with this ISO statement, the team believes defining system function is necessary for product system modeling. Following this definition, in the next step, determining the system boundaries, we should consider only those processes that relate to the capture, transport, and storage activities. The life cycle of carbon capture is adopted from a previous study on holistic assessment of carbon capture and utilization value chains without the utilization phase (Pieri et al., 2018).

The functional unit (FU) used for this study was 63 MT of CO2 captured over 30 years from emitters and delivered to the injection site. This number referred to the CarbonSAFE Phase II project proposal prepared by Battelle Memorial Institute. Despite having a dedicated functional unit, some social impact indicators and reference flows might not be explicitly tied to the FU

(Housseinijou et al., 2014). This is one major difference between environmental and social LCA.

5.1.4 Scope of the Study

Since the overarching objective of this project is upholding social justice principles of carbon capture sequestration in Southeastern Michigan, we limited the geographical scope to US-based production activities. However, due to globalization and the interconnectedness of multiple sectors, some inputs might come from different countries and regions. In this case, the GTAP model uses average values for each sector and provides a homogenous framework. The homogeneity safeguards the comparability of the results and provides a consistent view of the supply chain (SHDB v5 documentation, 2023).

5.1.5 Product system

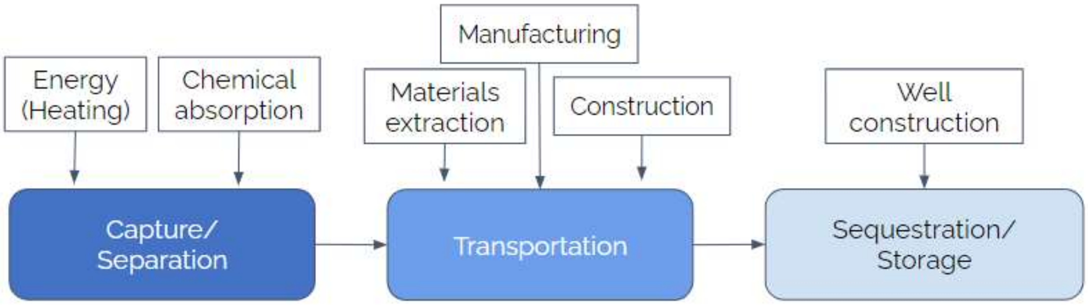


Figure 17. Carbon Capture Sequestration Product System (adopted from Piere et al., 2018)

1. Carbon Capture

   Carbon capture is the most extensively studied component of any carbon removal value chain, particularly in the application of CCS (Piere et al., 2018). As previously mentioned in the literature review section, there are three main carbon capture categories: post-combustion carbon capture, pre-combustion carbon capture, and oxyfuel combustion carbon capture. This study focused on post-combustion carbon capture mainly because of the initial plan to integrate a carbon capture technology into the existing Natural Gas Combined Cycle (NGCC) plant. In the post-combustion process, CO_2 is separated from the flue gas stream, which is composed mainly of N_2, CO_2, and

H2O (Koytsoumpa et al., 2018). The typical amine process is widely applied in the post-combustion process based on chemical absorption with a monoethanolamine (MEA) solvent (Herzog & MIT Energy Laboratory, 1999). The process allows flue gas to contact an MEA solution in the absorber. The MEA selectively absorbs the CO_2 and is then sent to a stripper. In the stripper, the CO_2-rich MEA solution is heated using the recycled heat from the gas combustion process to release almost pure CO_2 (Olabi et al., 2022,). The lean MEA solution is then recycled to the absorber. After evaluating the above processes, two GTAP sectors are determined to be the major contributors to this process: Electricity as the energy source for the heating process and Chemicals, Rubber, Plastic products for the chemical adsorption process.

Some techno-economic analyses had been conducted to evaluate the total cost of carbon capture from natural gas processing. Two studies from the National Energy Technology Laboratory (NETL) and Adikhari et al., 2023 showed that the capture cost was \$16.2/ton of CO_2. With a total of 63 MT CO_2 captured over 30 years, the estimated total capture cost is \$1.02 billion in 2022 USD since this cost estimate was performed in 2022. The SHDB v5 uses 2011 USD as its input model, thus, the dollar amount input needs to be converted to 2011 USD, which results in \$791 million. The contribution from the electricity sector is 44%, and 56% from the chemical, rubber, plastic sector. We use an environmental impact assessment of post-combustion CO_2 capture technologies from Galusnyak et al., 2022 as the contribution proxy for each sector.

2. Carbon Transportation

Transportation of captured CO_2 can be achieved using pipelines, truck tankers, railroad tankers, or ships. For this study, we focused on in-land pipeline applications. Three major activities were involved in this process: materials extraction, pipeline manufacturing, and pipeline construction.

Because of the corrosive properties of CO_2 when in contact with water, materials with high corrosion resistance, such as stainless steel or reinforced carbon, should be used for CO_2 transport purposes (Jatmoko & Kusrini, 2018). Stainless steel is commonly used for the transport of corrosive fluids due to its high strength at high pressure. Since the capturing site and injection site might be located several hundred miles apart, high pressure will be required to transport the CO2 from point A to point B. Therefore, in this study, we assumed the utilization of stainless steel pipe grade to accommodate this technical consideration. As a sector proxy, we used the GTAP minerals sector to represent the materials extraction process

There are two most common pipe manufacturing types: seamless and welded. For the purpose of simplicity, we assumed the seamless pipe manufacturing process. This process involves the creation of stainless steel pipes without any welding or seams. A solid cylindrical billet is pierced to form a hollow tube, which is then elongated and shaped using a series of hot and cold working processes. We represented this activity by using the GTAP ferrous metals as the sector proxy.

According to the U.S. Department of Transportation, pipeline construction activities start with determining possible routes and acquiring the right-of-way (ROW) to build, operate, and maintain the pipelines. Then, the selected route of the pipeline must be cleared. Construction work and equipment passage may require temporary workspace outside the right-of-way. The temporary use of additional space is negotiated with the landowner. The site preparation crew installs silt fences along the edges of streams and wetlands to prevent erosion of disturbed soil. Trees inside the right-of-way are cut down, and the timber is removed or stacked alongside the right-of-way. The brush is commonly shredded or burned. Once the route has been cleared, the process continues with pipe stringing, trenching, bending, and welding. Lastly, all newly constructed hazardous liquid and natural gas transmission pipelines must be pressure tested before they can be placed into service. The GTAP construction and gas distribution sectors were chosen as proxies in the pipeline construction model.

According to the CarbonSAFE Phase II project proposal, the total CAPEX is $47.5 million, and the OPEX is $0.884 million/year. The total cost of carbon transportation for 30 years was $74.02 million. This dollar value needs to be converted to 2011 USD, which results in $57.39 million. The contribution from minerals, ferrous metals, construction, and gas distribution sectors was 44%, and 56% from the chemical, rubber, plastic sector. We use a carbon footprint assessment of pipeline transportation performed by Huang et al., 2021 as the contribution proxy for each sector.

3. Carbon Sequestration

This activity starts with the injection site identification based on the geological and geophysical information to confirm storage capacity and stratigraphic barrier to ensure safe, permanent storage. Once the site is identified, the contractor must obtain a drilling permit from the local government and land owner. Then, the process proceeds with the drilling operations to drill the well to a pre-determined safe depth. Finally, CO_2 that has been separated and transported from the location of the emitters will flow into the well to be safely stored in the formation. The workflow of this process predominantly follows the general construction process. Therefore, we chose the GTAP construction sector as the proxy in the model.

For this process, we referred to the estimated carbon sequestration project cost from CarbonSAFE phase II documentation. The total carbon sequestration, including CAPEX and OPEX, cost is $418 million, which is equal to $324 million in 2011 USD value. Since only one sector contributes to this process, we don’t assign a contribution factor for this sector.

5.1.6 System Boundaries

The system boundary was considered from cradle-to-gate LCA. Given that the objective of the analysis is to identify the social impacts of the CCS project, we only looked at the impacts of carbon capture, transport, and sequestration processes. At this stage, we were a CO_2 agnostic source, so we decided to exclude the evaluation of the emitters’ system processes. These emitters might come from various types of industries, which have unique processes. That being said, including all kinds of activities will be difficult. We also excluded the end-of-life phase, such as material recycling and site restoration, as we expect that this project will last at least 30 years. So, with the long project lifetime, the assessment beyond 30 years produced a lot of uncertainties. The detailed sectory and country proxies for each process system can be found in Table 5.

Table 5. CCS Process System Summary

Process System	CO_2 Capture, Transport, Sequestration

Reference sector and country	Minerals: USA Construction: USA Gas Manufacturer and Distribution: USA Chemical, rubber, plastic products: USA Ferrous metals: USA Electricity: USA
System Boundary	Cradle-to-gate: (i) carbon capture, (ii) carbon transportation, (iii) carbon sequestration

5.2 Inventory Analysis

5.2.1 Activity Variable

Activity variable data is used as a vector to the magnitude of the supply chain where an issue or opportunity is found (in $ and labor intensity). In other words, data on worker hours helps identify where human activity is occurring in supply chains. As a result, worker hours intensity is one of the criteria proposed to prioritize decisions and actions. Moreover, if work intensity is essential in a specific country and sector, not only the impacts affect all other categories of relevant stakeholders (local community, society) (SHDB v5 Documentation, 2023). Thus, despite worker hours might not be directly linked to local communities and society, they remain the most meaningful activity variable to use to assess the magnitude of an issue within the context of the product system as a whole. As a reference flow target for the product system, we refer to the average worked hours per year in the US based upon analog industry experience (Jordan & Benson, 2013). The total average annual worked hours is 1,102 million hours following a typical oil and gas operation. Table 6 provides detailed breakdown of each process system reference flow.

Table 6. Functional Unit and Reference Flow

Process	**Analog Process**	**Functional Unit**	**Reference Flow (worker hours)**
Capture	Equipment and capture fluid		547 million

	manufacturing	63 MT of CO2 captured over 30 years	
Transportation	O&G pipeline-related construction		375 million
	Pipeline transportation		
Sequestration	Drilling wells		795 million
	Support activities (monitoring)		
		Total	**1,719 million**

PwC and American Petroleum Institute (2023) performed a study that showed the share of employment directly and indirectly supported by oil and gas industry, in this study Michigan contributed 5.2% of the state's total. Based on this contribution percentage, we allocate the total worker hours for Michigan, which is estimated at around 1.72 billion worker hours for 30 years.

5.2.2 Hotspot Assessment

As part of the life cycle inventory, we performed a hotspot assessment of the countries and the respective product systems. Through this assessment, it can be determined which process has the highest worker hours contribution to the entire product system over 30 years. As shown from the Sankey diagram in Figure 18, carbon sequestration generates the highest worker hours (76.87%) followed by carbon capture (20.31%) and carbon transportation (2.82%) in the last place.

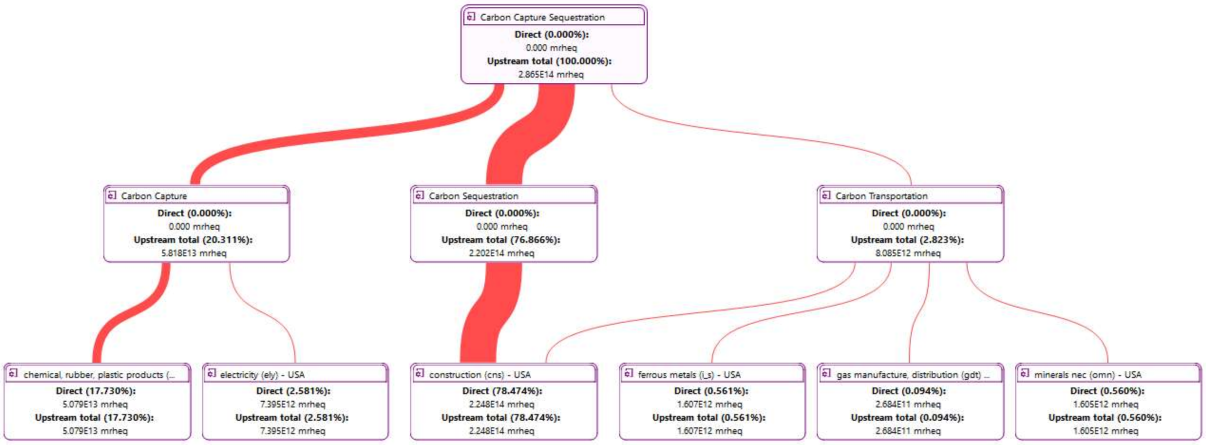
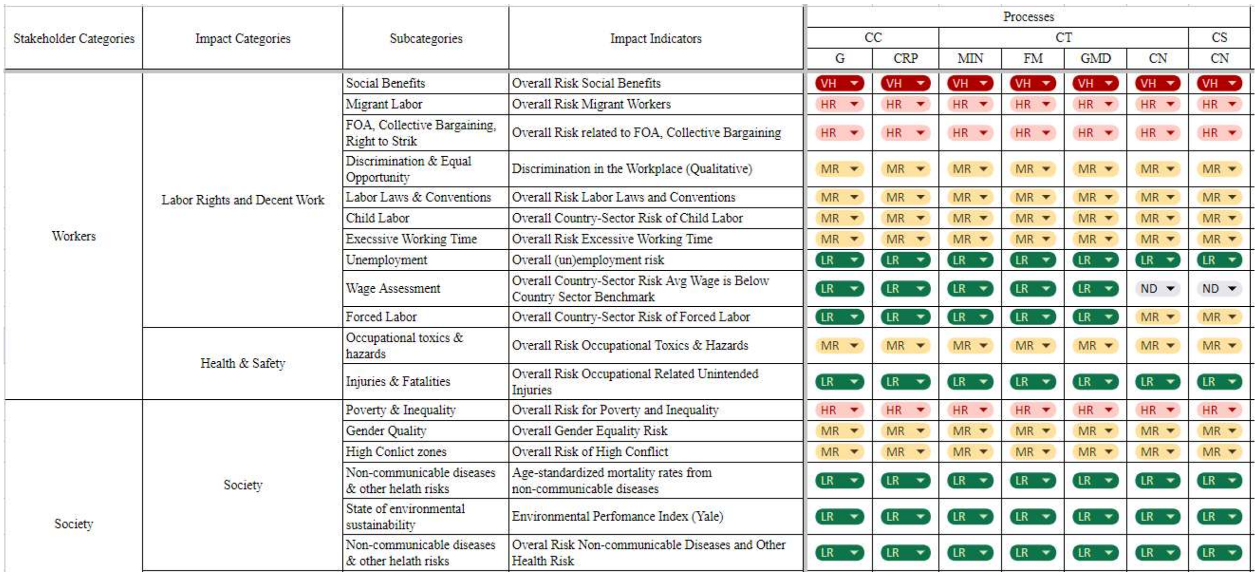


Figure 18. Carbon Capture Sequestration Sankey Diagram (Hotspot Assessment)

The SHDB classifies impact indicators into three categories of stakeholders: workers, society, and the local community. Within these groups, workers are identified as having the highest risk across the entire product system. The three most critical impact indicators to prioritize are social benefits (very high), migrant workers (high), and collective bargaining rights (high). In the society category, poverty and inequality present a higher risk than other indicators in this group. Meanwhile, within the local community category, the rights of indigenous peoples are considered to be at relative risk.



Stakeholder Categories	Impact Categories	Subcategories	Impact Indicators	Processes						
				CC		CT				CS
				G	CRP	MIN	FM	GMD	CN	CN
Workers	Labor Rights and Decent Work	Social Benefits	Overall Risk Social Benefits	VH	VH	VH	VH	VH	VH	VH
		Migrant Labor	Overall Risk Migrant Workers	HR	HR	HR	HR	HR	HR	HR
		FOA, Collective Bargaining, Right to Strik	Overall Risk related to FOA, Collective Bargaining	HR	HR	HR	HR	HR	HR	HR
		Discrimination & Equal Opportunity	Discrimination in the Workplace (Qualitative)	MR	MR	MR	MR	MR	MR	MR
		Labor Laws & Conventions	Overall Risk Labor Laws and Conventions	MR	MR	MR	MR	MR	MR	MR
		Child Labor	Overall Country-Sector Risk of Child Labor	MR	MR	MR	MR	MR	MR	MR
		Execssive Working Time	Overall Risk Excessive Working Time	MR	MR	MR	MR	MR	MR	MR
		Unemployment	Overall (un)employment risk	LR	LR	LR	LR	LR	LR	LR
		Wage Assessment	Overall Country-Sector Risk Avg Wage is Below Country Sector Benchmark	LR	LR	LR	LR	LR	ND	ND
		Forced Labor	Overall Country-Sector Risk of Forced Labor	LR	LR	LR	LR	LR	MR	MR
	Health & Safety	Occupational toxics & hazards	Overall Risk Occupational Toxics & Hazards	MR	MR	MR	MR	MR	MR	MR
		Injuries & Fatalities	Overall Risk Occupational Related Unintended Injuries	LR	LR	LR	LR	LR	LR	LR
Society	Society	Poverty & Inequality	Overall Risk for Poverty and Inequality	HR	HR	HR	HR	HR	HR	HR
		Gender Quality	Overall Gender Equality Risk	MR	MR	MR	MR	MR	MR	MR
		High Conlict zones	Overall Risk of High Conflict	MR	MR	MR	MR	MR	MR	MR
		Non-communicable diseases & other helath risks	Age-standardized mortality rates from non-communicable diseases	LR	LR	LR	LR	LR	LR	LR
		State of environmental sustainability	Environmental Perfomance Index (Yale)	LR	LR	LR	LR	LR	LR	LR
		Non-communicable diseases & other helath risks	Overal Risk Non-communicable Diseases and Other Health Risk	LR	LR	LR	LR	LR	LR	LR

Figure 19. Risk Level of Each Impact Indicator (Hotspot Assessment)

5.2.3 Data Quality

In this study, we use the Social Hotspot Database (SHDB) as the main data source. I create a straightforward process to measure the data quality through a pedigree matrix in Table 7. According to Eisfeldt and Ciroth (2017), there are five data quality aspects that describe how well the data is fit for the study:

Table 7. Pedigree Matrix for Data Quality Check

Indicator	**Score**				
	1	**2**	**3**	**4**	**5**
Reliability of the sources	Statistical study, or verified data from primary data collection from several sources	***Verified data from primary data collection from one single source or non-verified data from primary sources or data from recognized secondary sources***	Non-verified data partly based on assumptions or data from non-recognized sources	Qualified estimate (e.g., by an expert)	Non-qualified estimate or unknown origin
Completeness conformance	***Complete data for country-specific sector/country***	A representative selection of country-specific	Non-representative selection, low bias	Non-representative selection, unknown bias	Single data point/completeness unknown
Temporal conformance	***Less than 1 year of difference of the time period of the dataset***	***Less than 2 years of difference of the time period of the dataset***	***Less than 3 years of difference of the time period of the dataset***	***Less than 4 years of difference of the time period of the dataset***	***Age of data unknown or data with more than 5 years of difference of the time period of the dataset***
Geographical conformance	***Data from the same geography (country)***	A country with similar conditions or the average of countries with slightly	Average of countries with different conditions, geography under study	Average of countries with different conditions, geography under study	Data from unknown or distinctly different regions

		different conditions	included, with large share, or country with slightly different conditions	included, with small share, or not included	
Further technical conformance	***Data from the same technology (sector)***	***Data from similar sector, e.g., within the same sector hierarchy, or average of sectors with similar technology***	***Data from slightly different sector, or average of different sectors, sector under study included, with large share***	***Average of different sectors, sector under study included, with small share, or not included***	Data with unknown technology/sect or or from distinctly different sector

Evaluation score

- Reliability: SHDB data is exclusively from recognized secondary sources (2)
- Completeness: SHDB uses complete data for country and sector-specific (1)
- Temporal conformance: Depending on source and country, some country statistics are only revised every 5-10 years
- Geographical conformance: SHDB data are country-specific (1)
- Further technical conformance: Data from the same technology (sector) (1), data from similar sector; for data from similar sector, SHDB uses a multitude of classification systems (2-3); when data on different sectors is not available, SHDB use country data (4)

5.3 Impact Assessment Results

The specific characterization method that we used for the impact assessment is Social Hotspot 2022 Category Method - Endpoint. This method weights the main impact categories (labor & decent works, health & safety, society, governance, community) equally. In this impact assessment, we limited the assessment to three main stakeholders: workers, society, and the local community, since the SHDB indicators can only be assigned to these categories. That being said, these categories are the most frequently defined stakeholders in the literature review performed by Backes & Traverso (2022).

Figure 20 showed a summary of the SHDB impact assessment for the CCS. The impact assessment results were aggregated into 5 impact categories and 27 impact subcategories. We did not set a specific weight, and SHDB automatically assigned equal weight for each category. In addition, we could see the impact assessment results based on the process system stage. The impact assessment was expressed in medium risk hour equivalent (mrheq) as a result of characterization using the country and sector-specific risk level. In case some risk levels were not available, we assigned those inventory to the medium risk category.

Stakeholder Categories	Stakeholders Weight	Impact Categories	Impact Weight	Subcategories	Subcategories Weight	Impact Indicators	Characterization Factors (mrheq/work hours)							Impact Assessment Results (mreq)							Impact Categories Results (mrheq)	Stakeholders Categories Results (mrheq)
							CC		CT				CS	CC			CT			CS		
							G	CRP	MIN	FM	GMD	CN	CN	G	CRP	MIN	FM	MNF	CN	CN		
Workers	0.33	Labor Rights and Decent Work	0.5	Social Benefits	0.1	Overall Risk Social Benefits	0.9091	0.9091	0.9091	0.9091	0.9091	0.9091	0.9091	3.04E+12	2.08E+13	6.60E+11	6.61E+11	1.10E+11	8.92E+13	8.92E+13	5.27E+14	6.50E+14
				Migrant Labor	0.1	Overall Risk Migrant Workers	0.45455	0.45455	0.45455	0.45455	0.45455	0.45455	0.45455	1.52E+12	1.04E+13	3.30E+11	3.30E+11	5.50E+10	4.46E+13	4.46E+13		
				FOA, Collective Bargaining, Right to Strik	0.1	Overall Risk related to FOA, Collective Bargaining	0.45455	0.45455	0.45455	0.45455	0.45455	0.45455	0.45455	1.52E+12	1.04E+13	3.30E+11	3.30E+11	5.50E+10	4.46E+13	4.46E+13		
				Discrimination & Equal Opportunity	0.1	Discrimination in the Workplace (Qualitative)	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	3.04E+11	2.08E+12	6.60E+10	6.61E+10	1.10E+10	8.92E+12	8.92E+12		
				Labor Laws & Conventions	0.1	Overall Risk Labor Laws and Conventions	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	3.04E+11	2.08E+12	6.60E+10	6.61E+10	1.10E+10	8.92E+12	8.92E+12		
				Child Labor	0.1	Overall Country-Sector Risk of Child Labor	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	3.04E+11	2.08E+12	6.60E+10	6.61E+10	1.10E+10	8.92E+12	8.92E+12		
				Execssive Working Time	0.1	Overall Risk Excessive Working Time	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	0.09091	3.04E+11	2.08E+12	6.60E+10	6.61E+10	1.10E+10	8.92E+12	8.92E+12		
				Unemployment	0.1	Overall (un)employment risk	0.009091	0.009091	0.009091	0.009091	0.009091	0.009091	0.009091	3.04E+10	2.08E+11	6.60E+09	6.61E+09	1.10E+09	8.92E+11	8.92E+11		
				Wage Assessment	0.1	Overall Country-Sector Risk Avg Wage is Below Country Sector Benchmark	0.009091	0.009091	0.009091	0.009091	0.009091	0.09091	0.09091	3.04E+10	2.08E+11	6.60E+09	6.61E+09	1.10E+09	8.92E+12	8.92E+12		
				Forced Labor	0.1	Overall Country-Sector Risk of Forced Labor	0.009091	0.009091	0.009091	0.009091	0.009091	0.09091	0.09091	3.04E+10	2.08E+11	6.60E+09	6.61E+09	1.10E+09	8.92E+12	8.92E+12		
		Health & Safety	0.5	Occupational toxics & hazards	0.5	Overall Risk Occupational Toxics & Hazards	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.67E+12	1.15E+13	3.63E+11	3.64E+11	6.05E+10	4.91E+13	4.91E+13	1.23E+14	
				Injuries & Fatalities	0.5	Overall Risk Occupational Related Unintended Injuries	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.67E+11	1.15E+12	3.63E+10	3.64E+10	6.05E+09	4.91E+12	4.91E+12		
Society	0.33	Society	0.5	Poverty & Inequality	0.167	Overall Risk for Poverty and Inequality	0.7143	0.7143	0.7143	0.7143	0.7143	0.7143	0.7143	2.39E+12	1.64E+13	5.19E+11	5.19E+11	8.64E+10	7.01E+13	7.01E+13	2.34E+14	4.58E+14
				Gender Quality	0.167	Overall Gender Equality Risk	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	4.77E+11	3.27E+12	1.04E+11	1.04E+11	1.73E+10	1.40E+13	1.40E+13		
				High Conlict zones	0.167	Overall Risk of High Conflict	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	4.77E+11	3.27E+12	1.04E+11	1.04E+11	1.73E+10	1.40E+13	1.40E+13		
				Non-communicable diseases & other helath risks	0.167	Age-standardized mortality rates from non-communicable diseases	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	4.77E+10	3.27E+11	1.04E+10	1.04E+10	1.73E+09	1.40E+12	1.40E+12		
				State of environmental sustainability	0.167	Environmental Perfomance Index (Yale)	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	4.77E+10	3.27E+11	1.04E+10	1.04E+10	1.73E+09	1.40E+12	1.40E+12		
				Non-communicable diseases & other helath risks	0.167	Overal Risk Non-communicable Diseases and Other Health Risk	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	0.014286	4.77E+10	3.27E+11	1.04E+10	1.04E+10	1.73E+09	1.40E+12	1.40E+12		

Figure 20. Screenshot of Excel-based model for life cycle assessment

Impact Assessment Results (mrheq) = Inventory Results (work hours) x Characterization Factor (mrheq/work hours)

Dividing the impact assessment result into different processes in the life cycle was important in order to display as to which process the most problems occur. As shown in Figure 21, carbon transportation contributed 44.6% of the total impacts of CCS. This was mainly attributed to the associated risks of building pipeline infrastructure from the point source emitter to the injection/sequestration site. The next large contribution to the entire product system was carbon sequestration (43.9%). This process generally followed the typical oil and gas well construction, which consists of drilling and monitoring the wells.

Carbon capture only contributed 11.4% because this process attached to the existing facilities, such as power plants and manufacturing plants, without the need for massive retrofitting of the facility. The impact assessment yielded a different result compared to the hotspot assessment, which was solely based on the worker hours.

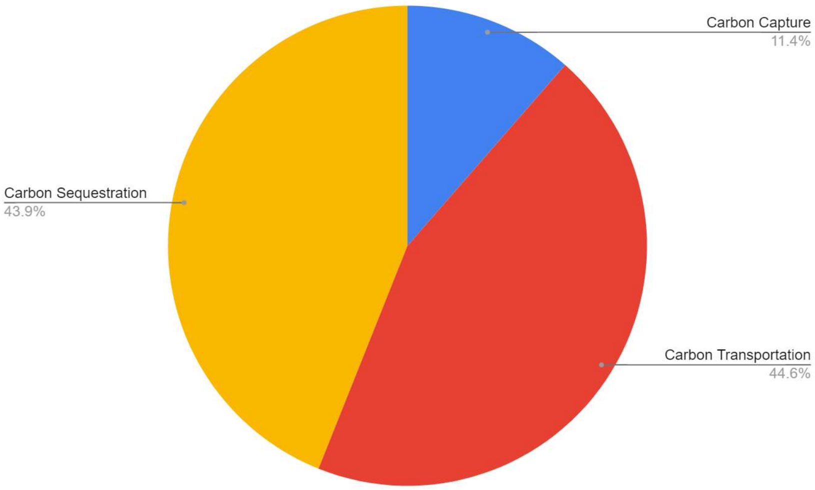


Figure 21. Impact Assessment Results for each process system

The second way to display the results wass to distribute the impact assessment result according to stakeholder categories, as shown in Figure 22. While Figure 23 presents the results based on the impact categories. According to the UNEP/SETAC guideline, there is no standardized way to display the impact assessment result. However, after analyzing the results, it was decided to group the results based on the impact categories to have more granular analyses of the impact of each impact category.

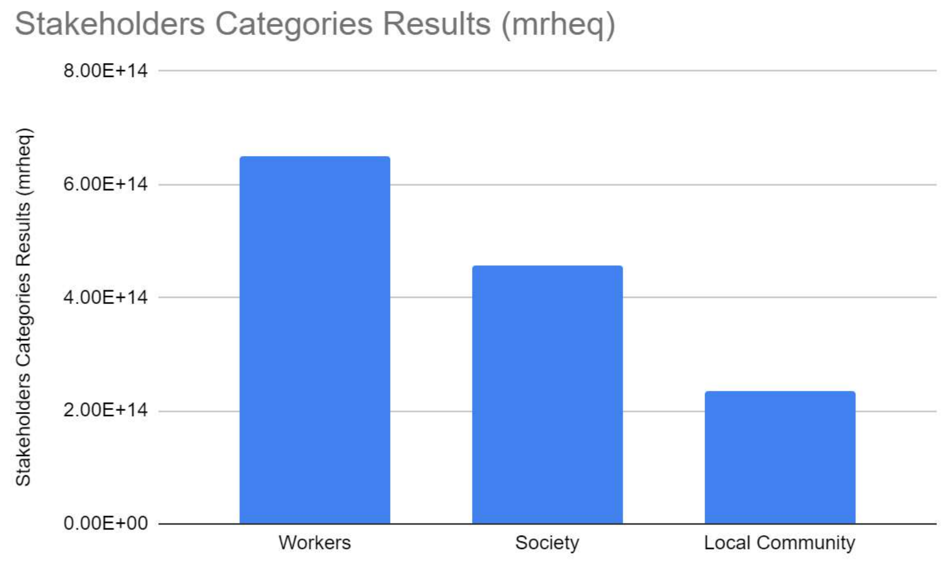


Figure 22. Impact Assessment Results for Each Stakeholder Category

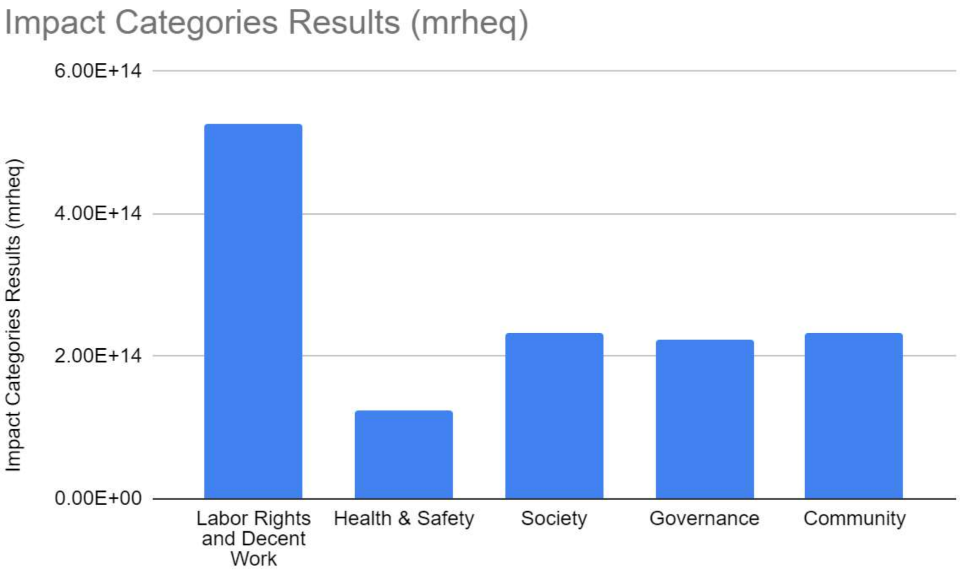


Figure 23. Impact Assessment Results for Each Impact Category

Table 8. Aggregation subcategories into impact categories

Impact Categories	**Subcategories**
Labor Rights & Decent	Social Benefits

Work	
	Migrant Labor
	FOA, Collective Bargaining, Right to Strike
	Discrimination & Equal Opportunity
	Labor Laws & Conventions
	Child Labor
	Excessive Working Time
	Unemployment
	Wage Assessment
	Forced Labor
Health and Safety	Occupational toxics & hazards
	Injuries and Fatalities
Society	Poverty & Inequality
	Gender Equality
	High Conflict zones
	Non-communicable diseases & other health risks
	State of environmental sustainability
	Non-communicable diseases & other health risks
Governance	Corruption
	Legal System
	Democracy & freedom of speech
Local Community	Indigenous Rights
	Access to healthcare
	Property rights

	Access to Electricity
	Access to improved sources of drinking water
	Access to improved sources of sanitation

Chapter 6. Stakeholders Engagement Results

Concerning the thematic focus of our project, our team engaged in detailed discussions with various stakeholders, including government officials from both state and federal agencies, participants from the value chain private sectors, and a diverse group of scholars. We conducted five key informant interviews, each lasting between 25 to 30 minutes, with an average duration of 28 minutes. Additionally, our team visited the Central Power Plant in Ann Arbor where we had an insightful discussion on relevant topics. We also participated in several international, national, and regional conferences, engaging with numerous researchers and stakeholders. These interactions have provided us with valuable insights and results, which have significantly shaped the direction and outcomes of our project.

6.1 Interview Summary

First of all, we summed the main contents of each interview transcript, the results of which are as follows:

Participant 1 (P1), who works at the Office of the Environmental Justice Public Advocate in Michigan, emphasized the multifaceted approach theoffice is taking to address environmental justice and support communities through the transition towards more sustainable and equitable environmental practices. P1 responses reflect a comprehensive and inclusive approach to addressing environmental justice, emphasizing community involvement, data-driven strategies, and cross-sector collaboration to ensure equitable environmental policies and practices. Initiatives mentioned include:

1. The establishment of the interagency Environmental Justice Response Team and the Michigan Advisory Council on Environmental Justice (MACEJ), aimed at integrating environmental justice across state government functions and advising on policies with a diverse representation from frontline communities, organizations, and various sectors.
2. Development and utilization of the Environmental Justice Screening Tool (EJ Screen) to identify communities affected by environmental and socioeconomic vulnerabilities, which is publicly accessible for community, industry, and government use.
3. Implementation of specific projects, such as the community resiliency planning pilot in the 48217 River Rouge area, focusing on public health and resilience in communities heavily

impacted by industry and environmental issues. This project is community-driven, aiming to address public health concerns, environmental resilience, and provide meaningful opportunities for community engagement.

4. The office has also been allocated $20 million for environmental justice grants, which can be applied to various community needs, including air quality monitoring and public health projects.
5. P1 Highlighted the office's collaboration with the Office of Climate and Energy to ensure the state's healthy climate plan addresses environmental justice concerns.
6. On working with utility companies, P1noted active communication and advisory roles, particularly around integrated resource plans and potential environmental impacts.
7. Regarding the Justice 40 Initiative, P1 Discussed efforts to ensure that federal funding benefits disadvantaged communities, with a focus on utilizing funds to prioritize and support these communities effectively.

Participant 2 (P2), a faculty at a research university, provided insights on the critical role of Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) technologies in achieving global climate goals. P2 emphasized the necessity of these technologies to bridge the gap towards limiting global warming to below 2 degrees Celsius, highlighting the urgent need for substantial carbon dioxide removal by mid-century and the importance of emission reductions across various sectors. The main contents include:

1. P2 advocates for the United States to continue leading in technology development and funding for CCS and CDR, underscoring the government's role in taking on risks and supporting demonstrations to advance social license and understanding of these technologies. P2 stresses the importance of precise communication about technology impacts on communities and the avoidance of false precision to gain public trust.
2. Regarding the social justice aspects of CCS deployment, he distinguishes between CCS and CDR, noting their separate implications and the need for a justice-first approach in project development. P2 suggests that technology deployments should prioritize justice, engage communities earnestly, and seek to design meaningful community benefit agreements. P2 believes that while there are unavoidable hard decisions with CCS regarding emission

abatement and its impacts, leading with justice can help reconcile techno-economic arguments with social justice objectives.

3. P2 mentions existing and forthcoming policies designed to maximize community benefits from CCS projects, including the Justice 40 initiative and incentives for energy communities under the IRA. He calls for stricter regulations to ensure equitable processes and benefits from these technologies.
4. Through their work, P2 contributes to shifting the academic and practical paradigms toward prioritizing justice in carbon management research and deployment strategies. Their collaborations with organizations like The Nature Conservancy exemplify efforts to engage with communities, educate on carbon management technologies, and advocate for best practices in project development that align with social justice principles.
5. P2 highlights the importance of social life cycle assessments (SLCA) in quantifying the impacts of CCS technologies on communities, advocating for transparent communication of both positive and negative impacts to enable informed decision-making. P2 identifies transport and storage aspects of CCS as primary public concerns, emphasizing the need for clear communication on risk mitigation and regulatory processes to address safety and environmental risks.

Participant 3 (P3), who works at Environmental and Energy Affairs at the Michigan Chamber of Commerce, shared his perspectives on Carbon Capture, Utilization, and Sequestration (CCUS) technologies as essential tools for decarbonizing Michigan's economy. He highlighted the state's legislative advancements in renewable energy and the critical role of carbon capture in reducing emissions from energy-intensive industries. He noted the importance of CCUS in supporting manufacturing processes and attracting new businesses to Michigan due to the potential for lower emissions. The main contents include:

1. P3 emphasized that the economic viability of carbon capture projects is heavily reliant on federal incentives, such as the 45Q tax credits introduced by the IRA. P3 pointed out the existing market demand for carbon dioxide in various industries and expressed optimism about the growth of the carbon removal market, aided by subsidies.
2. Addressing policies and legislation, he underscored the competitive and regulatory pressures on multinational companies from the EU and the Paris Agreement, which drive investments

towards reducing carbon footprints. P3 mentioned efforts in Michigan to create a state-run program for CCUS facilities, highlighting the state's initiative to gain regulatory authority for such facilities.

3. In tackling opposition to CCUS projects, he advocated for framing carbon capture as a means to improve air quality beyond the climate change narrative. P3 discussed the economic and environmental benefits of CCUS, including replacing declining oil and gas revenue and enhancing local air quality.
4. P3 stressed the geological advantage Michigan has for CCUS, particularly the Mount Simon formation, which could make sequestration more economically feasible. He called for science-driven policy and regulatory frameworks to manage CCUS implementation responsibly.
5. Collaborative efforts with governmental entities, the private sector, and nonprofits were identified as crucial for advancing CCUS projects. He mentioned the formation of broad coalitions, including labor and environmental groups, to support Michigan's CCUS initiatives.
6. P3 highlighted the potential community benefits of carbon dioxide removal, especially in improving southeastern Michigan's air quality and environmental legacy. P3 advocated for educating communities about the positive impacts of CCUS on local air quality and the environment.

Participant 4 (P4), a distinguished professor, shared insights on the necessity and potential deployment strategies for carbon removal technologies to address climate change. P4 emphasized the critical role of these technologies in mitigating global warming and the impossibility of achieving below 2 degrees Celsius temperature rise without them. P4 highlighted the importance of rapidly reducing emissions, adapting to climate changes, and removing CO_2 to address the excess already present in the atmosphere. Their perspective underscores the complexity of integrating carbon management technologies with social justice principles, and his emphasis on community engagement, economic transitions, and leveraging Michigan's unique resources offers a comprehensive approach to advancing sustainable decarbonization solutions. The main contents include:

1. Regarding deployment in hard-to-abate sectors and electricity generation, he suggested prioritizing the closure of coal-fired power plants and exploring renewable natural gas sources, like biogas, to complement the electrical grid. He also touched on the need for local CO_2 capture in certain scenarios and the potential for biogas to contribute significantly to natural gas supply.
2. P4 discussed the social justice aspects of deploying large-scale carbon removal technologies, considering the potential for job transitions from the oil and gas industries to the emerging CO_2 capture and utilization fields. P4 stressed the importance of community engagement, transparent communication, and the establishment of trust, particularly in communities affected by legacy pollution. P4 also suggested leveraging existing skills within the oil and gas workforce for the new carbon management industry.
3. On engaging with communities and conveying complex scientific information, P4 advised using accessible language and engaging in meaningful conversations to build relationships before presenting technical details. P4 emphasized the importance of understanding community perspectives and addressing their needs and concerns in the context of carbon management projects.
4. P4 also highlighted the Justice40 initiative and the Inflation Reduction Act, including the 45Q tax credits, as significant steps toward incentivizing carbon capture and utilization. P4 pointed out Michigan's geological advantages for CO2 storage and the potential economic and environmental benefits of becoming a leader in carbon management. P4 suggested consulting with local experts, utility companies, and industry stakeholders to gather diverse perspectives and align technological deployments with community benefits and environmental justice goals.

Participant 5 (P5), working at a research university after having extensive experience in an energy company , offers valuable insights into the deployment of carbon removal technologies. P5 acknowledged the essential role these technologies play in achieving net-zero emissions, particularly highlighting the unavoidable need to address residual carbon dioxide concentrations and the inevitable, albeit limited, reliance on carbon capture for critical, hard-to-decarbonize sectors. The main contents include:

1. P5 foresees a cautious growth trajectory for the carbon capture and storage (CCS) sector, emphasizing its current nascent stage and the technological and commercial hurdles it faces. Despite the potential exponential market growth, P5 anticipates only a modest expansion over the next decade due to the starting point being pilot-scale and minimal commercial deployments.
2. Regarding policies, P5 admits to a lack of detailed knowledge about specific incentives but is aware of broader attempts to integrate equity and justice in infrastructure siting and economic development, such as the Justice40 initiative. However, P5 notes unfamiliarity with the application of these frameworks within the carbon dioxide removal industry.
3. P5 stresses the importance of equitable deployment of carbon removal technologies, acknowledging the historical and ongoing environmental injustices associated with energy production. P5 points out the global mobility of carbon emissions, contrasting it with the local and inequitable distribution of non-carbon pollution. Any effort to reduce atmospheric carbon concentrations, therefore, aligns with broader equity goals, as climate change disproportionately affects impoverished communities and those of color worldwide.
4. Addressing local impacts, P5 envisions carbon removal facilities potentially bringing jobs and economic development to communities, especially those transitioning away from fossil fuel-based industries. P5 emphasizes the importance of thoughtful implementation and community consultation to ensure such projects align with local priorities and do not displace valued community assets.
5. P5 calls for developing rigorous storage standards to ensure the safety and permanence of carbon sequestration, a concern for those wary of CCS technologies. P5 suggests Michigan's geological suitability for CO_2 storage could be leveraged, pending the establishment of secure storage protocols that mitigate the risk of unintended releases.

6.2 Interview Analysis

After summarizing the contents of above interview, the table below systematically presents the results of the overall analysis of all interviews:

Table 9. Interview Themes Analysis

Category	**Description**	**Example Quote**	**# of Participants**

Environmental Justice	Participants discussed the importance of ensuring CCS projects do not disproportionately impact disadvantaged communities and highlighted the need for equitable distribution of benefits.	"Climate change is maybe the single least equitable, most ingest phenomenon the world has ever seen..."	4
Technological Feasibility and Adoption	This category encompasses perspectives on the technical challenges, potential, and realistic timelines for CCS deployment.	"It's so nascent right now. And there's a lot of challenges from what I understand..."	3
Community Engagement and Participation	Interviewees emphasized the significance of engaging with communities in a meaningful way to gain support for CCS projects and address any concerns.	"You will first have to get to know each other. You will not want to go in and in the first meeting, talk about your plans..."	4
Policy and Legislation	The discussion around policies, including incentives for CCS and legislative support for carbon removal efforts, was a focal point.	"...with the Inflection Reduction Act in the U.S. and other policies around the world, there has been a surge in carbon dioxide removal…"	2

Economic Impacts and Opportunities	Participants highlighted the potential economic benefits of CCS, such as job creation, but also the need to manage economic transitions for communities reliant on fossil fuel industries.	"Carbon dioxide removal technology in these communities...could be a really nice transition to the clean energy economy..."	3
Safety and Storage Standards	Concerns and considerations about the safety of CO2 storage and the need for strict regulations to ensure environmental protection were mentioned.	"...developing really, really tight and secure standards around what that storage needs to look like would be the first step..."	2
Climate Change Mitigation	The role of CCS in broader efforts to mitigate climate change and reduce global carbon emissions was discussed as a crucial aspect of the technology's adoption.	"...anything that can reduce the concentration of carbon in the atmosphere and reduce climate impacts is a positive for equity."	3
Infrastructure and Siting Challenges	The challenges related to the physical infrastructure of CCS, including siting and community acceptance, were noted as significant hurdles.	"I would suspect that it is simply trying to find the right location..."	3

The interviews underscored the critical importance of engaging local communities in the deployment of CCS technologies. It was highlighted that CCS not only holds the potential to address global carbon reduction goals but also presents an opportunity to support economic development and job creation in regions transitioning from fossil fuel dependence. However, successful implementation hinges on thoughtful engagement to ensure that these projects align with local values and do not exacerbate existing social inequities. Experts emphasized the necessity of clear, transparent communication and genuine consultation with communities to address concerns about potential local impacts, such as land use changes and infrastructure development.

From our engagements at various international, national, and regional conferences, we gathered that while experts and policymakers are acutely aware of the significance of climate change and the role of CCS, there is a notable disconnection with the general public, who often do not share the same level of concern or understanding. This gap underscores the urgent need to broaden public awareness and acceptance of CCS strategies, focusing on how they can be integrated into local contexts without social disruption. Discussions also highlighted the need for precise definitions of Disadvantaged Communities, the implementation of Social Lifecycle Assessment methods, and the improvement of data and software used in these processes.

During our visit to the Central Power Plant in Ann Arbor, the proactive approach of the CPP team was evident. They maintain rigorous compliance with federal, state, and local environmental and safety regulations, continuously striving for improvement by adhering to the principles of respect, collaboration, solution-orientation, and proactivity. This commitment is part of a broader university effort initiated in 2021, following the President's Commission on Carbon Neutrality's final report. The University of Michigan has set ambitious carbon neutrality goals, including reducing greenhouse gas emissions from purchased electricity to net zero by 2025 and eliminating all campus emissions by 2040. This visit provided insights into how such facilities can align their operational strategies with these broader environmental goals, thereby serving as a model for integrating CCS technologies in similar contexts to achieve substantial reductions in carbon emissions.

Chapter 7. Discussion and Conclusion

7.1 Discussion

Our research sought to develop an understanding of how to incorporate justice principles into the development of carbon capture sequestration (CCS). This study mainly focused on impact analysis using multiple tools, such as geospatial, social life cycle assessment, and stakeholder engagement. The team leveraged those impact analyzes to guide and ensure an equitable, inclusive, and just transition. Here, we summarized our main findings for each of our main sections and discussed some lessons learned and recommendations that stakeholders can learn when it comes to large-scale technological climate mitigation efforts.

7.1.1 Geospatial Analysis

The spatial distribution of greenhouse gas (GHG) emissions and burden indices in Southeastern Michigan reveals several important issues that have far-reaching implications for regional policy-making, social justice and environmental management strategies.

First, the geographical clustering of GHG emission and burden indices highlighted the significant impact of large emission facilities in a given region. For example, the high emissions in Monroe and St. Clair counties are largely due to two large industrial facilities in the area. This finding highlights the importance of heavy industry layouts for regional environmental impacts and suggests that strategies to reduce GHG emissions and improve environmental burdens need to focus on these high-emission facilities. Further, the comparison of urban versus suburban GHG emissions and burdens reveals the complex challenges facing Southeastern Michigan. Urban areas, especially Detroit and surrounding cities, have a higher burden, but their GHG emissions are not always proportional to this. This may be related to the relatively high population density and smaller sources of industrial emissions in urban areas. At the same time, low population density in the suburbs helps reduce the burden, but GHG emissions from industrial facilities in Monroe County also affect these areas. It is important to note that in our study we only looked at emissions from facilities. According to the EPA 2021 report, industry and electricity production together account for only 48% of the country's GHG emissions, with the remaining half of GHG emissions being generated by transportation, agricultural production, and commercial housing. Another point to note is that facility-level GHG emissions are likely to be inaccurate due to different collection, calculation and reporting methods across facilities (Wegener et al., 2019). It is always necessary to consider gaps in data accuracy when conducting further analysis.

In analyzing the types of GHG emissions in Southeastern Michigan and their year-over-year changes, we found that despite a downward trend in overall emissions, particularly during the COVID-19 pandemic. It is important to note, however, that the rebound in emissions following the end of the pandemic suggests that the urgent need to restore normalcy and stabilize economies will lead to a rapid increase in emissions (Kumar et al., 2022). History tells us that it is unrealistic to reduce emissions by reducing human activity or slowing economic development. This highlights the need for more sustained and systematic strategies to reduce emissions, for example, renewable energy such as solar, wind, hydropower, biomass and geothermal energy are all good directions. Cleaner and more environmentally friendly, they can reduce global dependence on fossil fuels and help reduce global GHG emissions by simultaneously meeting global energy demand (Ellabban et al., 2014).

Moreover, economic and racial differences play a key role in the geographic distribution of the burden. For example, the cities of Troy and Pontiac, despite their geographic proximity, have significant differences in GHG emissions, burden, and economic status of their residents. As Declet-Barreto et al. (2022) highlighted, within six miles of a power plant, people of color outnumber the white population by 23.5%. Within five miles, the population in poverty areas exceeded that in non-poverty areas by 15.3%. This disparity not only reflects the role of economic factors in environmental impact but also highlights how race and socioeconomic status are intertwined with environmental injustice. This also explains why our study focused on DAC areas, which are characterized by low-income and high populations of people of color.

Discussing the distribution of DAC in terms of burden, we can see that in areas with high GHG emissions and high burden, especially in the cities of Detroit and Pontiac, the majority of residents belong to DAC. Policy interventions targeting DAC can not only improve the environmental quality of these communities but also help drive socioeconomic equity. However, even if we pointed out the importance of focusing on DAC, it is always difficult to implement it, because DAC is underrepresented in the news media, scientific research is under-done, and government representatives are underserved (Fernandez‑Bou et al., 2021). Even though Justice

40 aims to ensure that at least 40 percent of the total benefits of certain federal investments go to disadvantaged communities, the prioritization of these resources and the results of their implementation have yet to be evaluated.

Admittedly, our study cannot establish a direct cause-and-effect relationship between GHG emissions and Burdens. That requires taking in more variables to measure the complexity of the relationship. Secondly, we ignored the role of policy factors. Regional GHG emissions and Burden index are closely related to regional policies. We hope to see relevant policy analysis in future studies.

7.1.2 Social Life Cycle Assessment

In this section, an identification of significant social issues and opportunities, followed by an evaluation of the study (limitations and future improvement) will be discussed in detail. Below are several significant social issues that we have identified:

A. *Workers - Labor Rights and Decent Work*

The most significant societal issues regarding the carbon capture sequestration life cycle in the US were within the labor rights and decent work category. This category generated the highest impact compared to other impact categories. Looking at the hotspot assessment, this result was mainly driven by the three impact subcategories, such as social benefits (very high), migrant workers (high), and collective bargaining rights (high).

Social benefits refer to non-monetary employment compensation. Social benefits are typically offered to full-time workers but may not be provided to other classes of workers, such as part-time, contractual, home workers. Four basic categories of social security benefits are often included and are paid based upon the record of worker's earnings: retirement, disability, dependents, and survivors' benefits. Social security is designed to provide a guaranteed income in retirement to protect seniors against the risk of outliving their savings. According to 2023 Social Security Trustees Report, Old Age, Survivors, Disability Insurance (OASDI) trust funds will be depleted in 2034 and that the program faces a long-run actuarial deficit (Goda & Biggs, 2023). The deficit is mainly caused by severe inflation and lower-than-expected wages. This situation might impact an immediate and permanent payroll tax rate increase, across-the-board benefit reduction, and some combination of both.

Migrant workers are individuals who move from their home region or country to another region or country for employment purposes. These movements can be within their own country (internal migration) or across international borders (international migration). For the context of this study, we focused only on migration of workers within the US. Migrant workers often seek employment opportunities in sectors such as agriculture, construction, and services, and their migration can be temporary or permanent, depending on the nature of the work and the agreements with employers. Managing large infrastructure projects, like CCS, involves a significant number of workers. Such projects can lead to increased demand for skilled labor, which may result in shortages and the need for migrant workers or temporary workers to fill the gaps. This situation can pose some risks to local workers in Michigan with the incoming wave of skilled labor from other states.

One set of fundamental rights that workers are to enjoy concerns freedom of association and the right for collective bargaining (International Labor Organization, 2023). Reflecting on the 2023 United Auto Workers (UAW) strike, key issues included demands for increased wages to offset inflation, an end to the tiered employment system, and enhanced worker protections, especially in light of the industry's shift toward electric vehicles. The strike ended with agreements that largely met UAW demands, including significant wage increases and improved benefits for workers. The US Bureau of Labor Statistics shows that 458,900 workers were involved in "major work stoppages" in 2023. With the emergence of new industries like CCS, we need to ensure the similar space will be adequate for the workers to raise their voices.

B. *Workers - Health and Safety*

Individuals spend a considerable amount of time in their places of work. Therefore, potentially harmful materials that they are exposed to at their workplace play a significant role in their overall health. This impact category generated a medium risk level. The US Environmental Protection Agency (EPA) published updated Toxics Release Inventory (TRI) data for 2022, highlighting toxic chemical waste management, releases, and pollution prevention activities at over 20,000 industrial and federal facilities across the country. Commercial carbon capture and sequestration (CCS) operations handle large quantities of carbon dioxide (CO_2), which presents unique challenges and hazards. Key concerns include managing the phase behavior of CO_2 under different conditions, as its properties can significantly vary with temperature and pressure changes. Additionally, the potential for large-scale CO2 releases poses risks of asphyxiation and toxic exposure to workers, requiring stringent hazard management practices (Spitzenberger & Flechas, 2023).

C. *Workers - (Un)Employment*

According to ILO, unemployment is for all persons above a specific age who, during a reference period, were without work (not receiving payment), currently available to work, and looking for work. This impact category generates a low risk, which means the average unemployment is less than 5% and the average change is <0%, indicating that unemployment has been reduced in the last 2 years. A study by Chen et al. exhibited the socio-economic effects of CCUS investment based on the dynamic GTAP model. The results indicated that CCUS investment may accumulate \$67.09 billion and \$776.61 billion from 2026 to 2030 and 2056 to 2060, respectively. Furthermore, ADB and IEA investment scenarios showed that CCUS industrial investment may indirectly create about 12,796 and 103,886 jobs, respectively, and US\$ 85 million and US\$ 692 million of labor employment income, respectively, in 2030 (Chen & Jiang, 2022). Based on this analysis, we see potential positive impacts that CCS can bring to economic development, if all stakeholders work together to align the objective to mitigate climate change in a sustainable, equitable, and just way.

D. *Society - Poverty and Inequality*

Based on the SHDB assessment, poverty and inequality possess a high risk level. The poverty rate is the ratio of the number of people whose income falls below the poverty line. Additionally, a popular indicator often used to describe inequality is the GINI coefficient. The GINI coefficient is the index measuring the inequality of the distribution of income. It measures inequality on a scale from 0 to 1, where higher values indicate higher inequality. The US has a Gini Coefficient of 0.42 which is relatively higher than other developed countries such as Canada, UK, France, Germany (Hasell, 2023). This study shows the high risk of the inequality of benefits generated. According to the Climate and Economic Justice Screening Tools (CEJST), communities are identified as disadvantaged communities if they are in a census tract that are at and above the 65th percentile for low income. Despite the Southeastern Michigan region being known for its industrial capabilities, many communities live under the Federal poverty level.

E. *Society - State of Environmental Sustainability*

This category describes the risk associated with the state of environmental sustainability. Based on the assessment, the category exhibits a low risk. As produced by Yale, the Environmental Performance Index (EPI) uses 32 performance indicators across 11 issue categories (Wolf et al., 2022). These indicators provide a gauge how close a country is to established environmental policy targets. This result indicates that we are, in this case the State of Michigan, are heading in the right direction to address the environmental challenges that every nation faces. In general, high scorers exhibit long-standing policies and programs to protect public health, preserve natural resources, and decrease GHG emissions. The data further suggest that countries making concerted efforts to decarbonize their electricity sectors have made the greatest gains in combating climate change, with associated benefits for ecosystems and human health. It can be shown through Michigan Healthy Climate Plan and US long-term decarbonization plan that include carbon capture sequestration in their plan.

F. Governance - Legal System

The US legal system supports large scale infrastructure projects, including CCS, through various mechanisms that span federal, state and local regulations, incentives, and policies designed to facilitate development and deployment. The overall risk of this category is medium based upon the SHDB model. As the CCS technology and projects evolve, there might be some legal challenges related to property rights, environmental impacts, and regulatory compliance. Environmental and permitting regulations are some important guardrails to keep the development and deployment of CCS on track.

G. Local Community - Indigenous Rights

The situation of indigenous peoples is often severely disadvantaged, faced with systemic discrimination at all levels of society, excluded from access to natural resources, displaced by environmental disasters or wars, entrenched in extreme poverty and more. Land and natural resources are central to the livelihood and culture of local communities and indigenous populations. The risk level of this category is high at several system processes, which means that the county has not ratified ILO Convention 169 and/or endorsed the UN Declaration for the countries with an indigenous population. The Native American Population in Michigan is 57,785, which accounts for 0.6% of the state's total population (Stacker, 2021). The development of Carbon Capture Sequestration (CCS) projects may have several implications for

Indigenous communities, including potential impacts on land rights, environmental concerns, and cultural heritage sites. It's essential to involve Indigenous peoples in the decision-making processes from the early stages of CCS projects to ensure that their rights are respected and that they benefit from any development on their ancestral lands. Effective consultation and participation can help in identifying and mitigating potential negative impacts while maximizing positive outcomes for Indigenous communities.

H. Evaluation of the S-LCA

The primary objective of this study was to identify potential social issues through hotspot analysis of a carbon capture sequestration project. The focus was on the product systems, including specifically contributing sectors to each unit process. In order to assess the potential social issues, we utilized the Social Hotspot Database (SHDB) as the primary database. This database is considered common in performing initial social assessment of a product and technology. Since the CCS project is still in the early planning stage, we believe that this type of assessment is a great starting point for identifying some potential consequences of developing large-scale carbon capture sequestration. Although it would have been desirable to be able to do on-site visits and collect site-specific data. However, we found it difficult to obtain site-specific data due to time constraints and the lack of information available for each specific contributor/organization in every system process (capture, transportation, sequestration).

Throughout the study, we were consistent in following the SHDB guidelines while performing the S-LCA despite the limitations. The first limitation was that there was no available assessment of users and value chain actors, as these two stakeholders are important in following the UNEP/SETAC S-LCA guidelines. To evaluate the risks of these two categories, they required site-specific data, and SHDB did not have the capability to capture this scope. Additionally, SHDB used country-sector-specific data based on the GTAP input-output model, which creates another limitation when evaluating a specific area or region. The best alternative option to accommodate this limitation is scoping the study only for the US although the overall study aims for Southeastern Michigan.

Transparency of the results is something that we considered as essential, apart from triangulating the data, we made use of as credible and up-to-data as possible and tried to document all assumptions and sources. However, we must acknowledge that assumptions and biases might be missed when creating the life cycle model. This is due to the difficulties in finding relevant data, the possibility to gather on-site visits, and lack of knowledge and complexity of the social realm.

7.1.3 Stakeholder Engagement

The exploration of Carbon Capture and Sequestration (CCS) through expert interviews underscores its critical role in achieving net-zero emissions and mitigating the inequitable impacts of climate change. Despite consensus on the necessity of CCS, the technology is in its infancy, facing significant technological and commercial hurdles. Experts anticipate modest deployment over the next decade, given the current pilot-scale initiatives and the anticipated market growth. This highlights the nascent state of CCS technologies and the long path ahead towards commercialization and widespread implementation.

Policies and legislation, such as the Justice40 initiative, are recognized as vital for supporting decarbonization efforts. However, there exists a knowledge gap regarding the direct support these policies provide to CCS advancements, indicating a need for clearer policy communication and implementation strategies. This gap underscores the importance of integrating equity and justice into CCS projects, ensuring that policies are not only formulated but also effectively communicated and applied.

The socio-economic dimensions of CCS deployment are emphasized, with experts pointing out the current energy system's inequitable distribution of health impacts. The potential of CCS to offer economic benefits in communities transitioning from fossil fuels is acknowledged, yet it necessitates thoughtful implementation and genuine community engagement. This aspect reveals the dual challenge of ensuring technological feasibility while also achieving equitable outcomes.

Experts highlight the necessity of developing rigorous CO_2 storage standards to mitigate sequestration risks, citing Michigan's geological potential as a strategic advantage. However, concerns about local opposition underscore the need for transparent communication and community engagement, addressing safety and environmental impact concerns of CCS projects.

In conclusion, the interviews reveal the complex interplay between technological deployment and social justice considerations in CCS projects. They advocate for a community-informed approach, emphasizing the need for accessible policy information, safe storage standards, and socio-economic impact consideration. These findings illustrate the limitations in current CCS understanding and engagement, stressing the importance of collaboration among policymakers, researchers, and communities for a just transition to carbon neutrality.

The exploration and analysis of Carbon Capture and Sequestration (CCS) through expert interviews, while providing valuable insights, also encounter several limitations: First, the limited scope of perspectives. The insights derived are primarily based on a selected group of experts, which might not encompass the full range of stakeholders involved in CCS projects. This includes potential gaps in perspectives from communities directly impacted by CCS projects, policymakers, and individuals from the industrial sector, which might provide a more rounded view of the social, economic, and environmental implications. Second, technological focus with less emphasis on practical implementation. While the interviews offer a deep dive into the technological necessity and potential of CCS, there might be an underrepresentation of the practical challenges and on-the-ground realities of implementing CCS projects. This includes detailed considerations of logistics, cost, local environmental impact assessments, and real-world examples of community engagement practices. Third, limited quantitative Data and Economic Analysis. The discussion largely centers on qualitative insights without a strong emphasis on quantitative data or detailed economic analysis, which are crucial for understanding the scalability, cost-effectiveness, and economic viability of CCS technologies.

7.1.4 Recommendation

Based on the comprehensive analysis of the impacts of carbon capture sequestration (CCS) in Southeastern Michigan, especially concerning disadvantaged communities and environmental justice, our recommendations aim to align technological deployment with socio-economic equity. Our geospatial analysis recognizes the significance in addressing social justice issues within Cluster 2 located in Detroit and Pontiac city, so we should pay more attention to the region. To ensure this, we advocate for targeted policy intervention and the establishment of engagement frameworks that prioritize transparency and community involvement.

First, enhancing workforce readiness through training, apprenticeships, and scholarships specifically tailored for local workers is essential. This recommendation promotes procedural justice by involving local communities in the economic benefits of CCS, ensuring they have equitable access to job opportunities created by these projects. It also ensures that the economic benefits of CCS technologies are distributed fairly among those most affected by the projects.

Furthermore, maintaining transparency and open communication is critical. We recommend the regular updating of project progress through monthly presentations, and the creation of a dedicated website. This should be supplemented with active social media engagement to ensure widespread accessibility to information. This upholds Procedural Justice by ensuring community participation in ongoing processes.

Educational programs about climate change mitigation and adaptation should be developed to empower local communities. This connects with Restorative Justice, empowering historically marginalized communities with knowledge that fosters agency and participation.

Additionally, establishing a government-led task force focused on ensuring justice and equity in CCS projects could provide a structured platform for ongoing dialogue and feedback from the community. This task force should focus on fostering two-way communication, ensuring that community feedback directly influences project execution. It reflects procedural justice, which provides a formal avenue for community voices, and retributive justice, which addresses grievances and promotes accountability.

Finally, the creation of a social investment fund by a consortium (eg. CarbonSAFE) could support the growth of small and medium enterprises within Cluster 2. This would promote Distributive Justice by funneling economic gains back into the community and Restorative Justice by aiding in the economic revival of areas affected by environmental and industrial challenges.

By integrating these recommendations, CCS projects in Southeastern Michigan can serve as a model for balancing technological advancement with social equity, ensuring that all community members benefit from these initiatives.

7.2 Conclusion

The geospatial analysis indicates that power plants are major contributors to emissions, accounting for about 60% of the total. Yet, there is a clear downward trend in Michigan's GHG emissions, suggesting effective emissions control. This analysis also highlights the existence of areas with varied levels of GHG emissions and socio-economic burdens, particularly in

Southeastern Michigan, where disparities are stark and social justice issues are concentrated. Importantly, it identifies clusters where emissions and burdens are either both high or low, with a specific call to target areas for social justice interventions. We advocate targeting Cluster 2 as the primary goal for addressing social justice issues and providing the project’s benefits.

S-LCA highlights that carbon transportation and carbon sequestration generate the highest risk, particularly concerning labor rights, decent work conditions, and impacts on local communities and indigenous rights. The analysis underlines critical social considerations, such as the need for social security, the management of migrant workers, the right to collective bargaining, and the need to address poverty, inequality, and indigenous rights in the context of CCS development projects. On the other hand, CCS potentially creates positive socioeconomic impacts through employment and associated benefits for ecosystem and human health.

Stakeholder engagement highlights the perceived critical role of CCS in achieving net-zero emissions while acknowledging the technology's nascent stage and the challenges it faces. There is a consensus on the importance of supportive policies and legislation, such as the Justice40 initiative. Still, a recognized knowledge gap exists regarding these policies' direct support to CCS. Furthermore, the equitable distribution of economic and health impacts of the current energy system, the importance of community engagement, and rigorous CO2 storage standards are emphasized to ensure the success and acceptance of CCS projects.

It is clear that successful implementation of CCS in Michigan requires a multi-faceted approach that not only addresses the technological and commercial hurdles but also takes into account the socio-economic and environmental justice implications. Effective GHG emissions control, especially from major sources like power plants, combined with targeted social justice interventions in heavily burdened clusters, is crucial. Addressing labor rights, community engagement, and indigenous rights within the context of CCS projects is paramount to ensuring an equitable and just transition to net-zero emissions. Transparent communication, thoughtful implementation, and genuine stakeholder engagement are essential to overcoming local opposition and leveraging Michigan's geological potential for CCS. This holistic approach will enable the region to navigate the complex interplay between technological advancement, environmental sustainability, and social equity.

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Appendices

Exhibit 1. The burdens, explanation and sources.

Name	**Categories**	**Explanation**	**Sources**
Low income	All categories	Percent of a census tract's population in households where household income is at or below 200% of the Federal poverty level, not including students enrolled in higher education.	U.S. Census
Expected agriculture loss rate	Climate	Expected agricultural value at risk from losses due to fourteen types of natural hazards. These hazards have some link to climate change. They are: avalanche, coastal flooding, cold wave, drought, hail, heat wave, hurricane, ice storm, landslide, riverine flooding, strong wind, tornado, wildfire, and winter weather. The rate is calculated by dividing the agricultural value at risk by the total agricultural value.	FEMA National risk index from 2014-2021
Expected building loss rate	Climate	Expected building value at risk from losses due to fourteen types of natural hazards. These hazards have some link to climate change. They are: avalanche, coastal flooding, cold wave, drought, hail, heat wave, hurricane, ice storm, landslide, riverine flooding, strong wind, tornado, wildfire, and winter weather. The rate is calculated by dividing the building value at risk by the total building value.	FEMA National risk index from 2014-2021
Expected population loss rate	Climate	Expected fatalities and injuries due to fourteen types of natural hazards each year. These hazards have some link to climate change. They are: avalanche, coastal flooding, cold wave, drought, hail, heat wave, hurricane, ice storm, landslide, riverine flooding, strong wind, tornado, wildfire, and winter weather. Population loss is defined by the Spatial Hazard Events and Losses and National Centers for Environmental Information's (NCEI). It reports the number of fatalities and injuries caused by the hazard. An injury is counted as one-tenth (1/10) of a fatality. The NCEI Storm Events Database classifies both direct and indirect injuries. Both types are counted as population loss. The total number is divided by the population in the census tract to get the population loss rate.	FEMA National risk index from 2014-2021
Projected flood risk	Climate	A high precision, climate-adjusted model that projects flood risk for properties in the future. The dataset calculates how many properties are at risk of floods occurring in the next thirty years from tides, rain, riverine and storm surges, or a 26% risk total over the 30-year time horizon. The risk is defined as an annualized 1% chance. The tool calculates tract-level risk as the share of properties meeting the risk threshold. The risk does not consider property value.	First Street Foundation, Climate Risk Data Access from 2022
Projected wildfire risk	Climate	A 30-meter resolution model projecting the wildfire exposure for any specific location in the contiguous U.S., today and with future climate change. The risk of wildfire is calculated from inputs associated with fire fuels, weather, human influence, and fire movement. The risk does not consider property value.	First Street Foundation, Climate Risk Data Access from 2022
Energy cost	Energy	Average household annual energy cost in dollars divided by the average household income.	DOE, LEAD Tool from 2018
PM2.5 in the air	Energy	Fine inhalable particles with 2.5 or smaller micrometer diameters. The percentile is the weight of the particles per cubic meter.	EPA office of Air and Radiation(ORA), Fusion of model and monitor data from

			2017
Asthma	Health	Share of people who answer “yes” to both of these questions: “Have you ever been told by a health professional that you have asthma?” and “Do you still have asthma?”.	CDC, PLACES Data from 2016-2019
Diabetes	Health	Share of people ages 18 years and older who have been told by a health professional that they have diabetes other than diabetes during pregnancy.	CDC, PLACES Data from 2016-2019
Heart disease	Health	Share of people ages 18 years and older who have been told by a health professional that they had angina or coronary heart disease.	CDC, PLACES Data from 2016-2019
Low life expectancy	Health	The tool reverses the percentiles for this burden. This means that census tracts with lower numbers have higher life expectancies and that census tracts with higher numbers have lower life expectancies.	CDC, U.S. Small-Area Life Expectancy Estimates Project (USALEEP) from 2010-2015
Housing cost	Housing	Share of households that are both earning less than 80% of Housing and Urban Development’s Area Median Family Income and are spending more than 30% of their income on housing costs.	Department of Housing and Urban Development (HUD), Comprehensive Housing Affordability Strategy dataset from 2014-2018
Lack of indoor plumbing	Housing	Housing without indoor kitchen facilities or complete plumbing facilities.	Department of Housing and Urban Development (HUD), Comprehensive Housing Affordability Strategy dataset from 2014-2018
Lead paint	Housing	Share of homes built before 1960, which indicates potential lead paint exposure. Tracts with extremely high home values (i.e. median home values above the 90th percentile) that are less likely to face health risks from lead paint exposure are not included.	U.S. Census, American Community Survey from 2015-2019
Proximity to hazardous waste facilities	Legacy pollution	Number of hazardous waste facilities (Treatment, Storage, and Disposal Facilities and Large Quantity Generators) within 5 kilometers (or nearest beyond 5 kilometers), each divided by distance in kilometers.	EPA, Treatment, Storage, and Disposal Facilities (TSDF) data from 2020 calculated from EPA's RCRA database as compiled by EPA's EJScreen
Proximity to Superfund sites	Legacy pollution	Number of proposed or listed Superfund or National Priorities list (NPL) sites within 5 kilometers (or nearest one beyond 5 kilometers), each divided by distance in kilometers.	EPA,CERCLIS database from 2020 as compiled by EPA’s EJScreen
Proximity to Risk Management Plan (RMP) facilities	Legacy pollution	Count of Risk Management Plan (RMP) facilities within 5 kilometers (or nearest one beyond 5 kilometers), each divided by distance in kilometers. These facilities are mandated by the Clean Air Act to file RMPs because they handle substances with significant environmental and public health risks.	EPA, RMP database from 2020 as compiled by EPA’s EJScreen

Diesel particulate matter exposure	Transportation	Mixture of particles in diesel exhaust in the air, measured as micrograms per cubic meter.	EPA, National Air Toxics Assessment (NATA) from 2014 as compiled by EPA's EJScreen
Transportation barriers	Transportation	Average relative cost and time spent on transportation relative to all other tracts.	Department of Transportation (DOT), Transportation access disadvantage from 2022
Traffic proximity and volume	Transportation	Number of vehicles (average annual daily traffic) at major roads within 500 meters, divided by distance in meters.	Department of Transportation (DOT),Traffic data from 2017 as compiled by EPA's EJScreen
Underground storage tanks and releases	Water and wastewater	Weighted formula of the density of leaking underground storage tanks and the number of all active underground storage tanks within 1,500 feet of the census tract boundaries.	EPA,Calculated from EPA's UST Finder from 2021 as compiled by EPA's EJScreen
Wastewater discharge	Water and wastewater	Risk-Screening Environmental Indicators (RSEI) modeled toxic concentrations at stream segments within 500 meters, divided by distance in kilometers.	EPA, Risk-Screening Environmental Indicators (RSEI) model from 2020 as compiled by EPA's EJScreen
Linguistic isolation	Workforce development	Share of households where no one over age 14 speaks English very well.	U.S. Census, American Community Survey from 2015-2019
Low median income	Workforce development	Low median income calculated as a share of the area's median income.	U.S. Census, American Community Survey from 2015-2019
Poverty	Workforce development	Share of people living at or below 100% of the Federal poverty level.	U.S. Census, American Community Survey from 2015-2019
Unemployment	Workforce development	Number of unemployed people as a share of the labor force.	U.S. Census, American Community Survey from 2015-2019
High school education	Workforce development	Share of people aged 25 years or older who didn't graduate from high school.	U.S. Census, American Community Survey from 2015-2019

Exhibit 2. CCS Project Cost Assumption

Carbon Capture	Cost of Capture*	16.2	$/ton CO2
	Total Cost	1020.6	$M
Carbon Transportation	CAPEX	47.5	$M
	OPEX/yr	0.884	$M/yr
	Total CAPEX	47.5	$M
	Total OPEX	26.52	$M
	Total Cost	74.02	$M
Carbon Storage	CAPEX	237.7	$M
	OPEX	180.7	$M
	Total Cost	418.4	$M

Sector	Contribution	Country	Cost ($M 2022)	Cost ($M 2011)
Chemicals	56%	USA	571.5	443.16
Gas/electricity	44%	USA	449.1	348.25
			Total	**791.41**
Sector	Contribution	Country	Cost ($M 2022)	Cost ($M 2011)
Minerals	20%	USA	14.8	11.48
Ferrous Metals	40%	USA	29.6	22.95
Construction	25%	USA	18.5	14.35
Gas distribution	15%	USA	11.1	8.61
			Total	**57.39**
Sector	Contribution	Country	Cost ($M 2022)	Cost ($M 2011)
Construction	100%	USA	418.4	324.21
			Total	**324.21**