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Integration of Environmental Sustainability and Decision Making: Case Studies of Civil Infrastructure

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INTEGRATION OF ENVIRONMENTAL SUSTAINABILITY AND DECISION MAKING: CASE STUDIES OF CIVIL INFRASTRUCTURE

by

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INTEGRATION OF ENVIRONMENTAL SUSTAINABILITY AND DECISION MAKING: CASE STUDIES OF CIVIL INFRASTRUCTURE

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Sustainable development is important in the planning and design of critical civil infrastructure systems. However, decision making related to these systems currently lacks meaningful sustainability considerations. To fill this gap, this research explores the life cycle impacts of wastewater and energy infrastructure using case studies, life cycle assessment methodologies, and stakeholder discussions. Environmental and economic impacts, which are more commonly quantified, as well as more difficult to quantify societal factors, are explored. The goal of this research is to help inform decision making and facilitate the consideration of the three pillars of sustainability (e.g., economic, environmental, and social) during the planning and design stages for critical civil infrastructure systems.

The life cycle environmental impacts of construction and operations of small mechanical wastewater treatment plant (WWTP) case studies were quantified to provide industry practitioners with suggestions for how they can improve a WWTP's sustainability. Next, the life cycle environmental impacts of resilience and recovery infrastructure for case study WWTPs affected by flooding were quantified and compared. Economic and social tradeoffs of resilient infrastructure were considered as well, to

highlight which factors drive decision making related to resilience for design engineers, funding agencies, and community leaders.

In addition, the life cycle environmental impacts of a case study renewable energy system were quantified, and social tradeoffs were identified. The results of this study emphasize the potential benefits, beyond costs, of novel renewable energy designs, which is important to note as the renewable energy sector continues to grow. Next, stakeholder discussions were used to identify barriers and benefits of implementing irrigation lagoons. Testimonial videos and guidance documents were developed to help improve the information exchange between relevant stakeholders that are interested in irrigation lagoon systems. Lastly, a literature review was conducted to explore the current status of life cycle sustainability assessments of critical civil infrastructure systems to encourage stakeholders to address all three pillars of sustainability in decision making processes.

This dissertation is dedicated to my family: my mom and dad, my brother, and the late PJ, for their endless love and support.

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I appreciate all of the people that I have worked with on my projects, including the community members, wastewater treatment plant operators, consulting engineers, and state agencies. I would also like to thank my colleagues at UNL, including Dr. Shaobin Li, Matthew Thompson, Andrew Pham, and Andrew Hansen for their help with my projects, and for allowing me to help with their projects. I also thank the faculty and staff in the Department of Civil and Environmental Engineering at UNL, for all of their support and encouragement since I began my undergraduate program.

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Lastly, I would like to thank my family. They push me every day to be the "best in the west," and I cannot thank them enough for their constant support and guidance. I will forever cherish the luxury I had during the last few years to visit home, eat lunch with my mom, listen to my dad's stories, and play tennis with my brother. And of course, I must recognize PJ and Cash, who are both greatly loved. I appreciate and love you all.

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CHAPTER 1 INTRODUCTION

1.0 Background

This research explores the life cycle impacts of critical civil infrastructure systems (namely wastewater and energy systems) using case studies, life cycle assessment (LCA) methodologies, and stakeholder perspectives to help inform decision making. Limiting civil engineering planning and design to short term or capital cost considerations can result in choosing a system that can have significant long – term impacts (environmental, economic, and social), especially if faced with unexpected hardship. Thus, it is important to understand both the commonly quantified (e.g., environmental and economic) factors and the more difficult to quantify (e.g., societal/value) factors that influence critical civil infrastructure decision making to promote sustainable solutions.

Although this dissertation is comprised of four seemingly individual projects, these projects have discrete commonalities among them. First, while the projects focus on the commonly quantified environmental and economic impacts, each project also addresses, to some extent, the more difficult to quantify societal impacts (i.e., impacts not directly impacting the economy or environment). These difficult to quantify additional impacts, referred to in this dissertation as societal and/or social impacts, were oftentimes found to be the driving factors influencing critical civil infrastructure decision making. There are well-established methodologies to capture and quantify the economic and environmental considerations, which tend to be the factors frequently at the forefront of decision making. In contrast, because the societal impacts can be difficult to quantify, their consideration may be overlooked. However, the societal impacts identified by the projects within this dissertation were found to greatly influence decision making,

especially when the economic and environmental impacts were similar between alternatives.

Second, similar methodologies are used for each project. Chapters 2, 3, and 4 use similar, standardized LCA methodologies to quantify environmental impacts. Chapters 2 and 4 discuss economic implications, and Chapter 3 uses generalized wastewater treatment plant (WWTP) cost models to address economic impacts. Chapters 2, 3, and 4 each discuss the more difficult to quantify social impacts. Chapter 5 builds on these projects and their methodologies by addressing how influential stakeholders' perspectives can be when deciding to implement sustainable critical civil infrastructure. The methods used throughout this dissertation encourage consideration of a broad range of impacts for different critical infrastructure systems, which is needed to achieve the goal of adequately informing decision making.

Lastly, all projects included in this dissertation are case study based. Using case studies can help explain, describe, and explore complex issues in a practical context (Crowe et al., 2011). The use of case studies in this research enables the reader to consider the integration of sustainable civil infrastructure and decision making. Overall, this research shows the importance of bridging sustainability and decision making.

1.1 Research Contribution

Critical civil infrastructure decision making lacks meaningful sustainability considerations in its current state. This research contributes to the larger body of knowledge a consistent and reliable framework for identifying important environmental, economic, and social factors to encourage sustainability considerations in critical civil infrastructure decision making. To emphasize its consistency, this framework is presented

in Chapter 2, and is applied to different critical civil infrastructure systems in multiple locations under various conditions throughout the remaining chapters. Another major contribution of this work is the comprehensive analysis of environmental impacts through LCA methodologies. The detailed analysis was achievable due to the large quantity of detailed data collected for numerous case studies. Acquiring case study data, particularly for environmental LCA studies, is a major challenge to comprehensive analyses, as the data is not always easily accessible and is oftentimes scattered among many different institutions and organizations. Figure 1.1 summarizes the research contribution of this dissertation.

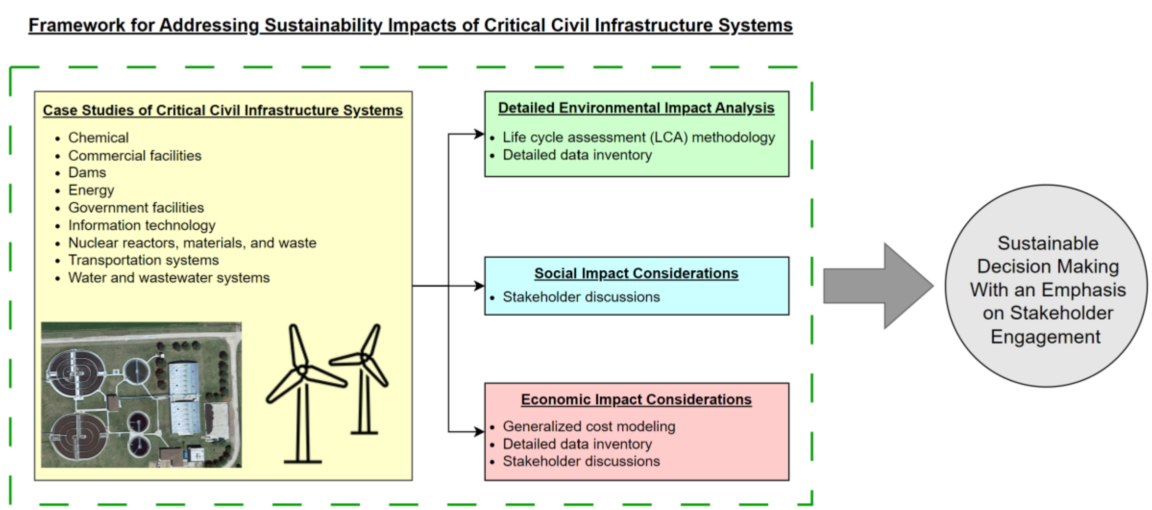


Figure 1.1 Graphical summary of the consistent and reliable framework developed and applied by this research

1.2 Research Motivation

Investment in critical civil infrastructure and collaborations between involved stakeholders must be prioritized. As defined by CISA (2020), there are 16 critical infrastructure sectors, including energy and water and wastewater. Infrastructure systems are considered to be critical if disruptions to them cause detrimental impacts on the

country's security, economy, and public health and safety (CISA, 2020; ASCE, 2021). According to the American Society of Civil Engineers (ASCE), there are 18 civil infrastructure sectors, including energy and wastewater (ASCE, 2021). Thus, the focus of this research is on critical civil infrastructure associated with the wastewater and energy sectors. Each of the critical civil infrastructure sectors are interconnected. For example, the energy sector provides power which the wastewater sector relies on to properly function, and the wastewater sector can provide power generation opportunities that can influence the energy sector.

Both energy and wastewater infrastructure systems in the United States (US) are aging. According to the ASCE 2021 report card, America's infrastructure is rated as a C-, which means it is mediocre and requires attention (ASCE, 2021). As climate change persists and these systems continue to age, replacements and upgrades will be necessary. Specific consideration of the potential environmental impacts of a system can promote sustainable development and can enhance the safety, reliability, and resilience of critical civil infrastructure in the US. In November of 2021, President Biden signed the $1.2 trillion infrastructure bill into law to help invest in America's aging infrastructure. The bill included provisions for the energy and water/wastewater sectors [$65 billion dedicated to rebuilding the electric grid, $55 billion dedicated to upgrading water and wastewater infrastructure, and $50 billion dedicated to resiliency, particularly with respect to droughts, floods, and cybersecurity (Lobosco and Luhby, 2021)]. The Infrastructure Bill will facilitate many civil engineering projects in the years to come, creating more competition for these critical projects and their funding applications. In addition to the cost-benefit analyses typically conducted for funding applications,

environmental assessment tools like LCA can help distinguish winning applications as the competition intensifies (Walpole, 2021).

LCA is a tool that can be used to evaluate a range of environmental impacts associated with a product, system, or service over its entire lifetime without shifting or omitting burdens to different stages of life (Dong et al., 2018). LCA is the most mature environmental assessment tool used today, as it has a set of international standards (ISO, 2006). Public and private sectors use LCA to promote products or choose alternatives. Although LCA is not a legal requirement, it can give a good overview of potential environmental impacts of a product/system/service to help inform decision making.

Sustainable development is important in critical civil infrastructure planning and decision making (Fischer and Amekudzi, 2011). As defined by the World Commission on Environment and Development in 1987, sustainable development is “development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs.” Sustainable development encompasses environmental, economic, and social considerations. This concept is becoming more prominent in today’s world, as evidenced by the United Nations proposing 17 Sustainable Development Goals (SDG) through a global partnership (United Nations, 2015).

This research directly connects to many of the global Sustainable Development Goals, as summarized in Table 1.1.

Table 1.1 Relationship between the research and the United Nations Sustainable Development Goals (United Nations, 2015)

United Nations Sustainable Development Goal	SDG Description	Connection to Research
2 ZERO HUNGER	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	Chapter 5
3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages.	Chapter 2 Chapter 3 Chapter 4 Chapter 5
4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.	Chapter 2 Chapter 3 Chapter 4 Chapter 5
6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all.	Chapter 2 Chapter 3
7 AFFORDABLE AND CLEAN ENERGY	Ensure access to affordable, reliable, sustainable, and modern energy for all.	Chapter 4
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.	Chapter 2 Chapter 3 Chapter 4 Chapter 5
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable.	Chapter 2 Chapter 3 Chapter 4 Chapter 5
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and production patterns.	Chapter 4
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts.	Chapter 3 Chapter 5
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalize the global partnership for sustainable development.	Chapter 2 Chapter 3 Chapter 4 Chapter 5

Chapter 2 analyzes wastewater treatment infrastructure in slow growing or shrinking communities to help inform decision makers about what may lead to an environmentally sustainable WWTP. Chapter 3 considers wastewater treatment infrastructure faced with flooding disasters in small and large communities and encourages decision makers and stakeholders to consider resilient WWTP designs. Chapter 4 examines the environmental sustainability of a novel renewable energy system to inform decision makers about the life cycle impacts, beyond costs, of a US based system. Chapter 5 evaluates the potential benefits that various stakeholders may receive (e.g., water security, sustainable agriculture, low environmental impacts of the system, and increased resilience) if irrigation lagoons are widely implemented in Nebraska. In each of these Chapters, environmental, economic, and social impacts are discussed to ensure alignment with the goals of sustainable development.

1.3 Research Objectives

The goal of this research is to explore the life cycle impacts of critical civil infrastructure to help inform decision making and facilitate consideration of environmental, economic, and societal impacts in planning and design stages. The research uses case studies and works closely with stakeholders (e.g., consulting engineers, decision makers, community members/leaders) to provide practical guidance regarding sustainability of critical civil infrastructure systems.

The five big picture objectives of this research are listed below.

1. Quantify the life cycle environmental impacts of construction and operations of 16 small mechanical WWTP case studies to provide industry practitioners with initial guidance towards what may constitute a more or less sustainable

WWTP in a slow growing and/or shrinking community from an environmental perspective.

2. Analyze the tradeoffs between recovery and resilience for case studies of wastewater infrastructure faced with flooding to highlight the potential environmental benefits of investing in resilient critical infrastructure for design engineers, funding agencies, and community leaders.
3. Quantify and compare the life cycle environmental impacts of a case study offshore wind farm in the US to inform decision makers about the potential benefits, beyond costs, of a novel US based system.
4. Use stakeholder discussions to identify barriers to and benefits of implementing irrigation lagoons in practice to improve the information exchange between relevant stakeholders.
5. Synthesize Objectives 1 – 4 by exploring the current status of sustainability assessments of critical civil infrastructure systems and encouraging decision makers to address the difficult to quantify societal factors.

1.4 Structure of the Dissertation

This dissertation is organized as described below. Figure 1.2 shows a visual representation of the dissertation structure.

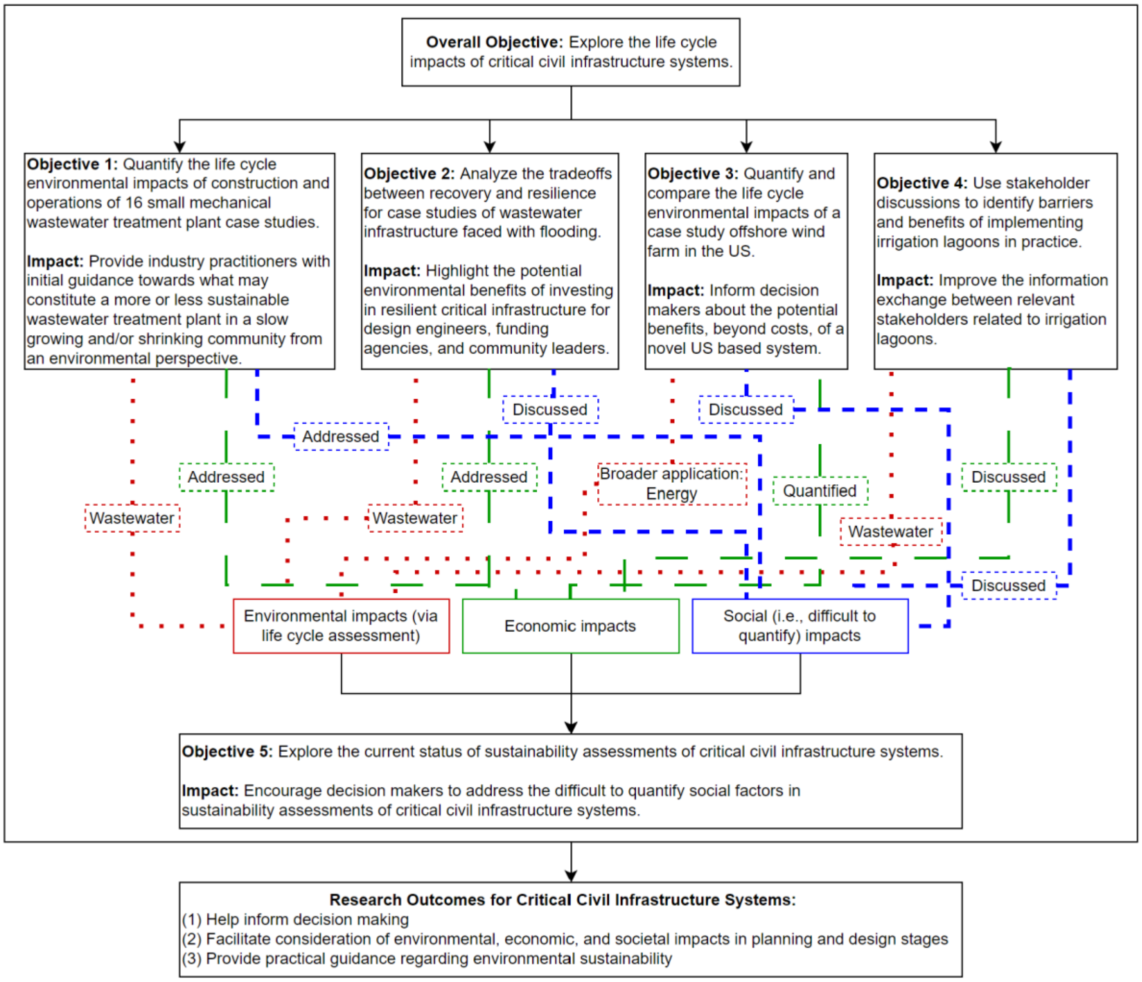


Figure 1.2 Objectives diagram for exploring the life cycle impacts of critical civil infrastructure systems

Chapter 2 assessed the environmental sustainability of the construction and operations of 16 small mechanical WWTPs. This project is an extension of the author's Master's Thesis, completed in December 2019. Substantial modifications were made to the original project and additional analyses were conducted. Chapter 2 aims to synthesize the thesis findings to create a more holistic set of recommendations that are broadly applicable, following approaches used elsewhere (e.g., Dvorak et al., 2008). The modified version includes the addition of: (1) relevancy discussion to highlight how the

results of this study may be applicable to sites beyond the Nebraska cases studied, (2) multiple regression analysis to identify factors driving the variability in the LCA construction impacts, (3) more detailed discussion of the capacity utilization ratio to identify relationships between construction and operations, (4) analysis of the limitations of the work, and (5) discussion of future work needed to address data gaps and statistical conclusions. In addition to the major changes made to the project, this project is included in the dissertation due to its relevance as part of the larger body of work. This project helped to provide a fundamental LCA framework and methodology for the remaining projects. The methodology is well described in Chapter 2 and helps provide the reader with a baseline understanding of LCA and its applications.

Chapter 3 uses case studies to identify tradeoffs of recovery and resilience for wastewater infrastructure faced with flooding. This chapter uses the generalized LCA methodology discussed in Chapter 2 to quantify the environmental impacts associated with recovery and resilience infrastructure in the wastewater sector. Chapter 3 highlights that LCA can be used in conjunction with economic and social evaluations to better understand a community's decision making process.

Chapter 4 evaluates the life cycle environmental impacts of a proposed offshore wind farm in the US. This chapter applies the generalized LCA methodology used in Chapters 2 and 3 to quantify the environmental impacts of renewable energy infrastructure. This chapter highlights that the LCA methodologies and detailed framework used in Chapters 2 and 3 can be applied to other critical civil infrastructure systems beyond wastewater, which is a major contribution of this work.

Chapter 5 identifies barriers and benefits of wastewater reuse for agriculture in Nebraska. This chapter builds upon previously conducted studies that used the LCA framework applied in Chapters 2 – 4 by focusing specifically on the more difficult to quantify, societal factors. This chapter shows that these societal factors may override economic and environmental benefits in the decision making process.

Chapter 6 synthesizes the research presented in Chapters 2 – 5 to emphasize the connections between each project and their overall contribution to the literature. This chapter emphasizes the need to integrate environmental sustainability into decision making. Additionally, this synthesis highlights that there are impacts that are commonly quantified (e.g., economic and environmental), but there are also impacts that tend to be more difficult to quantify (e.g., social/societal) that oftentimes end up driving decision making and thus must be considered as well.

Chapter 7 summarizes the main conclusions of the dissertation and recommends areas for future research.

1.5 List of Publications

This research generated several peer-reviewed publications, which are described below. Some of these are part of this dissertation as chapters, and others are collaborative efforts beyond this dissertation. The authors' contribution to each article is explained below. First are the dissertation chapters that have been/are to be published.

1. Chapter 2 was published in the Journal of Environmental Management (Moussavi et al., 2021). As first author, Sussan Moussavi contributed to the conceptualization, methodology, formal analysis, investigation (data collection), writing of the original draft, and reviewing, editing, and

visualization. Coauthors and their contributions include Matthew Thompson (methodology, reviewing, and editing), Shaobin Li (methodology, reviewing, and editing), and Bruce Dvorak (conceptualization, reviewing, editing, and supervision).

2. Chapter 3 is in preparation for submittal to the Journal of Infrastructure Systems. As first author, Sussan Moussavi contributed to conceptualization, methodology, formal analysis, investigation (data collection), writing of the original draft, reviewing, editing, and visualization. Coauthors and their contributions include Bruce Dvorak (conceptualization, reviewing, editing, visualization, and supervision), and Philip Barutha (conceptualization, reviewing, and editing).
3. Chapter 4 is currently under review for possible publication in Renewable and Sustainable Energy Reviews. As first author, Sussan Moussavi contributed to conceptualization, methodology, formal analysis, investigation (data collection), writing of the original draft, reviewing, editing, and visualization. Coauthors and their contributions include Philip Barutha [conceptualization, investigation (data collection), reviewing, editing, and supervision], and Bruce Dvorak (conceptualization, reviewing, editing, visualization, and supervision).
4. Parts of Chapter 5 are expected to be submitted for publication in the Journal of Extension. Additionally, parts of Chapter 5 are expected to be published as a NebGuide through Nebraska Extension. As first author, Sussan Moussavi contributed to conceptualization, methodology, formal analysis, investigation (data collection), writing of the original draft, reviewing, editing, and

visualization. Coauthors and their contributions include Bruce Dvorak (conceptualization, reviewing, editing, visualization, and supervision).

5. Chapter 6 is expected to be submitted for publication in one of the following journals: Sustainable Cities and Societies, Environmental Sustainability, American Society of Civil Engineers (Journal of Environmental Engineering or Journal of Infrastructure Systems), or Environmental Science & Technology. As first author, Sussan Moussavi contributed to conceptualization, methodology, formal analysis, writing of the original draft, reviewing, editing, and visualization. Coauthors and their contributions include Bruce Dvorak (conceptualization, reviewing, editing, visualization, and supervision) and Kaycie Lane (conceptualization, reviewing, editing, and visualization).

In addition, throughout the PhD program, Sussan Moussavi collaborated with other researchers on the publications described below. A description of the relevance of these publications to this dissertation is also provided.

1. A peer-reviewed journal article published in Sustainable Production and Consumption used a hybrid inventory approach to analyze the environmental impacts of corn production practices in Nebraska (Li et al., 2021). This paper used case studies and LCA methodology, similar to the projects in this dissertation, and served as a foundation for the methodologies used in this dissertation. As coauthor, Sussan Moussavi contributed to the writing (review & editing) of this work.

2. A peer-reviewed journal article published in Water Research quantified the potential mitigation of environmental impacts for WWTPs based on various design and operational scenarios (Pham et al., 2021). This study was developed based on Chapter 2 of the dissertation. The same methodological approach was taken in this study as in Chapters 2 and 4 of the dissertation. LCA and case studies were both used, and much of the case studies used in Chapter 2 were used for this study as well. The results presented in Chapter 2 highlight the environmental implications of overdesign and potential environmental impacts associated with non-process related components in a small WWTP. This paper used that information as a starting point to further analyze how environmental impacts of each can be minimized under certain design conditions. On a large scale, this study utilized the results from Chapter 2 to focus on design practices that may reduce environmental impacts of small WWTPs. As coauthor, Sussan Moussavi contributed to the conceptualization, methodology, and writing (review & editing) of this work.
3. A peer-reviewed journal article published in Water Research compared the environmental life cycle impacts and land use tradeoffs of lagoon and mechanical WWTPs (also known as water resource recovery facilities) across Nebraska (Thompson et al., 2022). The methodologies used in this study were similar to those used in this dissertation, particularly in Chapters 2 – 4. This study used the results of Chapter 2 (mechanical WWTP results) and compared them to lagoons. The lagoon environmental impacts served as a foundation for Chapter 5 of this dissertation; this study showed the low environmental impact

of lagoons, and Chapter 5 aims to identify barriers to implementation of lagoons in Nebraska. As coauthor, Sussan Moussavi contributed to the conceptualization, methodology, formal analysis, investigation (data collection), and writing (review & editing) of this work.

4. A peer-reviewed journal article is expected to be published in the Journal of Environmental Engineering that discusses the environmental, economic, and additional impacts of reducing inflow and infiltration in small wastewater collection systems (Hansen et al., 2023). As coauthor, Sussan Moussavi contributed to the methodology, investigation (data collection), reviewing, and editing of this work.

References

ASCE. (2021). Infrastructure Report Card. Accessed 4/25/2023 from https://infrastructurereportcard.org/

CISA. (2020). Cybersecurity and Infrastructure Security Agency. Accessed 4/25/2023 from https://www.cisa.gov/critical-infrastructure-sectors

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., & Sheikh, A. (2011). The case study approach. BMC medical research methodology, 11(1), 1-9. https://doi.org/10.1186/1471-2288-11-100

Dong, Y., Miraglia, S., Manzo, S., Georgiadis, S., Sørup, H.J.D., Boriani, E., Hald, T., Thöns, S. and Hauschild, M.Z. (2018). Environmental sustainable decision making–The need and obstacles for integration of LCA into decision analysis. Environmental Science & Policy, 87, 33-44. https://doi.org/10.1016/j.envsci.2018.05.018

Dvorak, B. I., Morley, M., & Denning, P. (2008). Relative impact on GAC usage rates of operating strategies for treatment of contaminated groundwater. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 12(2), 60-69. https://doi.org/10.1061/(ASCE)1090-025X(2008)12:2(60)

Fischer, J. M., & Amekudzi, A. (2011). Quality of life, sustainable civil infrastructure, and sustainable development: Strategically expanding choice. Journal of urban planning and development, 137(1), 39-48. DOI: 10.1061/(ASCE)UP.1943-5444.0000039.

Hansen, A. (2023). Reducing I/I in Small Collection Systems: Environmental, Economic, and Other Impacts. M.S. Thesis, Environmental Engineering, University of Nebraska-Lincoln.

ISO. (2006). Environmental management - life cycle assessment - principles and framework ISO 14040. Int. Org. Stand. Accessed 4/25/2023 from https://www.iso.org/standard/37456.html

Li, S., Thompson, M., Moussavi, S., & Dvorak, B. (2021). Life cycle and economic assessment of corn production practices in the western US Corn Belt. Sustainable Production and Consumption, 27, 1762-1774. https://doi.org/10.1016/j.spc.2021.04.021

Lobosco and Luhby. (2021). Here's what's in the bipartisan infrastructure package. CNN Politics. Accessed 4/25/2023 from https://www.cnn.com/2021/07/28/politics/infrastructure-bill-explained/index.html

Moussavi, S., Thompson, M., Li, S., & Dvorak, B. (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of

construction and operations. Journal of Environmental Management, 292, 112802. https://doi.org/10.1016/j.jenvman.2021.112802

Pham, A., Moussavi, S., Thompson, M., & Dvorak, B. (2021). Environmental life cycle impacts of small wastewater treatment plants: Design recommendations for impact mitigation. Water Research, 207, 117758. https://doi.org/10.1016/j.watres.2021.117758

Thompson, M., Moussavi, S., Li, S., Barutha, P., & Dvorak, B. (2022). Environmental Life Cycle Assessment of small water resource recovery facilities: Comparison of mechanical and lagoon systems. Water Research, 215, 118234. https://doi.org/10.1016/j.watres.2022.118234

United Nations. (2015). The 17 Goals. Accessed 4/25/2023 from https://sdgs.un.org/goals

Walpole. (2021). How will the bipartisan infrastructure law change the civil engineering industry? American Society of Civil Engineers. Accessed 4/25/2023 from https://www.asce.org/publications-and-news/civil-engineering-source/article/2021/12/08/how-will-the-bipartisan-infrastructure-law-change-the-civil-engineering-industry

CHAPTER 2 ASSESSMENT OF SMALL MECHANICAL WASTEWATER TREATMENT PLANTS: RELATIVE LIFE CYCLE ENVIRONMENTAL IMPACTS OF CONSTRUCTION AND OPERATIONS

This chapter is published: Moussavi, S., Thompson, M., Li, S., & Dvorak, B. (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of construction and operations. Journal of Environmental Management, 292, 112802. https://doi.org/10.1016/j.jenvman.2021.112802 Used with permission.

2.0 Abstract

Many slow growing and shrinking rural communities struggle with aging or inadequate wastewater treatment plants (WWTPs), and face challenges in constructing and operating such facilities. Although existing literature has provided insight into the environmental sustainability of large facilities, including both the construction and operational phases, these studies have not examined small, rural facilities treating less than 7,000 cubic meters per day (1.8 million gallons per day) of wastewater in adequate depth and breadth. In this study, a detailed inventory of the construction and operational data for 16 case studies of small WWTPs was developed to elucidate their environmental life cycle impacts. An attributional life cycle assessment framework was followed. The results show that the environmental impacts of both the construction and operational phases are considerable. Energy use was the dominant contributor to the operational environmental impact, and improving energy efficiency of a plant may reduce the environmental impacts of a small WWTP. Construction impacts can vary considerably between facilities (e.g., coefficient of variation for the construction impacts ranged from 60% to 78% depending on the impact category). Process-related factors (e.g., concrete

and reinforcing steel used in basins) are typically sized using the design flow; thus, much of the variability in construction impacts among plants stems from the non-process related infrastructure. Multiple regression analysis was used as an exploratory tool to identify which non-process related plant aspects contribute to the variable environmental impact of small WWTPs. These factors include aluminum, cast iron, and capacity utilization ratio (defined as the ratio of average flow to design flow). Thus, industry practitioners should consider these factors when aiming to reduce environmental impacts of small WWTPs related to construction. Scenario sensitivity analyses found that the environmental impact of construction became smaller with longer design life, and end-of-life consideration does not heavily influence the environmental sustainability of a WWTP.

2.1 Introduction

Wastewater treatment plants (WWTP) are essential infrastructure systems in today's society, as these facilities treat raw wastewater to protect public health and the environment. According to the United States Department of Agriculture (USDA), 78% of the roughly 15,000 WWTPs in the US treat less than 3,785 cubic meters per day (1 million gallons per day) and serve small communities (USDA, 2020a). In most US states, including Nebraska, between 90% and 95% of the publicly owned WWTPs serve small communities (US EPA, 2016a). Additionally, 95% of non-metropolitan counties in the US experienced a growth rate of less than 10% in the last decade, emphasizing that many of these small communities are slowly growing or declining in population (USDA, 2020b).

Many of these slow growing and shrinking rural communities serving less than 10,000 people and with an average daily wastewater flow rate of less than 7,000 cubic meters per day (1.8 million gallons per day) currently struggle with aging or inadequate WWTPs and face challenges in constructing and operating these facilities (US EPA, 2016b; US EPA, 2020). Although small WWTPs serve only 7% of the US population in total, roughly 80% of the WWTPs expected to be constructed will serve small communities (US EPA, 2016a). It is anticipated that these newly built WWTPs will ultimately serve 1.1 million people and have an estimated economic need of $5.5 billion (US EPA, 2016a).

Many small communities across the US report that meeting federal and local wastewater requirements are some of their most expensive infrastructure projects (ASCE, 2017). Loan programs are becoming increasingly available to small, slow growing communities that often times have fewer financing options when it comes to wastewater infrastructure upgrades and replacements (Pearson, 2007; US EPA, 2020). For example, the USDA recently announced their intentions to help rural communities facing challenges related to wastewater infrastructure (USDA, 2020b). The Environmental Protection Agency (EPA) has also stated that their goal is to ensure long-term economic and environmental sustainability in rural communities (USDA, 2020b). Both agencies have committed to making rural systems a funding priority in the future, realizing the large scale, national impact such systems may have.

Existing loan programs, such as the Clean Water State Revolving Fund (CWSRF) and the Rural Utilities Service Water and Environmental Programs, aid small communities in constructing and operating wastewater treatment systems (USDA,

2020c). The current loan programs include general language encouraging sustainable design of small community infrastructure, but there is currently little guidance as to what key considerations may be to minimize the environmental impact from the construction of small community wastewater infrastructure.

Loan programs, although mainly intended to reduce economic impacts, may indirectly facilitate noticeable environmental impacts. The CWSRF requires a design planning period of at least 20 years, leading to the issue of overbuilding a WWTP's infrastructure (NDEE, 2019a) to meet the future needs of the oftentimes optimistic, anticipated population growth of a small community. Overbuilding refers to the idea that a plant may be built to handle a larger flow rate than currently experienced to allow for community growth. Although WWTPs in small towns are typically designed with multiple pumps, basins/tanks, and equipment according to flow rate based design standards (GLUMRB, 2014), small communities that apply for loan programs may intentionally overbuild the WWTPs with the consideration that there will not be another funding opportunity available for upgrades and improvements for another 20 years (NYSDEC, 2014). Therefore, it is imperative that municipalities aim to meet the fluctuating demand for wastewater treatment more closely, realizing the potential environmental impacts of an overbuilt facility (Amores et al., 2013).

Life cycle assessment (LCA) can be used to directly measure the potential life cycle environmental impacts of various products and technologies (Kamali et al., 2019; Li et al., 2020). It is widely assumed that WWTPs have only positive impacts on the environment, as the main purpose of a WWTP is to treat raw wastewater to protect public health and the environment. However, the construction and operation of WWTPs of all

sizes can create negative environmental impacts at a local, regional, and global level (Seifert et al., 2019).

Although existing literature has provided some insight into the environmental sustainability profiles of large wastewater treatment facilities (Corominas et al., 2013; Morera et al., 2017), these studies have not explicitly examined small facilities in adequate depth and breadth, particularly including both the construction and operation stages. As highlighted by Morera et al. (2020) and Nguyen et al. (2020), both of which found the construction phase to be an important contributor to the overall environmental impact of large WWTPs, the existing literature lacks studies using detailed construction inventory data. With the inevitable future upgrades and replacements needed for wastewater infrastructure, and the necessity to ensure reduced public and environmental health risks, it is increasingly important to avoid shifting the environmental burden from operational aspects to infrastructure development in order to have a more holistically sustainable system (Nelson, 2005).

Studies of WWTPs that included the construction stage in their system boundaries generally found that the contribution of construction is higher than 5% to the total environmental impact (Corominas et al., 2013), with some studies (specifically those analyzing conventional activated sludge systems) finding the construction to account for up to 43% of the total environmental impact (Ortiz et al., 2007). Mo et al. (2018) found that the construction and operation phases of small drinking water facilities present high volumetric energy intensities and carbon footprints because of their lack of economies to scale, which suggests that small WWTPs will present similar results. Devi and Palaniappan (2017) found that the construction impacts become more significant as the

energy efficiency of WWTP operations increase, which is important to note as many WWTPs are improving their energy efficiency to reduce operational costs (Hanna et al., 2018; Thompson et al., 2020). Similarly, Emmerson et al. (1995) used limited system boundaries and a limited construction and operational data inventory set (much of which was obtained from literature) to conduct an LCA of three WWTPs treating less than 200 cubic meters per day and found the construction stage was important for facilities with lower operating costs. These findings suggest that the environmental impacts associated with construction may be an important portion of the overall environmental impact of small WWTPs, as the initial construction can be a large share of the total life cycle environmental impact relative to operations for small facilities (Emmerson et al., 1995; Li et al., 2010; Corominas et al., 2013; Morera et al., 2017).

Based on current literature, construction impacts merit consideration. The significance of this research is highlighted by the use of multiple regression analysis (MRA) as an exploratory tool to identify non-process related factors independent of flow that can offer practitioners areas for potential environmental impact reduction. Suggestions and guidance as to what aspects of a small WWTP merit greater focus in the design and construction phase to reduce environmental impacts, realizing that many aspects of conventional WWTP designs are often constrained by standard design guidelines, will be provided to practicing engineers to bridge the gap between theory and practice.

This research is among the few studies focused on small WWTPs treating less than 7,000 m^3/d in slow growing communities, as most LCA studies related to WWTPs analyze large plants. The sample size of 16, to the best of our knowledge, is the first

study to include this many case studies based on detailed construction and operational inventories. The detailed and site-specific inventories enhance the published literature by reducing the number of assumptions made related to the site-specific inventories of WWTPs and increases the validity of the contribution of construction to the overall environmental impacts of small WWTPs. The exploratory use of MRA has not yet been used to understand the relationship between inventory and flow rate, with the goal of identifying key factors that may offer potential reduction of environmental impacts related to the construction of small WWTPs. The objective of this research is to provide industry practitioners with initial guidance towards what may constitute a more or less sustainable WWTP in a slow growing and/or shrinking community from an environmental perspective. Although operations (e.g., water emissions and energy) are generally the current focal point of environmental sustainability in the wastewater sector, construction of WWTPs may also present notable environmental impact reduction potential. It is of the upmost importance to gain a comprehensive understanding of the environmental impacts related to small WWTPs to encourage sustainable development of small community infrastructure. Thus, the authors are motivated to answer two key research questions: (1) Is the construction phase an important contributor to the total environmental impact of a small WWTP? (2) Which inventory inputs can be identified by MRA to potentially present the greatest opportunities to modify WWTP designs to reduce environmental impacts, without straying from common design guidelines and practices? Ultimately, this research will utilize case studies to discuss environmental impacts of small WWTPs, and to highlight where a design engineer, community leader, regulator, or

other stakeholder could modify construction practices to reduce overall WWTP environmental impacts.

2.2 Methodology

An attributional LCA framework was followed in this study to comprehensively model the environmental impacts of small WWTPs based on the data inventory (Weidema et al., 2018). Each of the four LCA phases were completed (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation). The interpretation phase included an MRA.

2.2.1 Goal and scope

The goal of this study is to quantify the environmental impacts regarding the construction and operation phases of 16 small mechanical WWTP case studies from a life cycle perspective (Moussavi, 2019). More detailed methods, as well as additional case study data, are provided in Moussavi (2019). The product system analyzed in this study includes four types of small mechanical WWTPs most commonly employed in small, rural communities (US EPA, 2000a): 1) extended aeration (EA), 2) extended aeration – package (EA-P), 3) oxidation ditch (OD), 4) sequence batch reactor (SBR). These technologies are mechanical technologies, as they use mechanical components (e.g., pumps, blowers, etc.) to treat wastewater. These technologies are all biological aeration processes and are relatively similar in terms of the overall wastewater treatment process.

As shown in Figure 2.1, the primary treatment, tertiary treatment, and auxiliary functions (e.g., buildings, sidewalks, aluminum safety railings) highlighted in red, blue, and green respectively, are similar for all three types of plants, and only the secondary treatment process varies among technology, although all of the secondary treatment

processes are modifications of the activated sludge process. Additionally, aerobic digestion is being used with each technology. These very slight variations in the secondary treatment process show the high degree of similarity among most parts of a small mechanical WWTP's infrastructure and operations.

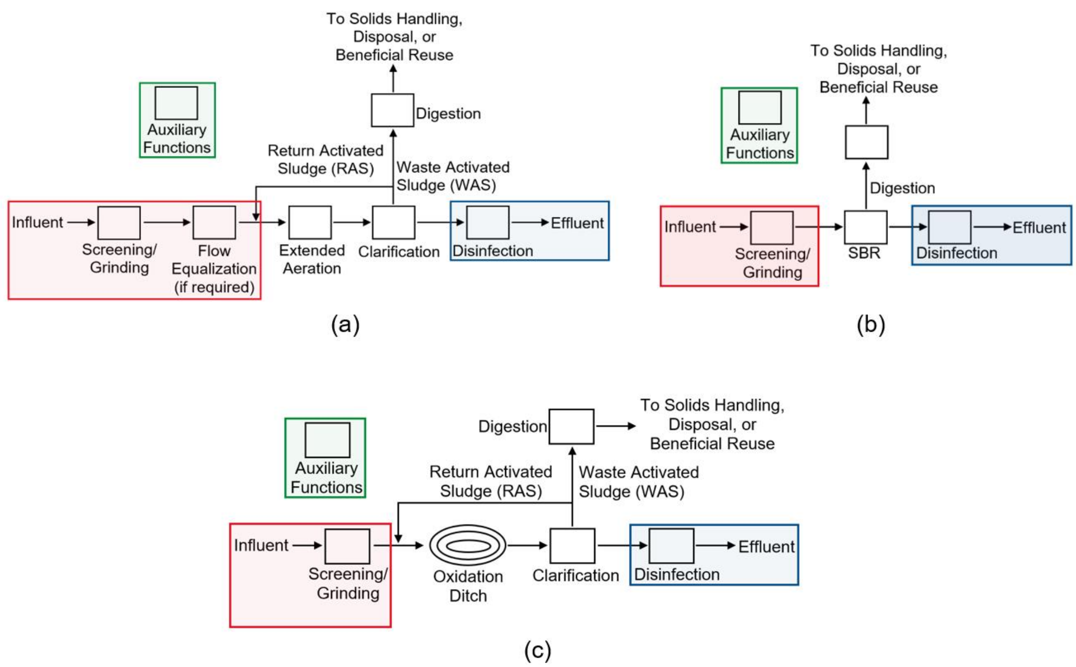


Figure 2.1 Process flow diagram of mechanical WWTP technologies studied. (a) extended aeration, (b) sequence batch reactor, (c) oxidation ditch. Primary treatment (red), tertiary treatment (blue), auxiliary functions (green). Modified from US EPA, 2000a.

It was assumed that the four technologies studied are similar in terms of operations, consistent with what Hanna et al. (2018) found when looking at the energy intensity of small mechanical WWTPs. Hanna et al. (2018) used energy data collected from 83 and 71 small WWTPs in Nebraska and Pennsylvania, respectively, to benchmark the energy intensity of small WWTPs that are similar to the ones studied in this research. Nebraska and Pennsylvania WWTPs were found to be similar in terms of energy intensity, suggesting that the construction impacts are likely similar as well since both

states use the same design guidelines (GLUMRB, 2014). This further suggests that small Nebraska systems represent a wide range of systems based on similar design guidelines. Hanna et al. (2018) also found factors such as capacity utilization ratio (CUR, defined as the ratio of average flow to design flow) and climate-controlled floor area to be some of the significant factors influencing the energy intensity of small plants, rather than the specific technology employed at the plant. Although the impacts may vary slightly among technologies, the sample size of 16 plants is small, and site-specific factors dominate variability between plants; thus, environmental impacts in this study are not compared based on the secondary treatment technology (i.e., EA, EA-P, OD, and SBR).

The function of the product system is to treat raw municipal wastewater in order to meet regulatory agencies' requirements to ensure safety for humans and the environment. Therefore, the functional unit utilized in this study is one cubic meter of treated wastewater, consistent with relevant literature (Corominas et al., 2013, 2020; Morera et al., 2017). System boundaries were chosen to account for both the construction and operational phases of the mechanical WWTPs. The distinction between the construction phase and the operational phase was determined to be an important part of this research. The construction phase comprises of the civil works used to construct the WWTP and the equipment at the WWTP. The operational phase comprises of the energy use, water emissions from the treated effluent, air emissions from the biological treatment process, and soil emissions from biosolids land application. The WWTP operational life was assumed to be 20 years based on common US design standards (GLUMRB, 2014). WWTPs can be demolished at the end of their useful life, or the facilities may be retrofitted for continued operations. Due to the lack of data availability surrounding the

demolition of WWTPs, the end-of-life phase was only considered as a possible scenario in a sensitivity analysis.

2.2.2 Life cycle inventory

A list of the specific communities analyzed in this study and their respective plant type, recorded population (United States Census Bureau, 2010), and flow rates (US EPA, 2019) are presented in Appendix A Table A1. Each community was assigned a unique letter, based on the relative amount of construction impact associated with the plant, as a means of identification. These 16 plants were chosen as case studies because of their reasonable representativeness of small systems in terms of flow rate, technology type, and energy intensity, as well as the availability of the utility and construction data (Moussavi, 2019). Additionally, this study focuses on WWTPs serving communities of less than 3,000 people, since this size range is representative of slow growing and shrinking rural communities in the US. The utility data for the chosen plants were readily available based on a previous study conducted by Hanna et al. (2018). The utility data was collected for a minimum of 12 months, but oftentimes up to three years. The plants also completed the construction process during one or two stages, allowing for complete construction plans to be accessible. A majority of the plants were built between 1975 and 2012, and only three of the plants were built earlier than 1975. The more recent build dates allowed easier access to and readability of construction plans and documents.

Inventory data used in this research was comprised of foreground data and background data, based on a similar study conducted by Morera et al. (2017). Foreground data refers to the data that can be measured at point of use. Foreground data collected includes energy usage, water and soil characteristics, air emissions from the biological

treatment process, and construction inventories. Energy usage was collected from utility bills provided by the communities. Water and soil characteristics were obtained from the Nebraska Department of Environment and Energy (NDEE) and the US EPA's Enforcement and Compliance History Online (ECHO) databases (NDEE, 2019b; US EPA, 2019). Sludge data quality was compared with literature values and was deemed accurate as collected (Metcalf and Eddy, 2014). Sludge production rates were estimated using a linear regression of sludge land application rates versus average effluent flow rate. Air emissions from the biological wastewater treatment process are rarely included in WWTP LCA studies (Morera et al., 2017), and such emissions are not recorded by the NDEE. Consequently, air emissions associated with the biological treatment process were assumed to be a release of methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) into the atmosphere. Empirical relationships were developed using actual water use data from the facilities and literature values to estimate the air emissions from the biological treatment process (Foley et al., 2010). Construction inventories were collected from engineering design documents, as well as from literature (Devi and Palaniappan, 2017). Transportation distance of construction materials was assumed to be 40 kilometers (km) based on typical values used in literature (Morera et al., 2017).

Background data refers to data that is measured and stored within the Ecoinvent database, as well as data that was used to create and refine foreground resources. Background data was collected using the Ecoinvent Database v3.3 (Wernet et al., 2016). This background data was used when data was not able to be collected on-site, or when the processes were too complicated to model using only directly collected data. Ecoinvent data was specifically used for background processes such as the US electricity

grid mix, processes required to produce building materials and equipment, and transportation inputs and outputs. The dataset chosen for each input and output in the LCA model was based on user judgment, as well as literature (Morera et al., 2017). It should be noted that there are underlying assumptions related to background processes for the Ecoinvent data. Users should understand these assumptions to ensure that the selected data aligns with their goal and scope.

All collected data inventory were aggregated and organized, with the appropriate conversions to a mass basis normalized by the flow over 20 years made. A complete list of this data inventory is provided in Appendix A Table A2. Figure 2.2 represents the total inventory data set within the selected system boundary for the specified product system, with each input's and output's respective units.

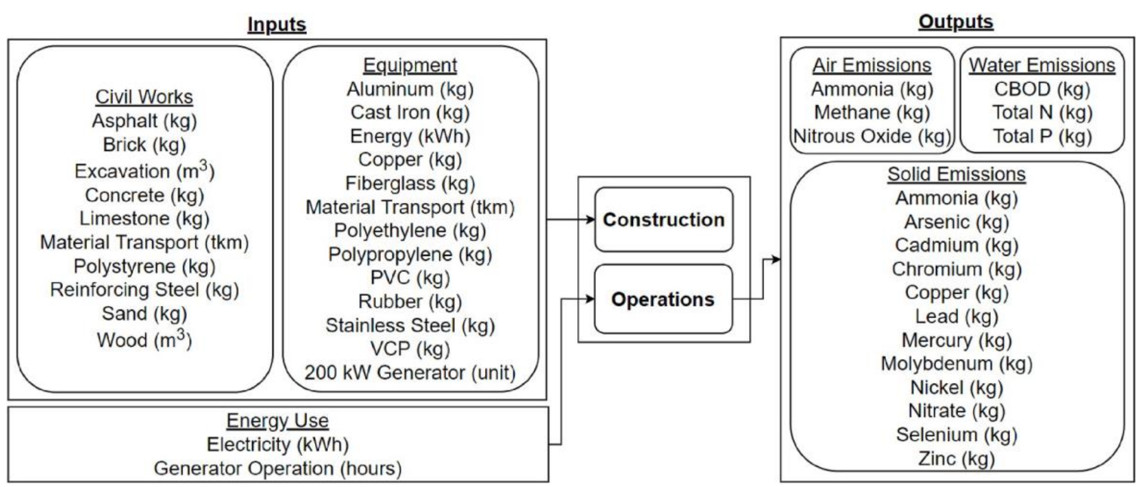


Figure 2.2 Product system data inputs and outputs

2.2.3 Life cycle impact assessment

SimaPro v8.4, compliant with the International Organization for Standards (ISO) 14040 series (ISO, 2006), was used to conduct the life cycle impact assessment (LCIA). A collection of environmental impacts for each inventory item were calculated based on the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

(TRACI) impact assessment method v2.1 (Bare et al., 2002). TRACI was chosen for the current study due to its ability to represent regional and global environmental impacts, as well as its specificity to US systems and processes. In this study, the specific environmental impacts analyzed include the impact categories of ozone depletion [kilograms (kg) chlorofluorocarbons-11 (CFC) equivalents (eq)], global warming [kg carbon dioxide (CO_2) eq], smog [kg ozone (O_3) eq], acidification [kg sulfur dioxide (SO_2) eq], fossil fuel depletion [megajoule (MJ) surplus], eutrophication [kg nitrogen (N) eq], ecotoxicity [comparative toxic units (CTU_e)], carcinogens (CTU_h), noncarcinogens (CTU_h), and respiratory effects (kg particulate $matter_{2.5}$ (PM)]. These impact categories are further normalized based on a US factor to evaluate different categories on the same basis (Ryberg, 2014).

2.2.4 Scenario sensitivity and uncertainty analyses

ISO Standards state that results obtained during the LCIA phase should reflect results of any sensitivity analyses performed (ISO, 2006). The results of an LCA may be highly sensitive to specific variables. Scenario sensitivity analyses can specifically test the study's system boundaries and assumptions. A scenario sensitivity analysis varies a single variable in a model to see how changing that variable may affect the LCIA results. While this is not a strict mathematical model of sensitivity, this method can clearly illustrate the significance of certain variables to an impact category. In the case of LCA, this is often a path taken to further communicate the results (Bjorklund et al., 2002; Guo and Murphy 2012).

Analyses were performed to examine the sensitivity of the results based on two scenarios: (1) plant design life and (2) end-of-life for reinforced concrete. For (1), the

environmental sustainability profile of each case study was developed for plant design lives of 10, 20, 30, 40, 50, and 60 years. These design lives were chosen based on the reported system lifespans of the case studies. This analysis aims to present the environmental impacts associated with the best and worst case build dates. For (2), two scenarios were analyzed: 100% wasting of reinforced concrete and 100% recycling of reinforced concrete. This analysis provides insight as to which end-of-life process may have a more environmentally sustainable footprint. Uncertainty analysis was performed by considering the variability of the case studies. The uncertainty values for the environmental impacts for each impact category were obtained by calculating the minimum, mean, and maximum values of the data, similar to Morera et al. (2017). Error bars were developed to show the relative variability among the results for a specified impact category. A larger error bar in a given impact category corresponds to a more variable data set (Molinos-Senante et al., 2014). Uncertainty of the background data is not considered.

2.2.5 Multiple regression analysis

MRA can be used as an exploratory tool to further investigate possible factors driving the variability in LCA construction impacts (e.g., Lin et al., 2018). It is important to note that MRA, as used in this study, is not intended to be a predictive model due to the limited dataset. Rather, it was used as a means of identifying possible parameters that may influence the variability in the construction impact.

The dependent variable was calculated by multiplying the normalized environmental impact from the construction of each plant for each impact category by the respective impact category's TRACI normalization factor, and multiplying that product

by the respective plant average flow rate to get a net environmental impact. This was done to put the impact on the same non-normalized scale as the raw input data (e.g., mass of cast iron). Independent variables were chosen from the data inventory via a stepwise method, based on each variable's F statistic and significance, using a significance level of 0.05. The variables identified as drivers to the variability in environmental impact of construction (i.e., the independent variables) were plant design flow, plant average flow, cast iron used mainly for piping, and aluminum used mainly for handrails and grating. Other studies (Fraas and Munley, 1984; Ruiz-Rosa et al., 2016) found variables like average flow rate and CUR to be important for overall WWTP cost modeling.

2.3 Results and Discussion

2.3.1 Average environmental sustainability profile of 16 case studies

This study intends to show the potential environmental impacts of both the construction and operations of small WWTPs. The individual LCA results of each of the 16 case studies (see Appendix A Table A3) were first averaged together to create a general environmental sustainability profile of a small WWTP in Nebraska. Because there is great variability among the LCA results of each case study, this average profile serves as a baseline to visualize the amount of variability seen among the cases studied. To compare impacts on the same basis, the normalized and characterized average environmental profile of the 16 case studies are presented in Figure 2.3a and Figure 2.3b, respectively. The unit for the normalized environmental impact is "(environmental impact per 1 m^3 of treated wastewater)/(environmental impact per US citizen per year)" for a specific impact category based on the normalization factors provided by the Updated US and Canadian Normalization Factors for TRACI v2.1 (Ryberg, 2014). The

unit for the relative environmental impact is the "process contribution as a percentage of the total impact" of a specific impact category. In Figure 2.3a, the error bars illustrate the variability in the inventory inputs, and consequently the LCA results, among the 16 plants. It is important to note that each impact category has unique units (See Appendix A Table A4) to quantify the environmental impact per functional unit; thus, the 10 impact categories cannot be compared against each other.

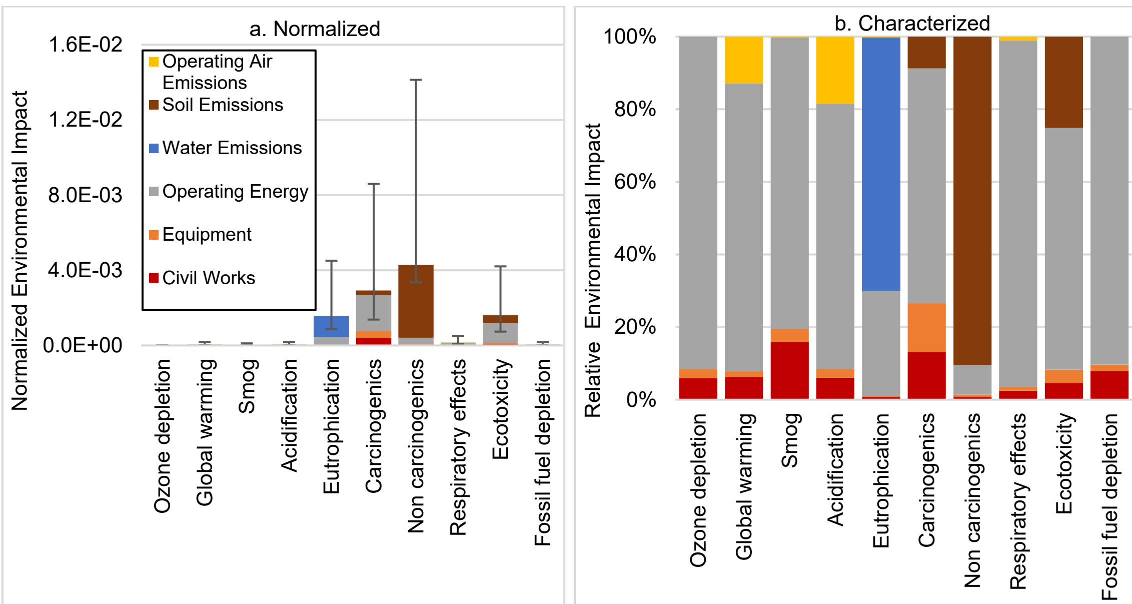


Figure 2.3 Average normalized (a) and relative (b) total environmental impact over 20 years of the 16 case studies with error bars placed on (a) showing the variability in inventory inputs

According to the LCA Handbook, the cutoff criteria for a process to have a considerable contribution to an impact category is at least 5% (Zampori et al., 2016). When considering the contribution of operating energy to the average environmental burden, the contribution is greater than 50% for all but two impact categories. For each impact category affected, almost all of the environmental burden associated with the operating energy process is due to electricity usage (e.g., for mechanical processes and

machinery used for operations). Although the operating energy process is the dominating contributor to the environmental impact for most impact categories, it should be noted that if the electric grid moves towards renewable resources, the relative contribution of the operating energy may decrease for some impact categories (Polruang et al., 2018). Figure 2.3b also shows that the contribution of the construction process (civil works and equipment) to the overall burden for all but two impact categories (noncarcinogenics and ecotoxicity) is greater than 5%, with respiratory effects at 4%. A relatively large amount of environmental impact associated with construction is due to reinforced concrete production and cast iron piping production for many of the impact categories. Operating air emissions contribute marginally to the overall environmental impact of a small WWTP in most impact categories except global warming and acidification. Operating air emissions contribute noticeably to these impact categories due to aeration processes during secondary wastewater treatment. It should be noted that the high contribution of soil emissions to the non-carcinogenic impact category is likely an overestimation of toxic metal impacts, as current TRACI methods conduct characterization assuming the total metal concentration in the environment is bioavailable and toxic (Ryberg et al., 2014).

The impacts of both construction and operations are relevant for the small WWTPs illustrated in Figure 2.3, even when accounting for the variability among the individual plant life cycle inventories. The findings presented in Figure 2.3 are consistent with relevant literature, which has found that construction may account for between 5% and 43% of the total environmental impact of a WWTP depending on technology and size of the WWTP studied (Ortiz et al., 2007; Corominas et al., 2013). For the impact

categories of eutrophication, carcinogenics, non-carcinogenics, and ecotoxicity, there are large error bars, as shown in Figure 2.3a. This implies that there is a high variability among the inventory input data used to develop the average environmental sustainability profile of the 16 case studies. This variability can be attributed to site-specific factors such as operational efficiency and construction resources.

2.3.2 Influence of energy efficiency on the environmental impact of a WWTP

Operating energy is the dominating process contributing to the overall environmental impact of a facility in most impact categories. The energy efficiency of a plant can be evaluated by comparing its energy impact to a regression estimate of its energy intensity (i.e., plant average annual electricity usage divided by plant average annual flow rate) based on similar Nebraska WWTPs (Hanna et al., 2018). The Hanna et al. (2018) model predicts the expected energy intensity of a small WWTP based on factors such as climate-controlled floor area, CUR, and average flow rates. If a facility is operating efficiently, the actual energy intensity will be similar to or smaller than the regression value for similar plants. In cases where the actual energy intensity exceeds the regression estimated energy intensity, there are likely operational inefficiencies (e.g., lack of automation or inadequate screening) associated with that plant. In other words, a more operationally efficient plant creates less environmental impact from the operating energy it uses. Figure 2.4 shows the relationship between the actual and regression estimated energy intensities for each WWTP.

When comparing the actual energy intensity to the regression estimate of energy intensity, it can be seen in Figure 2.4 that most regression estimated energy intensities (Plants A, B, C, F, G, I, J, M, N, O, and P) are lower than the actual energy intensity.

This is expected, as a majority of the plants in this study are less energy efficient than the regression average of Nebraska plants. This is, in part, because many of the case studies chosen for this research were previously involved in a technical assistance project that prioritized the inclusion of plants with a high potential for energy efficiency improvements (Hanna et al., 2018; Thompson et al., 2020).

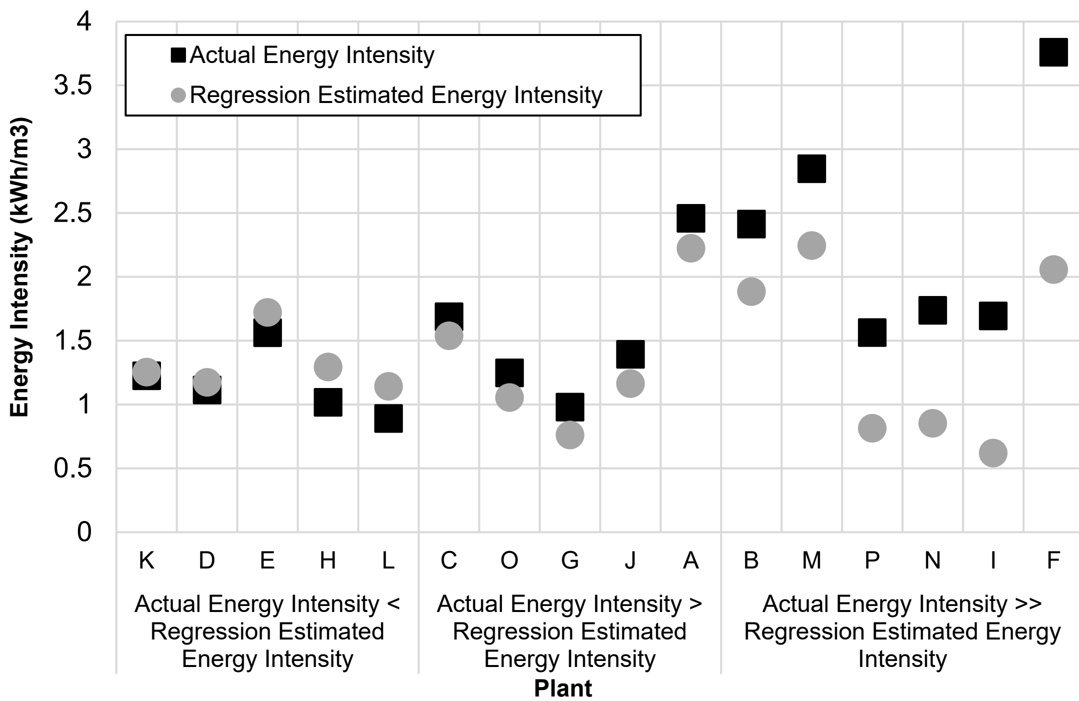


Figure 2.4 Actual energy intensity and regression estimated energy intensity for each plant, grouped based on the difference between actual and regression estimated values

Operating inefficiencies are best highlighted in Figure 2.4 by Plants B, F, I, M, N, and P, where there is a large vertical distance between the actual energy intensity and the regression estimate of energy intensity. These plants have the greatest opportunity for energy efficiency improvements. Plants F, N, and I have the largest differences between actual and regression estimated energy intensity. Plant F experiences inflow and infiltration (I&I) issues, oil and grease buildup from local cafes, and over 30-year-old

basins. Plant N has significant I&I problems, variable flows due to a nearby egg processing facility, 25-year-old pumping equipment, operator overturn, damaged water lines due to freezing, non-programmable thermostats, and fluorescent lighting. In discussion with the facility operator and on-site electrical measurements of unit operations, it was discovered that Plant I has inadequate screening, leading to tumbleweeds clogging the mechanical aerators and mixers, which causes a larger motor load resulting in faster burnout and higher energy use.

Because the operating energy is the dominating contributor to the overall environmental sustainability of a small mechanical WWTP in most impact categories, the energy efficiency of a plant is important to consider. An operationally inefficient WWTP may suffer from increased environmental impacts associated with operations because more energy must be used to treat less wastewater.

2.3.3 Identification of key parameters influencing the variability in construction impact

Although operating energy is most often the largest contributor to the overall environmental profile of a facility, construction is also a notable contributor and exhibits significant variability for a given impact category as shown in Figure 2.3a, consistent with literature (Nguyen et al., 2020). The coefficient of variation for the construction impacts ranged from 60% to 78% depending on the impact category, emphasizing the variability in construction impact among the 16 case studies. Nguyen et al. (2020) found that the construction phase impact was largely due to the large amount of concrete and reinforced steel used for plant construction. While this finding is consistent with the current study's findings, the amount of concrete and reinforcing steel used in a WWTP's

infrastructure is heavily dependent on design flow and follows strict design guidelines. Therefore, to answer the second research question raised, MRA was used as an exploratory tool to further investigate which inventory inputs, beyond those that scale with design flow, drive the variability in LCA impacts related to the construction phase in order to provide recommendations for non-process related environmental impact reductions. A significance level, α, of 0.05 was used for this exploratory analysis. The carcinogenic impact category was focused on in this study due to its association with human health, although the results presented are fairly representative of the remaining impact categories.

The independent variables identified by MRA as drivers to the variability in environmental impact of construction include plant design flow, plant average flow, cast iron, and aluminum. Plant design flow and plant average flow are related via the CUR. Although concrete and reinforcing steel, in addition to aluminum and cast iron, make up a large portion of the construction inventory for each plant (see Appendix A Figure A1), concrete and reinforcing steel were not identified by the MRA to be drivers to the variability in the environmental impact from construction. This is again because resources such as cast iron and aluminum may vary based on factors beyond design flow (e.g., plant layout and user/safety preferences), whereas resources such as concrete and reinforcing steel are used mainly in infrastructure that scales in size based on design flow standards (e.g., basins). Therefore, construction impacts related to cast iron and aluminum may be directly reduced through construction practices such as implementing alternative plant layouts and using alternative piping materials, whereas construction impacts related to concrete and reinforcing steel may be indirectly reduced by using a

design flow rate closer to the average operational flow rate. Cast iron and aluminum will be discussed further in the subsequent sections.

These construction related factors may be among the best to consider if a design engineer or stakeholder is looking for areas to directly reduce the environmental impacts related to construction of a small WWTP, although factors beyond these (e.g., CUR) also merit consideration. The results shown in Table 2.1 represent the MRA results for the carcinogenic impact category. However, similar trends were observed among the 10 TRACI impact categories (see Appendix A Table A5) with the exception of aluminum, which was not as prevalent in some of the impact categories. The amount of aluminum at each plant varied highly, with some plants having minimal use. These key factors are discussed in more detail in the subsequent sections.

Table 2.1 Multiple regression analysis results for the construction impact to the carcinogenic impact category

Regression Term	Coefficient	P-value
Intercept	-1.50E-02	1.58E-01
Plant Design Flow	4.38E-01	4.03E-06
Plant Average Flowrate	-4.88E-01	1.37E-04
Cast Iron	4.43E-06	2.98E-07
Aluminum	4.85E-06	4.58E-03
Adjusted R Square	0.99	
F - Test	6.01E-12	

2.3.3.1 Influence of CUR on construction and operational impacts

The CUR of a plant refers to the plant average flow divided by the plant design flow, both factors identified by the MRA. These factors define how overbuilt a plant may be in terms of construction relative to the operational flow it treats (Corominas et al., 2020). As highlighted by the negative coefficient for plant average flow rate in Table 2.1, it is expected that as the plant average flow increases, the construction impact to

carcinogenics may decrease. As the plant average flow increases (i.e., CUR increases), the plant begins to treat a flow rate closer to the design flow, resulting in more efficient operations and better use of the infrastructure built to accommodate the design flow.

Often in engineering, for a growing or large facility, it is expected that there is a tradeoff of better energy efficiency (i.e., lower operating energy impacts) with more upfront infrastructure investment (i.e., higher construction impacts) (Devi and Palaniappan, 2017). However, this idea may not hold true for a small and potentially shrinking community, where a low CUR (i.e., the plant is treating less flow than it was designed to treat) may override the impact of additional infrastructure investment. Many small plants have not been constructed to include automation such as dissolved oxygen monitoring or aeration output control (e.g., variable frequency drives, timers) due to the perceived high capital cost of including such automation (Thompson et al., 2020). This leads to operational equipment (e.g., blowers and pumps) being selected only on the basis of the design flow rate, resulting in potentially less efficient operations when the facility is experiencing flows lower than the design flow rate. A small plant with a low CUR may be less energy efficient in its operations due to operational overdesign (e.g., overaerating), which may heavily influence the operational impact of a plant without necessarily affecting the construction impact.

Figure 2.5 shows the relationship between the normalized carcinogenic impact from construction and the normalized carcinogenic impact from operating energy. Each CUR is noted next to the letter representing each plant on the symbol representing the mechanical treatment process. Figure 2.5 illustrates that for each technology category, a high normalized carcinogenic impact from construction, weakly correlates to a high

normalized carcinogenic impact from operating energy, consistent with the previously mentioned hypothesis for small communities (i.e., for each technology category, the normalized carcinogenic impact from construction increases as the normalized carcinogenic impact from operating energy increases).

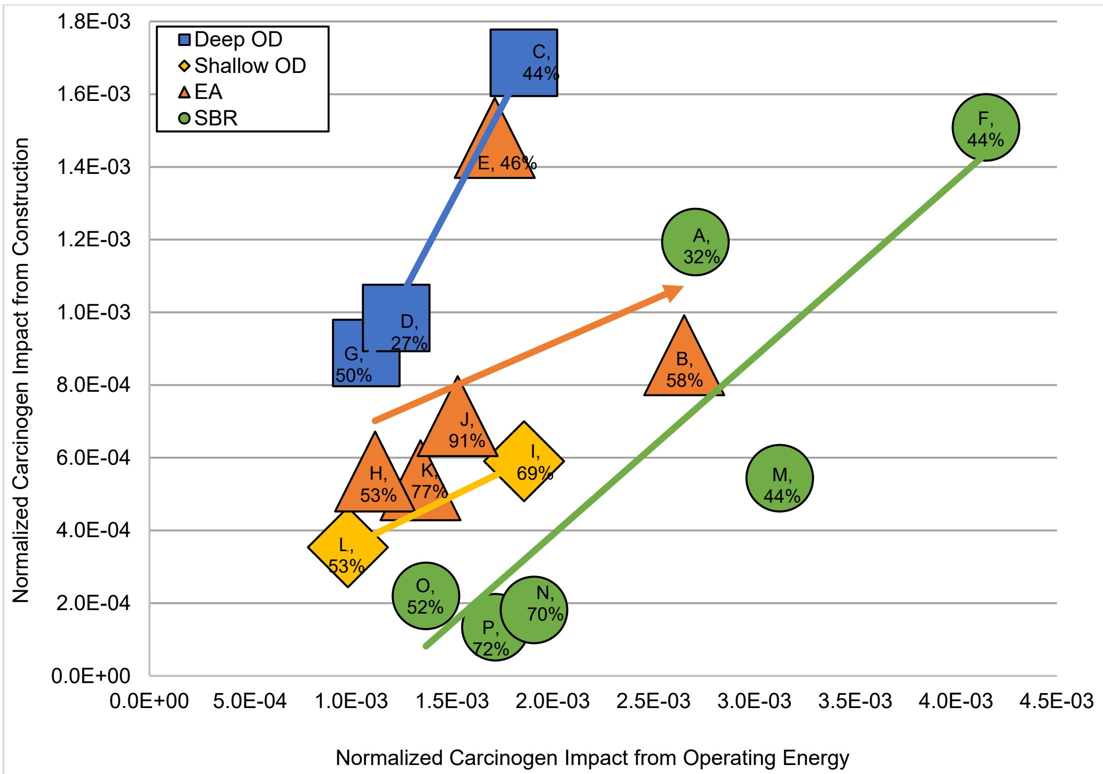


Figure 2.5 Normalized carcinogenic impact from the construction process for each plant vs. normalized carcinogenic impact from operating energy for each plant, categorized by plant technology, with plant identification and respective CUR placed inside shape

Many of these facilities were designed assuming an increasing population and flow but experienced declining flows due to losses of local industrial flows and stagnant or declining populations. Some plants, such as Plant D, might be expected to have a much higher operating energy impact due to its extremely low CUR. Plant D's location to the lower left in Figure 2.5 is likely a result of an exceptional degree of plant automation. As most nonmetropolitan regions of the US are declining or slow growing in terms of

population (USDA, 2023), Figure 2.5 emphasizes that, unless there is a compelling reason to anticipate a high wastewater flow rate growth, overdesigning a WWTP's infrastructure in a small, nonmetropolitan community should be discouraged as it is a poor use of natural resources.

Figure 2.5 also depicts the relationship between construction and operating energy impacts and CUR. This complex relationship can be most clearly seen when isolating deep ODs. The intended operational benefit of a deep OD basin versus a shallow and wide basin, according to conversations with consulting engineers, is the more efficient oxygen transfer in the deep basins as well as the ability to have a smaller construction footprint for an OD. However, for deep ODs, as the operating energy impact increases, the construction impact increases, and the CUR decreases (with the exception of Plant D) with the increasing impacts from Plant G to Plant C. Figure 2.5 shows that in cases like the ODs, certain factors (e.g., the increased construction impact associated with the additional infrastructure required to build the deep basins) may override the intended operational benefit, as there are no clear energy usage benefits observed in this data for the deep ODs, as intended by design engineers. This is highlighted by the decreasing CUR from Plant G to Plant C where, even as the construction impact increased, the decreasing CUR likely led to less efficient operations. Therefore, as WWTPs become more energy efficient, the environmental impact from operating energy decreases and construction impacts become relatively more important. Additionally, there is a 27%–75% decrease in environmental impact from the construction phase, depending on the impact category, between the plant with the lowest CUR and the highest CUR (see

Appendix A Table A6). This further emphasizes the influence that idle, underused infrastructure may have on small plants' environmental impact related to construction.

As stated earlier, the intention of this research is not to compare plant technologies against each other. There is a high degree of similarity in small mechanical WWTP infrastructure and operations, and although the impacts may vary slightly among technologies, the sample size is too small to see any significant differences between the secondary treatment technologies studied.

2.3.3.2 Additional factors driving the variability in construction impacts

Additional factors beyond the CUR identified in the MRA as drivers to the variability in construction impacts include cast iron and aluminum. Cast iron is mainly used as a piping material in older WWTPs. The amount of cast iron piping at a plant, depending on plant layout and land topography, may contribute between 4% and 61% to the total carcinogenic construction impact (see Appendix A Table A7 for values for each of the case studies). Additionally, cast iron piping is an older piping material associated with high environmental impacts. Newer WWTPs are moving towards PVC piping in lieu of cast iron piping (US EPA, 2000b). Therefore, older WWTPs may have a higher construction impact due to cast iron piping compared to newer WWTPS. Aluminum varies from plant to plant depending on user/safety preferences for grating and handrails. Aluminum may contribute between 1% and 18% to the total carcinogen construction impact (see Appendix A Table A7).

The factors identified as primary contributors to construction impact variability are non-process related, whereas process-related factors such as reinforcing steel and concrete related to basin sizing, which are designed to treat a specified design flow, did

not appear to have as much variability associated with them. The amount of non-process related materials (e.g., cast iron and aluminum) used in a plant's infrastructure directly influences the environmental impacts related to construction. Process-related factors may be more standardized across plants and scale with size due to design standards, which are largely based on flow rate (GLUMRB, 2014). Larger facilities may inherently have more construction impacts on an absolute number basis, regardless of the variability in non-process related resources, to meet design requirements. When normalized by flow, the construction impacts of small facilities may account for a relatively higher portion of the total impacts when compared to large facilities. This trend is also observed for the cost of WWTPs. Friedler and Pistany (2006) found that as WWTPs get smaller, construction costs become a larger portion of the total cost, consistent with observations of the limited data set collected in the current study.

2.3.4 Scenario sensitivity analyses

Two analyses of different scenarios were conducted. The scenarios analyzed included various design lives and the end-of-life scenarios.

2.3.4.1 Influence of design life on construction impacts

The original study utilized a plant design life of 20 years, consistent with the 10 State Standards for design of a WWTP (GLUMRB, 2014). It is assumed that flow rate and operational impacts are constant over time. Some construction renovations have been completed at certain WWTPs over the years, however this analysis assumes a worst-case scenario build date. Plant design lives of 10 to 60 years were chosen as scenarios to examine the influence of design life on the relative environmental impacts for the case studies as shown in Figure 2.6.

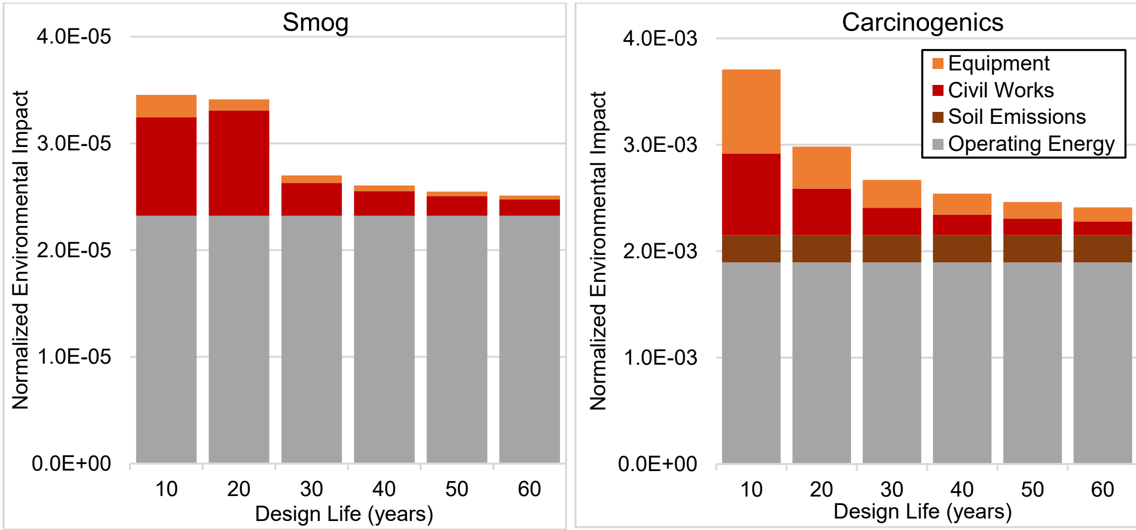


Figure 2.6 Average normalized environmental impact from construction for the 16 case studies for six design life scenarios for impact categories where there is a noticeable influence of design life on the impact of construction

As shown in Figure 2.6, the impact of construction to the impact categories of both smog and carcinogenics decreases with an increased design life scenario, or as the construction impact is normalized over a longer time period. This is consistent for all impact categories. All operational processes have a constant normalized environmental impact regardless of the design life due to the assumed constant annual operations.

2.3.4.2 Influence of end-of-life consideration on the environmental impact of a small WWTP

The original LCA did not account for the end-of-life phase (e.g., demolition of a WWTP) due to the infrequent demolition of small WWTPs and consequentially, a lack of data available on this phase. However, the end-of-life phase may be an important consideration in LCA studies of small WWTPs due to the environmental impacts embedded within end-of-life processes, as the chosen process may decrease the overall environmental impact to one category at the cost of another (Morera et al., 2017). To

illustrate the relative impact of end-of-life, Figure 2.7 provides the potential environmental impacts associated with one of two possible end-of-life processes for final disposal at a WWTP: 1) 100% recycling of reinforced concrete 2) 100% wasting of reinforced concrete. Reinforced concrete was evaluated because it is a large and essential portion of a WWTP's built infrastructure. A transport distance of 40 km, consistent with the original LCA conducted, was assumed for both end-of-life scenarios.

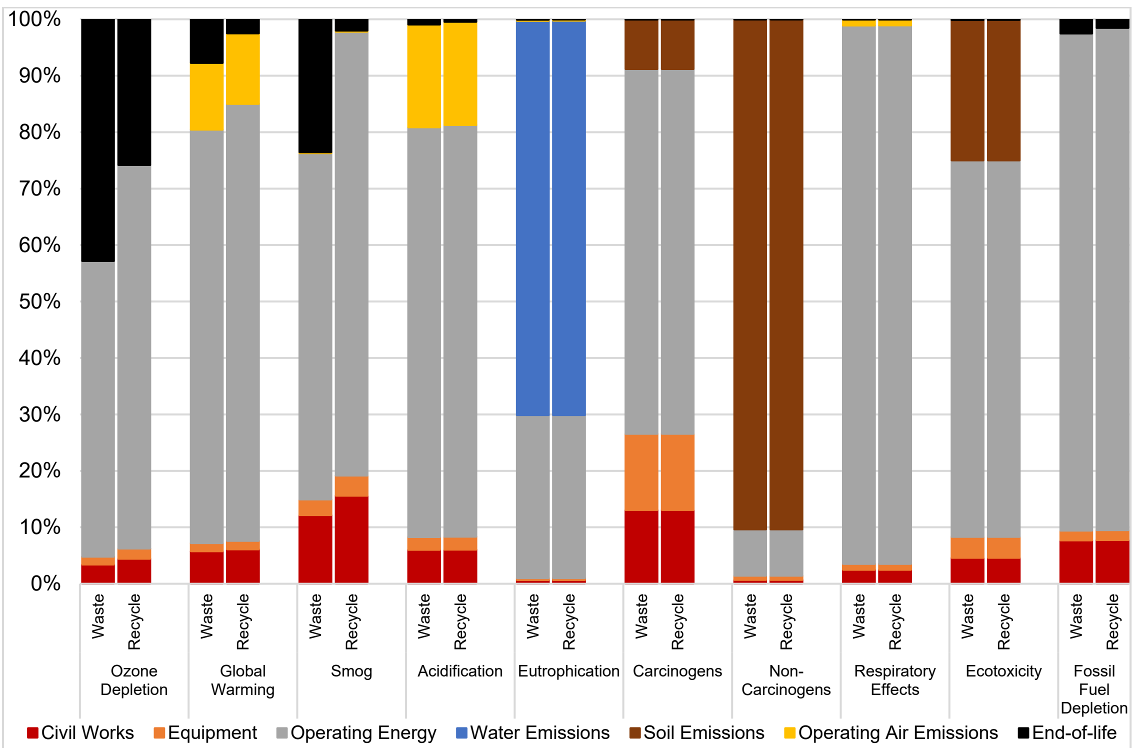


Figure 2.7 Average relative environmental impacts for the 16 case studies comparing two end-of-life scenarios for the average amount of reinforced concrete used at a plant for each impact category

As shown in Figure 2.7, the environmental impacts associated with either end-of-life scenario are relatively small compared to the total life cycle impacts for most impact categories. However, in the case of ozone depletion and smog, there is a noticeable relative impact depending on the end-of-life scenario implemented. For ozone depletion,

Figure 2.7 shows that wasting reinforced concrete during the end-of-life phase can account for 43% of the total environmental impact of a plant, whereas recycling may only account for 26% of the total. Similarly, for smog, Figure 2.7 shows that wasting reinforced concrete can account for 24% of the total environmental impact, whereas recycling reinforced concrete only accounts for 2% of the total impact.

Both the waste treatment and recycling processes are energy, resource, and waste intensive processes, and can therefore contribute a notable environmental impact to the life cycle profile of a small WWTP. The wasting process releases substantial air emissions (e.g., greenhouse gases) due to the energy consumed by the machinery used to demolish the construction waste. The diesel associated with transporting the waste to the final destination, the deposition of inert material at a landfill, and the particulate matter emitted into the atmosphere are also contributing inputs to the wasting process. The recycling process also requires energy for the machinery and fuel for transportation. In addition, the recycling process emits particulate matter. However, literature suggests that the largest advantage of the recycling process is the avoided impacts associated with wasting for final disposal (e.g., landfilling, quarrying, and transportation) (Marinković et al., 2013). Although Figure 2.7 shows the recycling process has lower potential environmental impacts compared to the wasting process, recycling is not always a viable option for small, rural facilities. Due to this minimal difference between the two process options, it is recommended that a small community implement the most feasible process.

2.3.5 Limitations and recommendations

Reliable LCA is important for helping industry practitioners make informed suggestions and to develop decision-making guidelines. The foreground data inventory

used in this study is considered to be reasonably reliable, although it holds some limitations. Areas of data limitation include operating air emissions, sludge production rates, electricity usage, study sample size, and end-of-life inventory. Operating air emissions are seldom included in WWTP LCA studies (Morera et al., 2017), and both WWTP operating air emissions and sludge production rates are rarely documented through the NDEE or other databases. Moreover, the communities did not maintain air emissions records, and most communities did not maintain sludge production rate records. Thus, operating air emissions were estimated using empirical relationships between the actual water data of each plant and relevant literature values (Foley et al., 2010), and sludge production rates were estimated using a simple linear regression model based on data points available through the NDEE. Although the environmental impacts due to air emissions and soil emissions were relatively small for most impact categories, with the exception of non-carcinogenics for soil emissions, more thorough, site-specific studies are recommended to monitor and record air emissions resulting from the biological wastewater treatment process, as well as more precise sludge production rates for small community WWTPs.

The study represented each case study's electricity usage by using an average rate based on one to three years' worth of actual plant electricity usage. Electricity usage and the associated environmental impacts may vary year to year. However, even with such variability, the ultimate result of the research is not expected to change, and electricity is likely to remain the largest relative impact for a majority of the impact categories.

The sample size of 16 is not large, and site-specific factors dominate much of the variability between plants. But given the extensive work to compile the detailed

construction and operational data, this is the first study of its kind to use as many as 16 case studies. It is recommended that future studies use as much site-specific data as possible. Lastly, there is limited data availability regarding the end-of-life phase for small WWTPs. Therefore, this phase was limited to a sensitivity scenario analysis. Future work may consider a detailed end-of-life phase of small WWTPs in their system boundaries to highlight potential environmental offsets due to demolition and disposal.

2.4 Conclusions

WWTPs are vital civil infrastructure systems. As small, rural communities struggling with aging or inadequate WWTPs upgrade and renovate their WWTPs, it is especially important that long-term environmental sustainability is considered. The goal of this study was to use case studies to discuss the environmental impacts related to both the construction and operation of small WWTPs. A detailed data inventory was collected and analyzed using LCA methodology and MRA to identify factors that influence the variability in environmental impacts among the case studies.

The implications this study has for small communities seeking wastewater infrastructure loans includes initial guidance on how to make potential sustainability improvements. Both the operational and construction impacts are important stages contributing to the life cycle environmental impacts of a small WWTP. When considering the contribution of operating energy to the overall average environmental burden to each impact category, the contribution of this process is over 50% for most impact categories. Environmental impacts from operating energy are influenced by energy efficiency. Many operational inefficiencies can be attributed to issues within the plant such as lack of process automation. When considering the contribution of

construction to the overall average environmental burden to each impact category, the contribution of this process is over 5% for most impact categories. Environmental impacts from construction are highly variable from plant to plant.

As WWTPs become more energy efficient, the environmental impact from operating energy decreases and construction impacts become relatively more important. The variability in construction impacts is largely driven by key factors unrelated to flow and identified by MRA, including CUR, cast iron, and aluminum. These are areas that a practicing engineer may consider when balancing environmental tradeoffs related to construction. Strategies that may directly reduce construction related environmental impacts include minimizing the use of non-process related materials, such as cast iron and aluminum, through alternative plant site layouts and site selection or limited usage for appurtenances like railings and grating, respectively. Additionally, building a plant to operate closer to current flow rates (i.e., increasing CUR) will reduce construction related environmental impacts by indirectly reducing the contribution of process related factors, such as concrete and reinforcing steel, to the overall environmental impact.

Lastly, different scenarios may influence the life cycle environmental impacts of a small WWTP. Environmental impacts from construction, regardless of impact category, decrease with increased design life under the assumption of constant operations. End-of-life consideration does not heavily influence the environmental sustainability of a small WWTP.

References

American Society of Civil Engineers (ASCE). (2017). Infrastructure report card. Retrieved November 23, 2020 from https://www.infrastructurereportcard.org/cat-item/wastewater/.

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A., & Castells, F. (2013). Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. Journal of cleaner production, 43, 84-92. https://doi.org/10.1016/j.jclepro.2012.12.033.

Bare, J. C. (2002). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. Journal of industrial ecology, 6(3-4), 49-78. https://doi.org/10.1162/108819802766269539.

Björklund, A. E. (2002). Survey of approaches to improve reliability in LCA. The International Journal of Life Cycle Assessment, 7, 64-72. https://doi.org/10.1007/BF02978849.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: state of the art. Water research, 47(15), 5480-5492. https://doi.org/10.1016/j.watres.2013.06.049.

Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A., & Short, M. D. (2020). The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. Water Research, 184, 116058. https://doi.org/10.1016/j. watres.2020.116058.

Devi, L. P., & Palaniappan, S. (2017). A study on energy use for excavation and transport of soil during building construction. Journal of cleaner production, 164, 543-556. https://doi.org/ 10.1016/j.jclepro.2017.06.208.

Emmerson, R. H. C., Morse, G. K., Lester, J. N., & Edge, D. R. (1995). The life-cycle analysis of small-scale sewage-treatment processes. Water and Environment Journal, 9(3), 317-325. https:// doi.org/10.1111/j.1747-6593.1995.tb00945.x.

Fraas, A. G., & Munley, V. G. (1984). Municipal wastewater treatment cost. Journal of Environmental Economics and Management, 11(1), 28-38. https://doi.org/10.1016/0095-0696(84)90029-9.

Friedler, E., & Pisanty, E. (2006). Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. Water research, 40(20), 3751-3758. https://doi.org/10.1016/j. watres.2006.08.015.

Foley, J. M., Rozendal, R. A., Hertle, C. K., Lant, P. A., & Rabaey, K. (2010). Life cycle assessment of high-rate anaerobic treatment, microbial fuel cells, and microbial electrolysis cells. Environmental science & technology, 44(9), 3629-3637. https://doi.org/10.1021/es100125h.

Great Lakes - Upper Missouri River Board of State and Provincial Public Health and Environmental Managers (GLUMRB). (2014). Recommended standards for wastewater facilities. Retrieved November 23, 2020 from https://www.broward.org/WaterServices/Engineering/Documents/WWSTenStateStandardsWastewater.pdf.

Guo, M., & Murphy, R. J. (2012). LCA data quality: sensitivity and uncertainty analysis. Science of the total environment, 435, 230-243. https://doi.org/10.1016/j.scitotenv.2012.07.006.

Hanna, S. M., Thompson, M. J., Dahab, M. F., Williams, R. E., & Dvorak, B. I. (2018). Benchmarking the Energy Intensity of Small Water Resource Recovery Facilities: Hanna et al. Water Environment Research, 90(8), 738-747. https://doi.org/10.2175/106143017X15131012153176.

ISO. (2006). Environmental management - life cycle assessment - principles and framework ISO 14040. Int. Org. Stand. Retrieved November 23, 2020 from https://www.iso.org/standard/37456.html.

Kamali, M., Hewage, K., & Sadiq, R. (2019). Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. Energy and Buildings, 204, 109479. https://doi.org/10.1016/j.enbuild.2019.109479.

Li, S., Qin, Y., Subbiah, J., & Dvorak, B. (2020). Life cycle assessment of the US beef processing through integrated hybrid approach. Journal of Cleaner Production, 265, 121813. https://doi.org/10.1016/j.jclepro.2020.121813.

Li, X., Zhu, Y., & Zhang, Z. (2010). An LCA-based environmental impact assessment model for construction processes. Building and Environment, 45(3), 766-775. https://doi.org/ 10.1016/j.buildenv.2009.08.010.

Lin, M., Afshari, A., & Azar, E. (2018). A data-driven analysis of building energy use with emphasis on operation and maintenance: A case study from the UAE. Journal of Cleaner Production, 192, 169-178. https://doi.org/10.1016/j.jclepro.2018.04.270.

Marinković, S. B., Ignjatović, I., & Radonjanin, V. (2013). Life-cycle assessment (LCA) of concrete with recycled aggregates (RAs). In Handbook of recycled concrete and demolition waste (pp. 569-604). Woodhead Publishing. https://doi.org/10.1533/9780857096906.4.569.

Metcalf, Eddy, A.E.C.O.M. (2014). Wastewater Engineering Treatment and Resource Recovery. McGraw-Hill Education, ISBN 9780073401188.

Mo, W., Cornejo, P. K., Malley, J. P., Kane, T. E., & Collins, M. R. (2018). Life cycle environmental and economic implications of small drinking water system upgrades to reduce disinfection byproducts. Water research, 143, 155-164. https://doi.org/ 10.1016/j.watres.2018.06.047.

Molinos-Senante, M., Gómez, T., Garrido-Baserba, M., Caballero, R., & Sala-Garrido, R. (2014). Assessing the sustainability of small wastewater treatment systems: A composite indicator approach. Science of the total environment, 497, 607-617. https://doi.org/10.1016/j.scitotenv.2014.08.026.

Morera, S., Corominas, L., Rigola, M., Poch, M., & Comas, J. (2017). Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. Water research, 122, 614-623. https://doi.org/10.1016/j.watres.2017.05.069.

Morera, S., Santana, M. V., Comas, J., Rigola, M., & Corominas, L. (2020). Evaluation of different practices to estimate construction inventories for life cycle assessment of small to medium wastewater treatment plants. Journal of Cleaner Production, 245, 118768. https:// doi.org/10.1016/j.jclepro.2019.118768.

Moussavi, S. (2019). Environmental Sustainability Assessment of Small Nebraska Mechanical Water Resource Recovery Facilities: Impacts of Construction and Operations. MS Thesis. University of Nebraska-Lincoln. Retrieved December 23, 2020 from https://digitalcommons.unl.edu/civilengdiss/150/.

NDEE (2019a). Clean water state revolving loan fund (for wastewater treatment facilities). Nebraska Dep. Environ. Energy. Retrieved November 23, 2020 from http://deq.ne.gov/NDEQProg. nsf/OnWeb/CWSRLF.

NDEE (2019b). Public records search. Nebraska Dep. Environ. Energy. Retrieved November 23, 2020 from https://ecmp.nebraska.gov/publicaccess/viewer.aspx?&MyQueryID 340

Nelson, K. L. (2005). Small and decentralized systems for wastewater treatment and reuse. In Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop (Vol. 10, No. 29, p. 54). National Academies Press. https://doi.org/10.17226/ 11241. No. 29.

New York State Department of Environmental Conservation Division of Water (NYSDEC). (2014). New York state design standards for intermediate sized wastewater treatment systems. Dep. Environ. Conserv. Retrieved November 23, 2020 from https://www.dec.ny.gov/permits/9 5768.html.

Nguyen, T. K. L., Ngo, H. H., Guo, W., Chang, S. W., Nguyen, D. D., Nguyen, T. V., & Nghiem, D. L. (2020). Contribution of the construction phase to environmental impacts of the wastewater treatment plant. Science of the Total Environment, 743, 140658. https://doi.org/10.1016/j.scitotenv.2020.140658.

Ortiz, M., Raluy, R. G., & Serra, L. (2007). Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. Desalination, 204(1-3), 121-131. https://doi.org/10.1016/j.desal.2006.04.026.

Pearson, M. (2007). US Infrastructure Finance Needs for Water and Wastewater. Rural Community Assistance Partnership (RCAP), Community Resource Group, Washington, DC, USA.

Polruang, S., Sirivithayapakorn, S., & Talang, R. P. N. (2018). A comparative life cycle assessment of municipal wastewater treatment plants in Thailand under variable power schemes and effluent management programs. Journal of Cleaner Production, 172, 635-648. https://doi.org/10.1016/j.jclepro.2017.10.183.

Ruiz-Rosa, I., García-Rodríguez, F. J., & Mendoza-Jiménez, J. (2016). Development and application of a cost management model for wastewater treatment and reuse processes. Journal of cleaner production, 113, 299-310. https://doi.org/10.1016/j. jclepro.2015.12.044.

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16, 329-339. https://doi.org/10.1007/s10098-013-0629-z.

Seifert, C., Krannich, T., & Guenther, E. (2019). Gearing up sustainability thinking and reducing the bystander effect–A case study of wastewater treatment plants. Journal of environmental management, 231, 155-165. https://doi.org/10.1016/j.jenvman.2018.09.087.

Thompson, M., Dahab, M. F., Williams, R. E., & Dvorak, B. (2020). Improving energy efficiency of small water-resource recovery facilities: Opportunities and barriers. Journal of Environmental Engineering, 146(7), 05020005. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001723.

United States Census Bureau. (2010). Retrieved November 23, 2020 from https://www.census.gov/programs-surveys/decennial-census/decade.2010.html.

US EPA. (2000a). Wastewater technology fact sheet – package plants. Report # EPA 832-F- 00-016 U. S. Environ. Protect. Agency. Retrieved December 22, 2020 from https://www.epa.gov/sit es/production/files/2015-06/documents/package_plant.pdf.

US EPA. (2000b). Wastewater technology fact sheet – pipe construction and materials. U. S. Environ. Protect. Agency. Retrieved November 23, 2020 from https://www3.epa.gov/npdes/pu bs/pipe_construction.pdf

US EPA. (2016a). Clean watersheds needs survey report to congress. U. S. Environ. Protect. Agency. Retrieved December 22, 2020 from https://www.nrc.gov/docs/ML1802/ML18023A363.pdf.

US EPA. (2016b). Learn about small wastewater systems. U. S. Environ. Protect. Agency. Retrieved November 23, 2020 from https://www.epa.gov/small-and-rural-wastewater-systems/learn-a bout-small-wastewater-systems.

US EPA. (2019). Enforcement and compliance history online. U. S. Environ. Protect. Agency. Retrieved November 23, 2020 from https://echo.epa.gov/.

US EPA. (2020). Smart growth in small towns and rural communities. U. S. Environ. Protect. Agency. Retrieved November 23, 2020 from. https://www.epa.gov/smartgrowth/smart-growth-small-towns-and-rural-communities#technicalassistanceprograms.

USDA. (2020a). USDA and EPA announce continued commitment to support rural water systems. U.S. Dep. Agric. Retrieved December 22, 2020 from https://www.usda.gov/media/press-relea ses/2020/02/20/usda-and-epa-announce-continued-commitment-support-rural-water.

USDA. (2020b). U.S. Dep. Agric. Retrieved December 22, 2020 from https://www.ers.usda. gov/topics/rural-economy-population/population-migration/#map.

USDA. (2020c). Water & environmental programs. U.S. Dep. Agric. Retrieved November 23, 2020 from https://www.rd.usda.gov/programs-services/all-programs/water-environmental-programs.

USDA. (2023). Population change rate. U.S. Dep. Agric. Retrieved May 8, 2023 from https://www.ers.usda.gov/data-products/atlas-of-rural-and-small-town-america/go-to-the-atlas/

Weidema, B. P., Pizzol, M., Schmidt, J., & Thoma, G. (2018). Attributional or consequential life cycle assessment: a matter of social responsibility. Journal of cleaner production, 174, 305-314. https://doi.org/10.1016/j.jclepro.2017.10.340.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230. http://link.springer.com/10.1007/s11367-016-1087-8

Zampori, L., Saouter, E., Schau, E., Cristobal, J., Castellani, V., & Sala, S. (2016). Guide for interpreting life cycle assessment result. Publications Office of the European Union: Luxembourg. https:// doi.org/10.2788/171315.

CHAPTER 3 IMPACTS OF FLOODING ON WASTEWATER INFRASTRUCTURE: TRADEOFFS OF RECOVERY AND RESILIENCE

3.0 Abstract

As climate change persists, the frequency and intensity of natural disasters has increased, emphasizing the need for resilient critical infrastructure. Flooding impacts water resource recovery facilities (WRRFs) by inducing operational and structural failures. Thus, proactive planning and design are essential to reduce vulnerability to flooding. This study analyzes sustainability tradeoffs of resilient and recovery infrastructure for WRRFs affected by flooding. A detailed inventory was collected for 10 reflective case studies to analyze life cycle environmental impacts of initial, recovery, and resilience infrastructure. Economic and additional impacts of flooding were evaluated using generalized WRRF cost models and anecdotes from relevant stakeholders, respectively. Generally, initial construction has a higher environmental and economic impact compared to recovery and resilience construction. Recovery construction tends to have higher environmental and economic impacts compared to resilience construction when major equipment replacements and repairs are necessary. Conversely, resilience construction tends to have higher environmental and economic impacts compared to recovery infrastructure when major construction activities and resources are required. If multiple flooding events occur during a facility's design life, recovery construction impacts increase based on the number of flood events and become larger compared to initial and resilience construction impacts, highlighting the uncertainty associated with recovery needs compared to the stability of resilience. Additional impacts of flood recovery were identified and discussed, including treatment

impacts, worker impacts, community impacts, and facility impacts, which were often driving factors considered by decision makers if resilient infrastructure was or will be implemented. This study aims to provide justification for communities, engineers, and funding agencies as they seek to protect critical wastewater infrastructure via resilient investments.

3.1 Introduction

Water resource recovery facilities (WRRFs), also referred to as wastewater treatment plants, are critical infrastructure systems that protect human health and the environment. WRRFs must meet stringent water quality regulations. Facilities are generally located in low-lying areas near bodies of water to allow for as much gravity flow as possible, which lowers pumping costs, but increases vulnerability to flooding (Hummel et al., 2018; Pant et al., 2018).

Many WRRFs in operation were built prior to 1970, which was before many of the requirements for protecting WRRFs from the 100-year flood started to appear (Sanders, 1997). The commonly adopted wastewater design standards in the U.S. recommend limited flood protection by requiring structures and equipment to be elevated one foot above the 100-year floodplain and ensuring the system can operate during a 25-year flood (GLUMRB, 2014). The location of the WRRF may be in or near a floodplain if the aforementioned requirements are met, but the location of existing floodplains can be uncertain, as federal floodplain maps tend to be outdated as shown in Appendix B Table B1 (FEMA, 2022). Thus, the current guidance intended for protection may not be enough (US EPA, 2014).

According to the American Society of Civil Engineers (ASCE), wastewater infrastructure in the U.S. is poor and at risk (ASCE, 2021c). Of the more than 16,000 publicly owned WRRFs in the U.S., many struggle with aging or inadequate infrastructure and outdated operations (US EPA, 2020). These challenges are intensified during natural disasters like flooding.

Infrastructure is costly to modify once built, especially in communities with limited resources. During natural disasters, a community is responsible for 100% of repair costs unless a presidential disaster is declared, during which the community is responsible for only 25% of repair costs (NDNR, 2015). This cost structure can help incentivize resilient investment. For example, the Multi-Hazard Mitigation Council (2019) considered the value of implementing above-code designs for utilities and select infrastructure prone to flooding, hurricanes, earthquakes, and fires, and found that an average of $6 (U.S. dollars) is saved for every federal dollar spent on resilience efforts.

Funding opportunities are available through the Federal Emergency Management Agency (FEMA) (e.g., National Flood Insurance Program and the 406 Mitigation Program) to help damaged communities recover or become resilient post-disaster. WRRFs should be one of the first utilities to apply for these opportunities, as many activities (e.g., hospitals, schools, industrial facilities, residential properties, etc.) in a community depend on sufficient wastewater treatment to protect the health and safety of the citizens. As climate change persists, the frequency and intensity of natural disasters continues to increase, emphasizing the need for resilient infrastructure.

3.1.1 Defining resilience and recovery

Defined by ASCE, resilience is, "the ability to plan, prepare for, mitigate, and adapt to changing conditions from hazards…" (ASCE, 2021a). As used in this study, resilience refers to protective infrastructure built with the intention of preventing substantial damage to a WRRF during a flood event. Resilience remains a low priority in WRRF design, and is typically simplified to redundancy, leading to high capital and operational costs over the lifetime of a plant faced with multiple disasters (Currie et al., 2014; GLUMRB, 2014).

Recovery, as used in this study, refers to a plant with limited protections against flooding in place at the time of the disaster, leading to the expenditure of significant resources over time to ensure the plant was fully operational post-disaster. Recovery efforts include restoring operations, removing debris, and repairing and/or replacing structures and equipment.

3.1.2 Impacts of flooding

Floods make up 34% of global natural disasters and are the most damaging of natural hazards, resulting in major economic, environmental, and social losses (NDNR, 2015; Petit-Boix et. al., 2017a). The impacts of flooding are disruptive and can lead to long-term impacts such as accidents during recovery activities or drinking water treatment challenges. (Allen et al., 2019).

WRRFs have environmental impacts embedded in their normal construction and operations, but these impacts can increase when floods occur (Moussavi et al., 2021). Flooding has negative impacts on WRRFs, such as operational (e.g., equipment failure, power outages, restricted plant access, etc.) and structural (e.g., basin damage, building

damage, etc.) failures. In addition, discharge of raw wastewater by flood damaged plants can lead to increased public health and environmental impacts (e.g., ecotoxicity and eutrophication) on receiving water bodies (Veronesi et al., 2014; Risch et al., 2018; Schaffer-Smith et al., 2020). Flood waters can be particularly dangerous due to agricultural chemicals, industrial loadings, sediment, etc. (NDEE, 2013).

3.1.3 Research motivation and novelties

This research aims to fill the literature gap of life cycle assessment (LCA) of flooded WRRFs. LCA can be used to measure the potential environmental impacts of a system (i.e., environmental sustainability) (Bocchini et al., 2014; Moussavi et al., 2021). Juan – Garcia et al. (2017) conducted a comprehensive literature review and found that only 17 peer reviewed papers and six technical reports directly assessed resilience related to wastewater systems. This represents a small portion of the overall literature related to resilient infrastructure or wastewater treatment systems. Out of the 23 studies found, only five studied acute events such as flooding. Additionally, Juan-Garcia et al., (2017) pointed out that reflective studies (i.e., using past experience to inform future decisions) are entirely missing from literature, which can be an important step in promoting practical application. While literature primarily focuses on coastal flooding, the Midwest is an area of concern with the changing climate (Olyaei et al., 2018; Balasbaneh et al., 2019). Flavelle et al. (2020) found 14.6 million properties are at risk of a 100-year flood event, including many areas in the Midwest.

A novelty of this study includes using LCA to evaluate the environmental impacts associated with recovery and resilience infrastructure for WRRFs using reflective case studies. Many studies have analyzed flooding impacts on urban and residential

infrastructure (e.g., Matthews, 2016), but none have conducted a tradeoff analysis (i.e., environmental, economic, and social) between flood recovery and resilience for WRRF infrastructure. Some literature looks at resiliency of WRRFs, but do not consider LCA impacts, as most studies explicitly separate environmental sustainability assessments from performance-based resilience assessments (Bocchini et al., 2014; Karamouz et al., 2016; Welsh-Huggins et al., 2020). Regarding resilience studies using LCA, Petit-Boix et al., (2017b) is one of few, and only considered stormwater management systems. Available WRRFs studies are mainly concerned with safety regulations, economic costs, and resource recovery potential rather than assessing the potential sustainability of resilience (Jafarnejad, 2020). Thus, this research aims to expand upon studies that considered these factors (Sanders, 1997).

Reflective case studies are useful, as certain aspects of resilience and recovery may not be clear until a system is exposed to a disaster (Matthews, 2016). Most studies focus on resilience designs by modeling the projected performance of infrastructure using probabilistic risk management approaches (Petit-Boix et al., 2017b). However, flooding has high uncertainty, and modeling the potential consequences and benefits of resilience and flooding can be difficult. A reflective analysis can help document true tradeoffs of resilience and recovery to provide stakeholders an alternative perspective for design.

The goal of this study is to analyze and discuss the tradeoffs of flood recovery and resilience using case study WRRFs, to provide engineers and decision makers justification for resilience wastewater infrastructure investments. The focus of this study is on the sustainability of the initial, recovery, and resilience infrastructure, and not on evaluating performance of the systems. To respond to outdated floodplain maps, limited

design guidance, and high repair costs, the vulnerability of critical wastewater infrastructure systems must be reduced. The objectives of this study are to 1) collect a detailed data inventory for each case study, 2) use LCA to quantify the life cycle environmental impacts of each case study's recovery and/or resilience efforts, and 3) discuss sustainability (i.e., environmental, economic, and social) tradeoffs between recovery and resilience for WRRFs affected by floods.

3.2 Methods

3.2.1 2019 Midwest flood event

In March of 2019, a bomb cyclone (i.e., winter hurricane) hit the Midwest, U.S. The storm was roughly equivalent in power to a category 2 hurricane, producing winds up to 80 mph (NEMA, 2020). The storm brought heavy snow and rain, blizzard conditions, rapid melting, breached berms/levees, and damaged infrastructure. This event was the costliest inland flooding event in U.S. history (Salas et al., 2019). Nebraska was hit hard by this storm, as 84 out of the 93 counties were impacted and reported damage to critical infrastructure (NEMA, 2020).

In many locations, the 2019 flood event was classified as a 100-year flood or a 500-year flood event (Masters, 2019). A 100-year flood means that the flood has a one percent chance of recurring each year, whereas a 500-year flood means that the flood has a 0.2 percent chance of recurring each year. It is important to note that the level of a 100-year or 500-year flood changes continually, as the determination is based on historical data of the magnitude and duration of precipitation events (Water Science School, 2018).

3.2.2 Case studies

This study considered two types of cases, both related to the 2019 Midwestern Flood: 1) plants that recovered from significant flood damage in 2019 and 2) plants that have or are implementing resilience measures to protect against flooding (either prior to the 2019 Midwestern Flood or because of the 2019 Midwestern Flood). A detailed description of the case studies is presented in Table 3.1. Each facility was assigned a unique number, ordered first by the type of case study and then population served. Each case study, with the exception of Case 8, was located within a FEMA flood hazard zone, which reflects how likely it is for the area to flood. These flood zones were last updated 12-19 years ago (see Appendix B Table B1).

Table 3.1 Detailed description of each case study, including the FEMA Flood Hazard Zone that the WRRF falls within (if applicable)

Case Study	Average Daily Flow (m^3/day)[1]	State	Population Served[2]	Resilience[3]	Recovery[3]	FEMA Flood Hazard Zone[4]
1	227,125	Nebraska	487,300	x	x	100 year flood
2	7,192	South Dakota	15,453	x	x	100 & 500 year flood
3	2,650	Nebraska	6,620	x	x	100 year flood
4	719	Nebraska	1,798	x	x	100 year flood
5	757	Nebraska	1,154	x	x	100 year flood
6	66,623	Iowa	85,617		x	100 year flood
7	644	Nebraska	1,248		x	100 year flood
8	379	Nebraska	1,167		x	no digital data available
9	10,940	Nebraska	24,967	x		100 & 500 year flood
10	76	Nebraska	172	x		100 year flood

[1]EPA, 2022
[2]US Census Bureau, 2020
[3]Based on discussions with communities and Nebraska Department of Environment and Energy
[4]FEMA, 2022

This study takes a reflective approach by specifically using cases involved in the 2019 Midwest Floods. States like Nebraska, Iowa, Missouri, and South Dakota suffered

major damage because of this flood (NOAA, 2019). Nebraska is especially prone to flood risk, as almost every community faces a risk from a 100-year flood (NDNR, 2015).

3.2.3 Environmental impact quantification

This study used a process based LCA methodology, similar to Thompson et al. (2022), to quantify the environmental impacts of flood recovery and resilience infrastructure for 10 case studies. The basic framework of an LCA study includes four steps: 1) goal and scope, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation.

The goal of this study is to analyze and discuss the tradeoffs between flood recovery and resilience using WRRF case studies to provide practical guidance for justifying resilient infrastructure investments. The product system is a Midwest WRRF that was affected by the major midwestern flood event in 2019, based on data availability and proximity. The WRRF sizes range from small to large, as the 2019 flooding disaster affected all sizes of plants. Case studies were selected based on availability of construction and operational data. The main function of a WRRF is to treat raw municipal wastewater to ensure public health requirements are met; thus, the functional unit for the LCA was chosen to be one cubic meter of treated wastewater, consistent with LCA WRRF literature (Moussavi et al., 2021).

The system boundary focused specifically on the WRRF and the flood event. Sewer lines and homes in the surrounding area were not included in the system boundary, as the physical boundary for the LCA is drawn only around the WRRF. Other difficult to quantify impacts, inherently social in nature, were anecdotally documented for the surrounding areas (e.g., sewage backup in homes, personnel and staff redirection, etc.),

but the LCA focused only on the WRRF infrastructure. Materials and equipment used to recover a damaged WRRF were considered for recovery cases, and materials and equipment used to construct any protection structures that allowed a plant to be resilient were considered for resilience cases. Life cycle impacts for the initial (i.e., embedded) construction, recovery construction, and resilience construction for each case study were calculated separately so comparisons could clearly be made.

The construction phase of a WRRF is important to consider when aiming to reduce life cycle environmental impacts (Corominas et al., 2013; Morera et al., 2017; Moussavi et al., 2021). Thus, the focus of this research was on the construction phase of a WRRF, which refers to the civil works and equipment used to construct the facility initially, to recover, or to be resilient. The LCA impact from initial construction was calculated for each case to provide a baseline value of the environmental impact of a facility without any recovery or resilience infrastructure in place. The operational life of each WRRF was assumed to be 20 years, based on the 10 States Standards (GLUMRB, 2014). LCA impacts of operations, including water emissions and operational energy usage, were discussed but not included in the analyzed system boundary.

The inventory data comprised of both foreground data and background data. The foreground data includes data directly collected, compared to background data collected indirectly via LCA databases (Moussavi et al., 2021). The foreground data collected for each case study included construction inventories, energy usage, and wastewater characteristics. Construction inventories were collected from each community's construction design documents (for embedded construction), damage records (for recovery cases), and resilience plans (for resilience cases). Energy usage was collected

from each community's utility bills, and wastewater characteristics were obtained from facility records and the U.S. EPA's Enforcement and Compliance History Online (ECHO) database (US EPA, 2022). Transportation distance of construction materials required for the embedded plant, recovery, or resilience was assumed to be 40 kilometers (km), unless otherwise noted by facility staff, based on typical values used in literature (Morera et al., 2017). Background data included upstream processes such as manufacturing, transportation, and production of resources, provided by the Ecoinvent Database v3.3. Figure 3.1 shows a list of the detailed data inventory collected.

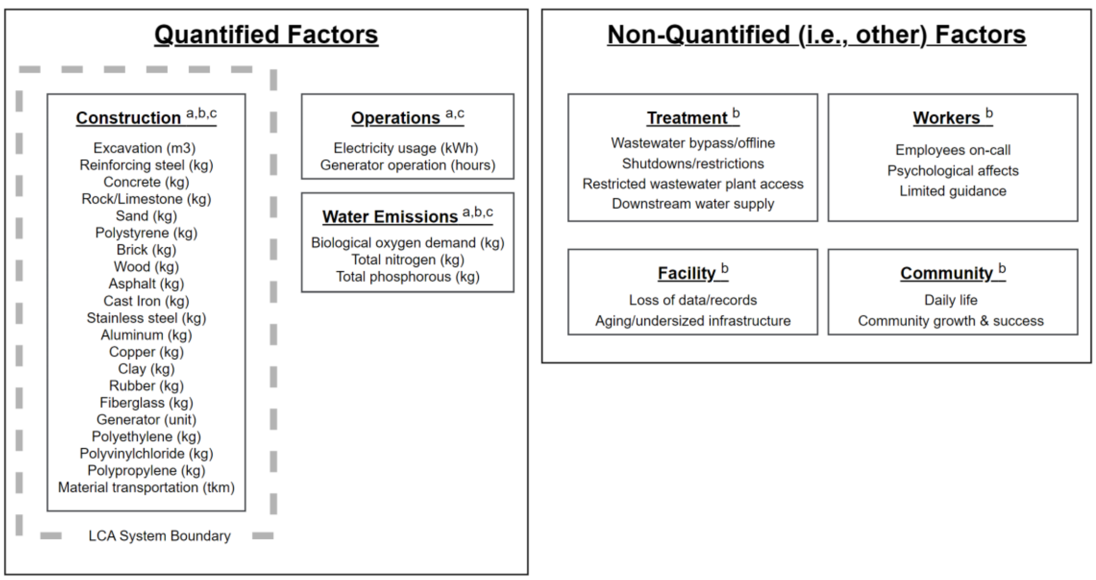


Figure 3.1 Detailed data inventory collected for each case study, including LCA inventory used to identify environmental impacts and inventory used to identify other, non-quantified impacts; (a) embedded WRRF inventory, (b) recovery inventory, (c) resilience inventory

All inventory data were converted to a mass basis and normalized by a defined time period. Initial construction data was normalized over a 20 year design life (GLUMRB, 2014). Recovery construction data was normalized over an assumed 20 year design life as well, based on the assumption that the flood occurred once in the design life

of a facility. This is likely an underestimation of the return frequency, however climate change and natural disaster projections are outside the scope of this study. Resilience construction data was normalized over a 50 year design life, as 50 years is the average time between the original build date of the case studies and the current year (2023), as shown in Appendix B Table B1.

To fulfill the first objective, a complete list of the detailed inventory collected is provided in Appendix B (Tables B2, B3 and B4), along with a brief description of the data collection process for obtaining reflective case study data, as this is a highly desired, but rare practice in related research (Juan-Garcia et al., 2017). This information is provided so other researchers can calibrate theoretical models with these case studies or use the case studies to improve practical application of research and encourage implementation of recommendations.

OpenLCA v1.10 was used to conduct the process based LCA. International Organization for Standards (ISO) 14040 series was followed to ensure consistency and reliability (ISO, 2006). The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) v2.1 was used as the impact assessment method, and the U.S. based normalization factors provided by Ryberg et al. (2014) were incorporated. The TRACI impact assessment method evaluates midpoint environmental impacts including ozone depletion, global warming, smog, acidification, fossil fuel depletion, eutrophication, ecotoxicity, carcinogens, non- carcinogens, and respiratory effects (Bare et al., 2002). TRACI is commonly used in LCA literature, and it is specific to U.S. systems and processes. It is important to include all impact categories to preserve information and avoid burden shifting (Grubert and Stokes-Draut, 2020).

3.2.4 Economic and other non-quantified impacts

Generalized WRRF cost curves were used to estimate the cost of initial construction for each case study (Hansen, 2023). It is difficult to quantify the present-day value of the initial construction for the case studies, as many were progressively built over the last 50 years (Appendix B Table B1). Thus, a generalized model was used to compare the WRRF's embedded construction cost with recovery and resilience projects. Cost estimates for recovery or resilience related projects were obtained from the design documents, if available.

Flood damage can have many societal impacts which can be difficult to quantify (Ashley et al., 2008; Wang et al., 2021). Thus, discussions with design engineers and facility operators were documented to highlight potential additional impacts of the flood (e.g., service disruptions, sewage backups in homes, staff redirection, etc.), which impacted the surrounding society.

3.3 Results and Discussion

A range of impacts associated with WRRFs faced with flooding are discussed to highlight the widespread tradeoffs of recovery and resilience for these critical infrastructure systems. WRRFs in recovery incur impacts post-flood due to failed operations, structural failure, and mechanical equipment replacement, whereas resilient WRRFs incur impacts pre-flood due to earthwork and the building of protective structures. A list of the documented recovery and resilience efforts for each case study is presented in Table 3.2.

Table 3.2 Main aspects of recovery and resilience with respect to infrastructure related to the environmental LCA inventory

Case Study	Recovery	Resilience
1	● Offline – 2 months ● Electrical failure ● Debris removal	● Raise town's berm by 2 feet
2	● Offline – 21 hours ● Equipment failure ● Sinkhole appearance	● Build facility to the 100 year floodplain ● Construct equalization basin ● Upgrade equipment ● Add effluent piping
3	● Offline – 18 months ● Equipment failure ● Flood barriers (sand bags) ● Can never reach pre-flood condition	● Build new facility 2 feet above the 500 year floodplain
4	● Offline – 1 week ● Infiltration ● Pump water out ● Structural failure (UV System)	● Construct wet well sewer lift station
5	● Offline – 3 weeks ● Pump water out	● Add pump to facility's existing berm
6	● Offline – 4 months ● Equipment failure ● Sand debris removal ● Infiltration	N/A
7	● Offline – 3 weeks ● Electrical failure ● Pump water out ● Sand debris removal	N/A
8	● Offline – 1 week ● Sand debris removal	N/A
9	N/A	● Facility's berm built 1 foot above the 500 year floodplain ● Add screw pump to facility's existing berm
10	N/A	● Entire plant elevated

As shown by Table 3.2, the most common recovery impact was that a WRRF discharged untreated sewage to receiving water bodies (i.e., went "offline"). Additionally, many recovery cases had equipment failure, as well as debris and water in

the plant that needed to be pumped out. The most common resilience approach, shown by Table 3.2, was adding elevation to the WRRF or existing berms. The aspects of resilience are either a direct response to the 2019 flood event, or a response based on prior flood events. Cases 6, 7, and 8 did not have any plans after the 2019 flood event to implement resilient infrastructure. Cases 9 and 10 did not have to recover from the 2019 flood event, as resilient infrastructure was already in place.

3.3.1 Environmental impacts

The initial WRRF construction impact was compared to the construction impacts associated with recovery and resilience, consistent with the system boundary. Figure 3.2 shows the normalized LCA results for the 10 TRACI impact categories for the first five cases (i.e., the cases that included both recovery and resilience aspects), to clearly show relationships between recovery and resilience construction impacts. The normalized results for all 10 case studies are provided in Appendix B Table B5 and Figure B1 to show relative values. The impact categories are grouped based on the media affected most by the respective impact category. Ecotoxicity, non-carcinogenics, eutrophication, respiratory effects, and acidification affect air, water, and soil media (Figure 3.2A – Figure 3.2E); carcinogenics, smog, global warming, fossil fuel depletion, and ozone depletion uniquely affect air media (Figure 3.2F – Figure 3.2J) (Bare et al., 2012).

An example of interpreting the diagrams in Figure 3.2 is shown by the results in 3.2A for the impact category of ecotoxicity. The x-axis represents the case study considered, and the y-axis represents the normalized environmental impact on a logarithmic scale. The normalized environmental impact unit is "(environmental impact per functional unit) / (environmental impact per year)." The bars presented for each case

study shown in Figure 3.2A display the ecotoxicity impact from initial construction normalized over a 20 year design life, the ecotoxicity impact from recovery construction normalized over a 20 year design life, and the ecotoxicity impact from resilience construction normalized over a 50 year useful life. Figures 3.2B – 3.2J can be interpreted in the same way as Figure 3.2A. Each impact category has unique units to quantify the environmental impact per functional unit; thus, the 10 impact categories cannot be compared against each other. Each impact category also has a specific normalization factor, provided by Updated U.S. and Canadian Normalization Factors for TRACI v2.1 (Ryberg et al., 2014).

Figure 3.2 shows a similar overall trend for each case study for each impact category, with the exception of Case 3, where the environmental impact of initial construction is larger than that of recovery or resilience. For each impact category, Cases 1, 4, and 5 have a higher environmental impact from recovery construction compared to resilience construction due to the large amounts of equipment used to recover. For Case 2, the environmental impact of recovery construction is higher than resilience in the impact categories affecting the air, water, and soil media (Figure 3.2A – Figure 3.2E) due to the equipment and production of metals and concrete required for repair, but the environmental impact of resilience is higher in the impact categories affecting only air media (Figure 3.2F – Figure 3.2J) due to the emissions associated with concrete and steel production for piping and basins. Case 3 plans to build an entirely new elevated WRRF that meets additional treatment requirements as a resilience measure. No other case study proposed constructing a new WRRF as a resilience measure, deeming Case 3 an outlier.

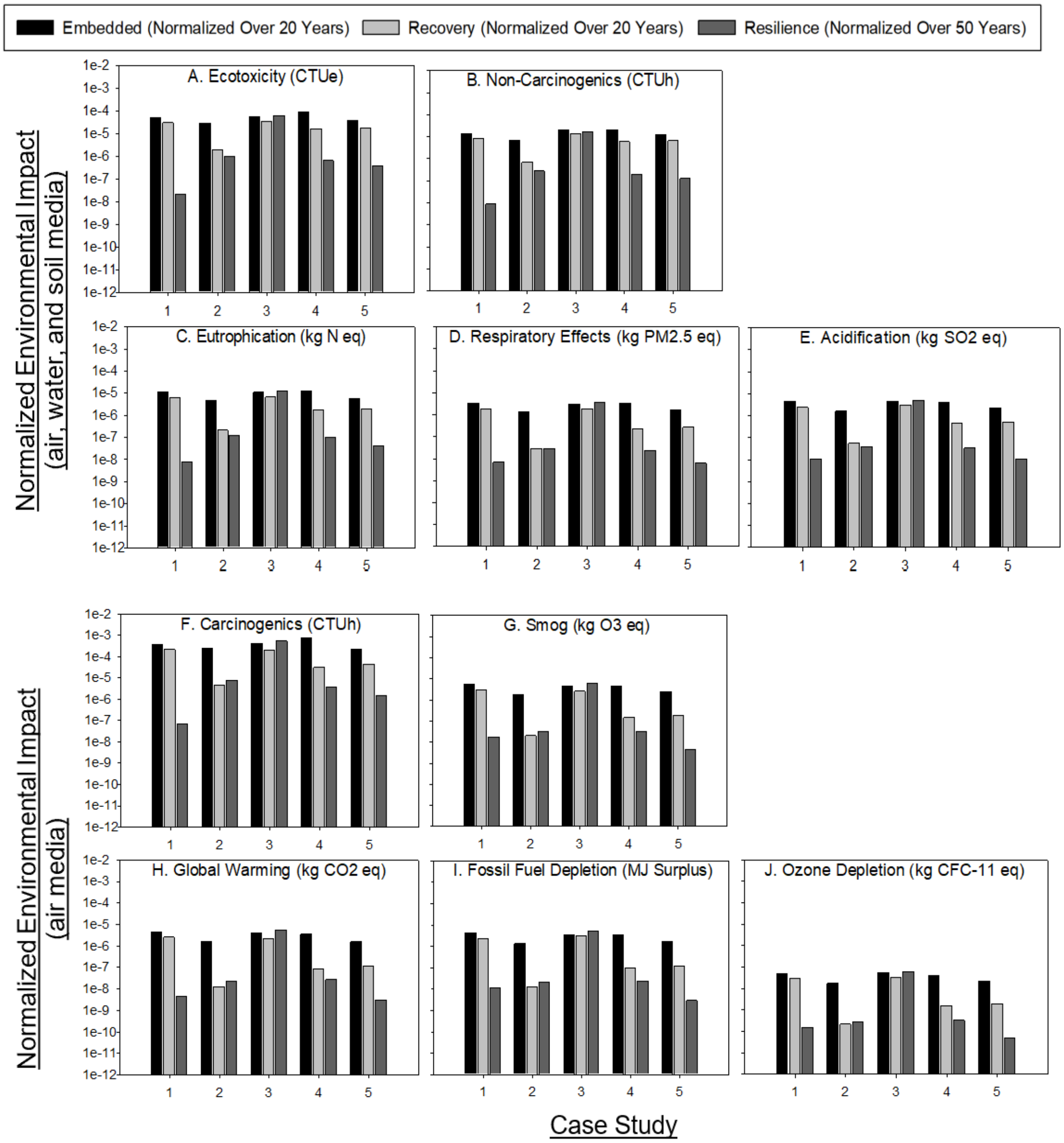


Figure 3.2 Normalized life cycle environmental impact of initial construction, recovery construction, and resilience construction for case studies that had both recovery and resilience impacts

The environmental impact of recovery construction is high when large amounts of equipment are replaced or used to remove debris or water. This was also observed for cases where concrete structures required minor repairs. Metal and concrete production results in noticeable air, water, and soil emission releases. The environmental impact of

resilience is high when major concrete, excavation, and cast iron piping additions and replacements are needed. Concrete and cast iron production, as well as excavation activities, release considerable air emissions. Building a new facility as a resilience measure, as proposed by outlier Case 3, has the highest impact of resilience for each impact category, due to the amount of construction activities and resources that are required to build an entirely new facility. The environmental impacts of elevating an existing plant, one of the more common resilience measures taken by the case studies, can vary based on facility size and desired elevation; this impact will increase if additional construction activities (e.g., adding basins, piping, and pumping) are proposed.

It is important to note that the construction impact of recovery is likely a conservative estimate because a one-time frequency (i.e., the 2019 flood) was considered. Based on historic flood data (Appendix B Table B6), it is likely that multiple flood events can occur within a WRRF's design life. If another flood similar to the 2019 Midwest Flood were to happen, the environmental impacts of recovery portrayed in Figure 3.2 would double, while the initial and resilience impacts would remain the same. According to NOAA (2023), there is 39.5% and a 9.5% chance that a 100-year flood or a 500-year flood event, respectively, will occur over the next 50 years. It is recommended that future work incorporates climate projection models and/or the accounting of multiple flood events over the 20 year design life of the case studies, to highlight how the recovery impact may change over time. WRRFs that suffered multiple flood events in the last 20 years may benefit most from being resilient, as they are more prone to flood damage based on historical data. Likewise, resilient infrastructure may not be protective for the

assumed 50 year useful life, which highlights the importance of continuing to use case studies to reflect on the impacts over a WRRF's operational life.

Water emissions and operational energy usage were considered to supplement the impacts within the defined system boundary. Because each case went offline during the recovery period, it was assumed that the eutrophication impact of raw wastewater discharges was as if the WRRF was not in operation (Sun et al., 2020). This is likely an underestimate, as the impacts of agricultural wastes, industrial loadings, and sediments in the flood waters were not estimated. Likewise, it was assumed there was no energy usage at a plant while it was offline. The recovery periods ranged from 21 hours to four months, which is short relative to the assumed design/operational life of a facility, and thus, meaningful LCA results were not observed. This is consistent with literature, which reports that isolated raw discharges are similar to treated effluents during floods due to high dilution factors in receiving water bodies (Risch et al., 2018).

3.3.2 Economic impacts

Generalized cost comparisons are presented in Figure 3.3 on a log-scale. Only Cases 1 – 4 had both resilience and recovery cost information available (Case 5's resilience plans are only in the planning phase). Cases 6, 7, and 8 were recovery cases, so no resilience costs were incurred. Cases 9 and 10 were resilience cases, but resilience cost information was not available. Initial construction costs were estimated based on a generalized WRRF cost model provided by Hansen (2023). This model was based on the U.S. EPA's cost models for constructing municipal WRRFs and confirmed using plant construction costs from the Nebraska Department of Environment and Energy (Hansen, 2023). It is difficult to project current WRRF costs due to the progressive way WRRFs

are built. Thus, the quantified costs are uncertain and imprecise, which is why the focus of this study is placed on the quantifiable environmental impacts.

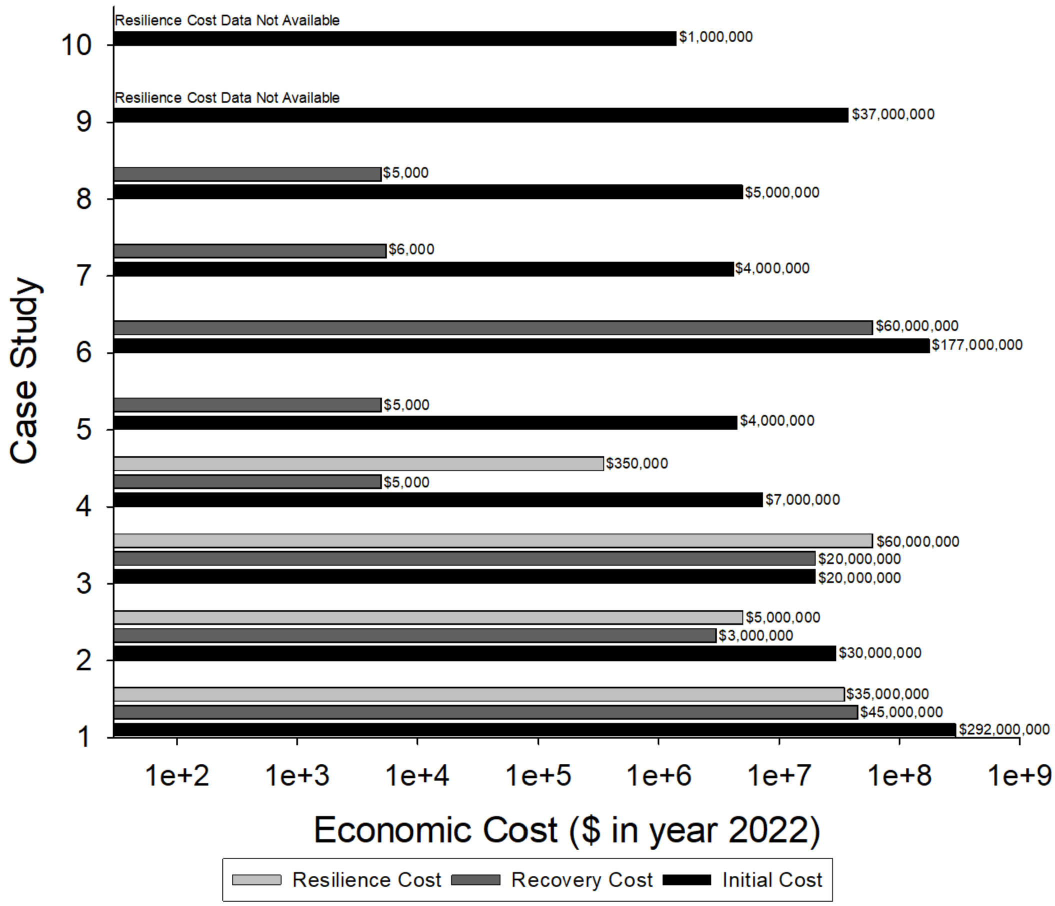


Figure 3.3 Recovery vs. resilience construction costs, as compared to initial construction costs for each case study, presented on a log-scale

Figure 3.3 shows for Cases 1 – 8, with the exception of outlier Case 3, the estimated initial construction cost is highest, consistent with the LCA results. Recovery costs were higher than resilience costs for Case 1 due to the large facility size, long shutdown times, and significant construction repairs. Resilience costs were higher than recovery costs for Case 2 and Case 4, as both cases proposed extensive construction projects as a resilience measure (e.g., additional piping, basins, equipment, etc.).

Although resilient construction has higher upfront economic costs compared to recovery construction, with the exception of Case 1, resilience costs are assumed to be fixed values compared to recovery costs, where the underlying assumption is that a disastrous flood occurs once during the WRRF's design life. As with the environmental impacts, if a similar flood event occurred, recovery costs would increase while resilience costs would remain stable. Thus, investing in resilient infrastructure can be thought of as buying comfort and security.

The generalized cost models used to estimate the economic impacts did not take into account economic discounting, which may change the economic impact of the initial, recovery, or resilience infrastructure. Additionally, Figure 3.3 only considers the economic impacts directly related to the WRRF. The economic impacts of WRRF flooding on the greater community (e.g., industry and community restrictions which ultimately affect employment, increased chemical usage and purchasing in downstream drinking water plants, increased labor requirements, damage to residential housing, etc.) are not included within the system boundary. However, it is likely that the economic impacts of these downstream recovery activities are considerable.

Regardless of the economic impacts, LCA results show there is an overall life cycle environmental benefit to resilient infrastructure. Additionally, there are many negative social impacts associated with recovery that were observed for the case studies. These impacts greatly drove the communities to make the decision to implement resilient infrastructure as a result of the 2019 (or previous) flooding event, to reduce vulnerability of the critical infrastructure.

3.3.3 Additional non-quantified impacts

The use of reflective case studies allowed for discussions with design engineers and facility operators about the additional impacts, beyond cost and environmental impacts, observed by communities during the flood event. These impacts are referred to in this study as other (or additional), non-quantified impacts (i.e., these impacts were not quantified in this study). Although these impacts were observed based on anecdotes, they had substantial effects on the community for each case study. Table 3.3 highlights the common additional impacts observed for case studies 1 to 8 that underwent recovery.

Table 3.3 Additional impacts of recovery, beyond environmental and economic impacts

	Impact/Case	1	2	3	4	5	6	7	8
Treatment	**Bypass and/or Offline**	x	x	x	x	x	x	x	x
	Community or Industry Shutdowns/Restrictions		x	x	x				
	Restricted Plant Access	x		x					x
	Downstream Water Supply Affected	x	x	x			x		
Workers	**Employees On-call**	x	x	x	x	x	x	x	x
	Psychological Affects			x					
	Limited Disaster Guidance Provided		x	x					
Community	**Daily Life Disruption**							x	x
	Emphasize Growth & Success		x	x			x		
Facility	**Loss of Data/Records**					x			
	Aging and/or Undersized		x	x	x		x		

*Case 9 had staff on-call, but they didn't have negative psychological impacts because plant was resilient
*Case 10 was resilient and did not have to recover

Wastewater treatment for each recovery case was affected by the flood. Each recovery case was forced to go offline during the flood due to flood water intrusion, debris accumulation, and power outages, contributing to daily life disruptions including community and industry shutdowns and restrictions, residential sewage backups, required use of portable toilets, and downstream drinking water treatment challenges (KC, 2019). In some cases, flood waters rose so high that the operators could not access the plant, leading to improper treatment.

Facility staff at each WRRF were affected during recovery. Each recovery case had facility staff on-call 24/7 for the duration of the recovery period, which contributed to worker atrophy and trauma. Case 3 reported that workers were psychologically affected, and many quit after operations resumed due to the unmatchable "high of being a hero." Cases 2 and 3 both reported that workers felt underprepared for a disaster of this magnitude, and they desired more disaster preparation guidance.

Surrounding communities were also impacted by the flood, emphasizing the important role wastewater infrastructure has in a community. The communities of Cases 7 and 8 dealt with daily life disruptions, such as industry job shutdowns, sewage backups in homes, and required use of portable toilets. Communities in Cases 2, 3, and 6 reported their economic success and community growth heavily depends on having a resilient WRRF, as vulnerable critical infrastructure is unattractive for business developers, residents, and visitors.

Facility staff at multiple cases reported facility impacts because of the flood event. Case 5 lost data and records, making it difficult to hire and transition new staff,

report data to the state, and operate properly. Facility staff at Cases 2, 3, 4, and 6 indicated that the flood showed how outdated and undersized the facility was.

3.3.4 The triple bottom line

The case studies highlight that investment in resilient infrastructure has environmental, economic, and societal tradeoffs. According to ASCE Policy Statement 418, sustainability includes economic, environmental, and social conditions (i.e., the triple bottom line). The environmental and economic impacts of the cases show, with the exception of one outlier, initial construction is more costly than recovering or adding resilience to a WRRF. The cases also show resilience may be more costly from an environmental and economic perspective than recovery, depending on construction activities and resources used. However, these impacts do not include impacts outside of the system boundary, and do not account for climate projections or discounting rates. In contrast, the additional impacts not quantified in this study for recovery are high, which largely drove decision making in favor of resilience investments in cases with resilient infrastructure in place prior to the 2019 flood. Additionally, recovery impacts are less certain compared to resilience impacts. The case studies show there are both negative and positive impacts of resilience from an environmental and economic perspective. However, there are only positive, avoided impacts of resilient wastewater infrastructure (other than indirect impacts resulting from any potentially increased environmental and economic costs) from a societal perspective. These results are supported by relevant literature, which has found resilient actions can prevent significant damage of infrastructure (Hennequin et al., 2018).

3.4 Limitations and Future Work

This study quantified the LCA impacts of WRRFs faced with flooding. Economic impacts were not quantified in detail due to the progressive nature of building WRRFs and lack of updated cost data available. The economic impacts did not consider discounting rates, which may increase the economic impact results over time. Social impacts on a community are difficult to quantify, and anecdotes were used to observe general societal impacts of the disaster. Furthermore, the quantified environmental impacts and exploratory economic and social impacts consider the WRRF as the system boundary. It is recommended that future work build upon this LCA of a critical infrastructure system by quantifying economic and social impacts, as well as downstream impacts a disaster may cause.

This study used a small number of reflective case studies to analyze systems in operation. Future work may refer to the data collection approach presented to obtain a statistically significant number of reflective case studies. Additionally, the study did not include climate projections or performance-based risk assessment, as it was outside the scope of the research, and the results identified by this study are independent of risk. If flooding frequencies were to be modeled to account for climate change, the economic, environmental, and social impacts may change significantly. Furthermore, the current study focused on a major flood event; thus, the impacts may be lower if a smaller flood occurs, or larger if multiple small to large sized floods occur over the design life of the plant. Thus, it is recommended that future work incorporates climate projections and performance-based risk assessments to capture uncertainty associated with the performance of recovery and resilience infrastructure under future flooding conditions.

Although this study focused on the 2019 Midwestern flooding event, the data collection methodology and the interpretation of the results is applicable to all regions where critical infrastructure is affected by natural disasters. The results will depend on the frequency and magnitude of the natural disaster.

3.5 Conclusions

As climate change continues to increase the frequency and intensity of natural disasters, it remains important to protect our critical infrastructure. This exploratory study serves to provide comprehensive documentation of the benefits of resilient wastewater infrastructure. Detailed data for 10 case studies was collected to evaluate the life cycle environmental impacts of initial, recovery, and resilience infrastructure. Economic and societal impacts of flooding were evaluated using WRRF cost models and discussions with relevant stakeholders, respectively.

Overall, it was found that investing in resilient wastewater infrastructure is an important step towards sustainability. From an environmental and economic perspective, the impacts of initial construction tend to be higher than the impacts of recovery and resilience construction. In recovery cases that required major equipment replacements and repairs, the environmental and economic impacts of recovery construction tended to be higher than those of resilience construction. Comparatively, in resilience cases that required major construction activities and resources, the environmental and economic impacts of resilience construction are greater than those of recovery construction. This study uniquely identified additional impacts of flooding for each case study, which turned out to be the driving factors for communities that decided to invest in resilient wastewater infrastructure prior to the 2019 flood event. Ultimately, this study aims to initiate the

discussion for civil and environmental engineering consultants, communities, and funding agencies on how to systematically identify tradeoffs of resilience and recovery for critical wastewater infrastructure, while encouraging resilience investments.

References

Allen, Thomas R., Thomas Crawford, Burrell Montz, Jessica Whitehead, Susan Lovelace, Armon D. Hanks, Ariel R. Christensen, and Gregory D. Kearney. (2019). Linking water infrastructure, public health, and sea level rise: Integrated assessment of flood resilience in coastal cities. Public Works Management & Policy, 24(1), 110-139. https://doi.org/10.1177/1087724X18798380

ASCE. (2021a). Policy Statement 518 – Unified definitions for critical infrastructure resilience. Retrieved January 13, 2023 from https://www.asce.org/advocacy/policy-statements/ps518---unified-definitions-for-critical-infrastructureresilience#:~:text=Resilience%20is%20the %20ability%20to,%2C%20economic%2C%20and%20ecological%20infrastructure.

ASCE. (2021b). Policy statement 418 - The role of the civil engineer in sustainable development. Retrieved February 15, 2023 from https://www.asce.org/advocacy/policy-statements/ps418---the-role-of-the-civil-engineer-in-sustainable-development

ASCE. (2021c). 2021 Report Card for America's Infrastructure. Retreieved May 8, 2023 from https://infrastructurereportcard.org/

Ashley, R., Blackwood, D., Butler, D., Jowitt, P., Davies, J., Smith, H., Gilmour, D. and Oltean-Dumbrava, C (2008). Making asset investment decisions for wastewater systems that include sustainability. Journal of Environmental Engineering, 134(3), 200-209. DOI:10.1061/(ASCE)0733-9372(2008)134:3(200)

Balasbaneh, A. T., Marsono, A. K. B., & Gohari, A. (2019). Sustainable materials selection based on flood damage assessment for a building using LCA and LCC. Journal of Cleaner Production, 222, 844-855. https://doi.org/10.1016/j.jclepro.2019.03.005

Bare, J. C. (2002). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. Journal of industrial ecology, 6(3-4), 49-78. https://doi.org/10.1162/ 108819802766269539.

Bare, J. C. (2012). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., & Zinke, T. (2014). Resilience and sustainability of civil infrastructure: Toward a unified approach. Journal of Infrastructure Systems, 20(2), 04014004. DOI: 10.1061/(ASCE)IS.1943-555X.0000177

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: state of the art. Water research, 47(15), 5480-5492. https://doi.org/10.1016/j.watres.2013.06.049

Currie, J., Wragg, N., Roberts, C., Tattersall, J., & Leslie, G. (2014). Transforming 'value engineering'from an art form into a science–process resilience modelling. Water Practice and Technology, 9(1), 104-114. https://doi.org/10.2166/wpt.2014.012

Federal Emergency Management Agency (FEMA). (2022). FEMA Flood Map Service Center. Retrieved February 15, 2023 from https://msc.fema.gov/portal/home

Flavelle, C., Lu, D., Penney, V., Popovich, N., and Schwartz, J. (2020). New Data Reveals Hidden Flood Risk Across America. The New York Times. Retrieved January 13, 2023 from https://www.nytimes.com/interactive/2020/06/29/climate/hidden-flood-risk-maps.html

Great Lakes - Upper Missouri River Board of State and Provincial Public Health and Environmental Managers (GLUMRB). (2014). Recommended standards for wastewater facilities. Retrieved January 13, 2023 from https://www.broward.org/WaterServices/Engineering/Documents/WWSTenStateStandardsWastewater.pdf.

Grubert, E., & Stokes-Draut, J. (2020). Mitigation life cycle assessment: Best practices from LCA of energy and water infrastructure that incurs impacts to mitigate harm. Energies, 13(4), 992. https://doi.org/10.3390/en13040992

Hansen, A. (2023). Reducing I/I in Small Collection Systems: Environmental, Economic, and Other Impacts. M.S. Thesis, Environmental Engineering, University of Nebraska-Lincoln.

Hennequin, T., Sørup, H. J. D., Dong, Y., & Arnbjerg-Nielsen, K. (2018). A framework for performing comparative LCA between repairing flooded houses and construction of dikes in non-stationary climate with changing risk of flooding. Science of the total environment, 642, 473-484. https://doi.org/10.1016/j.scitotenv.2018.05.404

Hummel, M. A., Berry, M. S., & Stacey, M. T. (2018). Sea level rise impacts on wastewater treatment systems along the US coasts. Earth's Future, 6(4), 622-633. https://doi.org/10.1002/2017EF000805

ISO. (2006). Environmental management - life cycle assessment - principles and framework ISO 14040. Int. Org. Stand. Retrieved January 13, 2023 from https://www.iso.org/standard/37456.html.

Jafarinejad, S. (2020). A framework for the design of the future energy-efficient, cost-effective, reliable, resilient, and sustainable full-scale wastewater treatment plants. Current Opinion in Environmental Science & Health, 13, 91-100. https://doi.org/10.1016/j.coesh.2020.01.001

Juan-Garcia, P., Butler, D., Comas, J., Darch, G., Sweetapple, C., Thornton, A., & Corominas, L. (2017). Resilience theory incorporated into urban wastewater systems

management. State of the art. Water research, 115, 149-161. https://doi.org/10.1016/j.watres.2017.02.047

Karamouz, M., Rasoulnia, E., Zahmatkesh, Z., Olyaei, M. A., & Baghvand, A. (2016). Uncertainty-based flood resiliency evaluation of wastewater treatment plants. Journal of Hydroinformatics, 18(6), 990-1006. https://doi.org/10.2166/hydro.2016.084

KC. (2019). KC Water Continues to experience water treatment challenges due to Missouri River flooding. Retrieved January 13, 2023 from https://www.kcwater.us/news/kc-water-continues-to-experience-water-treatment-challenges-due-to-missouri-river-flooding/

Masters, J. (2019). Historic Flooding in Nebraska, Iowa, and South Dakota in Wake of Bomb Cyclone. Weather Underground. Retrieved February 15, 2023 from https://www.wunderground.com/cat6/Historic-Flooding-Nebraska-Iowa-and-South-Dakota-Wake-Bomb-Cyclone

Matthews, J. C. (2016). Disaster resilience of critical water infrastructure systems. Journal of Structural Engineering, 142(8), C6015001. DOI: 10.1061/(ASCE)ST.1943-541X.0001341

Morera, S., Corominas, L., Rigola, M., Poch, M., & Comas, J. (2017). Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. Water research, 122, 614-623. https://doi.org/10.1016/j.watres.2017.05.069

Moussavi, S., Thompson, M., Li, S. and Dvorak, B., (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of construction and operations. Journal of Environmental Management, 292, p.112802. https://doi.org/10.1016/j.jenvman.2021.112802

Multi-Hazard Mitigation Council. (2019). Natural Hazard Mitigation Saves: 2019 Report. National Institute of Building Sciences. Washington, DC. Retrieved February 22, 2023 from www.nibs.org

National Oceanic and Atmospheric Administration (NOAA). (2019). Spring Outlook: Historic, widespread flooding to continue through May. Retrieved January 13, 2023 from https://www.noaa.gov/media-release/spring-outlook-historic-widespread-flooding-to-continue-through-may

National Oceanic and Atmospheric Administration (NOAA). (2023). Flood Return Period Calculator. Retrieved February 15, 2023 from https://www.weather.gov/epz/wxcalc_floodperiod

Nebraska Department of Environment and Energy (NDEE). (2013). Questions and Answers Regarding Wastewater Bypasses During a Flood. Retrieved January 13, 2023 from http://dee.ne.gov/NDEQProg.nsf/OnWeb/Disaster-2

Nebraska Department of Natural Resources (NDNR). (2015). Comprehensive Plans and Flood Risk: A Resource Guide for Nebraska Communities. Nebraska Department of Natural Resources. Retrieved January 13, 2023 from dnr.nebraska.gov

Nebraska Emergency Management Agency (NEMA). (2020). State of Nebraska Disaster Recover Action Plan. Retrieved January 13, 2023.

Olyaei, M. A., Karamouz, M., & Farmani, R. (2018). Framework for assessing flood reliability and resilience of wastewater treatment plants. Journal of Environmental Engineering, 144(9), 04018081. DOI: 10.1061/(ASCE)EE.1943-7870.0001422.

Pant, R., Thacker, S., Hall, J. W., Alderson, D., & Barr, S. (2018). Critical infrastructure impact assessment due to flood exposure. Journal of Flood Risk Management, 11(1), 22-33. https://doi.org/10.1111/jfr3.12288

Petit-Boix, A., Sevigné-Itoiz, E., Rojas-Gutierrez, L. A., Barbassa, A. P., Josa, A., Rieradevall, J., & Gabarrell, X. (2017a). Floods and consequential life cycle assessment: Integrating flood damage into the environmental assessment of stormwater Best Management Practices. Journal of cleaner production, 162, 601-608. https://doi.org/10.1016/j.jclepro.2017.06.047

Petit-Boix, A., Arahuetes, A., Josa, A., Rieradevall, J., & Gabarrell, X. (2017b). Are we preventing flood damage eco-efficiently? An integrated method applied to post-disaster emergency actions. Science of the total environment, 580, 873-881. https://doi.org/10.1016/j.scitotenv.2016.12.034

Risch, E., Gasperi, J., Gromaire, M. C., Chebbo, G., Azimi, S., Rocher, V., ... & Sinfort, C. (2018). Impacts from urban water systems on receiving waters–how to account for severe wet-weather events in LCA?. Water research, 128, 412-423. https://doi.org/10.1016/j.watres.2017.10.039

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16, 329-339. https://doi.org/10.1007/s10098-013-0629-z.

Salas, R.N., Knappenberger, P. and Hess, J.J., (2019). Lancet Countdown on health and climate change policy brief for the United States of America. Lancet Countdown. Retrieved January 13, 2023.

Sanders, D. A. (1997). Damage to wastewater treatment facilities from Great Flood of 1993. Journal of Environmental Engineering, 123(1), 54-60. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:1(54)

Schaffer-Smith, D., Myint, S. W., Muenich, R. L., Tong, D., & DeMeester, J. E. (2020). Repeated hurricanes reveal risks and opportunities for social-ecological resilience to flooding and water quality problems. Environmental Science & Technology, 54(12), 7194-7204. https://doi.org/10.1021/acs.est.9b07815

Sun, Y., Garrido-Baserba, M., Molinos-Senante, M., Donikian, N. A., Poch, M., & Rosso, D. (2020). A composite indicator approach to assess the sustainability and resilience of wastewater management alternatives. Science of The Total Environment, 725, 138286. https://doi.org/10.1016/j.scitotenv.2020.138286

Thompson, M., Moussavi, S., Li, S., Barutha, P., & Dvorak, B. (2022). Environmental Life Cycle Assessment of small water resource recovery facilities: Comparison of mechanical and lagoon systems. Water Research, 215, 118234. https://doi.org/10.1016/j.watres.2022.118234

United States Census Bureau. (2010). Retrieved January 13, 2023 from https://www.census.gov/programs-surveys/decennial-census/decade.2010.html.

US EPA. (2022). Enforcement and Compliance History Online. United States Environmental Protection Agency. Retrieved January 13, 2023 from https://echo.epa.gov/

US EPA. (2014). Flood Resilience A Basic Guide for Water and Wastewater Utilities. Retrieved January 13, 2023 from https://www.epa.gov/waterutilityresponse/flood-resilience-basic-guide-water-and-wastewater-utilities

US EPA. (2020). Smart growth in small towns and rural communities. U. S. Environ. Protect. Agency. Retrieved January 13, 2023 from https://www.epa.gov/smartgrowth/smart-growth -small-towns-and-rural-communities#technicalassistanceprograms.

Veronesi, M., Chawla, F., Maurer, M., & Lienert, J. (2014). Climate change and the willingness to pay to reduce ecological and health risks from wastewater flooding in urban centers and the environment. Ecological Economics, 98, 1-10. https://doi.org/10.1016/j.ecolecon.2013.12.005

Wang, Z., Dong, Y., & Jin, W. (2021). Life-cycle cost analysis of deteriorating civil infrastructures incorporating social sustainability. Journal of Infrastructure Systems, 27(3), 04021013. DOI: 10.1061/(ASCE)IS.1943-555X.0000607

Water Science School. (2018). The 100-Year Flood." United States Geological Survey. Retrieved February 15, 2023 from https://www.usgs.gov/special-topics/water-science-school/science/100-year-flood#overview

Welsh-Huggins, S. J., Liel, A. B., & Cook, S. M. (2020). Reduce, reuse, resilient? Life-cycle seismic and environmental performance of buildings with alternative concretes. Journal of Infrastructure Systems, 26(1), 04019033. DOI:10.1061/(ASCE)IS.1943-555X.0000510.

CHAPTER 4 ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF A NOVEL OFFSHORE WIND ENERGY DESIGN PROJECT: A UNITED STATES BASED CASE STUDY

4.0 Abstract

Renewable energy resources, particularly offshore wind energy, and their role in combating global climate change have gained significant interest in recent years. Considering the potential life cycle impacts of such systems is essential to support effective policy and decision making. This study used life cycle assessment to compare the environmental sustainability of an offshore wind farm case study employing a novel foundation design to one employing a conventional foundation design. Although literature related to the environmental sustainability of offshore wind facilities exists, these studies have not examined large scale United States based facilities using a detailed data inventory from a real case study. The results of this study show that alternative foundation designs can decrease the overall life cycle environmental impact of a large scale offshore wind farm. In general, the proposed novel design is favorable from a life cycle perspective compared to the conventional design, particularly in the impact categories of ecotoxicity, eutrophication, carcinogenics, noncarcinogenics, and respiratory effects. The energy payback time was calculated and found to be less than one year for both designs. Additional benefits of the novel design concept include lower material costs, quicker and easier installation, increased domestic job opportunities, decreased reliance on foreign supply chains, ability to expand the design to deeper and disaster prone waters globally, and increased support for current political goals. Scenario sensitivity analyses showed that the environmental impact of wind energy systems may

decrease with domestic sourcing of foundation materials and reuse of the foundation after decommissioning the wind farm.

4.1 Introduction

Due to global climate change, there is an increasing need for and interest in renewable energy resources. Countries around the world are striving to meet various climate change related goals, such as the European Union's goal that 27% of energy consumption will come from renewable energy sources by 2030 (Newell, 2018). Wind energy has been a recent focus of renewable energy discussions, as it is currently the most economically favorable renewable energy source in many areas, and it reduces the greenhouse gas (GHG) emissions from fossil fuels (National Research Council, 2007; Chipindula et al., 2018).

The United States (US) is one of the largest consumers of energy in the world, but it also has the capacity to produce large amounts of wind power (Dorrell, 2020). According to the US Department of Energy (DOE), the US has abundant offshore wind resources, largely located in deep waters, that can help provide renewable energy resources to the large US population living nearby coastal cities (Hartman, 2022; Office of Energy Efficiency & Renewable Energy, 2021). Unfortunately, the US lags behind many European and Asian countries in the development of offshore wind energy (Mathern et al., 2021). However, the idea of offshore wind energy is starting to become more popular in the US, as evidenced by recent milestones such as the US federal government's passage of the Inflation Reduction Act (H.R.-376) and their goal to deploy 30 gigawatts (GW) of offshore wind in the US by 2030 (White House, 2021). With

similar goals worldwide, it is becoming increasingly important to holistically study the impacts of these climate action goals.

Little knowledge exists for decision makers related to the life cycle environmental impacts of offshore wind systems in the US with site specific data. There is a critical need to further enable effective policy and planning to support the growing offshore wind energy infrastructure in the US, as the US is one of the major contributors to global emissions and consequentially climate change (Edenhofer et al., 2022). The goal of this research is to compare the life cycle environmental sustainability of a case study offshore wind farm in the US that employs a novel foundation design to an offshore wind farm with a conventional foundation design to help inform policy decisions that could lead to promoting sustainable energy technologies and help mitigate climate change worldwide (United Nations, 2015).

In general, most environmental assessments of offshore wind systems focus on European systems (Yang et al., 2018; Nian et al., 2019). This study adds to the existing literature a large scale US based case study. Of the limited US based assessments, most focus on hypothetical systems with substantial assumptions because of the limited number of operating systems in the US (Kaldellis and Apostolou, 2017).

The distinguishment between US and European systems addressed by this research is important, as environmental impacts are likely to vary based on location specific factors such as supply chains, construction practices, transportation methods, climate, topography, etc. (Tsai et al., 2016). Onat et al. (2020) found that the role of the supply chain in the overall life cycle environmental impacts associated with the construction industry is significant and must be acknowledged. It is also important to note

that European electricity sourcing is generally greener than that in the US, emphasizing that there may be large environmental impacts associated with electricity usage (e.g., electricity used for construction) for US offshore wind farms (Vetter, 2022). In addition to greener electricity sourcing, European countries have been found to have relatively higher energy efficiency and greener construction practices compared to the US, which will ultimately influence the environmental impact related to construction processes and system operations (Boesch and Hellweg, 2010). Electricity sourcing can be especially important for this study because of the proposed scale, which can require substantial electricity usage during the construction phase.

There is a need for more comprehensive environmental assessments of offshore wind systems using life cycle assessment (LCA). Many related studies only evaluated energy and carbon related impacts and, as a result, failed to evaluate other potential impacts that contribute to climate change such as eutrophication, fossil fuel depletion, and more (Noori et al., 2015; Huang et al., 2017; Kaldellis and Apostolou, 2017; Nian et al., 2019). There is also a lack of studies focused on integrating offshore wind systems' environmental impacts into daily design practice (Bonou et al., 2016). This study can be used as an anticipatory LCA to encourage sustainable development of offshore wind farms in the US. Anticipatory LCA acts similar to a design constraint, in that decisions can be made during project development to reduce environmental impacts based on the LCA results (Goswein et al., 2020). Because this research focuses on a case study currently in the development stage, this study can provide guidance for decision and policy makers to ensure optimal development of renewable energy systems.

The study will evaluate one case study offshore wind facility that is an actual proposed wind farm in the US (NYSERDA, 2022). This proposed novel design has not yet been examined using LCA and case study data. The goal of this study is to compare the environmental sustainability of the case study to a conventional design. Ultimately, this study aims to serve as a baseline model for sustainability analyses related to renewable energy infrastructure development in the US that can be used by decision makers, consultants, and the research community as system popularity increases. The specific research objectives, applied to the case study of interest, are as follows:

1. create a detailed data inventory using site specific data for the US based offshore wind case study,
2. compare the life cycle environmental impacts and energy payback time of the case study's novel design concept to a conventional offshore wind energy system with a focus on the foundation design, and
3. identify positive tradeoffs, beyond environmental impacts, that may result in favorability of the case study design.

This research will help lead the development of a generalized methodology for evaluating the environmental impacts of offshore wind energy projects in the design stage. This analysis will increase understanding of the environmental impacts of offshore wind development, as well as advance technical readiness of tools for minimizing impacts during the design phase. The results will help enable effective energy and environmental policy and planning for the growing offshore wind energy industry worldwide.

4.1.1 Motivation

The power sector accounts for 30% of the total US GHG emissions and is the largest source of GHG emissions in the US (Office of Energy Policy and Systems Analysis, 2016). Therefore, it is crucial that the power sector is analyzed in depth as the US strives to meet the policies and goals set forth by domestic and international entities. To help accomplish such goals, this project evaluates a conventional offshore wind energy system and an offshore wind energy system that includes a novel foundation design to see how the life cycle environmental impacts between the two systems compare.

Although this project considers the total life cycle of a case study offshore wind farm, the focus is drawn towards construction related stages (i.e., transportation, installation, and materials). It is well documented that nonrenewable energy systems have much greater environmental impacts during the operations and maintenance stage compared to the construction and installation stage. Comparatively, renewable energy systems tend to have very little environmental impact associated with the operations and maintenance stage compared to the construction related stages as shown in Figure 4.1 (Donnelly et al., 2010; O'Donoughue et al., 2014; NREL, 2021) using life cycle GHG emissions as an example impact measurement. Thus, it is important to consider the construction related stages of renewable energy systems in depth, as these can be large contributors to the environmental impact of the system. By considering the environmental impact of the construction related stages and conducting an alternatives analysis of various design concepts, decision makers can be more informed when it comes to design

and implementation choices.

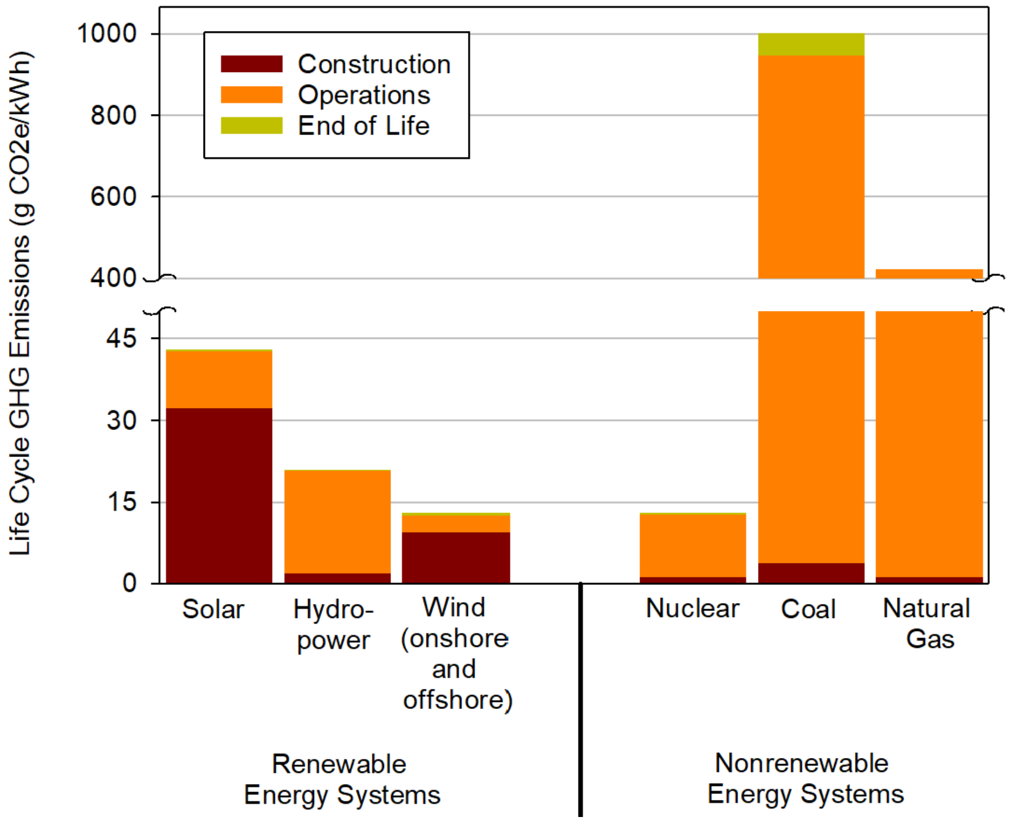


Figure 4.1 Life cycle GHG emissions separated by life cycle stage for renewable and nonrenewable energy systems as reported by Donnelly et al. (2010), O'Donoughue et al., (2014), and NREL (2021)

It is important to note that wind energy is not the only solution to help mitigate climate change impacts and meet related goals. However, adding wind to the energy grid mix will help diversify power supplies by taking advantage of the resources available, particularly in the US, to help reduce the overall environmental impact of the power sector.

This project is unique because it compares the life cycle environmental impacts of a conventional design to a novel design for offshore wind farms in the US, particularly

looking at one of the most prominent life cycle stages of renewable energy systems (construction and installation).

4.1.2 Case study description

The case study analyzed is an offshore wind project located on the US northeast coast that employs a novel foundation design and installation process. Deep waters can provide benefits that are not offered by onshore or shallow water wind facilities. Such benefits include higher wind speeds, consistent wind resources, mobility of structures, and locations out of sight from the shore (Hall and Lazarus, 2015). The 1,000 megawatt (MW) offshore wind facility is comprised of 67 wind turbines with a rated capacity of 15 MW each. The novel design includes a low cost, modular concrete suction pile support structure and a heavy-lift vessel alternative (Gaertner et al., 2020). The concept was designed for deep waters [50 meters (m) – 60 m] and long distances from shore [150 kilometers (km)] to take advantage of areas in the US with high wind energy potential (Office of Energy Efficiency & Renewable Energy, 2021). For context, Mathern et al. (2021) identified average characteristics for wind farms in Europe between 1991 – 2019, with the average turbine capacity being 8 MW, the average distance to shore being 60 km, and the average water depth being 35 m.

The conventional offshore wind support structure is currently a steel monopile foundation (Mathern et al., 2021). However, research shows that more than 60% of the total energy consumption for wind turbines in general is related to steel usage (Noori et al., 2015). Lenzen and Munksgaard (2002) found that the energy requirement for the construction of concrete towers is about half that of steel towers, suggesting that concrete foundations may have less energy requirements and environmental impacts compared to

steel foundations. Thomson et al. (2017) recommends minimizing the amount of steel used in offshore wind systems to reduce environmental impacts. These findings support the novel foundation design utilized by this study.

The case study design team completed the preliminary design of the support structure, cost analyses, and site assessments. The case study assumes a foundation fabrication site using a US east coast based supply chain. Although the case study is based on a site specific location, the design of the infrastructure is suitable for west coast deployment and deep waters worldwide due to the novel installation techniques.

4.2 Methods

LCA is a tool that measures the potential environmental impacts of a system over its entire life cycle (ISO, 2006). The basic framework of a typical LCA study follows four major steps: 1) goal and scope, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation. A process based LCA methodology was used, similar to the approach taken in Moussavi et al. (2021), to evaluate the potential environmental impacts related to the case study. Process based LCA is best used when process data is available because it increases accuracy and detail in the results and inventory (Yang et al., 2018).

4.2.1 Goal and scope

The main goal of this study is to compare the life cycle environmental impacts of a case study offshore wind farm in the US employing a novel foundation design to a conventional offshore wind farm design in order to inform decision makers about the environmental sustainability of such systems. The product system analyzed in this study is an offshore wind farm case study located on the east coast. This product system is an

actual proposed project in the development stage. Thus, most of the data inventory and design assumptions, as listed in Table 4.1, were provided by the case study's consultant stakeholders working on the design of the novel technology.

Table 4.1 Relevant case study characteristics and sources

Specification/Assumption		**Source**
Rated Power	15 MW	(NYSERDA, 2022)
Net capacity factor including losses	0.48	(NYSERDA, 2022)
Operating Lifetime	25 years	(NYSERDA, 2022)
Electricity production for farm	4,225,824,000 kwh/yr	(NYSERDA, 2022)
Average water depth at site	50 m	(NYSERDA, 2022)
Foundation Base Radius	35 m	(NYSERDA, 2022)
Number of Turbines in Farm	67 turbines	(NYSERDA, 2022)
Scheduled maintenance	1 event/year	(Arvesen et al., 2013) (Birkeland, 2011)
Distance between port and site	150 km	(NYSERDA, 2022)

The product system incorporates a novel foundation design for offshore wind turbines worldwide from a practical design perspective. Thus, this study uses LCA to analyze and compare a novel technology to the industry standards. Of the existing offshore wind studies, many only consider conventional designs in shallow water depths (Kaldellis et al., 2016; Kaldellis and Apostolou, 2017). This is noteworthy because studies have documented that the foundation is one of the largest contributors to the overall environmental impact of an offshore wind farm. Thus, alternative foundation designs should be considered to identify potential areas for environmental impact reduction. This will be the first offshore wind turbine designed with a fixed bottom concrete foundation for deep waters in the US studied using LCA.

The function of the product system is to deliver electricity to the grid. Therefore, the functional unit for this study is defined as 1 kilowatt hour (kWh) of wind electricity delivered to the grid, consistent with literature (Noori et al., 2015; Bonou et al., 2016; Tsai et al., 2016; Huang et al., 2017; Yang et al., 2018). The system boundaries of this study include assembly, operations and maintenance, and end of life stages of the case study offshore wind farm, consistent with the literature (Noori et al., 2015; Huang et al., 2017; Chipindula et al., 2018; Yang et al., 2018). Marine transportation between all stages is included in the accounting. The operations and maintenance stage assumes no major emissions during operations (Guezuraga et al., 2012). The end of life stage accounts only for decommissioning of the wind farm, as there is limited data on accurate recycling and disposal methods used for offshore wind infrastructure due to the novelty and longevity of these systems (Arvesen et al., 2013). The physical material boundary defined in this study begins with the port site and ends with the point of interconnection on land, as shown in Figure 4.2. Thus, the electrical collection system (e.g., submarine cables, offshore substations, and export cables) are included in the inventory. However, the material sourcing for the designs is not included in the original study, as the system boundary begins at the port site, and is instead addressed by a sensitivity analysis.

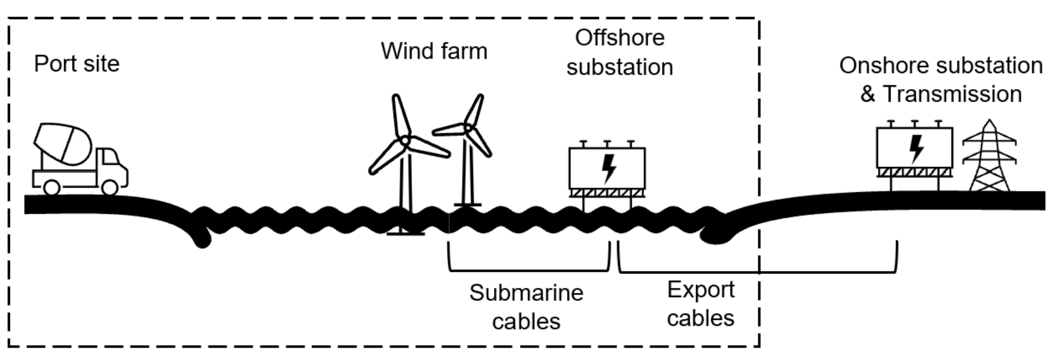


Figure 4.2 Physical material boundary of the case study

4.2.2 Life cycle inventory

The detailed data inventory was created by working closely with the wind project designers and the US DOE National Renewable Energy Laboratories (NREL). Inventory outside the scope of the case study's technical design were obtained from literature. There is currently limited field data available for offshore wind farms, particularly in the US. Consequentially, most studies rely on literature values, databases, and assumptions (Huang et al., 2017; Yang et al., 2018; Nian et al., 2019). Some studies obtained inventory data from offshore wind companies themselves (e.g., Vestas Wind Systems and Siemens Wind Power) (Dolan, 2007; Bonou et al., 2016). In comparison, this study largely uses data provided by industry practitioners. The foreground data inventory is comprised of project design drawings, product specifications, technical reports, literature, and discussions with experts in the field, consistent with and expanding upon methods used by previous similar studies (Tsai et al., 2016). Background data includes upstream processes (e.g., manufacturing and transportation data) provided by the Ecoinvent Database v3.3 (Wernet et al., 2016). A description of the detailed life cycle inventory data within the system boundary is provided in Table 4.2.

Table 4.2 System boundary of the novel design case study, including the collected detailed inventory

System Stage	Foreground Data	Material Quantity	Source of Material Quantity
Assembly	**Installation & Transportation**		
	Assist Tugs [tkm]	8.03E+05	(NYSERDA, 2022)
	Towing Tugs [tkm]	1.35E+08	(NYSERDA, 2022)
	Cable Lay Vessel [tkm]	1.41E+06	(NYSERDA, 2022)
	Crane [tkm]	2.27E+07	(NYSERDA, 2022)
	Steel IPS System with Pontoons [kg]	4.86E+06	(NYSERDA, 2022)
	Tower		
	Fiberglass Blades [kg]	1.19E+07	(Gaertner et al., 2020)
	Steel Tower [kg]	5.23E+07	(Gaertner et al., 2020)
	Direct Drive Generator - Iron [kg]	1.17E+07	(Gaertner et al., 2020)
	Direct Drive Generator - Copper [kg]	2.02E+06	(Gaertner et al., 2020)
	Direct Drive Generator - Steel [kg]	9.56E+06	(Gaertner et al., 2020)
	Steel Nacelle [kg]	3.83E+07	(Gaertner et al., 2020)
	Fiberglass Hub [kg]	1.15E+07	(Gaertner et al., 2020)
	Foundation		
	Concrete Foundation [kg]	7.04E+08	(NYSERDA, 2022)
	Foundation Posttensioning [kg]	2.98E+07	(NYSERDA, 2022)
	Foundation Reinforcing Steel Bar [kg]	3.14E+07	(NYSERDA, 2022)
	Concrete Suction Piles [kg]	5.04E+07	(NYSERDA, 2022)
	Suction Piles Posttensioning [kg]	1.28E+06	(NYSERDA, 2022)
	Suction Piles Reinforcing Steel Bar [kg]	1.15E+06	(NYSERDA, 2022)
	Submarine Cables & Offshore Substation		
	Submarine Cables - Copper [kg]	1.96E+06	(NYSERDA, 2022)
	Submarine Cables - Polyethylene [kg]	5.01E+05	(NYSERDA, 2022)
	Submarine Cables - Polypropylene [kg]	3.40E+05	(NYSERDA, 2022)
	Submarine Cables - Lead [kg]	2.30E+06	(NYSERDA, 2022)
	Submarine Cables - Galvanized Steel [kg]	3.40E+06	(NYSERDA, 2022)
	Steel Offshore Substation [kg]	1.09E+07	(Nian et al., 2019; NYSERDA, 2022)
Operations & Maintenance (25 years)	Crew Transfer - Barge [tkm]	2.55E+07	(Arvesen et al., 2013; NYSERDA, 2022)
	Crew Transfer - Helicopter [hrs]	3.30E+01	(Birkeland, 2011)
End of Life (Decommissioning)	Crew Transfer - Barge [tkm]	1.61E+08	(NYSERDA, 2022)

4.2.3 Life cycle impact assessment

The LCA was conducted using openLCA v1.10 software, which is an open source LCA software. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) impact assessment method v2.1 was used as the impact assessment method. TRACI was chosen as the impact assessment method for this study as it is specific to US systems and processes (Moussavi et al., 2021). TRACI midpoint impact categories analyzed, and their respective units, include ozone depletion [kilograms (kg) chlorofluorocarbons^{-11} (CFC) equivalents (eq)], global warming [kg carbon dioxide (CO_2) eq], smog [kg ozone (O_3) eq], acidification [kg sulfur dioxide (SO_2) eq], fossil fuel depletion [megajoule (MJ) surplus], eutrophication [kg nitrogen (N) eq], ecotoxicity [comparative toxic units (CTU_e)], carcinogens (CTU_h), noncarcinogens (CTU_h), and respiratory effects (kg particulate matter$_{2.5}$ (PM)]. Although Chipindula et al. (2018) and Weinzettel et al. (2009) focus on the environmental impacts for a wide range of impact categories, most literature focuses on GHG emissions and energy usage and ignores other impact categories (Lenzen and Munksgaard, 2002; Noori et al., 2015; Tsai et al., 2016; Yang et al., 2018). It is important to determine the environmental impacts related to a variety of impact categories because certain categories may be relevant for certain material inputs and life cycle stages. The benefit of analyzing diverse impact categories is to fully capture environmental tradeoffs of material inputs and the inventory, and to avoid shifting the environmental burden between impact categories.

4.2.4 Interpretation

The interpretation stage of the LCA includes a general overview of the environmental sustainability of the case study. A similar methodology as proposed in

Sections 4.2.1 – 4.2.3 was used to evaluate the LCA impacts of a conventional offshore wind turbine (i.e., with a steel monopile foundation design). The LCA results of the case study were compared against the novel technology to analyze the environmental benefits of the proposed novel design.

After the normalized TRACI midpoint impacts were evaluated on an individual basis, the single score was considered in "millipoints" (mPt) using a methodology presented by Li et al. (2021). The single score represents the overall environmental impact of the offshore wind farm and was calculated by summing the product of each TRACI midpoint impact and a corresponding weighting factor defined by Gloria et al. (2007). Although the weighting factors are subjective, they are based on recently available data, and this technique is becoming more accepted within the LCA community (Li et al,. 2021).

The LCA results of the novel technology were also compared against conventional and other renewable energy systems' environmental profiles, based on literature, to place the case study results into a practical context by providing guidance related to environmental tradeoffs of various power generation technologies.

The energy payback time (EPBT) of the case study was also calculated and compared against the conventional steel monopile system. EPBT is a common metric used in renewable energy research (Bonou et al., 2016; Kaldellis and Apostolou, 2017) and refers to the amount of time required to pay back the energy input over the project's life cycle. The equation for EPBT is as follows, based on Kaldellis and Apostolou (2017) and Bonou et al. (2016):

$$EPBT = (Cumulative\ energy\ demand)/(Energy\ generation\ per\ year)$$

The cumulative energy demand (CED) refers to the amount of energy required to build and operate the system over the system's entire life cycle. The energy inputs and outputs associated with each life cycle stage of the case study are accounted for. The CED impact assessment in openLCA, based on methods published by Ecoinvent, was used to calculate the CED of the case study. There are eight categories of energy resources (fossil, nuclear, primary forest, biomass, geothermal, solar, water, and wind) that can be considered with this impact assessment method (Frischknecht et al., 2007). Frischknecht et al. (2007) describes the main indicators for each of the energy resource categories in detail. The CED impact assessment method does not allow the energy resource categories to be combined or aggregated, and thus each CED calculation is made on an individual basis. The CED, or input energy, varies depending on the energy source. Thus, the CED will be different for the offshore wind farm depending on the energy source chosen. The energy generation per year was calculated based on the relevant case study characteristics provided in Table 4.1. The EPBT was calculated for five energy resources on an individual basis (i.e., assuming 100% of the energy sourcing comes from the specified energy resource). These categories were chosen based on the current main energy sources contributing to US electricity generation (US Energy Information Administration, 2022).

4.2.5 Sensitivity and uncertainty

Uncertainty should be addressed to increase transparency and reliability of LCA results, which is an essential component of communicating LCA results to stakeholders and decision makers. There are different types of uncertainty, identified by Huijbregts (1998). The current study aims to address parameter uncertainty (which is due to the

large amount of data required for a precise and complete inventory) and uncertainty due to choices (which is due to assumptions made related to the functional unit, system boundaries, cut-off rules, and data collection methods) (Cellura et al., 2011). To address these uncertainties in the current study, sensitivity analysis was used to assess how an independent variable (i.e., input data and assumptions) can influence the dependent variable (i.e., LCA outputs), following the procedures proposed by May and Brennan (2003).

Following the approach taken by Moussavi et al. (2021) and Cellura et al. (2011), two scenario sensitivity analyses were conducted. The scenario sensitivity analysis specifically addresses how varying a single variable can influence the LCA results, which is a common approach taken to communicate LCA results to interested parties (Bjorklund, 2002; Guo and Murphy, 2012). The first sensitivity analysis considers the influence of the supply chain on LCA results. The second sensitivity analysis considers the influence of end of life considerations on LCA results. Both of these analyses vary an assumption made related to the input data.

4.2.6 Inclusion of additional factors

There are additional benefits of a US based wind farm designed with a concrete foundation beyond environmental and economic impacts. Stakeholder discussions (e.g., agencies, consulting firms, regulators) and literature review were used to capture these additional benefits of the novel design. The stakeholders consulted were part of the case study's original design team/advisory panel (NYSERDA, 2022). The advisory panel consists of engineering consulting firms, US NREL, academic institutions, and construction companies. Meetings with the design team occurred over a two year time

period. During these meetings, documentation of potential additional factors took place. Additionally, this research team worked closely with the university led subdivision of the design team to help quantify additional benefits of the design. On occasion, individual meetings were held with specialized subdivisions of the design team to address specific factors (e.g., supply chain and transportation, politics, ecology, etc.). Access to the design team's secure drive was provided to collect further information from the finalized design reports. These discussions will help document expected job markets, installation times, and projected contributions to the continuously evolving renewable energy policies.

4.3 Results and Discussion

4.3.1 General environmental sustainability profiles

This study compares the potential life cycle environmental impacts of an offshore wind farm with a novel foundation design technology to a conventional offshore wind farm design. The LCA profile of the wind farm using the novel foundation design (referred to as Novel Design) is provided and compared to an offshore wind farm of the same capacity using a conventional steel monopile foundation design (referred to as Conventional Design). The inventory for Conventional Design was based on the NREL reference turbine (Gaertner et al., 2020). It is important to note that the tower, submarine cables & offshore substation, and operations & maintenance stages for both Novel Design and Conventional Design are assumed to be equivalent, as each are designed for the same capacity. The distinguishing factor between the designs, as emphasized by the goal and motivation of this study, is the construction and installation stages, including the foundation design. The end of life stage is also different between designs, as the decommissioning of materials is dependent on the foundation design.

Figure 4.3 shows the results of the LCA for the entire wind farm on a normalized basis to provide a holistic environmental assessment of the system. The normalized values of the results are provided in Appendix C Table C1. The unit for the normalized environmental impact is "(environmental impact per functional unit) / (environmental impact per year)." The environmental impact per year is impact category specific and is based on the normalization factors provided by Updated US and Canadian Normalization Factors for TRACI 2.1 (Ryberg et al., 2014). It is important to note that each impact category has its own units, as shown in Figure 4.3, and thus the impact categories must be evaluated on an individual basis and not compared against each other.

The results shown in Figure 4.3 indicate that in half of the impact categories (ecotoxicity, eutrophication, carcinogenics, noncarcinogenic, and respiratory effects), Novel Design has a lower environmental impact compared to Conventional Design. The remaining impact categories show that Conventional Design has a lower environmental impact compared to Novel Design. Although there are differences in the environmental profile of Novel Design and Conventional Design, both have a total environmental impact within the same order of magnitude as each other for each of the impact categories. The differences in the total environmental impact of each design are due to the different foundation designs and required installation and transportation techniques.

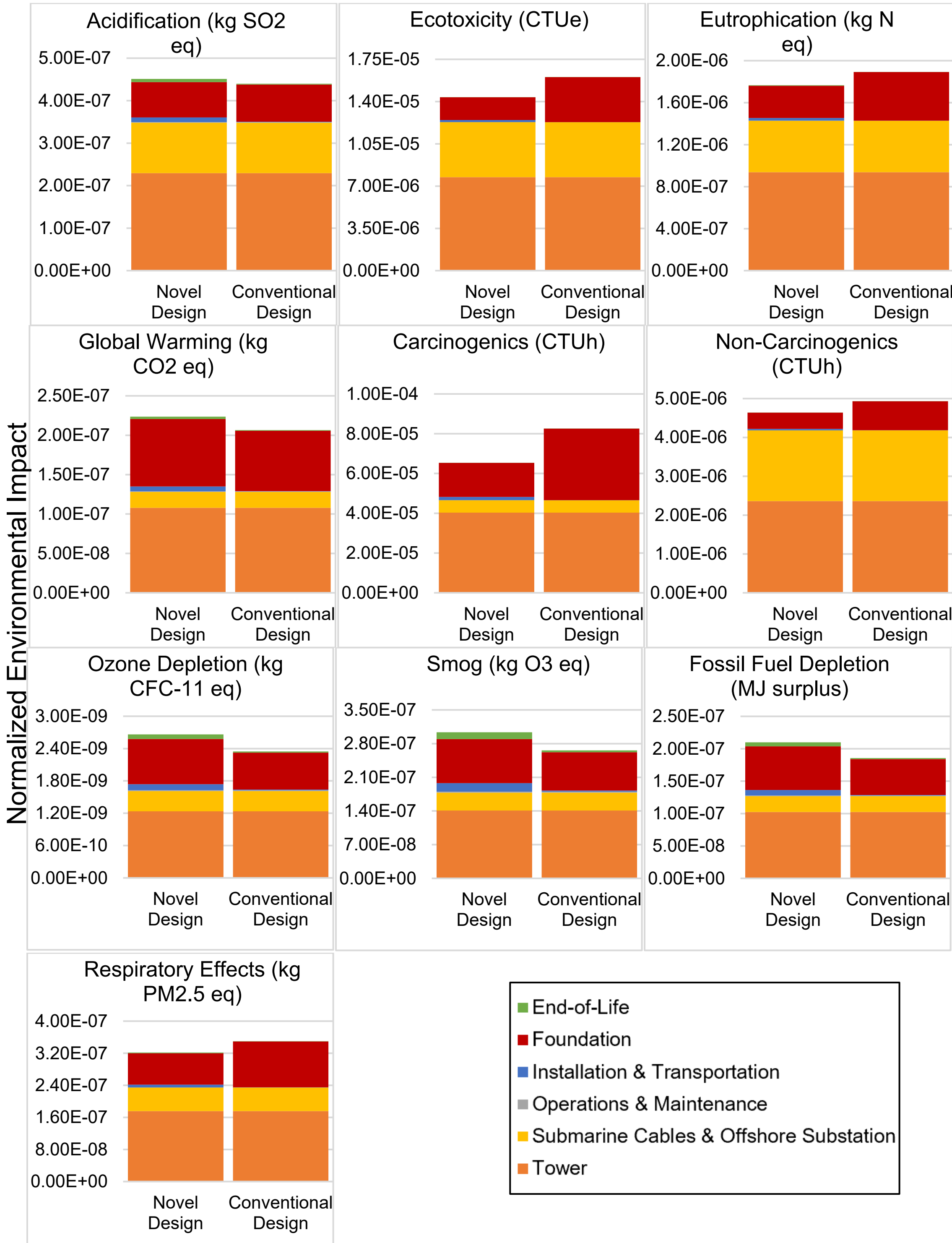


Figure 4.3 Normalized life cycle environmental impact of the overall wind energy system for Novel Design and Conventional Design

For both designs in each of the 10 impact categories, the tower is the largest contributor to the overall environmental sustainability of the wind farm (46% - 62%) due to the air and water emissions (e.g., chromium and CO_2) from the steel production of the tower components. For the impact categories of acidification, ecotoxicity, eutrophication, and noncarcinogenics, the main contributors to the overall environmental profile are the submarine cables and offshore substation (26% - 39%) for both designs. The environmental burden associated with the submarine cables and offshore substation for the wind farm is due to the air emissions (SO_2) and water emissions (zinc, phosphate, and chromium) associated with copper wiring production. For the impact categories closely related to global climate change (i.e., global warming, carcinogenics, ozone depletion, smog, fossil fuel depletion, and respiratory effects), the second largest contributor to the overall environmental profile, closely behind the tower, is the foundation. This emphasizes the need to consider LCA analysis of foundation designs. For each of the impact categories, the operations and maintenance stage contributes less than 1% and the end of life stage contributes less than 5% to the overall environmental impact of the offshore wind farm, regardless of the design. The environmental burden associated with the operations and maintenance and the end of life is due to air emissions [e.g., CO_2 and nitrogen oxides (NO_x)] and crude oil resource depletion resulting from marine and helicopter transportation.

Figure 4.4 shows the environmental single score comparison between the total life cycle of Novel Design and Conventional Design to compare all 10 of the impact categories on the same scale to help communicate results quickly to stakeholders.

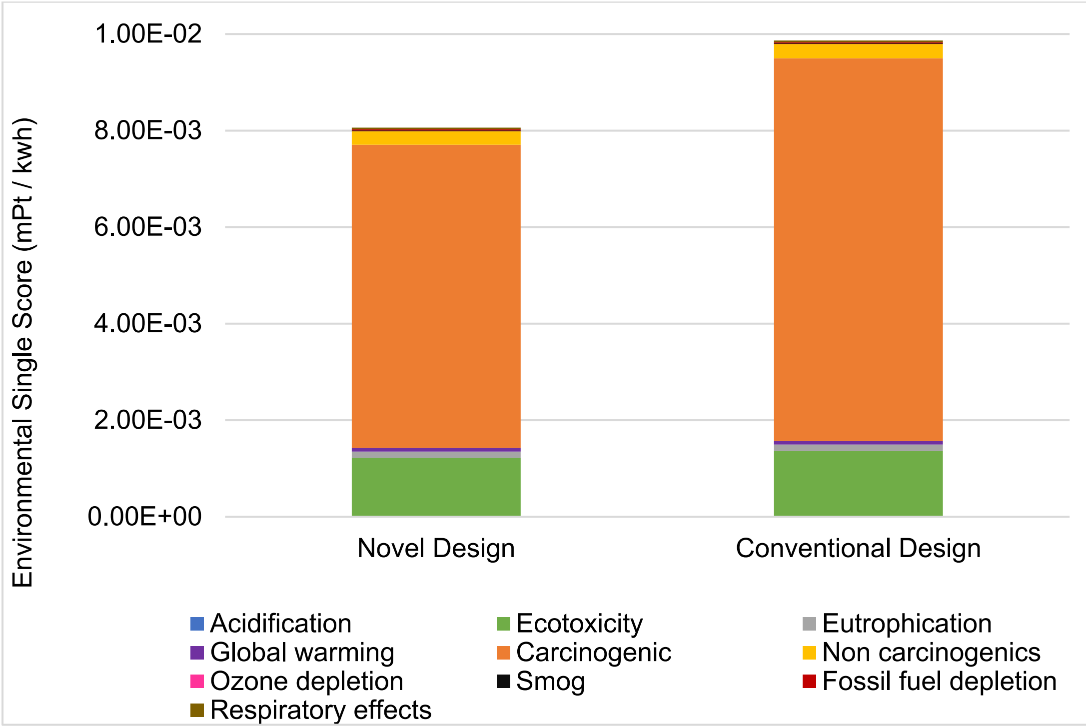


Figure 4.4 Environmental single score of 10 TRACI impact categories comparison between Novel Design and Conventional Design

As shown in Figure 4.4, Novel Design has the lower overall environmental single score (8.06E-03 mPt/kWh) due to the lower quantity of steel materials used in the design. Carcinogenics plays a large role in the environmental single score for both designs, mainly due to the chromium water emissions resulting from the treatment of slag and spoil for concrete production and the treatment of slag for steel production. Ecotoxicity also plays an important role in the environmental single score for both designs, due to the chromium water emissions resulting from the steel production required for the tower components. It should be noted that the global warming impact category has a high weight associated with it (Gloria et al., 2007), ultimately showing that certain impact categories (e.g., carcinogencis and ecotoxicity) have notably large environmental burdens that drive the single score.

The aggregated results of this study can be compared to literature results of other energy systems (renewable and nonrenewable) to put these results into context. Of the offshore wind studies conducted, most have found the manufacturing and construction, particularly for the foundation, are the largest contributors to overall life cycle energy consumption and environmental emissions evaluated, consistent with the LCA results of the current study (Bonou et al., 2016; Huang et al., 2017; Kaldellis and Apostolou, 2017; Chipindula et al., 2018; Yang et al., 2018). This study supports the literature which documents that the operation and maintenance contributes the least to total environmental impacts (Noori et al., 2015).

Table C2 and Table C3 in Appendix C provide a summary of selected literature values regarding the LCA breakdown of offshore wind energy systems and GHG emissions per functional unit for renewable and nonrenewable energy systems, respectively. Table C3 focuses on reported GHG emissions per functional unit, as many of the environmental assessments of energy systems found in literature reported this metric due to high interest. It is important to note that each study had varying functional units, system boundaries, and system characteristics, all of which can affect the results of an LCA study greatly. Thus, Table C2 and Table C3 aim only to provide context for the results of the current study.

4.3.2 Energy payback time

EPBT is a common tool that can help compare one energy system to another. EPBT refers to the amount of time it takes for an energy system to recover its energy consumption during construction by using the energy it produces (Varun et al., 2009). However, measures like EPBT can vary greatly depending on the resource and

technology, system boundary, and site specific factors, leading to the lack of clarity in reported literature (Walmsley et al., 2018). Thus, there is a need for site specific energy payback periods to be calculated for a given project prior to implementation.

A study that considered 45 energy projects and calculated EPBTs found that the average EPBT (in years) for natural gas was 0.02, coal was 0.14, hydro was 0.79, wind was 0.52, solar ranged between 3 - 13, geothermal ranged between 0.36 - 1.36, and nuclear was 0.12 (Walmsley et al., 2018).

As shown in Table 4.3, the EPBT for Novel Design and Conventional Design are both under one year for each of the eight energy source categories. The EPBT was calculated on an individual basis for each energy source, assuming 100% sourcing from each source. The EPBT for solar energy sourcing is the lowest for both designs, whereas the EPBT for fossil fuel sourcing is the highest for both designs. This is because solar energy, as a renewable resource, produces fewer GHG emissions compared to fossil fuel energy sourcing which has dirtier inputs including coal, oil, and natural gas. As shown in Table 4.3, the design concept with the lower EPBT varies based on the energy source.

The energy generated per year is the same for each design. However, the CED, or input energy, varies depending on the design concept due to the difference in materials and material quantities. Additionally, each energy source has different intrinsic input values that influence the respective CED. These factors combined led to the varying EPBT depending on the energy source. These results are reasonable based on reported literature values, although many of the EPBTs are lower than reported values due to the large scale and capacity of the novel design. The results shown in Table 4.3 highlight that, as renewable energy continues to replace conventional energy sources in the

electricity grid, life cycle environmental impacts incurred during the capital construction stage of wind energy systems may be reduced (Tsai et al., 2016).

Table 4.3 Energy payback times for Novel Design and Conventional Design for eight energy categories

	Payback Time (years)	
Energy Source	**Novel Design**	**Conventional Design**
Renewable resource - hydro	2.14E-02	2.43E-02
Renewable resource - wind	2.54E-03	2.66E-03
Renewable resource - solar	3.53E-05	3.48E-05
Nonrenewable resource - fossil fuels	2.71E-01	2.57E-01
Nonrenewable resource - nuclear	3.81E-02	3.93E-02

4.3.3 Detailed comparison of the environmental impacts of Novel Design vs Conventional Design

Renewable energy systems have high upfront construction and installation related environmental impacts and low operational and maintenance related environmental impacts compared to conventional energy systems. This highlights the need to focus on the construction related stages of the offshore wind farm case study. Because the foundation is the second largest contributor (ranging from 24% - 44%) to the overall environmental profile of the offshore wind farm, regardless of the foundation design, there is a strong need to analyze the foundation sustainability in depth. Figure 4.5 shows the aggregated material breakdown of the LCA profiles of the foundation and related components. The installation and transportation of the foundation are directly related to the foundation itself and are thus included in the comparative LCA of the foundation designs.

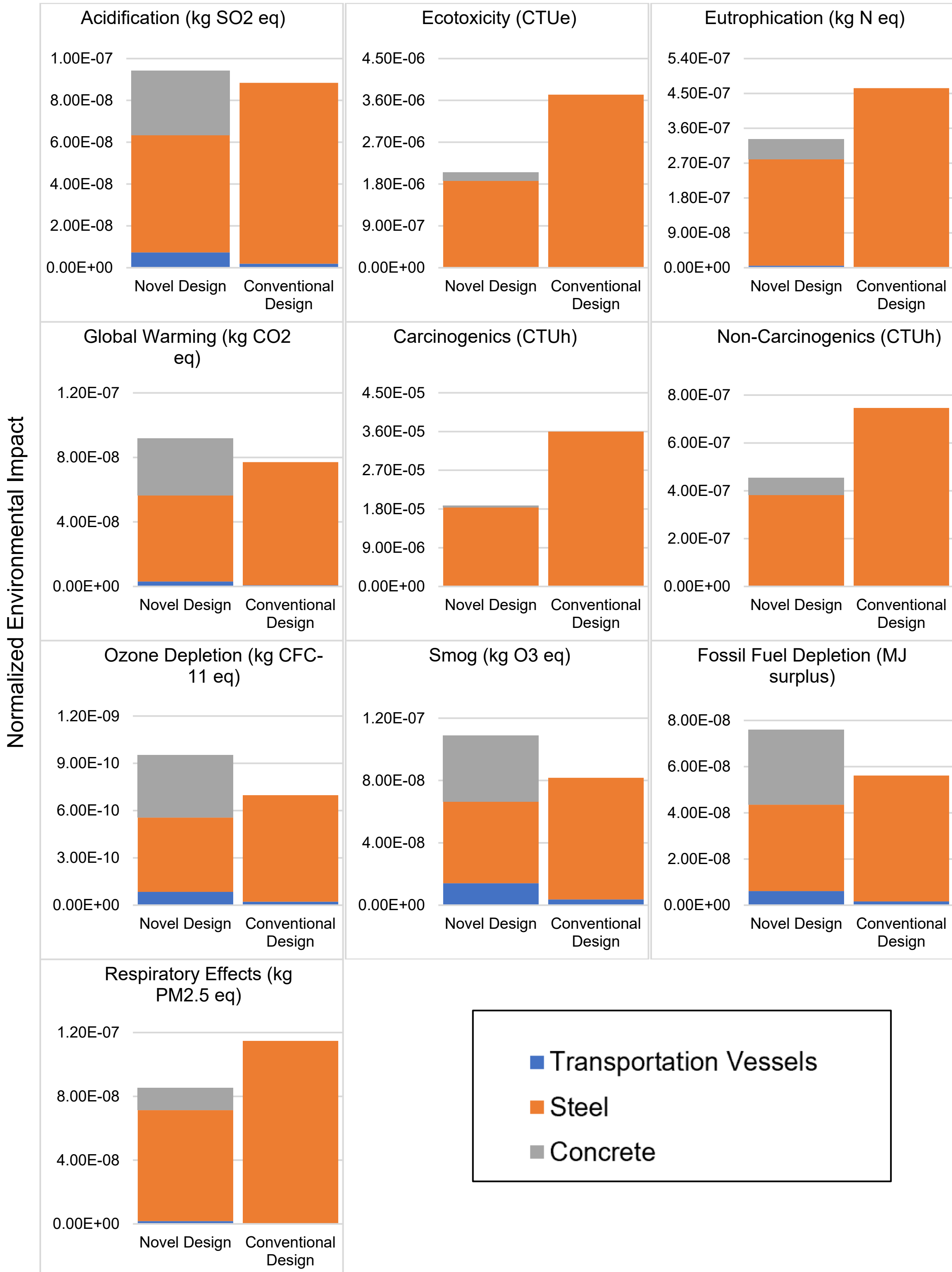


Figure 4.5 LCA material breakdown for the foundation and related components for Novel Design and Conventional Design

For each of the 10 impact categories, the steel quantity makes up the majority of the foundation and related components' environmental impact. For Conventional Design, 72.5% of the steel impact comes from the steel quantity used to construct the monopile foundation for each impact category. For Novel Design, between 44% and 53% of the steel impact comes from the steel quantity used for posttensioning and reinforcement of the concrete foundation for each impact category. The environmental burden associated with the steel foundation for Conventional Design is due to the air and water emissions, particularly CO_2 and chromium, resulting from the steel production.

Because the conventional design does not use concrete in the foundation design or related components, there is no environmental impact associated with concrete for these components for Conventional Design. For the novel design, 93% of the concrete impact for each impact category is due to the concrete material quantity used to construct the foundation, and only 7% is due to the concrete suction piles. The environmental burden associated with the concrete foundation is due to the CO_2 air emissions associated with clinker production and the chromium water emissions associated with treatment of slag.

For each of the 10 impact categories, the transportation vessels used to install the foundation have a higher impact for Novel Design compared to Conventional Design. This is because Novel Design proposes an installation method that requires an additional transportation vessel [Integrated Propulsion System (IPS)]. However, there are additional benefits of the installation system proposed for Novel Design (e.g., Jones Act, installation time, etc.) that are discussed in detail in Section 4.3.5. For Novel Design, the towing tugs created over 80% of the transportation vessels' impact, whereas for Conventional Design, the cranes created over half of the transportation vessels' impact, followed closely by the

monopile driver. The environmental burden associated with the transportation vessels is largely due to the air emissions (e.g., CO_2 and NO_x) they emit and the crude oil resource depletion resulting from the marine transportation.

As highlighted by Figure 4.5, the normalized environmental impact of Conventional Design's foundation and related components is higher than that of Novel Design's in half of the impact categories (ecotoxicity, eutrophication, carcinogenics, respiratory effects, noncarcinogenics), which is largely due to the high quantity of steel required for the monopile foundation design. In the remaining impact categories (acidification, global warming, ozone depletion, smog, fossil fuel depletion), Novel Design's foundation and related components has a higher normalized environmental impact than Conventional Design's due to the large quantity of concrete required to construct the foundation, as well as the additional transportation vessel needed to install the foundation. These results indicate that there exists a potential to limit a range of environmental impacts associated with offshore wind energy systems by considering alternative foundation designs. Although in half of the impact categories the environmental impact of the foundation and related components is higher for Novel Design compared to Conventional Design, there are additional considerations that can show the positive tradeoffs of Novel Design.

4.3.4 Scenario sensitivity analyses

Two analyses of various scenarios were conducted to determine the influence of uncertain variables on the LCA results. The scenarios analyzed included supply chain and end of life scenarios.

4.3.4.1 Influence of the material supply chain on LCA results

Transportation impacts can vary depending on assumptions made. Chipindula et al. (2018) and Lenzen and Munksgaard (2002) found that the transportation stage contributed relatively little to the overall environmental impact of offshore wind systems, even when considering international transportation routes. On the contrary, Yang et al. (2018) found that transportation was one of the largest contributors to the overall environmental impact of offshore wind systems.

In the original study, the port site is assumed to be the beginning of the physical material boundary, as it is assumed that there will be nearby access to the materials due to the location of the case study. Thus, the material transportation accounted for includes only the distance from port site to wind farm placement site (150 km). This scenario sensitivity analysis evaluates two scenarios by expanding the system boundary to show how materials sourcing may influence the LCA results. Scenario 1 refers to domestically sourcing (i.e., sourced from the US) the concrete foundation for Novel Design, as it is expected that there will be a batch plant on site, while much of the remaining metals and plastic materials are sourced from overseas. Scenario 2 refers to sourcing all materials required for Conventional Design (including the foundation) from overseas. It is a likely situation that any metals and plastic materials will be sourced from overseas, as much of the offshore wind industry is located outside of the US and thus many fabrication sites and material sourcing sites are located overseas (Benson, 2022). Figure 4.6 provides a comparison of the potential life cycle environmental impacts associated with varying transportation distances for the foundation.

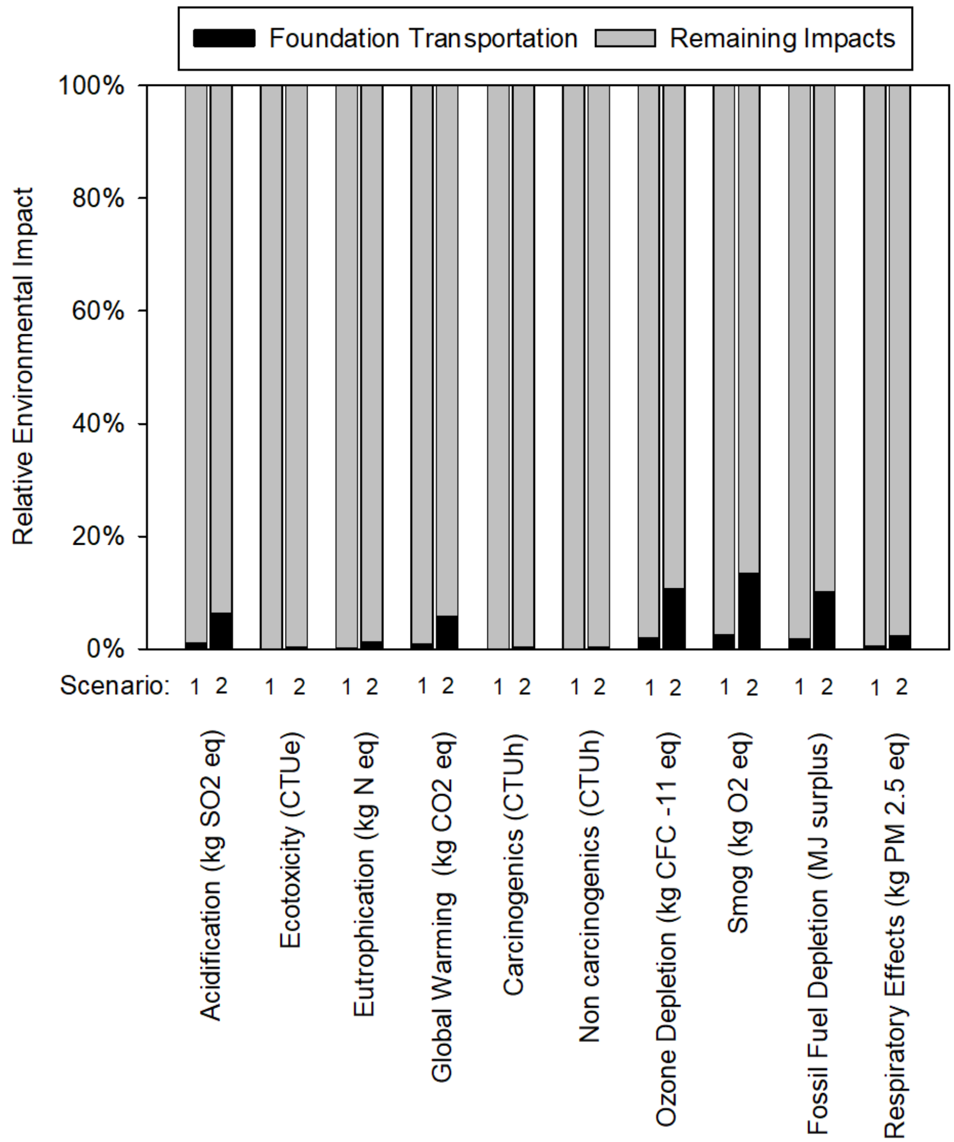


Figure 4.6 Comparison of the life cycle environmental impact of the foundation transportation for assuming a domestic supply chain for Novel Design (Scenario 1) and an overseas supply chain for Conventional Design (Scenario 2)

Figure 4.6 shows that for all impact categories, the environmental impact of the foundation transportation is lower for Scenario 1 compared to Scenario 2. For eight of the impact categories, there is one magnitude of difference between the scenarios. The drastic increase in impact is due to the much larger distance the materials must travel if sourced

from manufacturers overseas, resulting in an increase in the fuel required to transport the materials.

It is important to note that, as shown in Figure 4.6, the foundation transportation, regardless of scenario, is a very small portion of the overall life cycle impacts. This implies that other considerations should be made when determining where materials may be sourced from, such as convenience, cost, and availability of materials.

4.3.4.2 Influence of end of life considerations LCA results

The end of life stage considered in this study includes 100% decommissioning of the entire wind farm after the 25 year assumed useful life. It has been documented that certain concrete designs can remain in the ocean and serve as an artificial marine habitat (Kim, 2001). In addition, leaving the foundation in place could limit ecological disturbances to the seabed during the decommissioning stage (Januario et al., 2007). Thus, this scenario sensitivity analysis evaluates two scenarios. Scenario 1 refers to 100% decommissioning of the entire wind farm for Novel Design, and Scenario 2 refers to decommissioning of the entire wind farm for Novel Design with the exception of the foundation (i.e., the foundation is left in place for what is assumed to be indefinitely). Figure 4.7 shows the differences in impact for these two scenarios.

As shown in Figure 4.7, the environmental impact of Scenario 2 is lower than that of Scenario 1 for each impact category. However, it should be noted that the end of life stage is a small contributor to the overall environmental burden of the wind farm life cycle, as shown in Appendix C Table C4, and thus should be considered only if convenient and useful.

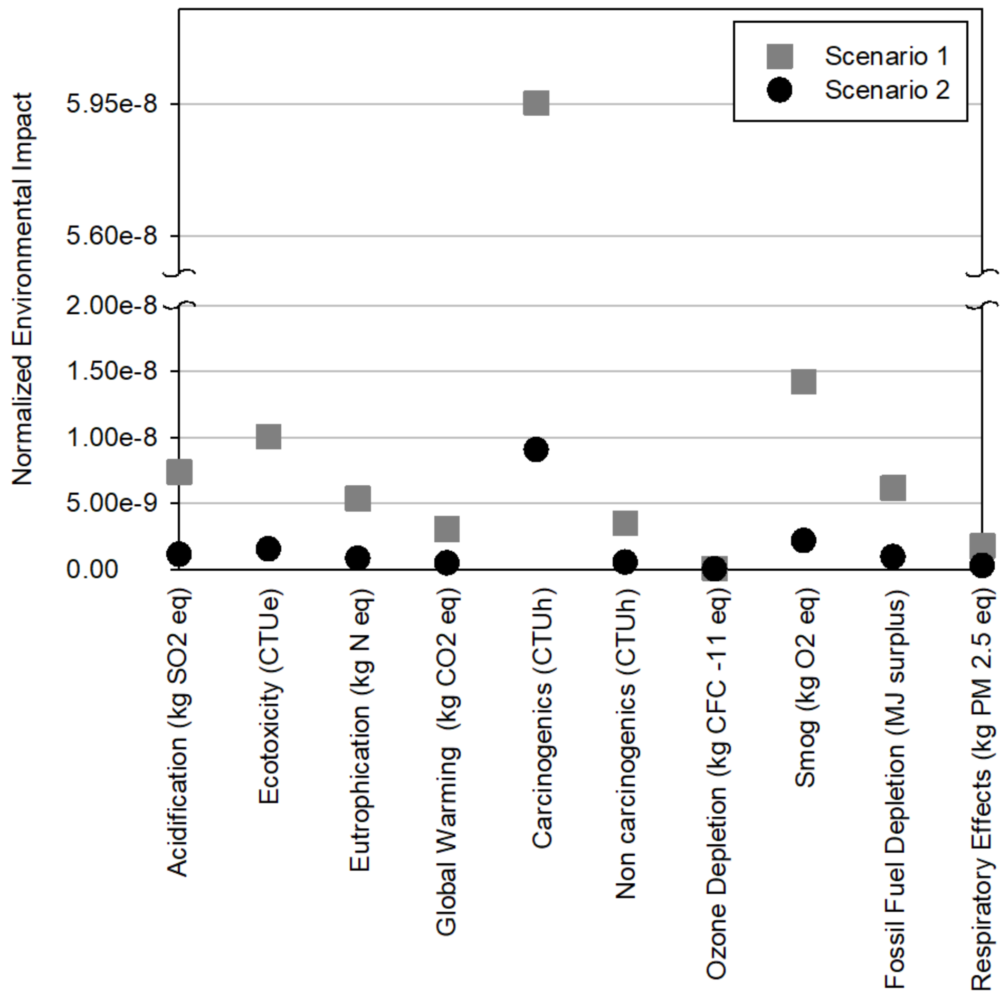


Figure 4.7 Comparison of the life cycle environmental impact of the end of life stage for Novel Design assuming a 100% decommissioning of the wind farm (Scenario 1) and decommissioning of the wind farm with the foundation left in place (Scenario 2)

4.3.5 Additional considerations

There are additional factors, beyond LCA impacts, of the US based Novel Design that should be considered. These considerations were identified via stakeholder discussions and supported by related literature. Stakeholders indicated that cost is their priority, but they acknowledged the importance of additional benefits of the novel engineering and design (e.g., environmental, mobilization, political, etc.), especially when faced with the dynamic nature of economics and politics. Environmental benefits of

the design can be determined based on LCA results as presented in this research, and can include ecological benefits as well (e.g., potential to leave foundations in place to support marine life). Additional benefits can be related to societal impacts, politics, and/or economics. Figure 4.8 provides a non-exhaustive list of the impacts that the proposed offshore wind farm may have. The following sections detail the additional considerations as identified by stakeholder discussions.

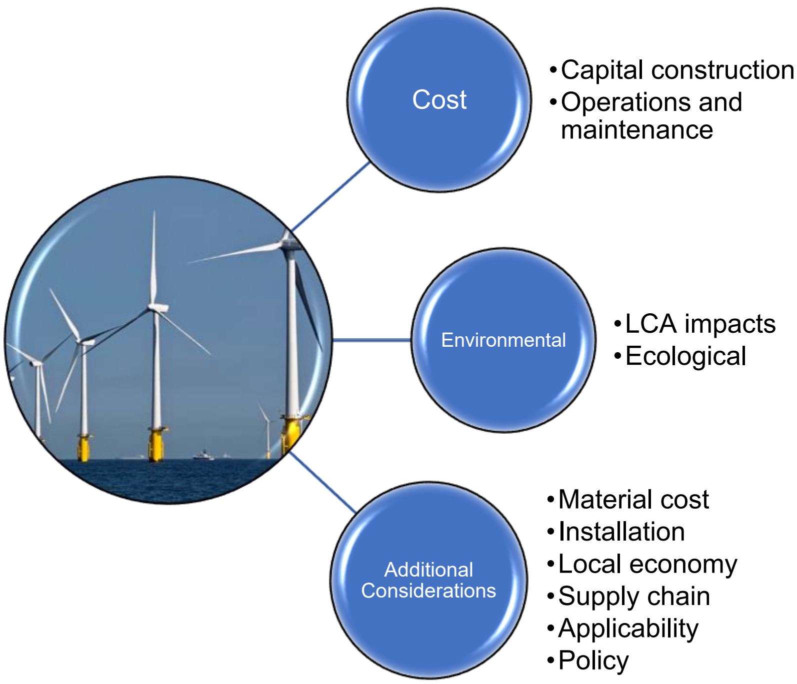


Figure 4.8 Impacts of the case study offshore wind farm using a novel foundation design adapted from Frangoul (2021)

4.3.5.1 Material cost benefits

The stakeholders estimated the cost of a conventional steel monopile foundation to be approximately \$200/kilowatt (kW) less than the novel concrete foundation design (NYSERDA, 2022). Although there is a larger capital cost for the foundation when the novel design concept is used, the cost estimates excluded consideration of a steel jacket

which would be an additional required expense associated with the conventional steel monopile foundation design.

4.3.5.2 Installation benefits

Perhaps one of the biggest barriers to offshore wind development in the US is the risk of violating the Jones Act (Grabow, 2021). The Jones Act requires that maritime commerce utilizes wind turbine installation vessels owned and operated by US citizens, however there is limited availability of such vessels (46 U.S. Code § 50101). The design team was able to design a novel installation technique that complies with the Jones Act.

An additional installation benefit of the case study was identified to be the speed of mobilization. Monopiles tend to have long installation times as they are installed one by one due to vessel limitations. The stakeholders stated that the novel installation technique can allow the concrete foundations to be installed in parallel and reduce installation times (NYSERDA, 2022). The stakeholders estimated a 127 day decrease in installation time when comparing the conventional monopile design to the novel concrete design. The reduction of installation time can also help limit potential exposure to weather delays. The novel installation technique can be installed without pile driving, which reduces impacts from noise and vibrations on surrounding marine life and endangered species. The technique is also expected to reduce health and safety risks associated with marine installation for workers, as it will limit the number of crew members involved in the installation. Other benefits of the installation technique identified by stakeholders include increased stability of the foundation during transportation and installation, as well as the ability to scale the technique to larger structures in the future.

4.3.5.3 Local economy impacts

The stakeholders estimated that, on a national level, utilization of the novel concrete foundation design in US wind farms could result in more than triple the number of jobs in the US compared to the use of steel monopiles (NYSERDA, 2022). This is because the steel monopiles are largely imported to the US. The number of jobs created is likely underestimated, as the design team has also proposed a US based novel fabrication method that they expect to be even more labor intensive than the average US concrete industry's intensity, resulting in more job opportunity.

4.3.5.4 Supply chain dependencies

Energy resources can be impacted by international relations, events, and policies. Investing in domestic renewable energy now can help reduce long term dependency on foreign supply chains that may be disrupted by events such as pandemics and wars. Additionally, each country has its own commitments and targets for renewable energy. For these reasons, the design team proposed to construct a US port for this study. With reliance on domestic versus foreign countries, materials may be more easily sourced, more domestic job opportunities may open, and delays in installation can be reduced.

4.3.5.5 Applicability of the design outside of the US

The stakeholders designed the case study with the intent of large scale application. Thus, the design can expand the opportunities to implement large turbines across various regions including those with deeper and more natural disaster prone waters.

4.3.5.6 Political implications

The novel foundation design concept can help governments achieve their renewable energy policies and goals by encouraging the development and implementation of offshore wind farms. The US DOE recently announced that offshore wind development should expand wind farms to deeper waters to increase wind capacity (Nian et al., 2019). Stakeholders designed this case study to be applicable in deep waters, suggesting that the novel foundation design concept promotes the US Government's goals. Additionally, the investment in renewable energy systems contributes to building a greener electricity grid.

4.4 Limitations and Future Work

This study did not conduct an independent LCA of other energy systems (e.g., coal, natural gas, solar, hydropower, etc.) and compare it to the case study LCA results. The current study uniquely used case study data to build the life cycle inventory for a renewable energy system to quantify the LCA impacts, rather than relying on hypothetical situations, literature values, and assumptions. Literature LCA values were consulted to provide context and motivation for the study. Future studies should consider a comparative LCA that analyzes case studies of various types of energy systems to obtain accurate environmental comparisons between renewable and nonrenewable energy systems.

The EPBT discussed in this study did not incorporate electricity grid mixes. Future studies should conduct an LCA and EPBT using a localized electricity grid mix to more accurately predict how the LCA results may change with a diverse electricity grid mix. Results may change if the electricity grid becomes greener (Moussavi et al., 2021).

Thus, this analysis should be done in future studies to accurately capture the downstream, long term contributions renewable energy systems may have.

The additional considerations discussed in Section 4.3.5 were not quantified. These factors were determined based on stakeholder discussions and were presented in this research to begin the discussion of such factors. It is recommended that future studies explore these factors further on a quantitative basis to help encourage renewable energy systems.

Lastly, the inventory of this study was based on a real case study in the development stage. This case study helps to highlight areas where there may be opportunities to reduce environmental impacts of offshore wind farm designs. This study focuses on the choice in foundation design, as this is one of the largest contributors to the overall LCA profile of an offshore wind farm. It is further recommended that future studies consider alternatives in other areas with high environmental impacts (e.g., suction bucket alternatives, tower alternatives, etc.).

4.5 Conclusions

There is an increasing need for and interest in renewable energy resources worldwide. The US has the ability to become a leader in offshore wind energy systems, however there is currently limited implementation of and knowledge about such infrastructure systems in the US especially related to life cycle environmental sustainability. The goal of this study was to compare the LCA profiles of an offshore wind facility case study employing a novel concrete foundation design (i.e., Novel Design) in the US to a conventional offshore wind farm employing a steel monopile foundation (i.e., Conventional Design). The detailed data inventory is unique among

LCA studies of wind energy systems, as many do not consider site-specific inventories. EPBTs for both designs were calculated, and additional benefits of the case study were identified via stakeholder discussions.

The LCA profile of Novel Design and Conventional Design are within the same order of magnitude for each of the impact categories analyzed, and the differences are due to the different foundation designs. The Novel Design has lower ecotoxicity, eutrophication, carcinogenics, noncarcinogenics, and respiratory effects impacts compared to the Conventional Design. The difference in environmental impact is due to the larger quantity of steel used in the Conventional Design, and the chromium water emissions and CO_2 air emissions associated with steel production. The Novel Design has a lower environmental single score (8.06E-03 mPt/kWh) compared to Conventional Design, implying that consideration of alternative foundation designs is merited to improve the environmental sustainability of renewable wind energy infrastructure in the US. Additionally, the EPBT for Novel Design and Conventional Design were both found to be under one year regardless of the energy sourcing used. Additional considerations (e.g., material costs, installation benefits, local economic impacts, supply chain dependencies, ability for worldwide application of the design, and political implications) also increase the favorability of the novel design concept.

Scenario sensitivity analyses revealed that different scenarios can influence the life cycle impacts of the case study. Domestic sourcing of the foundation has lower LCA impacts compared to overseas sourcing and can have positive additional social and political benefits. The end of life choice made for the case study can alter the environmental burden of the wind farm as well. For example, decommissioning a wind

farm but leaving the concrete foundations in place will reduce the overall life cycle environmental impact of the wind farm. However, the end of life stage is a small portion of the total life cycle environmental impact of the case study.

Overall, the renewable energy benefits associated with the expansion of offshore wind energy resources in the US provide positive environmental tradeoffs, in addition to the tradeoffs identified via stakeholder discussions. These tradeoffs can encourage serious consideration of the novel design, particularly because of the use of alternative materials and a faster construction and installation technique. The methodology and results of this study can be used to analyze the LCA profiles of other case study renewable energy systems to help inform policy and decision makers as the global energy sector continues to move towards renewable resources.

References

Arvesen, A., Birkeland, C., & Hertwich, E. G. (2013). The importance of ships and spare parts in LCAs of offshore wind power. Environmental science & technology, 47(6), 2948-2956. https://doi.org/10.1021/es304509r.

Benson T. (2022). Offshore wind has been slow to take off in the US. Here's what could change that. Popular Science. Retrieved September 18, 2022 from https://www.popsci.com/environment/offshore-wind-energy-development-us/

Birkeland C. (2011). Assessing the Life Cycle Environmental Impacts of Offshore Wind Power Generation and Power Transmission in the North Sea. Norwegian University of Science and Technology. Retrieved October 21, 2022 from http://hdl.handle.net/11250/257062

Björklund, A. E. (2002). Survey of approaches to improve reliability in LCA. The International Journal of Life Cycle Assessment, 7, 64-72. https://doi.org/10.1007/BF02978849.

Boesch, M. E., & Hellweg, S. (2010). Identifying improvement potentials in cement production with life cycle assessment. Environmental science & technology, 44(23), 9143-9149. https://doi.org/10.1021/es100771k.

Bonou, A., Laurent, A., & Olsen, S. I. (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. Applied Energy, 180, 327-337. https://doi.org/10.1016/j.apenergy.2016.07.058.

Cellura, M., Longo, S., & Mistretta, M. (2011). Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile. Renewable and Sustainable Energy Reviews, 15(9), 4697-4705. https://doi.org/10.1016/j.rser.2011.07.082.

Chipindula, J., Botlaguduru, V. S. V., Du, H., Kommalapati, R. R., & Huque, Z. (2018). Life cycle environmental impact of onshore and offshore wind farms in Texas. Sustainability, 10(6), 2022. https://doi.org/10.3390/su10062022.

Dolan S. (2007). Life Cycle Assessment and Energy Synthesis of a Theoretical Offshore Wind Farm For Jacksonville, Florida. University of Florida. Retrieved October 21, 2022 from https://tethys.pnnl.gov/publications/life-cycle-assessment-emergy-synthesis-theoretical-offshore-wind-farm-jacksonville

Donnelly R, Anibal C, Mohammed A, Wood N, Morgenroth M, Bridgeman A. (2010). An Assessment Of The Life Cycle Costs And GHG Emissions For Alternative Generation Technologies. Conference: 21st World Energy Congress (WEC), Montreal, Quebec: Retrieved October 21, 2022 from https://www.osti.gov/etdeweb/biblio/21397681

Dorrell, J., & Lee, K. (2020). The Politics of Wind: A state level analysis of political party impact on wind energy development in the United States. Energy Research & Social Science, 69, 101602. https://doi.org/10.1016/j.erss.2020.101602.

Edenhofer O, Pichs-Madruga R, Sokona Y, Minx J, Farahani E, Kadner S, et al. IPCC. (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: 2014. Retrieved October 21, 2022 from https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf

Esteban MD, Diez JJ, López JS, Negro V. (2011). Why offshore wind energy? Renewable Energy;36:444–50. https://doi.org/10.1016/j.renene.2010.07.009.

Frangoul A. (2021). A huge moment: U.S. gives go-ahead for its first major offshore wind farm. CNBC. Retrieved September 18, 2022 from https://www.cnbc.com/2021/05/12/us-gives-go-ahead-for-first-major-offshore-wind-farm-.html

Frischknecht R, Jungbluth N, Althaus H, Doka G, Heck T, Hellweg S, et al. (2007). Overview and Methodology. ecoinvent report No. 1. Swiss Centre for Life Cycle Inventories,. Dubendorf. Retrieved October 21, 2022 from https://ecoinvent.org/wp-content/uploads/2020/08/200712_frischknecht_jungbluth_overview_methodology_ecoinvent2.pdf

Gaertner E, Rinker J, Sethuraman L, Zahle F, Anderson B, Barter G, et al. (2020). Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, CO: Retrieved October 21, 2022 from https://www.nrel.gov/docs/fy20osti/75698.pdf

Gloria, T. P., Lippiatt, B. C., & Cooper, J. (2007). Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. Environmental science & technology, 41(21), 7551-7557. https://doi.org/10.1021/es070750+.

Göswein, V., Rodrigues, C., Silvestre, J. D., Freire, F., Habert, G., & König, J. (2020). Using anticipatory life cycle assessment to enable future sustainable construction. Journal of Industrial Ecology, 24(1), 178-192. https://doi.org/10.1111/jiec.12916.

Grabow C. (2021). The Jones Act Continues to Hamper the Development of Offshore Wind Energy. CATO Institute. Retrieved September 18, 2022 from https://www.cato.org/blog/jones-act-adds-costs-complications-offshore-wind-energy

Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. Renewable Energy, 37(1), 37-44. https://doi.org/10.1016/j.renene.2011.05.008.

Guo, M., & Murphy, R. J. (2012). LCA data quality: sensitivity and uncertainty analysis. Science of the total environment, 435, 230-243. https://doi.org/10.1016/j.scitotenv.2012.07.006.

Hall, D. M., & Lazarus, E. D. (2015). Deep waters: Lessons from community meetings about offshore wind resource development in the US. Marine Policy, 57, 9-17. https://doi.org/10.1016/j.marpol.2015.03.004.

Hartman L. (2022). Top 10 Things You Didn't Know About Wind Power. Office of Energy Efficiency & Renewable Energy Wind Energy Technologies Office. Retrieved September 18, 2022 from https://www.energy.gov/eere/wind/articles/top-10-things-you-didnt-know-about-wind-power

H.R.5376 - Inflation Reduction Act of 2022. n.d.

Huang, Y. F., Gan, X. J., & Chiueh, P. T. (2017). Life cycle assessment and net energy analysis of offshore wind power systems. Renewable Energy, 102, 98-106. https://doi.org/10.1016/j.renene.2016.10.050.

Huijbregts, M. A. (1998). Application of uncertainty and variability in LCA. The International Journal of Life Cycle Assessment, 3, 273-280. https://doi.org/10.1007/BF02979835.

ISO. (2006). Environmental management - life cycle assessment - principles and framework ISO 14040. Int. Org. Stand. Retrieved January 13, 2023 from https://www.iso.org/standard/37456.html.

Januario C, Semino S, Bell M. (2007). Offshore Windfarm Decommissioning: A proposal for guidelines to be included in the European Maritime Policy. European Wind Energy Conference. Retrieved October 21, 2022 from https://www.researchgate.net/publication/228636135_Offshore_Windfarm_Decommissioning_A_proposal_for_guidelines_to_be_included_in_the_European_Maritime_Policy

Kaldellis, J. K., Apostolou, D., Kapsali, M., & Kondili, E. (2016). Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. Renewable Energy, 92, 543-556. https://doi.org/10.1016/j.renene.2016.02.018.

Kaldellis, J. K., & Apostolou, D. (2017). Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. Renewable Energy, 108, 72-84. https://doi.org/10.1016/j.renene.2017.02.039.

Kim, C. G. (2001). Artificial reefs in Korea. Fisheries, 26(12), 15-18. https://doi.org/10.1577/1548-8446(2001)026<0015:ARIK>2.0.CO;2.

Lenzen, M., & Munksgaard, J. (2002). Energy and CO2 life-cycle analyses of wind turbines—review and applications. Renewable energy, 26(3), 339-362. https://doi.org/10.1016/S0960-1481(01)00145-8.

Li, S., Thompson, M., Moussavi, S., & Dvorak, B. (2021). Life cycle and economic assessment of corn production practices in the western US Corn Belt. Sustainable Production and Consumption, 27, 1762-1774. https://doi.org/10.1016/j.spc.2021.04.021.

Mathern, A., von der Haar, C., & Marx, S. (2021). Concrete support structures for offshore wind turbines: Current status, challenges, and future trends. Energies, 14(7), 1995. https://doi.org/10.3390/en14071995.

May, J. R., & Brennan, D. J. (2003). Application of data quality assessment methods to an LCA of electricity generation. The International Journal of Life Cycle Assessment, 8, 215-225. https://doi.org/10.1007/BF02978474.

Moussavi, S., Thompson, M., Li, S., & Dvorak, B. (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of construction and operations. Journal of Environmental Management, 292, 112802. https://doi.org/10.1016/j.jenvman.2021.112802.

National Research Council, Committee on Environmental Impacts of Wind Energy Projects, National Academies Press (US), Division on Earth, Life Studies, & Board on Environmental Studies. (2007). Environmental Impacts of Wind-Energy Projects. National Academy Press. https://doi.org/10.17226/11935.

Newell, D. (2018). Implementing wind power policy–institutional frameworks and the beliefs of sovereigns. Land Use Policy, 72, 16-26. https://doi.org/10.1016/j.landusepol.2017.12.031.

Nian, V., Liu, Y., & Zhong, S. (2019). Life cycle cost-benefit analysis of offshore wind energy under the climatic conditions in Southeast Asia–Setting the bottom-line for deployment. Applied Energy, 233, 1003-1014. https://doi.org/10.1016/j.apenergy.2018.10.042.

Noori, M., Kucukvar, M., & Tatari, O. (2015). Economic input–output based sustainability analysis of onshore and offshore wind energy systems. International journal of green energy, 12(9), 939-948. https://doi.org/10.1080/15435075.2014.890103.

NREL. (2021). Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update. Golden, CO: 2021. Retrieved October 21, 2022 from https://www.nrel.gov/docs/fy21osti/80580.pdf

New York State Energy Research and Development Authority (NYSERDA). (2022). A Low-Cost Modular Concrete Support Structure and Heavy-Lift Vessel Alternative – Final

Project Report. NYSERDA Report Number 146220. Prepared by Jason Cotrell, Gabriel Falzone, Markus Wernli, Virginie Amerlynck, Phil Barutha, Jan Flores, Julian Fraize, Matt Shields, Jamie Irvine, and Carlo Ortolani. Retrieved October 21, 2022 from nyserda.ny.gov/publications

O'Donoughue, P. R., Heath, G. A., Dolan, S. L., & Vorum, M. (2014). Life cycle greenhouse gas emissions of electricity generated from conventionally produced natural gas: systematic review and harmonization. Journal of Industrial Ecology, 18(1), 125-144. https://doi.org/10.1111/jiec.12084.

Office of Energy Efficiency & Renewable Energy. (2021). Wind Energy Maps and Data. Retrieved September 18, 2022 from https://windexchange.energy.gov/maps-data

Office of Energy Policy and Systems Analysis. (2016). Environment Baseline, Volume 1: Greenhouse Gas Emissions from the U.S. Power Sector. Retrieved October 21, 2022 from. https://www.energy.gov/sites/prod/files/2017/01/f34/Environment%20Baseline%20Vol.%201--Greenhouse%20Gas%20Emissions%20from%20the%20U.S.%20Power%20Sector.pdf

Onat, N. C., & Kucukvar, M. (2020). Carbon footprint of construction industry: A global review and supply chain analysis. Renewable and Sustainable Energy Reviews, 124, 109783. https://doi.org/10.1016/j.rser.2020.109783.

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16, 329-339. https://doi.org/10.1007/s10098-013-0629-z.

Thomson C, Escobar M del MP, Paulotto C, Harrison G. (2017). LCA of Three Innovative Offshore Wind Foundations: Comparative assessment of the environmental impacts of innovative technical solutions intended to optimise the offshore wind farm life cycle. Retrieved October 21, 2022 from https://www.research.ed.ac.uk/en/publications/lca-of-three-innovative-offshore-wind-foundations-comparative-ass

Tsai, L., Kelly, J. C., Simon, B. S., Chalat, R. M., & Keoleian, G. A. (2016). Life cycle assessment of offshore wind farm siting: effects of locational factors, lake depth, and distance from shore. Journal of Industrial Ecology, 20(6), 1370-1383. https://doi.org/10.1111/jiec.12400.

United Nations. (2015). The 17 Goals. Retrieved September 18, 2022 from https://sdgs.un.org/goals

US Energy Information Administration (EIA). (2022). What is U.S. electricity generation by energy source? Retrieved October 22, 2022 from. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

Varun, Bhat IK, Prakash R. (2009). LCA of renewable energy for electricity generation systems—A review. Renewable and Sustainable Energy Reviews;13:1067–73. https://doi.org/10.1016/j.rser.2008.08.004.

Vetter, D. (2020). U.S. Lagging Far Behind Europe On Renewables, New Report Shows. Forbes Retrieved October 21, 2022 from https://www.forbes.com/sites/davidrvetter/2020/03/09/us-lagging-far-behind-europe-on-renewables-new-report-shows/?sh=1de9b10833f4

Walmsley, T. G., Walmsley, M. R., Varbanov, P. S., & Klemeš, J. J. (2018). Energy Ratio analysis and accounting for renewable and non-renewable electricity generation: A review. Renewable and Sustainable Energy Reviews, 98, 328-345. https://doi.org/10.1016/j.rser.2018.09.034.

Weinzettel, J., Reenaas, M., Solli, C., & Hertwich, E. G. (2009). Life cycle assessment of a floating offshore wind turbine. Renewable Energy, 34(3), 742-747. https://doi.org/10.1016/j.renene.2008.04.004.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8

White House. (2021). Fact Sheet: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs. Retrieved September 18, 2022 from https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

Yang, J., Chang, Y., Zhang, L., Hao, Y., Yan, Q., & Wang, C. (2018). The life-cycle energy and environmental emissions of a typical offshore wind farm in China. Journal of Cleaner Production, 180, 316-324. https://doi.org/10.1016/j.jclepro.2018.01.082.

46 U.S. Code § 50101. n.d.

CHAPTER 5 TREATED WASTEWATER REUSE FOR NON-DIRECT FOOD CONSUMPTION CROPS IN NEBRASKA: BARRIERS AND BENEFITS OF MUNICIPAL IRRIGATION LAGOONS

5.0 Abstract

Reusing treated wastewater for agricultural purposes can provide many benefits to small, rural communities. Additionally, irrigation lagoons can be an attractive wastewater treatment technology in areas with high agriculture demands and low water availability. This descriptive study used stakeholder discussions to identify current barriers and benefits of irrigation lagoons. Results of the discussions were compiled into common topics, including implementation information, barriers, ownership structures, and agricultural issues. Dissemination materials were developed to help Extension Professionals distribute information regarding these systems to the communities they work closely with.

5.1 Introduction

Wastewater treatment plants (WWTP) have long been in existence to serve societal needs and maintain public health. The main function of a WWTP is to treat wastewater; thus, many people view these systems as dirty. However, in 2014, the Water Environment Federation formally replaced the term WWTP with “water resource recovery facility” (WRRF) to highlight the valuable resources (e.g., water, energy, nutrients, and biosolids) these systems can recover beyond performing their main duty (WEF, 2014).

As the population continues to grow, food demand grows, which increases the need for agricultural activities such as irrigation (Leonel and Tonetti, 2021). Reusing treated wastewater for agricultural irrigation can be a beneficial way to recover water

from WRRFs to replace and/or supplement traditional irrigation sources. This concept may become particularly important in the future as water resources continue to diminish and climate change leads to more climatic variability. It is important to note, however, that the amount of water from small community wastewater systems is very small relative to the current agricultural water use in many states within the United States (US). However, there are additional local benefits of reusing treated wastewater for agricultural purposes in small, rural communities, such as reduced wastewater treatment costs and lower operations and maintenance requirements.

The US Environmental Protection Agency (EPA) defines water reuse as, "the practice of reclaiming water from a variety of sources, treating it, and reusing it for beneficial purposes" (US EPA, 2023). Agricultural water reuse is defined by the US EPA to include treated wastewater that is reused by applying it to cropland (US EPA, 2023). Many countries, especially developing and arid countries, have long been reusing wastewater for irrigation purposes (Karki et al., 2019). Israel and Jordan are leaders in wastewater reuse for irrigation, and both have successfully established water policies and regulations to control safe reuse (Karki et al., 2019). In the US, there are no regulations for wastewater reuse at the federal level, although guidelines have been developed and made available to states (Ritter, 2021). Therefore, each individual state is able to implement regulations or guidelines for wastewater reuse, as desired. Furthermore, there is a need for more federal funding of reuse projects, to continue encouraging wastewater reuse. Table 5.1 describes the current information available regarding states with water reuse regulations and guidelines. The US lags behind many other countries in water reuse

for agriculture, as it only reuses 7% of its wastewater for agricultural purposes (Hrozencik and Marcel, 2021).

Table 5.1 US States with guidelines and regulations for water reuse for various sectors (Ritter, 2021; US EPA, 2023)

Guidelines and Regulations for:	**US States**
Water Reuse for Agricultural Activities[1]	Alabama, Arizona, California, Colorado, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Montana, Nebraska, Nevada, New Jersey, New Mexico, North Carolina, Oklahoma, Oregon, Pennsylvania, Rhode Island, Texas, Utah, Virginia, Washington, Wyoming
Centralized Non-Potable Reuse[2]	Arizona, California, Colorado, Georgia, Hawaii, Idaho, Massachusetts, Minnesota, Nevada, New Jersey, New Mexico, Oklahoma, Oregon, Pennsylvania, Texas, Utah, Vermont, Virginia, Washington, Wisconsin
Water Reuse for Consumption by Livestock[3]	Arizona, Hawaii, New Mexico, Oklahoma, Oregon, Virginia
Water Reuse for Landscaping[4]	Alabama, Arizona, California, Colorado, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Maryland, Massachusetts, Minnesota, Missouri, Montana, Nevada, New Hampshire, New Jersey, New Mexico, Ohio, Oklahoma, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, Wisconsin, Wyoming
Water Reuse for Impoundments[5]	Arizona, California, Hawaii, Massachusetts, Montana, Nevada, New Mexico, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington

[1]Refers to treated wastewater that is applied to cropland
[2]Applications include fire protection, commercial laundries, vehicle washing, street cleaning, snowmaking, dust control, soil compaction, etc.
[3]Refers to consumption by livestock only; does not include application of reused water to land
[4]Refers to non-edible vegetation in residential and non-residential areas
[5]Refers to recreational and ornamental areas

5.2 Irrigation Lagoons

Lagoon wastewater treatment systems are commonly used in small, rural communities of less than 3,000 people, such as those in Nebraska and the Great Plains

region, where limited funding and resources are available for constructing and operating wastewater infrastructure (US EPA, 2022b). These smaller communities often struggle with maintaining qualified staff to operate WWTPs. Additionally, these systems tend to be implemented in areas where land is commonly and readily available, and where evaporation exceeds precipitation on an annual basis. Furthermore, small, rural communities often struggle with aging and inadequate WWTPs, and many of these systems will require improvements or replacements in the coming years to meet increasingly stringent treatment requirements set forth by state agencies to control nutrients and ammonia levels (Moussavi et al., 2021; Thompson et al., 2023).

Lagoons treat wastewater naturally by using bacteria to metabolize organic matter (Qasim, 1999). Irrigation lagoons, the focus of this research, are a specific type of complete retention lagoon wastewater treatment technology that have the capability to apply treated wastewater, which is considered to be the final discharge of the wastewater treatment lagoon, onto cropland rather than discharging the treated wastewater to a nearby water body (i.e., controlled or continuous discharge lagoons) or indefinitely storing the treated wastewater until it evaporates (i.e., complete retention lagoons without irrigation capabilities) (119 Neb. Admin. Code, ch. 12, § 002; 123 Neb. Admin. Code, ch. 1).There are two main ways that irrigation lagoons are used in Nebraska. First, cities or agricultural producers may use the treated wastewater alone to irrigate their cropland. This is most common when a city is irrigating nearby pasture or grassland. Second, agricultural producers may use a hybrid irrigation system, where the treated wastewater is applied to the cropland, but additional irrigation sources (e.g., groundwater wells) are available for supplemental irrigation purposes. This hybrid irrigation system is more

common in Nebraska, as the treated wastewater alone generally does not meet all of the agronomic needs, which depends on factors such as seasonal variability.

Irrigation lagoons apply treated wastewater onto crops that are not directly consumed by humans (i.e., non-direct food consumption crops such as feed crops, fiber crops, and industrial crops), and have become an attractive alternative in small rural communities. The treatment process for irrigation lagoons begins with influent wastewater flowing by gravity or being pumped from the municipality to the lagoon site where it can undergo preliminary treatment, if applicable. The wastewater then enters the lagoon cells, where it remains for a specified detention time based on design factors, treatment requirements, and amount of wastewater. The wastewater exits the lagoon cells in three major ways: evaporation, seepage through the liner, and in the case of irrigation lagoons, land application onto nearby agricultural land. Biosolids may be periodically land applied.

Generally, when faced with the challenge of meeting updated treatment requirements, small, rural communities with existing wastewater treatment systems have two options: convert to a more advanced mechanical system or expand an existing lagoon system. Research has shown, however, that irrigation lagoons can provide a third alternative that can be cheaper to construct and operate, have lower operational and labor requirements, and have less life cycle environmental impacts, compared to mechanical systems (Thompson et al., 2023). Additionally, irrigation lagoons eliminate the need to expand the land footprint of an existing lagoon system to accommodate growing populations or to reach increased treatment requirements (Thompson et al., 2023).

Implementing wastewater reuse systems for irrigation is not common in the US due to limited guidance and regulations, public acceptance, and lack of system knowledge. A major implementation challenge for small, rural communities is obtaining agricultural producer and landowner cooperation. Although eminent domain (i.e., the power of the government to take private property) is an option available to communities looking to implement irrigation lagoons, many communities consider this a last resort to avoid community disruption. Therefore, it is important to begin considering the benefits of such systems, especially in small, rural communities that typically have the land resources available, rather than expending resources to construct and operate mechanical WRRFs, large storage lagoons, or discharging lagoons without irrigation capabilities, which can lead to very costly and time-consuming projects limited by stringent regulations.

There are existing funding opportunities available to help encourage irrigation lagoons. The Drinking Water and Wastewater Infrastructure Act of 2021 provides clear support for sustainability improvements in small community wastewater infrastructure. Additionally, the United States Department of Agriculture (USDA) is providing funding for agricultural producers in the US to conserve water and adopt climate-smart practices (Soncksen, 2023). However, small, rural communities are oftentimes underserved with regards to onsite financial and technical resources that can help identify wastewater treatment best practices from a technical, economic, and social perspective (US EPA, 2022b). In addition, the engineering design teams working with such communities typically do not have the revenue or resources to conduct reflective case studies and

educate every curious stakeholder about their projects while simultaneously completing their work.

5.3 Goals and Objectives

To ensure that disadvantaged communities have accessible resources to address wastewater challenges, support on the federal, state, and local level must be provided (US EPA, 2022b). Collaborative efforts between trusted stakeholders are key to tackling this challenge (US EPA, 2022b). Nebraska, for example, has found that approximately half of all agricultural producers using irrigation rely on Extension Professionals for information on irrigation management, finances, and conservation (Ringenberg et al., 2018).

Based on previously conducted studies, irrigation lagoons are in many cases better than alternative treatment systems (e.g., mechanical systems or complete retention lagoons), due to reduced land size, operational requirements, environmental sustainability, and capital construction costs (Thompson et al., 2022; Thompson et al., 2023). However, a key implementation challenge for small, rural communities is obtaining agricultural producer cooperation. Thus, using existing trusted relationships among relevant stakeholders in small, rural communities as an avenue to provide guidance and information related to irrigation lagoons can be a less intrusive and more accepting way to address questions and concerns about these systems.

The goal of this work is to conduct a descriptive study to help improve the information exchange surrounding irrigation lagoons. The specific objectives of the study are to 1) use stakeholder discussions to identify current barriers and benefits of irrigation lagoons in practice and 2) develop dissemination materials that address the barriers and benefits of real systems. This study does not consider technology advancements; instead,

a non-experimental, descriptive study, as suggested by Eck et al. (2020), was conducted to help provide equitable access to ideas for sustainable wastewater treatment and agricultural solutions in underserved communities. Extension Professionals are well positioned, based on their existing relationships, to utilize the dissemination materials created through this study to improve the information exchange surrounding irrigation lagoons between relevant stakeholders.

The niche of this study lies within the preparation of practical dissemination materials. These materials are intended to be used by Extension Professionals to strengthen the information exchange between and to improve the comfort level for relevant stakeholders and decision makers, especially agricultural producers and/or landowners. Thus, the primary target audience of this study is Extension Professionals that work with agricultural producers and/or landowners. Secondary target audiences include design engineers, government agencies, agricultural producers and/or landowners, wastewater operators, and community members (e.g., board members, leaders, and the general public).

The novelties of this study include the type of system studied, the case study location and approach, and the inclusion of data from communities and systems in operation. Most wastewater reuse perception studies focused on mechanical treatment technologies or advanced technologies for human food crop application, and only a very small amount (less than five) considered lagoons (Khan et al., 2008; Marinho et al., 2014). Mechanical WRRFs are generally very different than lagoons in terms of energy usage, operational requirements, and environmental impacts (Thompson et al., 2022). This can skew perceptions of feasibility and sustainability of irrigation lagoons.

Additionally, a considerable amount of the existing wastewater reuse studies considered wastewater reuse for non-agricultural purposes like landscape irrigation (Dery et al., 2019). When cropland was considered, the focus was largely on food-crops farmed for direct human consumption due to the popular topic of food security (Dery et al., 2019). Uniquely, this research focuses on irrigation lagoons that reuse treated wastewater for non-direct food consumption crops to address perceived barriers and benefits of the system.

There are very few US based studies available that analyzed irrigation lagoons currently in operation, even though the US is a major agricultural irrigator (Glick et al., 2019; Crites et al., 2021). Most studies focused on arid regions in the Middle East or developing countries with limited water resources available (Paola et al., 2018). This can alter the results greatly, as very dry areas may have little choice in technology implementation, and developing countries may have very little regulations, if any. Because the US has sufficient safety, health, and food regulations, there is much less concern for health risks compared to developing or arid countries, as highlighted by a majority of the studies (US EPA, 2022a). Nebraska in particular has not yet been included in an agricultural wastewater reuse perception study, despite the fact that Nebraska is the leading state for irrigated agricultural land in the US (USDA, 2011). Additionally, Nebraska has many wastewater treatment lagoons and cropland within a reasonable distance of each other, making it an ideal case study site to visualize where irrigation lagoons may be best placed due to factors like low transportation distances and less piping infrastructure requirements (Thompson et al., 2022).

The use of detailed data from operational systems is a major contribution to the literature and relevant audiences. There are numerous studies in the existing literature that analyzed hypothetical systems and the perceptions of stakeholders at a conceptual level. This lack of data for functioning systems contributes to the public's perceived health concerns and limits related policy development. Health impacts and contamination from reused wastewater can be perceived to be a much larger risk than in actuality, due to the dearth of information published regarding real systems reusing treated wastewater. Rather than assessing perceptions and opinions about a hypothetical scenario, documentation of operational projects can help alleviate misconceptions.

5.4 Stakeholder Discussions

Stakeholder discussions were used to identify barriers and benefits of case study irrigation lagoons in Nebraska. Stakeholder discussions are a good alternative to focus group research when trying to assess a community's educational needs, as they help establish trust and provide ample room for discussion (Ekins, 2018). Stakeholder discussions were used as opposed to other interview and survey measures, due to their flexibility and purpose. Stakeholder discussions do not require Institutional Review Board (IRB) approval, and they do not limit who is talked with and what topics are discussed. Additionally, the use of stakeholder discussions in this initial study allowed the focus to be placed on learning and understanding barriers and benefits, rather than strict quantification. The study focuses on small communities in Nebraska that irrigate non-direct food consumption crops. The case studies are located throughout Nebraska, US, as this is a practice currently done in the state.

The stakeholder discussions were conducted between November 2022 – April 2023. The stakeholder groups were identified following a snowball design method, which relies on referrals from initial groups to find additional groups (Knight and Chopra, 2013). Figure 5.1 provides a representation of the snowball design as used in this study.

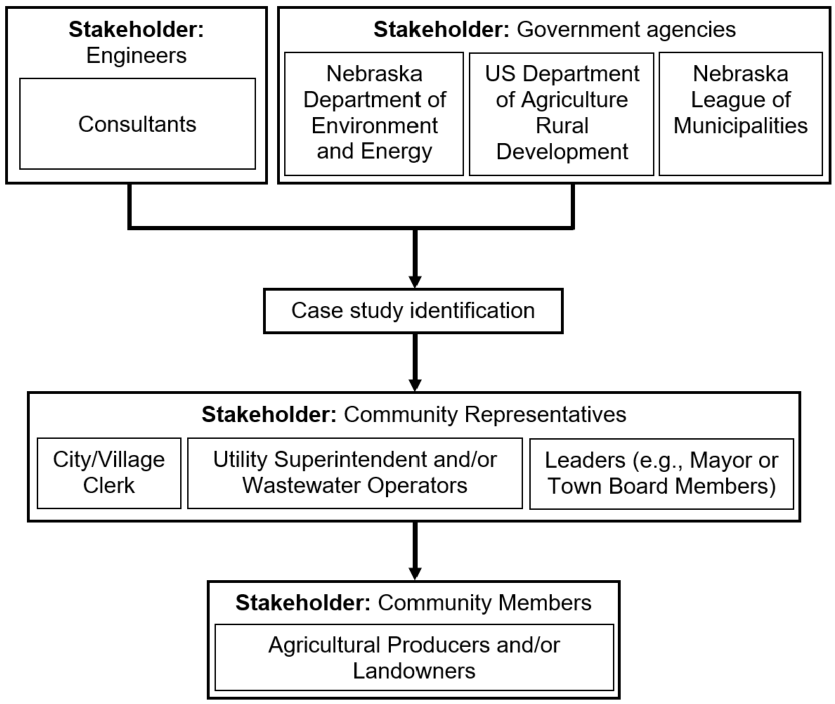


Figure 5.1 Snowball design for selecting stakeholders for discussions

The first stakeholder discussions were with engineers and governmental agencies including the Nebraska Department of Environment and Energy (NDEE), USDA, and the Nebraska League of Municipalities. These stakeholders were identified through relationships built by previous projects (Hanna et al., 2018; Moussavi et al., 2021; Pham et al., 2021; Thompson et al., 2022; and Hansen, 2023). Respondents were asked to identify potential communities in the state that they are aware of that utilize this system. This was sometimes difficult, as state law does not require permitting as long as the requirements of Nebraska Administrative Code Title 119 are met. However, the

engineers and government agencies were able to suggest communities, which led to the case study identification.

A list of recommended communities was developed. Communities were grouped by location, system, and if data was collected for the site in previous related projects. While most of the cases recommended currently have irrigation lagoons, some decided against implementation in recent years. Both groups were considered to ensure a wide range of perceived barriers were addressed. Data collection began with cold-calling community clerks and stating that the community was recommended by an engineer or government agency. In total, 11 communities responded and were willing to participate. A visual of the communities selected as case studies is provided in Figure 5.2, highlighting the various climatic regions covered by the case studies (Thompson et al., 2022). The clerks identified the wastewater operator or utility superintendent and provided contact information. Discussions were then held with wastewater operators and/or utility superintendents. At the end of each discussion, respondents were asked to contact the local agricultural producer that they work with for irrigation. Due to privacy concerns, the operators checked with the agricultural producers before providing the researchers with their information.

Each discussion was initiated by a set of open-ended questions about perceived barriers and benefits of irrigation lagoons, with opportunity to make additional comments and notes as desired related to the general topic. Discussions were led based on the topics of implementation, operations/management, and agricultural management, although ample opportunity to discuss additional topics related to the project was provided.

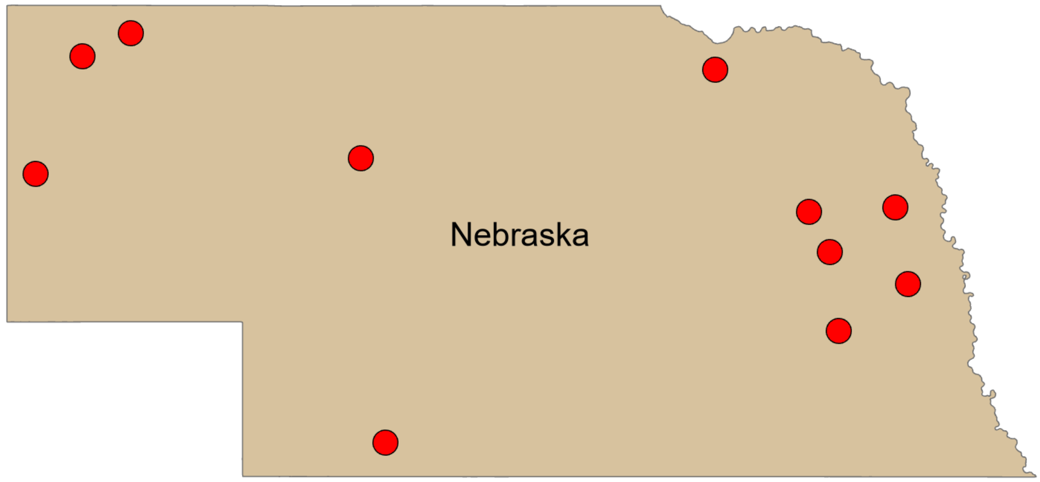


Figure 5.2 Selected case study locations throughout the state of Nebraska

At the beginning of each stakeholder discussion, the goal of the study was discussed. Each stakeholder was asked to provide a general overview of their system, including their general perception of the system. At the end of each discussion, stakeholders were asked if they were willing to participate in a video and/or written testimonial, and if they had any additional comments related to the general topic of irrigation lagoons. A list of the leading discussion questions is provided in Table 5.2. These questions were simply used to guide the discussion, when needed. Each discussion took between 30 minutes and 1.5 hours, depending on the level of discussion. As mentioned, these discussions were open-ended, and respondents were supplied questions to initiate conversation, but were not formally interviewed or surveyed. The intent of these stakeholder discussions was to assess the stakeholders' needs while building trust, and not to conduct a statistically significant survey of responses to direct questions (Ekins, 2018).

Table 5.2 Leading topics and questions used to initially guide stakeholder discussions

Topic	Question
Implementation	• Why did you implement an irrigation lagoon?[a,b] • After working with irrigation lagoons, what are some general things you have learned must be considered during design and implementation?[a] • What do you see as the biggest barriers to implementation?[a,b]
Operation & Management	• What are typical management, ownership, and financial structures for irrigation lagoons?[b,c] • Have you encountered updated property assessments as a result of implementation?[b,c] • Are there concerns with legal constraints as treatment requirements continue to evolve?[a,b] • Are there any on- and offsite health risks of these systems that you must consider/weigh?[a,b,c] • Is it common to receive complaints from community members, agricultural producers, operators, etc.?[a,b,c] • Can you confirm that there are some avoided impacts with these systems (e.g., avoiding effluent discharges, reduced land use from lagoons, reduced pumping requirements, etc.)?[a,b] • What would have been most useful to you (informational talks, classes, testimonies, talking with others, etc.), prior to working with an irrigation lagoon if anything?[b,c]
Agricultural Management	• Provide a general overview of the agriculture system (e.g., what do you grow, how much is irrigated with treated wastewater, how often do you use the wastewater, do you feel like the wastewater gives you a noticeable increase in yields).[c] • How was the cropland obtained?[b,c]

[a]Stakeholder: engineers and government agencies
[b]Stakeholder: community representatives (e.g., wastewater operators and utility superintendents)
[c]Stakeholder: community members (e.g., agricultural producers)

Commonalities among stakeholder responses were identified and grouped based on the general topics of implementation information, barriers to implementation, ownership structure, and agricultural issues (Struckmeyer et al., 2021). The results of the stakeholder discussions help highlight general information, barriers, and benefits regarding irrigation lagoon systems.

5.4.1 Implementation information

Irrigation lagoons are implemented in small, rural communities for various reasons and typically involve multiple stakeholders in the decision-making process. Operators and leaders in communities with operational irrigation lagoons said the main reasons for implementation were either to convert from a mechanical system or to avoid or limit expanding an existing lagoon system to move away from National Pollutant Discharge Elimination System (NPDES) permit requirements. Converting a mechanical WRRF to a lagoon system can be a result of old infrastructure and equipment, labor and operational costs, challenges with discharge compliance, shrinking populations, inflow and infiltration accommodation, and eligibility for funding. According to engineers, if a community's population is growing, existing lagoon systems may need to be expanded. However, if there is a lack of nearby land available for expansion, irrigation lagoons may be alternatively implemented to reduce the area of land required to adequately treat the wastewater.

There are many impacts that can be avoided by implementing an irrigation lagoon. Operators, engineers, and government agencies agreed that the major impacts avoided are operator time and labor requirements, as well as discharge permit requirements. In Nebraska, there is no need to obtain an NPDES permit for an irrigation lagoon, as it is considered to be Authorized by Rule (119 Neb. Admin. Code, ch. 12, § 002). Communities outside of Nebraska should work with local regulators and design engineers to determine if similar exemptions exist within their state. Engineers specified that avoiding discharges from a mechanical plant or discharging lagoon was a significant benefit, especially as treatment requirements continue to evolve and become more

demanding. Engineers added that there is a reduced land footprint compared to some other lagoon systems, which results in lower construction and materials costs, and thus lower life cycle environmental impacts (Thompson et al., 2022).

5.4.2 Barriers to implementation

There are many perceived barriers that can hinder irrigation lagoon success in small communities. According to the operators, engineers, and government agencies, the most common barriers to implementation include variability of the climate, availability of land nearby, and willingness of potential landowners and tenant agricultural producers. Climate (or seasonal) variability is a significant and common barrier amongst communities considering irrigation lagoons. This is because it is difficult to meet the needs of both the city and the agricultural producer simultaneously. Agricultural producers prefer to receive the water during dry times when their crops need water, whereas cities must dispose of water during wet times to avoid lagoon overflow. For example, during dry years the demand for irrigation is highest, but the availability of treated wastewater may be lower due to high evaporation and limited inflow (Thompson et al., 2023). Thus, irrigation lagoons are a good alternative under the right climatic conditions and with proper sizing.

Operators and community leaders stated that economic costs can also be a major barrier, consistent with literature (Crites et al., 2021). In communities that decided against implementing an irrigation lagoon, operators stated that the economic costs of purchasing cropland to irrigate onto and installing piping, a pump, and a pivot to pump water to the cropland were high. This is because economic costs can become substantial when having to pump long distances (Bakopoulou et al., 2010). However, if ideally located, irrigation

lagoons have been found to have reduced treatment costs compared to mechanical systems because they do not have to meet the stringent discharge requirements that mechanical systems must (Nebraska Natural Resources Commission, 2016; Leonel and Tonetti, 2021). Additionally, if the irrigation lagoon is located near the receiving cropland, lower energy usage is required to operate the system, leading to reduced energy costs and life cycle environmental impacts of the irrigation lagoon (Romeiko, 2019; Thompson et al., 2022).

Engineers and government agencies added that public perception, odor concerns, groundwater contamination, and a town's optimism for growth can be significant barriers. Wastewater operators and community leaders noted that the public was most concerned with odors when converting from a mechanical system to a lagoon system, but that these concerns tend to subside once the lagoon became operational due to effective treatment operations. The public also expressed concern about the potential for groundwater contamination due to seepage. However, engineers confirmed that geography and soil type are major considerations in the design and planning stages of irrigation lagoons to ensure groundwater is protected. Lastly, some towns feel that implementing an irrigation lagoon limits their ability to grow in population. Saliba et al. (2018) found that public acceptance of wastewater reuse increases if non-food crops are irrigated. Karki et al. (2019) also found that areas suffering from water scarcity and high crop demand are more likely to accept wastewater reuse.

Engineers had limited concerns, although one engineer expressed concern with potential water rights challenges. For example, a mechanical WRRF discharges effluent into local water bodies. If a community converts their mechanical system to an irrigation

lagoon, there will no longer be a discharge. However, in the engineer's experience, the amount of effluent being added to the water body from a small mechanical WWTP is often a small component of the stream flow, and thus water rights are generally not affected by this practice in Nebraska. It is recommended that communities in water scarce regions consider potential water rights challenges. In dry regions, a number of water rights feuds may actually be resolved, as surface water and groundwater irrigation withdrawals can be replaced or supplemented with treated wastewater (Ritter, 2021).

Engineers also mentioned that lack of knowledge of these systems leads to underutilization in the state and the country compared to the rest of the world. Engineers and government agencies indicated that city officials, engineers, the public, and wastewater operators were most involved in the decision-making regarding irrigation lagoon implementation; however, they stated that landowners/agricultural producers are generally not involved in the decision-making process. Saliba et al. (2018) found that excluding the landowners/agricultural producers limits knowledge and acceptance of the system due to safety concerns and fear of risk. Thus, this study aims to ensure that landowners/agricultural producers have a reliable way to gather information about these systems so that they may feel comfortable having a more active role in public meetings and decision-making.

In addition to helping identify barriers to implementation, the stakeholders provided suggestions for overcoming these barriers. The engineers mentioned that explaining the details of these systems to the public during public meetings can help resolve the public's concerns. Agricultural producers said that researching the system and talking with other producers using the system is helpful. The agricultural producers and

government agencies both mentioned that building and maintaining trust within a community is crucial. By targeting Extension Professionals, this study will be able to provide information related to irrigation lagoons via a trustworthy source in many small, rural communities.

5.4.3 Ownership structures

Ownership structures for each element of this system are important to both the community and the agricultural producer/landowner. The ownership and financial management structure of irrigation lagoons are similar across communities in Nebraska. Typically, the city pays for piping to the cropland, the center pivot (unless the agricultural producer owns one), center pivot maintenance, pumping, and soil and water monitoring. In some communities, agricultural producers paid for their own pumping electricity and center pivot maintenance. However, in general, the treated wastewater is essentially free water for the agricultural producer.

Cropland for the application of reused wastewater was observed to be obtained in one of three ways: 1) most commonly through a long-term agreement between a willing landowner and the city, 2) through a city purchase, or 3) very rarely through eminent domain. Long-term agreements are required by the NDEE funding agency. In these agreements, landowners and/or agricultural producers operate the pivot according to crop needs. In contrast, if the land is acquired by the city, then the city operates the system with the main objective being to keep from discharging to surface waters. In one case, the city threatened the landowners with eminent domain because the landowners were not convinced irrigation lagoons were safe and useful. The landowners eventually sold their land for a high price and moved to new land that did not accept wastewater reuse.

After talking with tenant agricultural producers, it was observed that the landowners are generally more hesitant to accept the water compared to the tenant agricultural producers, who realize that free water is a valuable commodity. In general, agricultural producers are willing to irrigate with treated wastewater as long as it is economically beneficial (Khanape et al., 2020). Funding opportunities may be available to communities interested in reuse. For example, the USDA Rural Development provides funding to states and local government entities for the acquisition, construction, or improvement of wastewater treatment systems, and the NDEE Clean Water State Revolving Fund provides funding to small communities for wastewater improvements, which can be combined with other federal and state funds.

Once the land is obtained, irrigation agreements related to system benefits between a landowner, city, and tenant agricultural producer, as applicable, are made, emphasizing the importance of building and maintaining trust within communities. Typically, long-term (duration of funding) lease agreements are made between the city and the landowner. Landowners and tenant agricultural producers oftentimes have a verbal and/or informal agreement. This is to avoid overpromising the unknown. As one community's agricultural producer and operator mentioned, they were overpromised nutrient benefits, water availability, and maintenance support. Although this community did not experience the benefits originally promised to them, they mentioned that while there are not many positives of their system, there are not necessarily any negatives either. By improving the information exchange between relevant stakeholders, this research can help landowners and tenant agricultural producers realize the uncertainty and variability of these systems, so as to not create false hope.

5.4.4 Agricultural issues

Agriculture practices and cropland can be affected by irrigation lagoon implementation. Each agricultural producer mentioned that the treated wastewater applied has little nutrient value due to effective treatment of the wastewater which removes harmful bacteria, suspended solids, pathogens, and in turn, much of the nutrients. Thus, similar crop yields were generally observed between cropland irrigated with treated wastewater and cropland irrigated with traditional irrigation water sources. However, it should be noted that if the cropland was previously dryland/rainfed, then increased crop yields can be expected from applying the treated wastewater, although the increase in yield is heavily dependent on the supply and demand of the treated wastewater (Thompson et al., 2023). One agricultural producer speculated that the higher water temperature of the treated wastewater may produce slightly higher crop yields compared to the cold well water. It should be noted that other regions in the world may find yield benefits when applying treated wastewater to their cropland. For example, agricultural producers in Italy, Spain, Tunisia, and Brazil all experienced higher crop yields when irrigating with treated wastewater (Leonel and Tonetti, 2021).

A common agricultural concern mentioned by producers was long term sodium build up in soils, which may lead to additional costs incurred from having to neutralize their cropland with chemicals. Some studies have found that there are generally no long-term salinity or nutrient related consequences, due to the low amount of both in the treated wastewater used for irrigation (Hanjra et al., 2012; Marinho et al., 2014). However, others have found that wastewater irrigation can lead to long-term salinization (Ofori et al., 2020). To avoid long term consequences of salinity, engineers should ensure

that irrigation lagoons are sized properly to limit evaporation and maximize salt-free rainfall capture, as freshwater blending can reduce salinity. Additionally, agricultural producers should consider alternative irrigation methods such as cyclical irrigation or blending interventions. Cyclical irrigation methods use treated wastewater in conjunction with freshwater sources. Blending interventions could be done if multiple willing landowners rotated between receiving treated wastewater and using traditional water sources for irrigation. Alternative crop selections that are more resistant to salinity consequences may also be of interest to agricultural producers. Lastly, as the agricultural producers mentioned during discussions, it is crucial that agricultural producers monitor and analyze the soils and crops to adequately manage salt build up from wastewater irrigation (Hoffman, 2010).

Cropland value is another important consideration for landowners and tenant agricultural producers. Agricultural producers stated that the cropland where treated wastewater is applied, although irrigated, is less valuable to them compared to a system with surface or groundwater rights because they do not have the ability to control their water usage or have a continuous source of water with only the treated wastewater supply. Thus, many agricultural producers choose to supplement their existing irrigation source with the treated wastewater to account for seasonable variabilities.

Irrigated cropland is known to be more valuable economically compared to dryland cropland (Brozovic and Islam, 2010; Guerrero et al. 2010). In discussions with Nebraska county assessors, the state of Nebraska generally views cropland irrigated with treated wastewater as irrigated cropland for assessment purposes, which increases the value of the land. However, there may be an opportunity for lower assessment values for

landowners converting from dryland to semi-irrigated land (i.e., land that is irrigated solely with treated wastewater), as this may not be considered a continuous water source because supplemental irrigation is not used. In addition, semi-irrigated land does not receive the same agronomic benefit as fully irrigated cropland due to it not having the full agronomic application of water. This information may be useful to landowners and tenant agricultural producers who wish to explore their current assessment values.

5.5 Dissemination Material

The information gathered by the stakeholder discussions must be shared with water policy leaders and decision makers, funding agencies, design engineers, and other community members, as a major contribution of this study is the dissemination component. The results from the stakeholder discussions were compiled and will be presented via a testimonial video and a NebGuide. These materials are provided in Appendix D and Appendix E, respectively. The dissemination materials are intended to be used mainly by Extension Professionals. The main responsibility of state agencies, design engineers, and wastewater operators are to ensure technical and legal requirements are met. Extension Professionals, on the other hand, can utilize existing relationships within the state to work with wastewater operators and agricultural producers by referring to this study to explain the system, address concerns, and answer questions to help encourage acceptance and improve the information exchange.

Design engineers, agricultural producers and/or landowners, wastewater operators, and community representatives may find the NebGuide more useful than the testimonial video. For example, the NebGuide could be used by landowners wanting to inform potential tenant agricultural producers about the variability of the system,

wastewater operators learning about the system, design engineers working with communities to modify an existing system, landowners looking to justify lower property assessments, etc. As noted by the stakeholder discussions, many agricultural producers and wastewater operators spent personal time researching irrigation lagoons and questioning other communities, yet many were still left with questions and concerns. This study provides streamlined information for those curious about irrigation lagoons to alleviate wastewater operators and agricultural producers, as well as others curious about the system.

The dissemination materials include a video and print-publication, as follows:

> *Testimonial Video:* The short video features informative narration about irrigation lagoons, as well as testimonials and experiences from the perspective of wastewater operators and agricultural producers. The video will be published with the NebGuide. The video script is provided in Appendix D.
>
> *NebGuide:* The NebGuide addresses common concerns observed by the stakeholder discussions and discusses the potential benefits of irrigation lagoons in Nebraska under various conditions. The NebGuide draft is provided in Appendix E.

5.6 Application of Study

Although this study is limited to irrigation lagoons located in Nebraska that reuse treated wastewater to irrigate non-direct food consumption crops, the methodologies and results can be adapted to similar systems in the US (see Table 5.1) and worldwide, particularly in areas of water scarcity or where wastewater treatment lagoons are

commonly employed. For example, irrigation lagoons may be an attractive technology in regions such as the Southwest US, which has lost much of its irrigated agricultural land over the last three decades due to water scarcity and has instead started to use surface waters which can end up being costly on both an environmental and economic scale (USDA, 2011; Knapp et al., 2018). Although Nebraska benefits heavily from its access to groundwater, groundwater sources are diminishing in other locations. Therefore, it is crucial to understand what additional sources of water are available so as to not lose valuable irrigated land over time (Leatherman et al., 2004; Guerrero et al., 2010). Additionally, Nebraska represents a wide range of precipitation and evaporation rates across the state, making it the ideal case study location (Thompson et al., 2022). Therefore, it is clear that Nebraska has the potential to serve as a leader in the widespread information exchange regarding irrigation lagoons.

5.7 Conclusions

Although irrigation lagoons are known to have vast benefits in terms of environmental and local economic impacts, it is oftentimes difficult to implement these systems due to limited agricultural producer cooperation. Much of the hesitation stems from a lack of guidance and information provided to agricultural producers. Thus, this descriptive study aimed to improve the information exchange surrounding irrigation lagoons. Stakeholder discussions were held with engineers, government agencies, and community representatives and members to identify barriers and benefits of irrigation lagoons. The results of these discussions were further developed into dissemination materials that can be used by various audiences to better understand irrigation lagoons. Due to their existing relationships with small, rural communities, Extension Professionals

should consider utilizing the dissemination materials developed by this research to improve the information exchange between stakeholders and decision makers involved in irrigation lagoon implementation and operation.

References

Bakopoulou, S., Polyzos, S., & Kungolos, A. (2010). Investigation of farmers' willingness to pay for using recycled water for irrigation in Thessaly region, Greece. Desalination, 250(1), 329-334. https://doi.org/10.1016/j.desal.2009.09.051

Brozovic, N., & Islam, S. (2010). Estimating the value of groundwater in irrigation (No. 320-2016-10392). DOI: 10.22004/ag.econ.61337

Crites, R., Beggs, R., & Leverenz, H. (2021). Perspective on land treatment and wastewater reuse for agriculture in the Western United States. Water, 13(13), 1822. https://doi.org/10.3390/w13131822

Dery, J. L., Rock, C. M., Goldstein, R. R., Onumajuru, C., Brassill, N., Zozaya, S., & Suri, M. R. (2019). Understanding grower perceptions and attitudes on the use of nontraditional water sources, including reclaimed or recycled water, in the semi-arid Southwest United States. Environmental research, 170, 500-509. https://doi.org/10.1016/j.envres.2018.12.039

Eck, C. J., Wagner, K., Chapagain, B., & Joshi, O. (2020). Postsecondary Students' Perceptions of Water Issues and Water-Related Educational Interests. The Journal of Extension, 58(3), Article 15. https://tigerprints.clemson.edu/joe/vol58/iss3/15

Ekins, J. (2018). Extension Involvement in Collaborative Groups: An Alternative for Gathering Stakeholder Input. Journal of Extension, 56(2). https://tigerprints.clemson.edu/joe/vol56/iss2/17

Glick, D. M., Goldfarb, J. L., Heiger-Bernays, W., & Kriner, D. L. (2019). Public knowledge, contaminant concerns, and support for recycled Water in the United States. Resources, Conservation and Recycling, 150, 104419. https://doi.org/10.1016/j.resconrec.2019.104419

Guerrero, B., Wright, A., Hudson, D., Johnson, J., & Ammoson, S. (2010). The economic value of irrigation in the Texas Panhandle. http://hdl.handle.net/2346/58864

Hanna, S. M., Thompson, M. J., Dahab, M. F., Williams, R. E., & Dvorak, B. I. (2018). Benchmarking the Energy Intensity of Small Water Resource Recovery Facilities: Hanna et al. Water Environment Research, 90(8), 738-747. https://doi.org/10.2175/106143017X15131012153176

Hanjra, M. A., Blackwell, J., Carr, G., Zhang, F., & Jackson, T. M. (2012). Wastewater irrigation and environmental health: Implications for water governance and public policy. International journal of hygiene and environmental health, 215(3), 255-269. https://doi.org/10.1016/j.ijheh.2011.10.003

Hansen, A. (2023). Reducing I/I in Small Collection Systems: Environmental, Economic, and Other Impacts. M.S. Thesis, Environmental Engineering, University of Nebraska-Lincoln.

Hoffman, Glenn. (2010). Water Quality Criteria for Irrigation. Nebraska Extension. Retrieved April 25, 2023 from https://extensionpublications.unl.edu/assets/pdf/ec782.pdf

Hrozencik, R. A. and Marcel A. (2021). Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity, EIB-229, U.S. Department of Agriculture, Economic Research Service. Retrieved May 8, 2023 from https://www.ers.usda.gov/publications/pub-details/?pubid=102927

Karki, B., Sharma, K. R., & Ghimire, A. (2019). Wastewater Reuse for Irrigation: A Review on Challenges and Prospects for Nepal. https://doi.org/10.3390/su9101734

Khan, M. A., Shaukat, S. S., & Khan, M. A. (2008). Economic benefits from irrigation of maize with treated effluent of waste stabilization ponds. Pak. J. Bot, 40(3), 1091-1098.

Khanpae, M., Karami, E., Maleksaeidi, H., & Keshavarz, M. (2020). Farmers' attitude towards using treated wastewater for irrigation: The question of sustainability. Journal of Cleaner Production, 243, 118541. https://doi.org/10.1016/j.jclepro.2019.118541

Knapp, T., Kovacs, K., Huang, Q., Henry, C., Nayga, R., Popp, J., & Dixon, B. (2018). Willingness to pay for irrigation water when groundwater is scarce. Agricultural Water Management, 195, 133-141. https://doi.org/10.1016/j.agwat.2017.10.013

Knight, A. J., & Chopra, H. (2013). Perceived Benefits and Barriers to Local Food Procurement in Publicly Funded Institutions. The Journal of Extension, 51(5), Article 9. https://tigerprints.clemson.edu/joe/vol51/iss5/9

Leatherman, J. C., Cader, H. A., & Bloomquist, L. E. (2004). When the well runs dry: The value of irrigation to the western Kansas economy. Kansas Policy Review, 26(1), 7-20.

Leonel, L. P., & Tonetti, A. L. (2021). Wastewater reuse for crop irrigation: Crop yield, soil and human health implications based on giardiasis epidemiology. Science of the Total Environment, 775, 145833. https://doi.org/10.1016/j.scitotenv.2021.145833

Marinho, L. E. D. O., Coraucci Filho, B., Roston, D. M., Stefanutti, R., & Tonetti, A. L. (2014). Evaluation of the productivity of irrigated eucalyptus grandis with reclaimed wastewater and effects on soil. Water, Air, & Soil Pollution, 225(1), 1-7. https://doi.org/10.1007/s11270-013-1830-8

Moussavi, S., Thompson, M., Li, S., & Dvorak, B. (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of

construction and operations. Journal of Environmental Management, 292, 112802. https://doi.org/10.1016/j.jenvman.2021.112802

Nebraska Natural Resources Commission. (2016). Water Sustainability Fund Application for Funding. Retrieved February 9, 2022 from: https://nrc.nebraska.gov/

Ofori, S., Puškáčová, A., Růžičková, I., & Wanner, J. (2021). Treated wastewater reuse for irrigation: Pros and cons. Science of The Total Environment, 760, 144026. https://doi.org/10.1016/j.scitotenv.2020.144026

Paola, V., Mustafa, A. A., & Giacomo, Z. (2018). Willingness to pay for recreational benefit evaluation in a wastewater reuse project. Analysis of a case study. Water, 10(7), 922. https://doi.org/10.3390/w10070922

Pham, A., Moussavi, S., Thompson, M., & Dvorak, B. (2021). Environmental life cycle impacts of small wastewater treatment plants: Design recommendations for impact mitigation. Water Research, 207, 117758. https://doi.org/10.1016/j.watres.2021.117758

Qasim, S. R. (1999). Wastewater Treatment Plants Planning, Design, and Operation (2nd ed.). Technomic Publishing.

Ringenberg, D., Kranz, W., Irmak, S., & Dvorak, B. (2018). Extending Extension's Outreach: Using Student Interns as a Resource for Obtaining Implementation of Irrigation Improvements. Journal of Extension, 56(4). https://tigerprints.clemson.edu/joe/vol56/iss4/2

Ritter, W. (2021). State Regulations and Guidelines for Wastewater Reuse for Irrigation in the US. Water, 13(20), 2818. https://doi.org/10.3390/w13202818

Romeiko, X. (2019). A comparative life cycle assessment of crop systems irrigated with the groundwater and reclaimed water in Northern China. Sustainability, 11(10), 2743. https://doi.org/10.3390/su11102743

Saliba, R., Callieris, R., D'Agostino, D., Roma, R., & Scardigno, A. (2018). Stakeholders' attitude towards the reuse of treated wastewater for irrigation in Mediterranean agriculture. Agricultural Water Management, 204, 60-68. https://doi.org/10.1016/j.agwat.2018.03.036

Soncksen, B. (2023). Inflation Reduction Act Funding for Climate-Smart Agriculture Available Nationwide. Retrieved May 8, 2023 from https://www.nrcs.usda.gov/conservation-basics/conservation-by-state/nebraska/news/inflation-reduction-act-funding-for-climate

Struckmeyer, K. M., Roberts, E., Gordon, S. R., Raczkoski, B. M., & Singh, C. (2021). Barriers to and Strategies for Engaging Extension Educators in Family Caregiver Education. Journal of Extension, 57(6). https://tigerprints.clemson.edu/joe/vol57/iss6/16

Thompson, M., Moussavi, S., Li, S., Barutha, P., & Dvorak, B. (2022). Environmental Life Cycle Assessment of small water resource recovery facilities: Comparison of mechanical and lagoon systems. Water Research, 215, 118234. https://doi.org/10.1016/j.watres.2022.118234

Thompson, M., Dvorak, B. (2023). Dynamic Environmental LCA of Municipal Lagoon Water Reuse for Agriculture: Case Studies and Spatial-Temporal Modeling. In Progress of publication.

USDA. (2011). Nebraska Leads the Nation in Irrigated Acres. Retrieved February 4, 2022 from https://www.nrdnet.org/programs/water

USDA. (2019). Water & Waste Disposal Loan & Grant Program in Nebraska. Retrieved April 10, 2023 from https://www.rd.usda.gov/programs-services/water-environmental-programs/water-waste-disposal-loan-grant-program/ne#overview

US EPA. (2022a). Basic Information about Water Reuse. US Environmental Protection Agency. Retrieved February 9, 2022 from https://www.epa.gov/waterreuse/basic-information-about-water-reuse

US EPA. (2022b). Lagoon Wastewater Treatment Action Plan: Supporting Small, Rural, and Tribal Communities. Retrieved May 8, 2023 https://www.epa.gov/system/files/documents/2022-10/Lagoon%20Action_Plan_FINAL.pdf

US EPA. (2023). Water Reuse and Recycling. Retrieved May 8, 2023 from https://www.epa.gov/waterreuse

WEF. (2014). Changing the Terms. Retrieved February 3, 2022 from https://news.wef.org/changing-the-terms/

S.914 - Drinking Water and Wastewater Infrastructure Act of 2021. Retrieved February 9, 2022 from https://www.congress.gov/bill/117th-congress/senate-bill/914/all-info

119 Neb. Admin. Code, ch. 12, § 002

123 Neb. Admin Code, ch. 1

CHAPTER 6 SUSTAINABILITY ASSESSMENTS OF CRITICAL CIVIL INFRASTRUCTURE SYSTEMS: A MINI-REVIEW AND PROJECT SYNTHESIS

6.0 Introduction

Sustainable development is important in critical civil infrastructure planning and decision making (Fischer and Amekudzi, 2011). As defined by the World Commission on Environment and Development in 1987, sustainable development is “development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs.” Sustainable development encompasses environmental, economic, and social considerations, also known as the triple bottom line (ASCE, 2021c). The concept of sustainable development is becoming more prominent in today’s world, as evidenced by the global United Nations proposing 17 Sustainable Development Goals (United Nations, 2015). However, in its current state, critical civil infrastructure decision making still lacks meaningful integration with assessments of all three pillars of sustainability, especially the social pillar. This study highlights the importance of capturing key social impacts that are of interest to stakeholders, in addition to environmental and economic impacts, early on in a critical civil infrastructure sustainability assessment to improve subsequent analyses and decision making.

As climate change persists and critical civil infrastructure systems continue to age, replacements and upgrades will be necessary to maintain the current quality of life without threatening future generations. There are 16 recognized critical infrastructure sectors, including energy and water and wastewater (CISA, 2020). Infrastructure systems are considered to be critical if disruptions to them cause detrimental impacts on the country’s security, economy, and public health and safety (CISA, 2020; ASCE, 2021b).

According to the American Society of Civil Engineers (ASCE), there are 18 civil infrastructure sectors, including energy and wastewater (ASCE, 2021a). Additionally, most critical civil infrastructure systems are public entities, but some are privately owned or owned by public/private partnerships. Regardless of ownership, these systems serve the public's needs, and thus face similar pressures regarding aspects like economic uncertainty, service availability and accessibility, and political change.

A common approach to comprehensively assessing the sustainability of infrastructure is life cycle sustainability assessment, which is a methodology that considers the three pillars of sustainability (i.e., economic, environmental, and social pillars) (Naves et al., 2019). However, this methodology is not standardized and often lacks sufficient inclusion and/or integration of each pillar (Li et al., 2018; Backes and Traverso, 2021). Economic and environmental sustainability are typically considered, while social sustainability is less frequently considered (Alberti et al., 2017; Naves et al., 2019). This is because there are well-established life cycle methodologies for quantifying economic and environmental impacts, such as life cycle costing (LCC) and environmental life cycle assessment (LCA), respectively. In addition, indicators chosen to assess environmental and economic sustainability, such as global warming potential and net present values, are typically similar across studies. In contrast, social sustainability is more challenging to quantify, and there is little consensus on how to address it (Sutherland et al., 2016; Naves et al., 2019; Costa et al., 2022).

Some studies use social-LCA (S-LCA) to explore and/or quantify social impacts. S-LCA is a non-standardized technical framework, based on the standardized environmental LCA framework, that allows the positive and negative social impacts of a

product to be considered (Benoit et al., 2010). However, as mentioned, there is inconsistency in the definitions, methodologies, and social impact indicators used to conduct S-LCA. From here on, this work defines social impacts as those that 1) are not directly associated with environmental or economic impacts, 2) are generally social in nature, and 3) expand beyond the normal sustainability considerations to include specific impacts that drive decision making. It is essential to realize that these additional social (i.e., difficult-to-quantify) factors are generally the factors driving decision making, especially when differences between the environmental and economic impacts of alternatives are relatively similar (Lane et al., 2023; Moussavi et al., 2023a,b).

The overall goal of this work is to encourage stakeholders and decision makers to address all of the potentially influential factors in life cycle sustainability assessments, including the social impacts, to further improve the integration of life cycle sustainability assessments and decision making for critical civil infrastructure projects. The objectives of this study are to 1) catalog the current methods applied to address the economic, environmental, and social sustainability of critical civil infrastructure projects, 2) identify research needs related to the social sustainability of critical civil infrastructure, and 3) propose an approach, based on the reviewed literature and authors' previous experience with energy and wastewater projects, for identifying and capturing the key, difficult to quantify social impacts. The results of this study are intended to better capture social elements in the existing life cycle triple bottom line approach and are broadly applicable to all critical civil infrastructure projects around the world. Early and thorough collection of social data can increase quantification opportunities of such factors, which can be

incorporated into decision making methodologies such as multicriteria decision making using a mixed methods approach.

6.1 Literature Review

This study used common methodologies to conduct a mini-literature review to catalog how life cycle sustainability is currently addressed in critical civil infrastructure literature (Meyer et al., 2011; Mehmeti and Canaj, 2022). The two major online databases "Science Direct" and "Google Scholar" were used to identify literature relevant to holistic sustainability assessments of critical civil infrastructure systems. A process flow diagram of the methodology is shown in Figure 6.1.

An initial search was done for literature published between 2013 and 2023 containing the following keywords: "infrastructure," AND "case study," AND "decision making," AND "three pillars," AND "economic," AND "environmental," AND "social," AND "triple bottom line," AND "life cycle sustainability assessment." To be considered, the literature had to contain each of these words within the entire article, to ensure that the studies considered specifically addressed the three pillars of sustainability for critical civil infrastructure case studies. This research focused on case studies, as sustainability impacts can be highly site specific and analyzing case studies can provide better insight into real impacts (Juan-Garcia et al., 2017). Only research and review articles that were open or full-text access either through the web or through the author's institution were included.

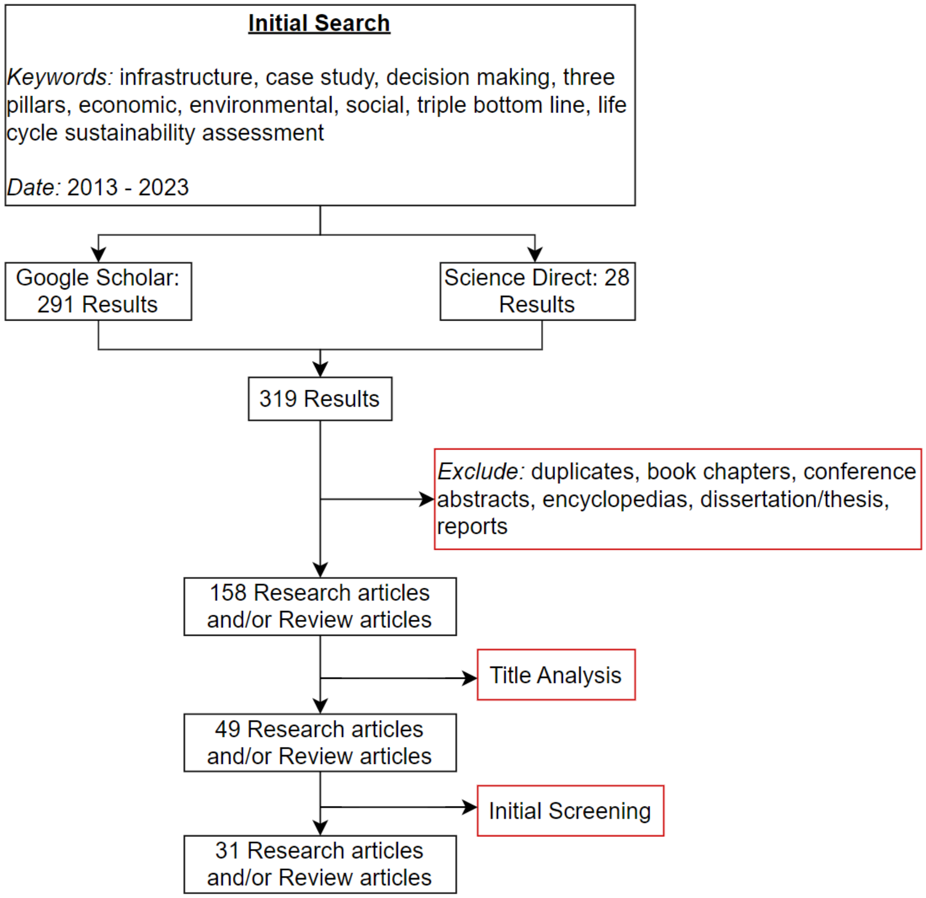


Figure 6.1 Process flow diagram of methodology used to select relevant literature

The initial search using the conditions described in Figure 6.1 produced 319 results from a variety of peer-reviewed journals. Because results were found among two different online databases, there were repetitive articles that were removed from the review. Following the removal of repetitive studies and those that were not review and/or research articles, a title analysis was completed. Only articles with relevant titles, meaning the title included at least one of the key words and mentioned a critical civil infrastructure system, were included. Following this analysis, an initial screening of the articles was performed by reading the articles' abstracts, to identify the articles'

relevance. This resulted in 31 articles being selected for full review, as shown in Appendix F Table F1.

Because this review focuses on publications found using specific key words from two major online search databases for a defined time period, it is important to note that additional relevant publications are likely available. For example, the chosen studies focused on critical civil infrastructure systems as defined earlier in this study, and additional content may not have been found using the search terms due to the lack of inclusion of the specific key words. However, this study serves as an initial exploratory study into the relevant literature available to show the general scope and challenges related to sustainable decision making for critical civil infrastructure systems.

6.2 Review of International Literature

6.2.1 Types of research

Articles were found from 16 countries around the globe, emphasizing the continued need to conduct global case study sustainability assessments for critical civil infrastructure systems (See Appendix F Figure F1). 65% of the articles were published during the year 2020 or later, emphasizing the growing interest in comprehensive sustainability analyses worldwide (See Appendix F Figure F2). The articles were published in one of 20 different peer-reviewed journals, reflecting the multidisciplinary nature of this topic. The journals with multiple selected publications include The International Journal of Life Cycle Assessment, Sustainable Cities and Societies, Journal of Cleaner Production, Renewable and Sustainable Energy Reviews, and Sustainability (See Appendix F Figure F3). The critical civil infrastructure systems studied include

transportation, waste, general construction, energy, and broadband (See Appendix F Figure F4).

The goals of the selected studies varied (See Appendix F Figure F5). 55% of articles reviewed proposed a novel framework for analyzing the sustainability of critical civil infrastructure systems and subsequently conducted a sustainability analysis by applying the framework to a case study. 19% of the articles reviewed either proposed a novel framework or conducted a sustainability analysis, and 26% of the articles reviewed were solely literature review articles.

6.2.2 Discussion of sustainability impacts found in reviewed literature

Of the 31 articles reviewed that met the criteria for evaluation, environmental LCA was used 68% of the time to analyze the environmental sustainability of a case study critical civil infrastructure system. 19% of the studies used other defined assessment methodologies, and 13% did not consider environmental impacts. These results are expected, as LCA is currently the only standardized life cycle methodology. 65% of the studies used LCC to analyze the economic sustainability of critical civil infrastructure case studies, 26% used other methods, and 10% did not consider economic impacts. Although LCC is not currently a standardized methodology, LCC is well-established and well-accepted, as LCC thinking has been around since 1930 (Alejandrino et al., 2021).

In contrast, S-LCA methodologies were used by only 58% of the studies to analyze social sustainability, and 16% used other methods. The non-standardization and difficult to quantify, evolving nature of S-LCA leads to inconsistent methodologies being used to measure life cycle social impacts of critical civil infrastructure systems. In fact,

this oftentimes leads to their exclusion as a whole, as was observed in 26% of the reviewed studies, which can be detrimental to decision making and planning. Although using a version of S-LCA is the preferred approach to capture social impacts of a critical infrastructure system, as seen by the literature reviewed, the current S-LCA data collection methods cannot fully capture the site-specific values of all relevant stakeholders due to the variability in the methodologies, especially regarding data collection using generalized indicators (Alesia and Al-Jarallah, 2018; Ferrari et al., 2019; Backes and Traverso, 2021; Shrivastava and Unnikrishnan, 2021; Al-Yafei et al., 2022; Francis and Thomas, 2022). Intentionally choosing specific indicators is important, as these define the impacts that are to be captured.

6.2.3 Selection of sustainability impact indicators

Based on the reviewed literature, environmental and economic sustainability assessments generally included similar indicators of environmental and economic impacts across studies, such as global warming potential, toxicity, net present value, and payback time (Alejandrino et al., 2021). In contrast, the selected indicators of social sustainability varied greatly among the reviewed literature. Figure 6.2 shows a word cloud highlighting this variability among the indicators of social impacts used for S-LCA studies. Larger font sizes correspond to higher frequency of use (i.e., the larger the word, the more frequently it was used as an indicator among the S-LCA studies). These indicators have been grouped by general topics. Some social indicators, such as health and safety, employment, and human rights are commonly addressed, but are only considered at a general level and do not account for site specific values and impacts. As shown by Figure 6.2 there is substantial inconsistency among chosen indicators for S-

LCA, which is contrary to that of environmental and economic sustainability assessments.

Figure 6.2 Variability in social sustainability indicators chosen by the reviewed studies

The large number of indicators used to determine social impacts, as shown in Figure 6.2, can be overwhelming to researchers at the start of a project. This is confirmed by the observation that each study reviewed that conducted a version of S-LCA chose only a small subset of the numerous indicators listed in Figure 6.2 to address social impacts. However, choosing only a small subset of generalized indicators can easily lead to ignoring the subtle and site-specific elements of indicators that are most important to the relevant stakeholders.

The reviewed literature highlights that, while there are S-LCA frameworks available, there is a strong research need to further evolve the data collection methodologies for S-LCA to improve consistency to increase utilization.

6.3 Proposed Approach for Collecting Social Data for Subsequent Analyses

To address the current variability in S-LCA data collection methodologies, it is proposed that researchers use stakeholder discussions and/or semi-structured interviews, as done in Moussavi et al. (2023,a,b,c) and Lane et al., (2022), to collect social data for subsequent life cycle sustainability analyses of case study critical civil infrastructure systems. This proposed approach will help researchers characterize the specifics of the already available general social indicators (listed in Figure 6.2) at the beginning of a sustainability assessment, leading to fuller capture of the key elements driving decision making. This methodology is not proposing new or specific social indicators; rather, it is proposing a way for researchers to better identify and capture the site specific and valuable social elements of any given critical civil infrastructure system.

The proposed approach does not specify or recommend specific stakeholders to include in a study. Instead, the proposed approach assumes that the relevant stakeholders have already been identified for a given study. Ultimately, the key stakeholders chosen will be site specific and depend on the study's and client's goals.

In Appendix F Table F2, the authors propose examples of the topics/questions researchers may ask during semi-structured interviews and/or stakeholder discussions, based on their experiences conducting life cycle analyses of case study energy and wastewater systems. Key topic areas for these questions include system overview, system implementation, stakeholder involvement, operations, employment, and perceptions of

risk and resilience. These examples are proposed to be used in addition to the generalized social indicators identified in the literature and can be expanded upon further as this approach evolves. These questions can help researchers anticipate useful interview questions for collecting S-LCA data.

This methodology is proposed because the authors observed, through previous wastewater and energy projects, that community leaders and other relevant stakeholders realize that LCA and LCC tools do not always capture all of the potential impacts of a critical civil infrastructure system, especially those impacts that are site specific and/or outside of a defined system boundary. Any additional, oftentimes social impacts can be difficult to quantify if not included early on in a study. However, these impacts are typically very important for decision makers.

The proposed methodology will help researchers identify factors valued by key stakeholders, and the specifics of the general indicators (e.g., those in Figure 6.2) important for a project. Of the numerous indicators listed in Figure 6.2, each article that was reviewed tended to choose only a small subset of these indicators and analyzed them on a generalized basis. Choosing indicators can be a challenge due to the large number of choices. In fact, many of the studies reviewed acknowledged that the data collection was difficult due to the large quantities of data needed and limited guidance on how to collect this data. The proposed methodology will engage stakeholders upfront and allow researchers to identify what these stakeholders value most for a given project. Once the general indicators are chosen, stakeholder discussions and/or semi-structured interviews can be further used to identify the site-specific characteristics of each chosen indicator.

Figure 6.3 highlights examples of the site specific characteristics of select indicators, which were observed to have driven decision making for wastewater and energy related projects (Moussavi et al., 2021; Moussavi et al., 2023 a,b,c).

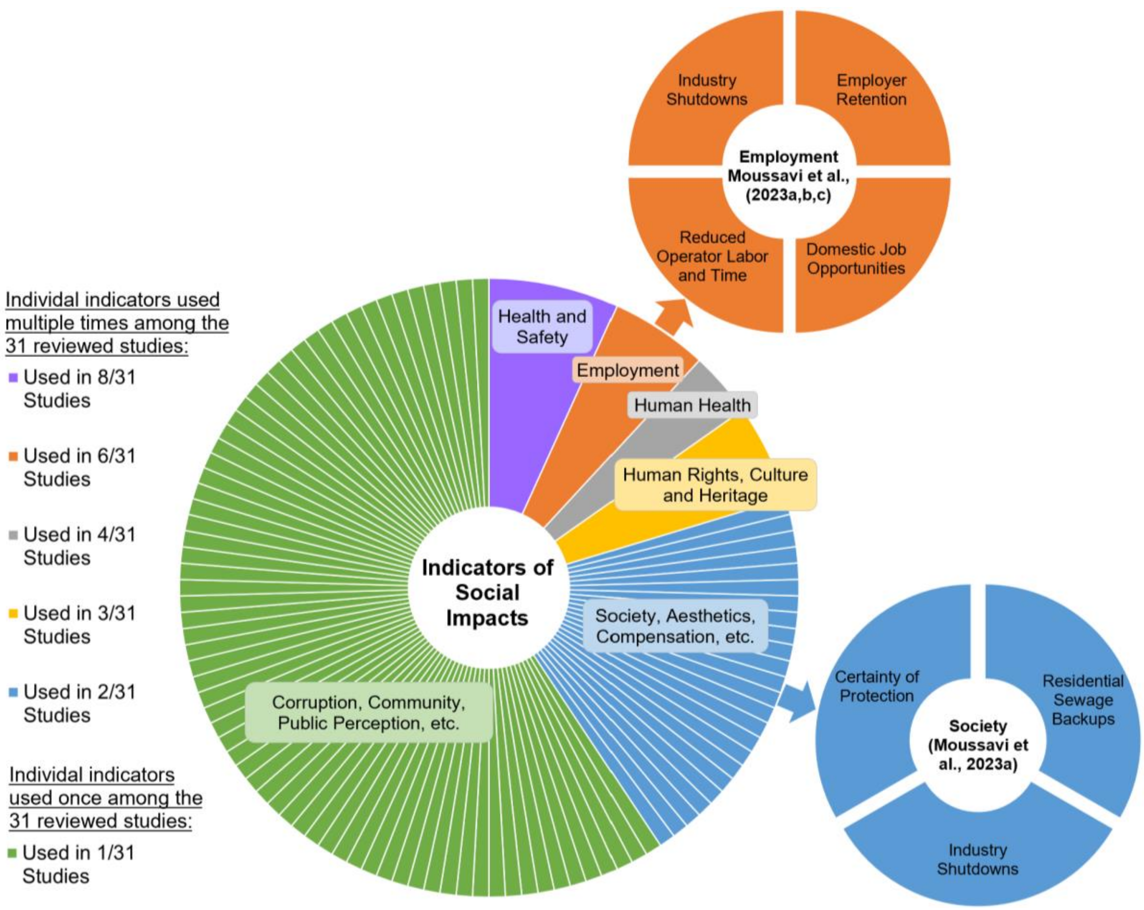


Figure 6.3 Share of the general indicators of social impacts used among the 31 reviewed studies. Site-specific characteristics of select general indicators (employment and society) are presented, as identified by Moussavi et al. (2023a,b,c)

By using stakeholder discussions, Moussavi et al. (2023a,b.c) found that the specific characteristics of the employment indicator were employer retention and industry shutdowns (2023a), domestic job opportunities (2023b), and reduced operator labor and time (2023c). Similarly, Moussavi et al., (2021) found that the specific characteristics of the health and safety indicator were auxiliary infrastructure preferences, and Moussavi et

al. (2023a) found that specific characteristics of the society indicator were residential sewage backups, industry shutdowns, and investing in security and certainty of protection. It's important to note that each of the specific indicator characteristics can be relevant for multiple general indicators. Thus, a major benefit of using reflective case studies and engaging stakeholders early on is that the site-specific drivers for decision making can be identified and considered in a way that reflects the stakeholders' values. To further justify proposing this data preparation and collection approach, the authors summarize numerous successful examples of using stakeholder discussions in their work to identify social and/or additional impacts that were highly valued by relevant stakeholders and decision makers, as shown in Appendix F Table F3. Additional studies have also successfully incorporated stakeholder discussions to identify social impacts of critical civil infrastructure (e.g., Youngblood et al., 2008; Pham et al., 2021; Thompson et al., 2022; Hansen et al., 2023).

A major benefit of using the stakeholder discussions as an approach to collect social impact data on critical civil infrastructure systems is that it allows for expansion upon factors that may not have been considered early on in a study. Capturing clients' values at the beginning of a project can also help refine system boundaries to ensure the valued impacts are being addressed and to avoid mistakes of past studies that simply add social/additional impacts at the end of a study with little thought and discussion. This approach also provides an avenue for stakeholders to discuss their perceptions and values, as well as what truly drives decisions related to critical civil infrastructure.

Although some studies currently use semi-structured interviews to identify social indicators, as identified by the literature review conducted, this study proposes that

researchers commit to using the semi-structured interviews and/or stakeholder discussions, in combination with reflective case studies, to identify the more difficult to quantify impacts that are not directly associated with environmental or economic impacts. Upfront consideration and thorough preparation for and collection of social data can lead to broader capture of social impacts and decision-making drivers. To the authors' knowledge, the proposed approach for identifying key social and other difficult to quantify factors for decision making related to critical civil infrastructure has not yet been proposed in the peer-reviewed literature. Using this methodology will improve the collection and inclusion of social impacts in the current life cycle sustainability assessment methodologies, which will ultimately provide stakeholders and decision makers with more comprehensive guidance and supplementary resources to make better informed decisions related to critical civil infrastructure.

There is a further need, which is outside the scope of this study, to further develop quantification of the factors identified by this proposed methodology. The proposed data collection approach can lead to fuller capture of life cycle social impacts and aid in subsequent qualitative and quantitative analyses (e.g., multicriteria decision making, weighting and scoring, analytic hierarchy process methodologies, etc.) using a mixed methods approach with an emphasis on stakeholder engagement (Creswell and Poth, 2012).

6.4 Opportunities for Future Action

This work identifies the current research need for further development of the data collection required for S-LCA of critical civil infrastructure and works to fill this research need. Additional components beyond the initial proposed approach are needed to fully

integrate sustainability impacts and decision making for critical civil infrastructure. For example, additional case studies and coding methodologies should be applied to future studies. This will be useful for subsequent qualitative and quantitative analyses, which can statistically analyze the findings from the stakeholder discussions and/or semi-structured interviews. Although quantifying sustainability impacts is a crucial part of sustainability assessments, the pure identification of key decision factors (i.e., social factors) as highlighted by the proposed data collection methodology are important as well, as this is lacking in the current relevant literature. Lastly, future work should aim to standardize the initial methodological approach proposed in this study, so that it can be consistently and broadly applied to life cycle sustainability assessments.

6.5 Conclusions

Systematically including social impacts, in addition to the commonly quantified environmental and economic impacts, in critical civil infrastructure planning and decision making is key to providing sustainably designed solutions to communities within the context of the global Sustainable Development Goals. To encourage addressing the social impacts in life cycle sustainability assessments of critical civil infrastructure systems, relevant literature was explored, and then a methodology to capture these impacts was proposed. The literature review highlighted that there is significant variability in how social impacts of critical civil infrastructure systems are identified, leading to diminishment of the importance of these factors and sometimes their exclusion in life cycle sustainability assessments. The authors propose a methodology that aims to fully capture these factors, by suggesting that researchers use semi-structured interviews and/or stakeholder discussions to collect social data that is pertinent to their clients'

values. The proposed methodology can strengthen subsequent qualitative and quantitative analyses (e.g., multicriteria decision making) through the early inclusion of important social factors, which will ultimately help encourage informed decision making. The proposed methodology, which is based on previous experience with multiple types of critical civil infrastructure projects, is broadly applicable to all critical civil infrastructure.

References

Aboushaqrah, N. N., Onat, N. C., Kucukvar, M., Hamouda, A. M. S., Kusakci, A. O., & Ayvaz, B. (2022). Selection of alternative fuel taxis: a hybridized approach of life cycle sustainability assessment and multi-criteria decision making with neutrosophic sets. International Journal of Sustainable Transportation, 16(9), 833-846. https://doi.org/10.1080/15568318.2021.1943075

Albertí, J., Balaguera, A., Brodhag, C., & Fullana-i-Palmer, P. (2017). Towards life cycle sustainability assessment of cities. A review of background knowledge. Science of the total environment, 609, 1049-1063. https://doi.org/10.1016/j.scitotenv.2017.07.179

Aleisa, E., & Al-Jarallah, R. (2018). A triple bottom line evaluation of solid waste management strategies: a case study for an arid Gulf State, Kuwait. The International Journal of Life Cycle Assessment, 23, 1460-1475. https://doi.org/10.1007/s11367-017-1410-z

Alejandrino, C., Mercante, I., & Bovea, M. D. (2021). Life cycle sustainability assessment: Lessons learned from case studies. Environmental Impact Assessment Review, 87, 106517. https://doi.org/10.1016/j.eiar.2020.106517

Alramadhan, D., Alabduljaleel, S., Almulla, D., & Aleisa, E. (2022). Multicriteria optimization for electric vehicles in an arid oil state based on a triple bottom line approach. The International Journal of Life Cycle Assessment, 1-19. https://doi.org/10.1007/s11367-021-02009-6

Al-Yafei, H., AlNouss, A., Aseel, S., Kucukvar, M., Onat, N. C., & Al-Ansari, T. (2022). How sustainable is liquefied natural gas supply chain? An integrated life cycle sustainability assessment model. Energy Conversion and Management: X, 15, 100246. https://doi.org/10.1016/j.ecmx.2022.100246

Amerson, A. M., Harris, T. M., Michener, S. R., Gunn, C. M., & Haxel, J. H. (2022). A Summary of Environmental Monitoring Recommendations for Marine Energy Development That Considers Life Cycle Sustainability. Journal of Marine Science and Engineering, 10(5), 586. https://doi.org/10.3390/jmse10050586

ASCE. (2021a). Infrastructure Report Card. 2021 Retrieved May 2, 2023 from https://infrastructurereportcard.org/

ASCE. (2021b). Policy Statement 518. Retrieved May 2, 2023 from https://www.asce.org/advocacy/policy-statements/ps518---unified-definitions-for-critical-infrastructure-resilience

ASCE. (2021c.) Policy Statement 418. Retrieved June 5, 2023 from https://www.asce.org/advocacy/policy-statements/ps418---the-role-of-the-civil-engineer-in-sustainable-development

Backes, J. G., & Traverso, M. (2021). Application of life cycle sustainability assessment in the construction sector: A systematic literature review. Processes, 9(7), 1248. https://doi.org/10.3390/pr9071248

Batuecas, E., Contreras-Lisperguer, R., Mayo, C., Díaz, R., Springer, C., & Pérez, F. J. (2021). Jamaican bioethanol: an environmental and economic life cycle assessment. Clean Technologies and Environmental Policy, 23, 1415-1430. https://doi.org/10.1007/s10098-021-02037-8

Benoît, Catherine, Gregory A. Norris, Sonia Valdivia, Andreas Ciroth, Asa Moberg, Ulrike Bos, Siddharth Prakash, Cassia Ugaya, and Tabea Beck. (2010). The guidelines for social life cycle assessment of products: just in time!. The international journal of life cycle assessment, 15, 156-163. DOI 10.1007/s11367-009-0147-8

Bhyan, P., Shrivastava, B., & Kumar, N. (2022). Systematic literature review of life cycle sustainability assessment system for residential buildings: using bibliometric analysis 2000–2020. Environment, Development and Sustainability, 1-29. https://doi.org/10.1007/s10668-022-02636-5

Costa, A. M., Mancini, S. D., Paes, M. X., Ugaya, C. M. L., de Medeiros, G. A., & de Souza, R. G. (2022). Social evaluation of municipal solid waste management systems from a life cycle perspective: a systematic literature review. The International Journal of Life Cycle Assessment, 27(5), 719-739. https://doi.org/10.1007/s11367-022-02057-6

Creswell, J.W., Poth, C.N. (2012). Qualitative Inquiry and Research Design: Choosing Among Five Approaches, third ed. SAGE Publication, Inc, Thousand oaks.

D'Adamo, I., Falcone, P. M., Imbert, E., & Morone, P. (2020). A socio-economic indicator for EoL strategies for bio-based products. Ecological Economics, 178, 106794. https://doi.org/10.1016/j.ecolecon.2020.106794

Dinh, T. H. & Götze, U. (2020). Integration of sustainability criteria and life cycle sustainability assessment method into construction material selection in developing countries: The case of Vietnam. Int. J. Sustain. Dev. Plan, 15, 1145-1156. https://doi.org/10.18280/ijsdp.150801

Dong, Y., Ng, S. T., & Liu, P. (2023). Towards the principles of life cycle sustainability assessment: an integrative review for the construction and building industry. Sustainable Cities and Society, 104604. https://doi.org/10.1016/j.scs.2023.104604

CISA. (2020) Cybersecurity and Infrastructure Security Agency. Retrieved May 2, 2023 from https://www.cisa.gov/critical-infrastructure-sectors

Ferrari, A. M., Volpi, L., Pini, M., Siligardi, C., García-Muiña, F. E., & Settembre-Blundo, D. (2019). Building a sustainability benchmarking framework of ceramic tiles based on life cycle sustainability assessment (LCSA). Resources, 8(1), 11. https://doi.org/10.3390/resources8010011

Fischer, J. M., & Amekudzi, A. (2011). Quality of life, sustainable civil infrastructure, and sustainable development: Strategically expanding choice. Journal of urban planning and development, 137(1), 39-48. DOI: 10.1061/(ASCE)UP.1943-5444.0000039.

Francis, A., & Thomas, A. (2022). A framework for dynamic life cycle sustainability assessment and policy analysis of built environment through a system dynamics approach. Sustainable Cities and Society, 76, 103521. https://doi.org/10.1016/j.scs.2021.103521

Goh, C. S., Chong, H. Y., Jack, L., & Faris, A. F. M. (2020). Revisiting triple bottom line within the context of sustainable construction: A systematic review. Journal of cleaner production, 252, 119884. https://doi.org/10.1016/j.jclepro.2019.119884

Govindan, K., Shankar, K. M., & Kannan, D. (2016). Sustainable material selection for construction industry–A hybrid multi criteria decision making approach. Renewable and Sustainable Energy Reviews, 55, 1274-1288. https://doi.org/10.1016/j.rser.2015.07.100

Hansen, A., Moussavi, S., Dvorak, B. (2023). "Reducing I/I in Small Collection Systems: Environmental, Economic, and Other Impacts." Journal of Environmental Engineering. In progress.

Hashemi, H., Ghoddousi, P., & Nasirzadeh, F. (2021). Sustainability indicator selection by a novel triangular intuitionistic fuzzy decision-making approach in highway construction projects. Sustainability, 13(3), 1477. https://doi.org/10.3390/su13031477

Hoque, N., Biswas, W., Mazhar, I., & Howard, I. (2020). Life cycle sustainability assessment of alternative energy sources for the Western Australian transport sector. Sustainability, 12(14), 5565. https://doi.org/10.3390/su12145565

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., & Hewage, K. (2015). AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. Journal of Environmental planning and management, 58(7), 1217-1241. https://doi.org/10.1080/09640568.2014.920704

Juan-Garcia, P., Butler, D., Comas, J., Darch, G., Sweetapple, C., Thornton, A. and Corominas, L., (2017). Resilience theory incorporated into urban wastewater systems management. State of the art. Water research, 115, pp.149-161. https://doi.org/10.1016/j.watres.2017.02.047

Khan, K., Depczyńska, K. S., Dembińska, I., & Ioppolo, G. (2022). Most Relevant Sustainability Criteria for Urban Infrastructure Projects—AHP Analysis for the Gulf States. Sustainability, 14(22), 14717. https://doi.org/10.3390/su142214717

Lane, K., Fuller, M., Dyment, T., & Gagnon, G. (2022). Co-development of a risk assessment tool for use in First Nations water supply systems: A key step to water safety plan implementation. International Journal of Hygiene and Environmental Health, 240, 113916. https://doi.org/10.1016/j.ijheh.2021.113916

Lane, K., Reckhow, D., Tobiason, J., & Kumpel, E. (2023). Triple-bottom-line approach for comparing point-of-use/point-of-entry to centralized water treatment. AWWA Water Science, 5(2), e1320. https://doi.org/10.1002/aws2.1320

Li, T., Roskilly, A. P., & Wang, Y. (2018). Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England. Applied energy, 227, 465-479. https://doi.org/10.1016/j.apenergy.2017.07.021

Mehmeti, A., & Canaj, K. (2022). Environmental Assessment of Wastewater Treatment and Reuse for Irrigation: A Mini-Review of LCA Studies. Resources, 11(10), 94. https://doi.org/10.3390/resources11100094

Meyer, S., Glaser, B., & Quicker, P. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environmental science & technology, 45(22), 9473-9483. https://doi.org/10.1021/es201792c

Moussavi, S., Thompson, M., Li, S., & Dvorak, B. (2021). Assessment of small mechanical wastewater treatment plants: Relative life cycle environmental impacts of construction and operations. Journal of Environmental Management, 292, 112802. https://doi.org/10.1016/j.jenvman.2021.112802

Moussavi, S., Dvorak, B., & Barutha, P. (2023a) "Impacts of Flooding on Wastewater Infrastructure: Tradeoffs of Recovery and Resilience." Journal of Environmental Engineering. *In progress.*

Moussavi, S., Barutha, P., & Dvorak, B. (2023b) "Environmental life cycle assessment of a novel offshore wind energy design project: a United States based case study." Renewable and Sustainable Energy Reviews. *In progress.*

Moussavi, S. & Dvorak, B. (2023c) "Treated wastewater reuse for non-direct food consumption crops in Nebraska: barriers and benefits of municipal irrigation lagoons." Journal of Extension. *In progress.*

Naves, A. X., Barreneche, C., Fernández, A. I., Cabeza, L. F., Haddad, A. N., & Boer, D. (2019). Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. Solar Energy, 192, 238-262. https://doi.org/10.1016/j.solener.2018.04.011

Onat, N. C., Kucukvar, M., & Tatari, O. (2014). Towards life cycle sustainability assessment of alternative passenger vehicles. Sustainability, 6(12), 9305-9342. https://doi.org/10.3390/su6129305

Onat, N. C., Kucukvar, M., Tatari, O., & Egilmez, G. (2016b). Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles. The International Journal of Life Cycle Assessment, 21, 1009-1034. https://doi.org/10.1007/s11367-016-1070-4

Onat, N. C., Kucukvar, M., Tatari, O., & Zheng, Q. P. (2016a). Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in US. Journal of Cleaner Production, 112, 291-307. https://doi.org/10.1016/j.jclepro.2015.09.021

Patel, K., & Ruparathna, R. (2021). Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach. International Journal of Construction Management, 1-10. https://doi.org/10.1080/15623599.2021.2017113

Pham, A., Moussavi, S., Thompson, M., & Dvorak, B. (2021). Environmental life cycle impacts of small wastewater treatment plants: Design recommendations for impact mitigation. Water Research, 207, 117758. https://doi.org/10.1016/j.watres.2021.117758

Ren, J., & Lützen, M. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. Renewable and Sustainable Energy Reviews, 74, 1003-1019. https://doi.org/10.1016/j.rser.2017.03.057

Romanovska, L., Osmond, P., & Oldfield, P. (2023). Life-cycle-thinking in the assessment of urban green infrastructure: Systematic scoping review. Environmental Research Letters. DOI 10.1088/1748-9326/accfae

Shrivastava, S., & Unnikrishnan, S. (2021). Life cycle sustainability assessment of crude oil in India. Journal of Cleaner Production, 283, 124654. https://doi.org/10.1016/j.jclepro.2020.124654

Sutherland, J.W., Richter, J.S., Hutchins, M.J., Dornfeld, D., Dzombak, R., Mangold, J., Robinson, S., Hauschild, M.Z., Bonou, A., Schönsleben, P. and Friemann, F. (2016). The role of manufacturing in affecting the social dimension of sustainability. CIRP Annals, 65(2), 689-712. https://doi.org/10.1016/j.cirp.2016.05.003

Thompson, M., Moussavi, S., Li, S., Barutha, P., & Dvorak, B. (2022). Environmental Life Cycle Assessment of small water resource recovery facilities: Comparison of mechanical and lagoon systems. Water Research, 215, 118234. https://doi.org/10.1016/j.watres.2022.118234

Tsalis, T., Avramidou, A., & Nikolaou, I. E. (2017). A social LCA framework to assess the corporate social profile of companies: Insights from a case study. Journal of Cleaner Production, 164, 1665-1676. https://doi.org/10.1016/j.jclepro.2017.07.003

United Nations. (2015). The 17 Goals. Retrieved May 2, 2023 from https://sdgs.un.org/goals

Walpole. (2021). How will the bipartisan infrastructure law change the civil engineering industry? American Society of Civil Engineers. Retrieved May 2, 2023 from https://www.asce.org/publications-and-news/civil-engineering-source/article/2021/12/08/how-will-the-bipartisan-infrastructure-law-change-the-civil-engineering-industry

Youngblood, D. J., Dvorak, B. I., & Hawkey, S. A. (2008). Indirect benefits of P2 technical assistance estimated using fuzzy set theory. Journal of Cleaner Production, 16(6), 771-779. https://doi.org/10.1016/j.jclepro.2007.02.017

CHAPTER 7 CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

7.0 Summary and Conclusions

In this dissertation, the life cycle sustainability of critical civil infrastructure case studies was assessed using tools such as environmental life cycle assessment and stakeholder discussions. The goal of this dissertation is to highlight important factors that decision makers should consider, to promote the sustainable development of critical civil infrastructure. Five specific objectives were set to achieve this goal: 1) quantify the environmental impacts of constructing and operating small mechanical water resource recovery facilities (WRRF), 2) analyze the environmental, economic, and societal impacts of recovery and resilience infrastructure for WRRFs faced with flooding, 3) evaluate the environmental and societal impacts of a novel offshore wind farm design, 4) identify barriers and benefits of implementing wastewater reuse in agriculture, and 5) explore the current status of sustainability assessments of critical civil infrastructure systems and propose a methodology for social data collection. A summary of the main conclusions of each objective is provided in the subsequent sections.

7.1 Assessment of Small Mechanical Wastewater Treatment Plants: Relative Life Cycle Environmental Impacts of Construction and Operations

Life cycle assessment (LCA) was performed to evaluate the environmental impacts of constructing and operating case study WRRFs. Environmental impacts of operations and construction were found to contribute to the overall environmental sustainability of a small mechanical WRRF, although operating energy usage contributes more than 50% of the overall impact to most impact categories considered. Operational impacts were influenced by energy efficiency, whereas construction impacts were

influenced by capacity utilization ratio (CUR), cast iron, and aluminum. Energy efficiency, CUR, and material usage varied site to site based on difficult to quantify factors (i.e., factors not associated with economics or the environment) such as safety preferences, a community's optimism for growth, and operator labor requirements. Decision-makers can consider modifying these factors to improve the environmental impact of small WRRFs, realizing such changes may have indirect economic and societal impacts.

7.2 Impacts of Flooding on Wastewater Infrastructure: Tradeoffs of Recovery and Resilience

Documentation of the environmental, economic, and societal impacts of investing in resilient wastewater infrastructure was explored for 10 case study WRRFs. LCA was conducted to quantify and compare the environmental impacts of resilient versus recovering wastewater systems. Economic impacts were evaluated using generalized WRRF cost models, and societal impacts were explored using stakeholder discussions. The economic and environmental impacts of capital construction are higher than the economic and environmental impacts of building subsequent recovery or resilience infrastructure. Economic and environmental impacts of recovery construction increase when cases must replace or repair major equipment, whereas economic and environmental impacts of resilience construction increase when cases must construct new basins, install new piping, and repair onsite buildings. Societal impacts (e.g., treatment impacts, worker impacts, surrounding community impacts, and general facility impacts) were found to be the driving factors leading decision makers to invest in resilient WRRF infrastructure. The identification of the environmental, economic, and societal tradeoffs

completed in this work can help communities justify investing in resilient wastewater infrastructure.

7.3 Environmental Life Cycle Assessment of a Novel Offshore Wind Energy Design Project: A United States Based Case Study

The life cycle environmental impacts of a novel offshore wind system design and a conventional offshore wind system design were quantified and compared for a US based case study. Although the environmental profiles of both designs are within the same order of magnitude, the novel design includes an innovative foundation design that has a lower environmental burden associated with impact categories of interest, such as carcinogens. Additional benefits, beyond environmental impacts, were observed for the novel design using stakeholder discussions. These benefits include low material costs, rapid installation times, limited dependency on foreign supply chains, political implications, and localized job opportunities. Energy payback times were also calculated, which revealed payback times of less than one year for either design, regardless of the energy source considered. This case study analysis shows that there are positive environmental, economic, and societal tradeoffs of novel renewable energy design concepts, which helps encourage consideration of such tradeoffs as the renewable energy sector grows.

7.4 Treated Wastewater Reuse for Non-Direct Food Consumption Crops in Nebraska: Barriers and Benefits of Municipal Irrigation Lagoons

Previous studies have clearly documented the potential environmental, economic, and societal benefits of implementing irrigation lagoons to encourage sustainable agricultural and wastewater treatment solutions. However, the challenge of obtaining

agricultural producer and landowner acceptance and cooperation to implement these systems remains, as these systems are still not widely implemented in small, rural communities in the US. Stakeholder discussions were used to identify barriers and benefits of case study irrigation lagoons in Nebraska, and the results of the discussions were developed into practical dissemination materials. The dissemination materials are intended to be used by professionals that hold existing relationships with relevant decision makers in prospective communities. Improving the information exchange related to irrigation lagoons between relevant stakeholders can help positively influence decision making regarding the widespread implementation and operation of irrigation lagoons.

7.5 Sustainability Assessments of Critical Civil Infrastructure Systems: A Mini-Review and Project Synthesis

Sustainable development of critical civil infrastructure systems should include economic, environmental, and social considerations. Economic and environmental impacts of critical civil infrastructure systems are commonly quantified by well-established methodologies such as LCA and life cycle costing. However, social impacts of critical civil infrastructure systems can be difficult to quantify and are less commonly addressed. A mini-literature review was conducted to explore how sustainability is currently evaluated for critical civil infrastructure systems, and where knowledge gaps exist. This review found that, while there are social LCA frameworks available, there is inconsistency in how social (i.e., difficult to quantify) factors are addressed. A supplemental approach for collecting social life cycle data is proposed, which includes the use of stakeholder discussions and semi-structured interviews. The inclusion of social factors early on in life cycle sustainability assessments of critical civil infrastructure can

improve the robustness of such studies and allow for further integration of social factors in multicriteria decision making.

7.6 Research Contribution

The major contribution of this dissertation is a consistent a reliable framework that captures environmental, economic, and social impacts of critical civil infrastructure systems to encourage sustainable decision making. This approach was applied to several types of critical civil infrastructure systems (e.g., wastewater and energy) to emphasize its broad applicability. This framework led to the comprehensive analysis of environmental impacts through LCA methodologies, which is another major contribution of this work. Such detailed life cycle analyses of case studies are rare, due to the major challenge of data collection. Lastly, this framework highlighted the importance of social aspects of critical civil infrastructure projects for relevant stakeholders and clients.

7.7 Suggestions for Future Research

This research aims to initiate the development of practical guidance for integrating sustainability in critical civil infrastructure decision making. However, further work is needed to develop an actionable and consistent framework that can be used by decision makers on a global scale for various infrastructure systems. Below are possible areas for future research to help achieve this goal.

- This dissertation studied two specific critical civil infrastructure systems (i.e., wastewater and energy). Additionally, the case studies were all based in the US. Although the methodologies and findings of the studies conducted are applicable worldwide, further research should consider using reflective case studies in different critical civil infrastructure sectors around the world to provide a comprehensive

analysis. Including a larger amount of reflective case studies from a global perspective can also help provide statistically significant results, which can aid in guiding sustainability related policies and decisions for critical civil infrastructure.

- The studies conducted in this dissertation focused largely on the commonly quantified impacts (i.e., economic and environmental impacts). Although societal impacts were discussed in the work, these impacts are difficult to measure and thus a limitation of this work is that these impacts were not quantified. As noted in Chapter 6, future research should work to use stakeholder discussions and/or semi-structured interviews to collect social data. Although social impacts are sometimes considered in the current relevant literature, there is a need for a consistent data collection framework that can lead to quantification and consideration of stakeholders' perspectives and values. Additionally, a framework that considers both the commonly quantified environmental and economic impacts, as well as the more difficult to quantify societal impacts that often drive decision making, should be developed.
- Lastly, the framework applied in this work considered environmental, economic, and/or social impacts at a fixed point in time. Because using reflective case studies was a major objective of this work, future projections of impacts were not considered, and the case study was focused on instead. It is expected that time variability will alter the environmental, economic, and social impacts of critical civil infrastructure decisions, and thus future studies should consider adding non-linear frameworks to model these impacts.

APPENDIX A Supplemental Information: Assessment of Small Mechanical Wastewater Treatment Plants: Relative Life Cycle Environmental Impacts of Construction and Operations

Table A1 Summary of communities analyzed

Plant	Plant Type[1]	2010 Community Population (people)	Design Average Daily Wastewater Flow Rate (m3/d)	Average Daily Wastewater Flow Rate (m3/d)
A	SBR	1581	681	216
B	EA-P	1561	833	488
C	OD	1661	984	432
D	OD	1670	3104	852
E	EA	471	303	144
F	SBR	513	227	98
G	OD	4488	6814	3437
H	EA-P	1942	1249	662
I	OD	941	606	413
J	EA	1181	697	632
K	EA	3569	1908	1473
L	OD	617	644	344
M	SBR	2209	1325	591
N	SBR	2906	1893	1321
O	SBR	2916	1514	784
P	SBR	3986	3142	2271

[1] Oxidation ditch (OD), Extended aeration (EA), Extended aeration - package (EA-P), Sequence batch reactor (SBR)

Table A2 Life cycle inventory normalized by 20 year flow

	Plant	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Plant Type	SBR	EA-P	OD	OD	EA	SBR	OD	EA-P	OD	EA	EA	OD	SBR	SBR	SBR	SBR
	Plant Design Flow (MGD)	0.180	0.220	0.260	0.820	0.080	0.060	1.800	0.330	0.160	0.184	0.504	0.170	0.350	0.500	0.400	0.830
	Plant Average Flowrate (MGD)	0.057	0.129	0.114	0.225	0.037	0.026	0.905	0.175	0.110	0.167	0.389	0.090	0.156	0.349	0.207	0.600
	Capacity Utilization Ratio	32%	58%	44%	27%	46%	44%	50%	53%	69%	91%	77%	53%	44%	70%	52%	72%
	Climate Controlled Floor Area (m^2)	214	251	121	102	28	56	279	46	33	279	650	72	576	334	318	232
CONSTRUCTION	**Civil Works**																
	Excavation (m^3)	1.01E-03	1.34E-03	2.44E-03	2.12E-03	3.77E-03	1.54E-03	4.84E-03	5.15E-03	1.19E-03	7.00E-04	1.16E-03	5.80E-04	1.35E-03	5.79E-04	5.52E-04	1.13E-04
	Reinforcing steel (kg)	1.98E-02	1.52E-02	3.10E-02	3.06E-02	2.45E-02	2.81E-02	2.60E-02	1.19E-02	1.03E-02	8.50E-03	9.95E-03	5.36E-03	9.75E-03	5.88E-03	5.09E-03	3.54E-03
	Concrete (m3)	2.74E-04	2.11E-04	4.30E-04	4.25E-04	3.40E-04	3.91E-04	3.59E-04	1.65E-04	1.43E-04	1.18E-04	1.38E-04	7.45E-05	1.35E-04	8.16E-05	7.06E-05	4.91E-05
	Rock/Limestone (kg)	2.28E-01	1.36E+00	1.88E-01	2.59E-01	8.10E-02	0.00E+00	1.78E-02	1.15E-01	6.48E-02	2.27E-04	1.44E-01	1.16E-01	1.45E-02	4.42E-02	4.08E-02	1.05E-02
	Sand (kg)	0.00E+00	2.18E-02	0.00E+00	0.00E+00	3.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Insulation (polystyrene) (kg)	1.14E-04	7.11E-05	2.69E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.73E-05	0.00E+00	0.00E+00	4.56E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Brick (kg)	9.17E-03	0.00E+00	0.00E+00	3.64E-01	0.00E+00	0.00E+00	2.39E-03	2.38E-03	0.00E+00	4.60E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Wood (m^3)	9.00E-06	4.55E-06	3.00E-06	0.00E+00	3.00E-07	1.00E-07	0.00E+00	0.00E+00	9.00E-10	0.00E+00	0.00E+00	6.00E-08	9.00E-09	2.00E-08	3.00E-08	0.00E+00
	Asphalt (kg)	0.00E+00	0.00E+00	0.00E+00	2.13E-03	0.00E+00	4.70E-04	0.00E+00	0.00E+00	0.00E+00	1.74E-02	0.00E+00	0.00E+00	4.77E-05	2.83E-04	2.02E-04	6.59E-05
	Material transport (tkm)	4.06E-02	8.40E-02	5.53E-02	7.40E-02	4.09E-02	4.27E-02	4.02E-02	2.34E-02	1.85E-02	1.57E-02	2.15E-02	1.33E-02	1.55E-02	1.09E-02	9.54E-03	5.83E-03
	Equipment, Piping, Fittings, and Valves																
	Cast Iron (kg)	1.23E-02	8.22E-03	1.43E-02	1.34E-03	1.26E-02	7.27E-03	5.57E-03	4.47E-03	9.79E-04	8.26E-03	5.17E-03	1.56E-03	4.13E-03	1.62E-03	1.10E-03	5.58E-04
	Stainless steel (kg)	5.47E-04	1.21E-03	3.39E-03	6.45E-04	1.63E-03	1.02E-02	2.79E-03	3.05E-04	5.95E-03	8.25E-04	1.42E-04	1.58E-03	1.98E-03	6.19E-04	7.94E-04	3.67E-04
	Aluminum (kg)	7.60E-04	5.09E-04	1.16E-03	9.23E-04	7.32E-03	1.90E-03	1.90E-03	6.17E-04	2.72E-03	7.43E-04	5.26E-04	3.05E-03	3.68E-04	1.46E-04	1.90E-04	1.31E-04
	Copper (kg)	3.32E-05	1.41E-05	4.37E-05	1.96E-05	2.92E-05	6.06E-05	5.74E-06	1.14E-05	2.26E-06	8.94E-05	1.14E-05	8.70E-06	2.22E-05	1.99E-05	8.40E-06	7.80E-06
	VCP (kg)	0.00E+00	0.00E+00	0.00E+00	2.46E-04	1.01E-02	0.00E+00	4.34E-05	3.95E-03	8.55E-04	0.00E+00	0.00E+00	4.32E-04	0.00E+00	0.00E+00	4.28E-04	8.80E-04
	Rubber (kg)	2.50E-05	9.28E-06	4.48E-05	2.47E-06	1.32E-05	1.98E-05	7.69E-07	1.55E-05	1.93E-06	4.48E-06	8.70E-05	3.62E-06	2.97E-06	6.64E-07	4.85E-07	1.11E-06
	Fiber glass (kg)	4.46E-05	0.00E+00	2.23E-04	5.95E-03	1.03E-04	1.46E-04	2.19E-04	0.00E+00	7.07E-04	0.00E+00	0.00E+00	2.02E-04	1.84E-04	8.06E-05	4.78E-05	1.88E-05
	200 kW generator (unit)	2.53E-07	1.21E-07	2.37E-07	2.41E-07	0.00E+00	0.00E+00	5.98E-08	8.90E-08	0.00E+00	0.00E+00	4.00E-08	1.59E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Polyethylene, PE (kg)	6.28E-05	3.40E-05	2.94E-05	0.00E+00	0.00E+00	1.58E-04	0.00E+00	7.65E-06	0.00E+00	0.00E+00	5.49E-06	1.21E-02	1.16E-04	6.66E-04	1.25E-04	0.00E+00
	Polyvinyl chloride, PVC (kg)	3.60E-06	0.00E+00	4.74E-04	3.02E-05	6.54E-05	5.52E-04	1.07E-05	0.00E+00	5.58E-05	8.61E-05	6.80E-05	1.55E-04	0.00E+00	8.95E-06	3.11E-05	3.88E-05
	Polypropylene (kg)	0.00E+00	0.00E+00	0.00E+00	6.29E-05	1.45E-05	0.00E+00	3.51E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Energy (kWh)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Material Transport (tkm)	6.08E-04	4.41E-04	8.66E-04	4.06E-04	1.40E-03	8.95E-04	4.65E-04	4.14E-04	4.97E-04	4.41E-04	2.65E-04	8.41E-04	3.00E-04	1.39E-04	1.20E-04	8.83E-05
OPERATION (20 years)	**Energy Use**																
	Electricity (kWh)	2.46E+00	2.41E+00	1.69E+00	1.11E+00	1.56E+00	3.76E+00	9.80E-01	1.02E+00	1.69E+00	1.39E+00	1.22E+00	8.90E-01	2.85E+00	1.74E+00	1.25E+00	1.56E+00
	Natural gas (kWh)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Generator operation (hrs)	3.28E-04	1.46E-04	1.65E-04	8.36E-05	0.00E+00	7.15E-04	2.07E-05	1.08E-04	0.00E+00	0.00E+00	4.83E-05	2.06E-04	1.21E-04	5.39E-05	9.10E-05	3.13E-05
	Water Emissions																
	CBOD (kg)	4.44E-03	4.28E-03	2.60E-03	8.60E-03	5.77E-03	4.04E-03	2.37E-03	6.46E-03	9.42E-03	1.79E-02	2.11E-03	9.15E-03	2.68E-03	1.13E-02	3.70E-03	7.31E-03
	Total N (kg)	7.10E-03	3.55E-02	1.25E-02	2.33E-02	1.65E-02	1.43E-02	6.44E-03	2.62E-02	2.42E-02	1.96E-02	2.35E-02	1.47E-02	4.40E-03	5.04E-03	9.19E-03	4.27E-03
	Total P(kg)	2.35E-03	4.29E-03	3.06E-03	4.57E-03	2.69E-03	3.95E-03	1.83E-03	1.91E-03	3.12E-03	3.00E-03	2.74E-03	2.26E-03	4.00E-03	1.75E-03	5.31E-03	1.64E-03
	Solid Emissions																
	Selenium (kg)	4.51E-06	3.03E-06	4.32E-06	3.11E-06	3.16E-06	4.11E-08	2.39E-06	2.37E-06	4.56E-06	1.40E-05	1.02E-06	6.43E-07	2.62E-07	8.44E-07	2.24E-06	2.88E-06
	Arsenic (kg)	1.49E-06	7.89E-07	1.08E-06	2.50E-06	2.34E-06	5.03E-08	1.60E-06	1.41E-06	8.34E-07	1.51E-06	1.05E-06	8.54E-07	4.01E-07	8.44E-07	2.98E-06	1.27E-06
	Nitrate (kg)	5.64E-04	8.12E-04	6.35E-04	6.66E-03	2.14E-05	5.20E-07	4.43E-05	9.23E-04	2.17E-04	4.07E-04	1.23E-04	4.68E-04	2.08E-05	5.97E-06	5.20E-06	1.40E-04
	Ammonia (kg)	1.31E-04	1.46E-03	6.34E-04	1.67E-05	4.68E-04	9.51E-07	8.46E-05	3.76E-04	1.26E-04	4.59E-05	1.55E-03	2.09E-04	6.35E-04	1.70E-04	1.18E-04	2.83E-03
	Molybdenum (kg)	3.60E-06	1.72E-06	1.09E-06	5.00E-06	5.26E-06	1.68E-08	5.35E-07	2.11E-06	1.50E-06	2.96E-08	1.10E-06	1.81E-06	4.30E-07	2.12E-06	1.68E-06	8.01E-06
	Zinc (kg)	5.46E-05	6.72E-05	7.44E-05	1.97E-04	4.89E-05	8.33E-07	9.04E-05	6.67E-05	6.16E-05	1.73E-04	8.51E-05	6.90E-05	4.09E-05	2.96E-05	2.42E-05	1.10E-04
	Lead (kg)	1.80E-05	8.61E-06	6.79E-06	1.38E-05	2.63E-05	5.01E-08	1.69E-06	9.88E-06	9.20E-06	1.71E-05	5.91E-06	9.06E-06	5.72E-06	1.06E-05	8.78E-06	5.16E-05

Nickel (kg)	3.60E-06	1.79E-06	2.31E-06	3.84E-06	5.26E-06	2.69E-08	1.58E-06	2.43E-06	2.28E-06	5.54E-06	1.76E-06	2.62E-06	1.15E-06	2.72E-06	2.09E-06	5.70E-06
Mercury (kg)	7.40E-08	5.94E-08	2.45E-07	3.80E-07	1.14E-07	2.80E-09	1.69E-07	1.16E-07	6.59E-08	1.48E-09	1.67E-08	5.56E-08	4.73E-08	4.22E-07	1.58E-08	1.26E-07
Chromium (kg)	3.60E-06	1.96E-06	4.14E-06	4.20E-06	5.26E-06	3.47E-08	3.97E-06	2.95E-06	2.13E-06	2.96E-08	2.01E-06	3.18E-06	1.29E-06	4.72E-06	1.85E-06	1.15E-05
Copper (kg)	3.75E-06	1.75E-04	1.54E-04	1.61E-04	3.30E-05	2.19E-06	1.20E-04	8.20E-05	7.07E-05	1.96E-04	6.48E-05	3.52E-05	1.13E-04	1.83E-05	2.30E-05	1.99E-04
Cadmium (kg)	4.06E-07	3.59E-07	2.20E-07	5.61E-07	1.05E-06	5.26E-09	1.43E-07	3.58E-07	3.10E-07	1.48E-08	2.17E-07	3.45E-07	8.59E-08	4.22E-07	4.08E-07	4.00E-06
Air Emissions																
Methane (kg)	7.50E-03	2.91E-03	8.38E-03	7.34E-03	3.85E-03	8.50E-03	4.99E-03	6.29E-03	2.93E-03	6.20E-03	4.01E-03	3.81E-03	7.89E-03	9.02E-03	7.16E-03	5.93E-03
Nitrous oxide (kg)	1.51E-04	2.77E-04	1.36E-04	1.96E-04	7.88E-05	7.06E-05	8.01E-05	3.17E-05	2.07E-04	3.60E-04	1.57E-04	1.70E-04	5.33E-05	1.51E-04	1.17E-04	3.65E-05
Ammonia (kg)	8.68E-04	9.64E-04	6.12E-04	7.35E-04	9.78E-05	4.41E-06	3.85E-04	1.50E-04	7.89E-04	1.99E-03	4.54E-04	7.88E-04	2.38E-04	9.19E-04	5.73E-04	1.51E-04
Flow (m^3)	1.58E+00	3.56E+00	3.16E+00	6.22E+00	1.02E+00	7.27E-01	2.50E+01	4.83E+00	3.04E+00	4.62E+00	1.08E+01	2.50E+00	4.31E+00	9.64E+00	5.72E+00	1.66E+01

Table A3 LCA results for each of the 16 case studies

Process / Plant	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Ozone Depletion																
Civil Works	6.16E-08	6.27E-08	9.01E-08	1.76E-07	7.13E-08	7.86E-08	7.56E-08	3.89E-08	3.02E-08	4.31E-08	3.03E-08	1.68E-08	2.80E-08	1.73E-08	1.61E-08	9.96E-09
Equipment	2.12E-08	1.38E-08	2.91E-08	2.21E-08	8.11E-08	3.32E-08	2.22E-08	1.15E-08	3.13E-08	1.74E-08	1.03E-08	3.55E-08	9.14E-09	2.99E-09	3.67E-09	2.40E-09
Operating Energy	1.17E-06	1.13E-06	7.99E-07	5.24E-07	7.23E-07	1.82E-06	4.56E-07	4.82E-07	7.85E-07	6.46E-07	5.72E-07	4.34E-07	1.33E-06	8.10E-07	5.87E-07	7.28E-07
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Global Warming																
Civil Works	4.69E-06	4.00E-06	7.07E-06	1.18E-05	5.56E-06	6.29E-06	5.90E-06	2.84E-06	2.35E-06	2.72E-06	2.30E-06	1.25E-06	2.20E-06	1.34E-06	1.21E-06	7.93E-07
Equipment	1.19E-06	8.35E-07	1.65E-06	1.01E-06	2.86E-06	1.73E-06	8.16E-07	5.44E-07	1.20E-06	8.70E-07	5.37E-07	1.24E-06	5.54E-07	1.16E-07	1.94E-07	1.08E-07
Operating Energy	7.09E-05	6.91E-05	4.85E-05	3.19E-05	4.44E-05	1.09E-04	2.79E-05	2.92E-05	4.82E-05	3.96E-05	3.50E-05	2.59E-05	8.13E-05	4.96E-05	3.58E-05	4.46E-05
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	9.60E-06	6.41E-06	1.03E-05	9.98E-06	4.94E-06	9.64E-06	6.13E-06	6.88E-06	5.57E-06	1.08E-05	6.07E-06	6.02E-06	8.80E-06	1.12E-05	8.82E-06	6.57E-06
Smog																
Civil Works	5.53E-06	6.15E-06	8.13E-06	1.36E-05	6.46E-06	6.97E-06	6.84E-06	3.66E-06	2.73E-06	3.06E-06	2.77E-06	1.55E-06	2.53E-06	1.56E-06	1.48E-06	8.84E-07
Equipment	1.24E-06	8.63E-07	1.74E-06	1.46E-06	3.03E-06	1.86E-06	8.91E-07	5.79E-07	1.33E-06	9.26E-07	5.50E-07	1.32E-06	5.90E-07	1.37E-07	2.09E-07	1.20E-07
Operating Energy	3.42E-05	3.22E-05	2.30E-05	1.50E-05	2.01E-05	5.40E-05	1.28E-05	1.39E-05	2.18E-05	1.79E-05	1.61E-05	1.31E-05	3.76E-05	2.28E-05	1.68E-05	2.04E-05
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	7.75E-08	3.01E-08	8.66E-08	7.58E-08	3.98E-08	8.78E-08	5.15E-08	6.50E-08	3.03E-08	6.40E-08	4.15E-08	3.94E-08	8.15E-08	9.32E-08	7.39E-08	6.13E-08
Acidification																
Civil Works	5.00E-06	4.96E-06	7.44E-06	1.23E-05	5.86E-06	6.49E-06	6.21E-06	3.15E-06	2.48E-06	2.98E-06	2.48E-06	1.37E-06	2.31E-06	1.42E-06	1.32E-06	8.22E-07
Equipment	1.89E-06	1.25E-06	2.57E-06	2.08E-06	4.56E-06	2.66E-06	1.35E-06	8.67E-07	1.92E-06	1.47E-06	8.01E-07	2.15E-06	8.29E-07	2.41E-07	3.00E-07	1.81E-07
Operating Energy	7.21E-05	7.00E-05	4.92E-05	3.24E-05	4.49E-05	1.11E-04	2.83E-05	2.97E-05	4.87E-05	4.01E-05	3.54E-05	2.65E-05	8.23E-05	5.02E-05	3.63E-05	4.51E-05
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	1.80E-05	2.00E-05	1.27E-05	1.52E-05	2.02E-06	9.13E-08	7.98E-06	3.11E-06	1.63E-05	4.12E-05	9.40E-06	1.63E-05	4.93E-06	1.90E-05	1.19E-05	3.12E-06
Eutrophication																
Civil Works	1.28E-05	1.06E-05	1.96E-05	2.64E-05	1.54E-05	1.76E-05	1.63E-05	7.70E-06	6.51E-06	6.78E-06	6.34E-06	3.43E-06	6.12E-06	3.71E-06	3.35E-06	2.21E-06
Equipment	6.89E-06	4.48E-06	9.64E-06	5.83E-06	1.15E-05	1.11E-05	4.42E-06	2.88E-06	6.35E-06	5.72E-06	2.48E-06	6.53E-06	3.18E-06	1.17E-06	1.17E-06	7.08E-07
Operating Energy	6.48E-04	6.36E-04	4.45E-04	2.93E-04	4.11E-04	9.92E-04	2.58E-04	2.68E-04	4.46E-04	3.67E-04	3.23E-04	2.35E-04	7.50E-04	4.57E-04	3.29E-04	4.12E-04
Water Emissions	6.82E-04	2.26E-03	1.03E-03	1.76E-03	1.16E-03	1.24E-03	5.69E-04	4.17E-04	1.59E-03	1.38E-03	1.48E-03	1.02E-03	7.97E-04	5.14E-04	1.21E-03	4.53E-04
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	4.76E-06	5.29E-06	3.36E-06	4.03E-06	5.37E-07	2.42E-08	2.11E-06	8.25E-07	4.33E-06	1.09E-05	2.49E-06	4.32E-06	1.31E-06	5.04E-06	3.15E-06	8.26E-07
Carcinogens																
Civil Works	4.89E-04	3.83E-04	7.60E-04	8.38E-04	6.01E-04	6.89E-04	6.38E-04	2.95E-04	2.53E-04	2.22E-04	2.45E-04	1.32E-04	2.39E-04	1.44E-04	1.26E-04	8.66E-05
Equipment	7.05E-04	4.99E-04	9.26E-04	1.47E-04	8.78E-04	8.20E-04	2.50E-04	2.68E-04	3.37E-04	4.92E-04	2.93E-04	2.21E-04	3.04E-04	3.71E-05	9.38E-05	4.73E-05
Operating Energy	2.71E-03	2.65E-03	1.86E-03	1.22E-03	1.71E-03	4.15E-03	1.08E-03	1.12E-03	1.86E-03	1.53E-03	1.34E-03	9.84E-04	3.12E-03	1.91E-03	1.37E-03	1.72E-03
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	2.61E-04	1.49E-04	3.30E-04	4.11E-04	3.89E-04	3.39E-06	2.87E-04	2.78E-04	1.61E-04	4.90E-05	1.31E-04	2.13E-04	9.85E-05	4.34E-04	1.44E-04	7.69E-04
Operating Air Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Non-Carcinogens																
Civil Works	3.73E-05	3.06E-05	5.70E-05	7.34E-05	4.49E-05	5.12E-05	4.75E-05	2.22E-05	1.90E-05	1.83E-05	1.84E-05	9.99E-06	1.78E-05	1.08E-05	9.82E-06	6.46E-06
Equipment	5.08E-05	3.32E-05	6.63E-05	2.72E-05	6.30E-05	6.22E-05	2.16E-05	1.97E-05	2.82E-05	3.93E-05	1.87E-05	2.60E-05	2.09E-05	5.63E-06	6.99E-06	4.08E-06
Operating Energy	4.97E-04	4.88E-04	3.41E-04	2.25E-04	3.15E-04	7.61E-04	1.98E-04	2.06E-04	3.42E-04	2.81E-04	2.47E-04	1.80E-04	5.75E-04	3.51E-04	2.52E-04	3.16E-04
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	2.99E-03	3.21E-03	3.88E-03	9.52E-03	3.16E-03	4.43E-05	4.24E-03	3.89E-03	3.00E-03	7.67E-03	3.77E-03	3.29E-03	1.97E-03	2.53E-03	1.40E-03	6.73E-03
Operating Air Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Respiratory Effects																

Civil Works	5.02E-06	5.27E-06	7.44E-06	1.03E-05	5.81E-06	6.47E-06	6.10E-06	3.04E-06	2.48E-06	2.52E-06	2.49E-06	1.39E-06	2.28E-06	1.42E-06	1.34E-06	8.24E-07
Equipment	2.17E-06	1.52E-06	3.03E-06	1.56E-06	4.51E-06	3.27E-06	1.39E-06	9.35E-07	2.05E-06	1.62E-06	9.34E-07	2.00E-06	1.03E-06	2.29E-07	3.56E-07	1.95E-07
Operating Energy	2.20E-04	2.15E-04	1.51E-04	9.94E-05	1.39E-04	3.36E-04	8.74E-05	9.08E-05	1.51E-04	1.24E-04	1.09E-04	7.97E-05	2.54E-04	1.55E-04	1.11E-04	1.39E-04
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	2.39E-06	2.65E-06	1.68E-06	2.02E-06	2.69E-07	1.21E-08	1.06E-06	4.13E-07	2.17E-06	5.48E-06	1.25E-06	2.17E-06	6.55E-07	2.53E-06	1.58E-06	4.14E-07
	Ecotoxicity															
Civil Works	9.24E-05	7.54E-05	1.42E-04	1.84E-04	1.12E-04	1.28E-04	1.18E-04	5.52E-05	4.72E-05	4.55E-05	4.58E-05	2.48E-05	4.43E-05	2.69E-05	2.39E-05	1.61E-05
Equipment	9.09E-05	6.02E-05	1.23E-04	5.00E-05	1.20E-04	1.30E-04	4.55E-05	3.59E-05	6.31E-05	7.22E-05	3.30E-05	5.48E-05	4.02E-05	1.20E-05	1.39E-05	8.13E-06
Operating Energy	1.53E-03	1.50E-03	1.05E-03	6.90E-04	9.67E-04	2.33E-03	6.07E-04	6.31E-04	1.05E-03	8.63E-04	7.59E-04	5.53E-04	1.76E-03	1.08E-03	7.73E-04	9.69E-04
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	1.29E-04	5.97E-04	5.62E-04	8.17E-04	2.02E-04	7.57E-06	5.03E-04	4.26E-04	3.13E-04	8.56E-04	3.42E-04	2.36E-04	3.81E-04	1.21E-04	1.19E-04	7.72E-04
Operating Air Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fossil Fuel Depletion															
Civil Works	4.93E-06	4.90E-06	7.20E-06	1.60E-05	5.56E-06	6.14E-06	5.91E-06	3.08E-06	2.35E-06	3.65E-06	2.39E-06	1.31E-06	2.19E-06	1.35E-06	1.26E-06	7.77E-07
Equipment	1.06E-06	7.33E-07	1.50E-06	1.49E-06	3.00E-06	1.60E-06	8.32E-07	5.53E-07	1.26E-06	7.88E-07	5.22E-07	1.30E-06	5.03E-07	1.22E-07	1.85E-07	1.14E-07
Operating Energy	7.15E-05	6.88E-05	4.86E-05	3.19E-05	4.38E-05	1.11E-04	2.76E-05	2.94E-05	4.75E-05	3.90E-05	3.47E-05	2.66E-05	8.07E-05	4.91E-05	3.57E-05	4.41E-05
Water Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Soil Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Operating Air Emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A4 TRACI impact category units, as defined by Ryberg et al. (2014)

Impact Category	Unit
Acidification	kg SO2 eq
Carcinogenics	CTUh
Ecotoxicity	CTUe
Eutrophication	kg N eq
Fossil Fuel Depletion	MJ Surplus
Global Warming	kg CO2 eq
Non-carcinogenics	CTUh
Ozone Depletion	kg CFC-11 eq
Respiratory Effects	kg PM2.5 eq
Smog	kg O3 eq

Table A5 Multiple regression analysis results for 10 TRACI impact categories highlighting factors that contribute most to variability among case study construction impacts

Impact Category/Regression Term	Intercept		Plant Design Flow		Plant Average Flowrate		Cast Iron		Aluminum		Adjusted R Square	F - Test
	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value		
Ozone Depletion	-1.01E-02	1.95E-01	2.95E-01	9.28E-06	-3.51E-01	1.64E-04	7.48E-07	2.90E-02	1.99E-06	7.35E-02	0.96	1.52E-08
Global Warming	-1.37E+05	5.60E-02	2.96E+06	2.60E-06	-3.43E+06	6.63E-05	8.68E+00	6.81E-03	1.77E+01	7.10E-02	0.97	2.75E-09
Smog	-8.57E+03	8.11E-02	2.00E+05	3.43E-06	-2.34E+05	7.83E-05	5.98E-01	7.26E-03	1.06E+00	1.13E-01	0.97	4.74E-09
Acidification	-4.72E+02	1.19E-01	1.22E+04	4.22E-06	-1.44E+04	9.25E-05	3.75E-02	7.14E-03	7.71E-02	7.02E-02	0.97	4.08E-09
Eutrophication	-3.09E+02	3.80E-02	6.41E+03	1.47E-06	-7.20E+03	5.23E-05	2.60E-02	5.00E-04	6.31E-02	5.03E-03	0.98	1.48E-10
Carcinogens	-1.50E-02	1.58E-01	4.38E-01	4.03E-06	-4.88E-01	1.37E-04	4.43E-06	2.98E-07	4.85E-06	4.58E-03	0.99	6.01E-12
Non-Carcinogens	-2.16E-02	3.27E-01	9.22E-01	4.43E-06	-1.06E+00	1.12E-04	5.81E-06	3.16E-05	7.39E-06	2.75E-02	0.98	1.71E-10
Respiratory Effects	-1.21E+02	5.16E-02	2.65E+03	1.87E-06	-3.03E+03	5.70E-05	1.13E-02	4.29E-04	2.33E-02	1.13E-02	0.98	2.44E-10
Ecotoxicity	-8.73E+05	1.05E-01	2.31E+07	2.29E-06	-2.61E+07	7.54E-05	1.27E+02	5.77E-05	2.28E+02	6.53E-03	0.99	8.29E-11
Fossil Fuel Depletion	-8.81E+04	3.10E-01	3.15E+06	1.61E-05	-3.83E+06	2.28E-04	6.16E+00	9.53E-02	6.02E+00	6.08E-01	0.93	3.36E-07

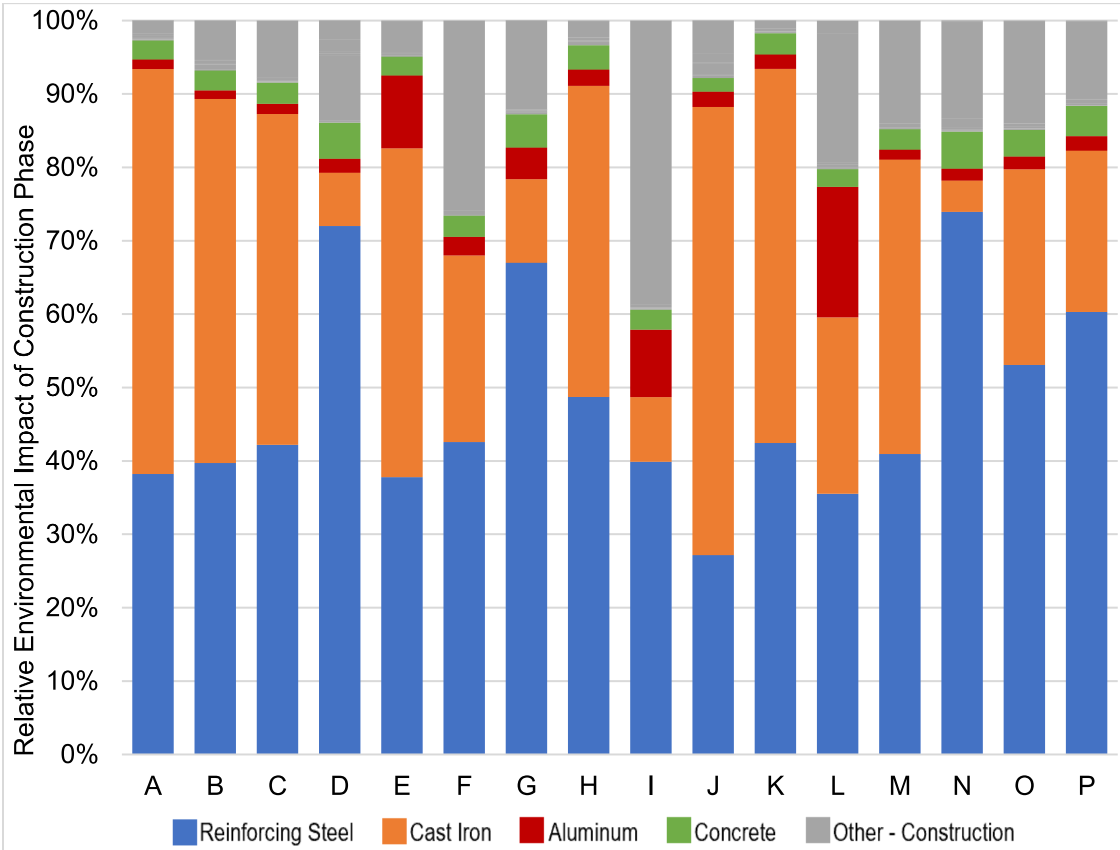
Table A6 Percent decrease in the construction environmental impact between the plant with the lowest CUR and the plant with the highest CUR for each impact category

Impact Category/Case	**Worst to Best Case**
Ozone Depletion	69%
Global Warming	72%
Smog	73%
Acidification	69%
Eutrophication	61%
Carcinogenics	27%
Non carcinogenics	43%
Respiratory Effects	65%
Ecotoxicity	50%
Fossil Fuel Depletion	75%

Table A7 Range of the 16 plants' contribution of aluminum or cast iron to the total construction impact for each impact category

Ozone Depletion	Aluminum 4% - 55% Cast Iron 1% - 12%
Global Warming	Aluminum 2% - 29% Cast Iron 1% - 17%
Smog	Aluminum 2% - 28% Cast Iron 1% - 15%
Acidification	Aluminum 3% - 38% Cast Iron 1% - 17%
Eutrophication	Aluminum 3% - 31% Cast Iron 1% - 17%
Carcinogenics	Aluminum 1% - 18% Cast Iron 4% - 61%
Non-carcinogenics	Aluminum 2% - 29% Cast Iron 2% - 41%
Respiratory Effects	Aluminum 3% - 32% Cast Iron 1% - 26%
Ecotoxicity	Aluminum 2% - 28% Cast Iron 2% - 32%
Fossil Fuel Depletion	Aluminum 1% - 31% Cast Iron 0% - 12%

Figure A1 Contribution of reinforcing steel, cast iron, aluminum, concrete, and other construction resources to the total construction impact for each plant



APPENDIX B Supplemental Information: Impacts of Flooding on Wastewater Infrastructure: Tradeoffs of Recovery and Resilience

Table B1 Original build dates and dates of latest FEMA flood hazard map update for each case study (FEMA, 2022)

Case Study	Original Build Date	Date of Latest FEMA Flood Hazard Map Update
1	1977	December 2005
2	1964	July 2010
3	1977	November 2010
4	1957	December 2004
5	1986	August 2005
6	1961	September 2011
7	1975	January 2008
8	2001	June 1987
9	1959	February 2005
10	1961	November 2010

Tables B2 – B4 describe the data collection process for this project. The research team was able to obtain detailed case study inventory data for each facility through networking, cold-calling, and site-visits. Developing a relationship with the communities allowed the research group to build trust, which helped overcome the typical reluctance of providing information.

The economic inventory for each case study included initial (i.e., embedded) construction costs, recovery construction costs, and resilience construction costs. The initial plant construction costs were estimated based on a generalized cost model (Hansen, 2023). The recovery and resilience construction costs were collected based on discussions with design engineers and facility operators. These costs were based on the cost estimates available for completed or proposed recovery or resilience projects.

The additional, non-quantified impacts for each case study were found through discussions with design engineers and facility operators during the site visits and over the phone. These discussions were open-ended and not guided. After the discussions were held, the findings from each were categorized due to observed similarities.

Table B2 and Table B3 provide a description of the detailed environmental data inventory that was collected for this study. Table B4 shows an example of the data collected to build the environmental LCA inventory, using Case Study 5. This process was completed for each of the 10 case studies. The values provided in Table B4 were divided by the lifetime flow (Table B2) before being entered into the LCA software to represent the quantity of material used over a specified lifetime.

Table B2 Detailed data collection process: relevant plant information

Plant Name	
Plant Type:	Extended aeration, sequence batch reactor, oxidation ditch, etc.
Plant Design Flow:	m^3/day (MGD)
Plant Average Flow:	m^3/day (MGD)
% Design Flow	$= \frac{\text{Plant average flow}}{\text{Plant design flow}}$
Lifetime flow (m^3)	$= \frac{\text{Plant average flow in million gallons per day} * 365 \text{ days/year} * \text{X years} * 10^6 \text{million gallons}}{264 \text{ gallons}/1\text{m}^3}$

Table B3 Detailed data collection process: environmental life cycle inventory

CONSTRUCTION	**Civil Works [1]**	
	Excavation	m^3
	Reinforcing steel	kg
	Concrete	kg
	Rock/limestone	kg
	Sand	kg
	Polystyrene	kg
	Brick	kg
	Wood	kg
	Asphalt	kg
	Equipment, Piping, Fittings, and Valves [1]	
	Cast iron	kg
	Stainless steel	kg
	Aluminum	kg
	Copper	kg
	Vitrified clay pipe	kg
	Rubber	kg
	Fiberglass	kg
	200 kW generator	unit(s)
	Polyethylene	kg
	Polyvinyl chloride	kg
	Polypropylene	kg
OPERATIONS	**Energy [1,2]**	
	Electricity	kwh
	Natural gas	m^3
	Generator operation	hours
	Water Emissions [3]	
	Carbonaceous biochemical oxygen demand	kg
	Total nitrogen	kg
	Total phosphorous	kg

Data Sourcing:
1 Construction design documents, damage records, resilience plans
2 Utility bills
3 Facility records, US EPA ECHO

Table B4 Detailed data collection process: example of Case Study 5 environmental life cycle inventory

INITIAL WRRF			
	Civil Works		
CONSTRUCTION	Excavation	1,023	m^3
	Reinforcing steel	18,793	kg
	Concrete	626,445	kg
	Rock/limestone	2,419,872	kg
	Polystyrene	391	kg
	Wood	15,767	kg
	Equipment, Piping, Fittings, and Valves		
	Cast iron	6,752	kg
	Stainless steel	7,735	kg
	Aluminum	718	kg
	Copper	180	kg
	Rubber	3	kg
	Fiberglass	813	kg
	200 kW generator	1	unit
	Polyethylene	464	kg
	Polyvinyl chloride	397	kg
OPERATIONS (20 Years)	**Energy**		
	Electricity	2,101,467	kwh
	Generator operation	520	hours
	Water Emissions		
	Carbonaceous biochemical oxygen demand	17,260	kg
	Total nitrogen	73,259	kg
	Total phosphorous	7,781	kg
RECOVERY WRRF			
	Equipment, Piping, Fittings, and Valves		
CONSTRUCTION	Cast iron	2,995	kg
	Stainless steel	695	kg
	Aluminum	110	kg
	Copper	146	kg
	Rubber	110	kg
	200 kW generator	1	unit
	Polyvinyl chloride	442	kg
OPERATIONS (20 Years)	**Energy**		
	Generator operation	504	hours
	Water Emissions		
	Carbonaceous biochemical oxygen demand	17,260	kg
	Total nitrogen	73,259	kg
	Total phosphorous	7,781	kg
RESILIENCE WRRF			
	Equipment, Piping, Fittings, and Valves		
CONSTRUCTION	Cast iron	271	kg
	Stainless steel	99	kg
	Aluminum	16	kg
	Copper	18	kg
	Rubber	7	kg
OPERATIONS (20 Years)	**Energy**		
	Electricity	5,253,668	kwh
	Generator operation	504	hours
	Water Emissions		
	Carbonaceous biochemical oxygen demand	43,150	kg
	Total nitrogen	183,148	kg
	Total phosphorous	19,452	kg

Table B5 Normalized LCA values of the initial construction, recovery construction, and resilience construction for each case study

	Ozone Depletion (kg CFC -11 eq)	Global Warming (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogens (CTUh)	Non carcinogens (CTUh)	Respiratory Effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil Fuel Depletion (MJ Surplus)
Case 1 Embedded	4.87E-08	4.35E-06	5.24E-06	4.36E-06	1.11E-05	3.78E-04	1.35E-05	3.01E-06	4.92E-05	4.13E-06
Case 1 Recovery	2.77E-08	2.41E-06	2.88E-06	2.31E-06	6.12E-06	2.15E-04	7.88E-06	1.61E-06	2.88E-05	2.20E-06
Case 1 Resilience	1.48E-10	4.39E-09	1.69E-08	9.88E-09	7.34E-09	6.68E-08	8.29E-09	6.41E-09	2.10E-08	1.08E-08
Case 2 Embedded	1.66E-08	1.49E-06	1.70E-06	1.51E-06	4.58E-06	2.47E-04	6.75E-06	1.19E-06	2.77E-05	1.33E-06
Case 2 Recovery	2.05E-10	1.20E-08	1.93E-08	5.14E-08	2.01E-07	4.67E-06	6.71E-07	2.64E-08	1.82E-06	1.25E-08
Case 2 Resilience	2.64E-10	2.22E-08	2.93E-08	3.56E-08	1.17E-07	7.86E-06	2.70E-07	2.61E-08	9.81E-07	1.98E-08
Case 3 Embedded	5.20E-08	3.64E-06	4.24E-06	4.40E-06	1.06E-05	4.10E-04	1.88E-05	2.84E-06	5.52E-05	3.44E-06
Case 3 Recovery	3.31E-08	2.11E-06	2.43E-06	2.94E-06	6.51E-06	2.05E-04	1.34E-05	1.70E-06	3.34E-05	3.18E-06
Case 3 Resilience	6.09E-08	5.15E-06	5.93E-06	4.85E-06	1.23E-05	5.43E-04	1.57E-05	3.39E-06	6.14E-05	5.11E-06
Case 4 Embedded	4.01E-08	3.29E-06	4.25E-06	3.83E-06	1.20E-05	7.32E-04	1.99E-05	3.18E-06	8.29E-05	3.23E-06
Case 4 Recovery	1.54E-09	8.48E-08	1.41E-07	4.27E-07	1.69E-06	3.14E-05	5.80E-06	2.07E-07	1.54E-05	8.98E-08
Case 4 Resilience	3.09E-10	2.59E-08	3.02E-08	3.17E-08	9.61E-08	3.62E-06	1.93E-07	2.15E-08	6.17E-07	2.28E-08
Case 5 Embedded	2.09E-08	1.51E-06	2.33E-06	2.14E-06	5.70E-06	2.14E-04	1.16E-05	1.53E-06	3.76E-05	1.62E-06
Case 5 Recovery	1.88E-09	1.11E-07	1.72E-07	4.85E-07	1.92E-06	4.47E-05	6.43E-06	2.48E-07	1.75E-05	1.13E-07
Case 5 Resilience	4.48E-11	2.98E-09	4.14E-09	9.82E-09	3.89E-08	1.42E-06	1.23E-07	5.77E-09	3.59E-07	2.74E-09
Case 6 Embedded	3.24E-08	2.90E-06	3.48E-06	2.91E-06	7.42E-06	2.52E-04	9.17E-06	2.01E-06	3.32E-05	2.75E-06
Case 6 Recovery	2.78E-10	1.84E-08	2.02E-08	2.97E-08	1.30E-07	7.46E-06	2.87E-07	2.73E-08	1.07E-06	2.52E-08
Case 7 Embedded	5.57E-08	4.08E-06	4.75E-06	4.89E-06	1.36E-05	7.18E-04	2.59E-05	3.29E-06	9.19E-05	4.42E-06
Case 7 Recovery	2.02E-09	1.23E-07	1.87E-07	5.16E-07	2.03E-06	4.30E-05	6.71E-06	2.65E-07	1.80E-05	1.25E-07
Case 8 Embedded	4.02E-08	3.41E-06	3.92E-06	3.96E-06	1.16E-05	6.23E-04	2.17E-05	2.80E-06	7.82E-05	3.07E-06
Case 8 Recovery	3.79E-12	4.24E-10	4.36E-10	4.82E-10	2.57E-09	2.00E-07	4.14E-09	6.35E-10	2.07E-08	3.06E-10
Case 9 Embedded	6.89E-08	4.22E-06	5.00E-06	5.82E-06	1.33E-05	5.09E-04	2.68E-05	3.59E-06	7.16E-05	4.08E-06
Case 9 Resilience	2.75E-09	1.37E-07	3.43E-07	2.43E-07	5.53E-07	3.46E-05	8.46E-07	2.21E-07	3.84E-06	2.05E-07
Case 10 Embedded	1.12E-07	8.82E-06	1.05E-05	1.12E-05	3.31E-05	1.12E-03	7.19E-05	7.07E-06	2.21E-04	9.02E-06
Case 10 Resilience	1.80E-10	5.51E-09	2.31E-08	1.37E-08	9.82E-09	9.08E-08	1.07E-08	9.80E-09	2.71E-08	1.32E-08

Table B6 Historic flooding events between 2000-2018 for each case study

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Historic Flooding (2000 - 2018)	August 2018	June 2005	August 2002	N/A	May 2004	June 2003	May 2004	May 2004	July 2000	August 2002
		July 2010	January 2007		June 2005	June 2004	February 2007	October 2005	May 2004	
		September 2016	May 2007		June 2010	April 2005	June 2010	August 2007	April 2012	
		July 2018	May 2008-June 2008		August 2017	June 2006		June 2014		
			March 2010			June 2007		February 2007		
			June 2010-August 2010			June 2011		March 2010		
			April 2011-May 2011					June 2010		
			June 2011-September 2011							
			June 2014							
			May 2016							

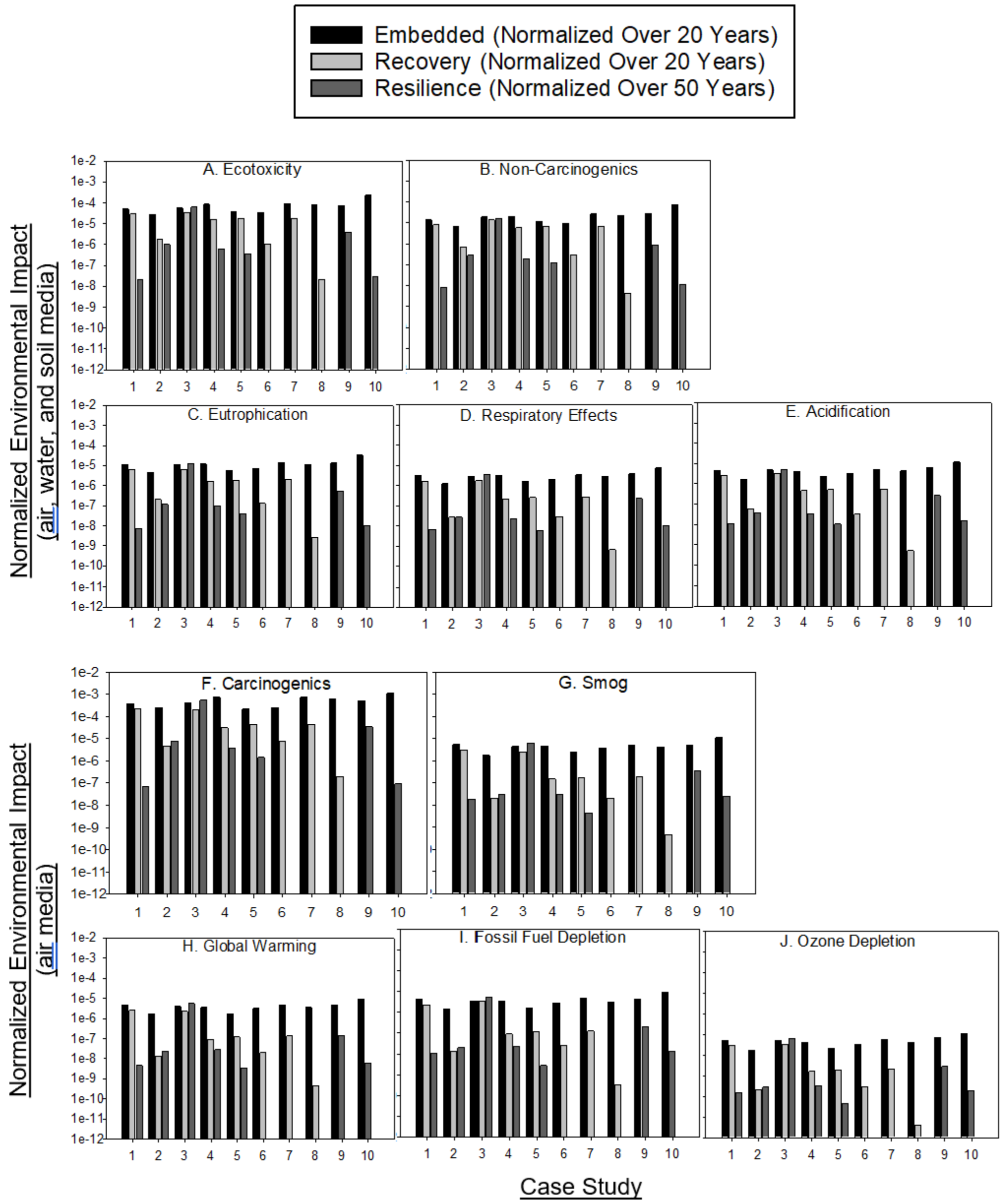


Figure B1 Normalized life cycle environmental impact of initial construction, construction related recovery, and construction related resilience for all case studies

APPENDIX C Supplemental Information: Environmental Life Cycle Assessment of a Novel Offshore Wind Energy Design Project: A United States Based Case Study

Table C1 Normalized life cycle environmental impact of the overall wind energy system for Novel Design and Conventional Design

		Installation & Transportation	Tower	Foundation	Submarine Cables & Offshore Substation	Operations & Maintenance	End of Life
Acidification (kg SO2 eq)	Novel Design	1.11E-08	2.29E-07	8.31E-08	1.19E-07	1.17E-09	7.39E-09
	Conventional Design	1.11E-09	2.29E-07	8.73E-08	1.19E-07	1.17E-09	2.03E-09
Ecotoxicity (CTUe)	Novel Design	1.74E-07	7.74E-06	1.88E-06	4.56E-06	1.59E-09	1.01E-08
	Conventional Design	1.50E-09	7.74E-06	3.72E-06	4.56E-06	1.59E-09	2.76E-09
Eutrophication (kg N eq)	Novel Design	2.56E-08	9.38E-07	3.07E-07	4.89E-07	8.48E-10	5.36E-09
	Conventional Design	8.02E-10	9.38E-07	4.63E-07	4.89E-07	8.48E-10	1.47E-09
Global warming (kg CO2 eq)	Novel Design	6.39E-09	1.08E-07	8.55E-08	2.03E-08	4.85E-10	3.06E-09
	Conventional Design	4.58E-10	1.08E-07	7.66E-08	2.03E-08	4.85E-10	8.39E-10
Carcinogenics (CTUh)	Novel Design	1.64E-06	4.03E-05	1.71E-05	6.29E-06	9.41E-09	5.95E-08
	Conventional Design	8.90E-09	4.03E-05	3.60E-05	6.29E-06	9.41E-09	1.63E-08
Non carcinogenics (CTUh)	Novel Design	3.62E-08	2.36E-06	4.19E-07	1.82E-06	5.53E-10	3.50E-09
	Conventional Design	5.23E-10	2.36E-06	7.46E-07	1.82E-06	5.53E-10	9.59E-10
Ozone depletion (kg CFC-11 eq)	Novel Design	1.14E-10	1.24E-09	8.37E-10	3.76E-10	1.34E-11	8.48E-11
	Conventional Design	1.27E-11	1.24E-09	6.86E-10	3.76E-10	1.34E-11	2.33E-11
Smog (kg O3 eq)	Novel Design	1.75E-08	1.41E-07	9.15E-08	3.71E-08	2.25E-09	1.42E-08
	Conventional Design	2.12E-09	1.41E-07	7.96E-08	3.71E-08	2.25E-09	3.89E-09
Fossil fuel depletion (MJ surplus)	Novel Design	8.52E-09	1.02E-07	6.74E-08	2.44E-08	9.76E-10	6.16E-09
	Conventional Design	9.21E-10	1.02E-07	5.52E-08	2.44E-08	9.76E-10	1.69E-09
Respiratory effects (kg PM2.5 eq)	Novel Design	6.79E-09	1.76E-07	7.85E-08	5.89E-08	2.81E-10	1.77E-09
	Conventional Design	2.65E-10	1.76E-07	1.15E-07	5.89E-08	2.81E-10	4.87E-10

Table C2 LCA breakdown showing each life cycle stage's contribution to the environmental impact of an offshore wind farm for selected LCA studies

Source	System	LCA General Breakdown
Bonou et al., 2016	Offshore Wind (2 - 6 MW turbines)	Materials 46% - 100% Manufacturing 1% - 30% Installation 1% - 27% Operation 1% - 2% Dismantling 1% - 22% End of Life 1% - 16%
Huang et al., 2017	Offshore wind farm (2 MW turbines)	Production 40.8% Installation 31.3% Operations and maintenance 12.7% End of life 15.3%
Yang et al., 2018	Offshore wind farm (5 MW turbines)	Foundation 39% Turbine 31% Transportation and installation 14% Decommissioning and recycling 7% Operations and maintenance 6% Cable and transformer 3%

Table C3 GHG emissions per functional unit for selected renewable and nonrenewable energy system studies

Source	System Type	System Size/Power Rating	Reported Values (GHG Emissions Related)
Varun et al., 2009	Renewable - Offshore & Onshore Wind farm	3 - 9,000 kW	9.7 - 123.7 gCO2/kWh
Varun et al., 2009	Renewable - Solar	3 - 2,500 kW	53.4 - 250 gCO2/kWh
Varun et al., 2009	Renewable - Thermal	1 - 100 MW	13.6 - 202 gCO2/kWh
Varun et al., 2009	Renewable - Biomass	80 - 509 MW	35 - 178 gCO2/kWh
Varun et al., 2009	Renewable - Hydro	3.2 - 4,000 MW	3.7 - 237 gCO2/kWh
Varun et al., 2009	Nonrenewable - Coal	-	975.3 gCO2/kWh
Varun et al., 2009	Nonrenewable - Oil	-	742.1 gCO2/kWh
Varun et al., 2009	Nonrenewable - Gas	-	607.6 gCO2/kWh
Varun et al., 2009	Nonrenewable - Nuclear	-	24.2 gCO2/kWh
Esteban et al., 2011	Nonrenewable - Coal	-	964 tCO2/GWh
Esteban et al., 2011	Nonrenewable - Oil	-	726 tCO2/GWh
Esteban et al., 2011	Nonrenewable - Gas	-	484 tCO2/GWh
Esteban et al., 2011	Nonrenewable - Nuclear	-	8 tCO2/GWh
Esteban et al., 2011	Renewable - Wind	-	7 tCO2/GWh
Esteban et al., 2011	Renewable - Photovoltaic	-	5 tCO2/GWh
Esteban et al., 2011	Renewable - Large Hydro	-	4 tCO2/GWh
Bonou et al., 2016	Onshore Wind farm	2.3 - 113 MW	5-6 gCO2/kWh
Bonou et al., 2016	Offshore Wind farm	4.0 - 154 MW	7.8 - 10.9 gCO2/kWh
Dolan, 2007	Wind farm	1.8 MW	24 kg CO2eq/MWh
Chipindula et al., 2018	Offshore wind farm	5 MW	6 - 9 kg CO2eq / kWh
Chipindula et al., 2018	Onshore wind farm	1-2 MW	5 - 7 kg CO2eq / kWh
Noori et al., 2015	Onshore and Offshore wind farms (literature review of 8 studies)	2-3 MW	5 - 8 GHG emissions/kWh
Nian et al., 2019	Offshore Wind farm (literature review of 12 studies)	< 5 MW	494 - 2,995 kgCO2eq/kW

Table C4 Contribution of the end of life stage to the total life cycle environmental impact of the case study

Impact Category	End of Life Scenario	End of Life Fraction of Total Life Cycle Environmental Impact
Acidification (kg SO2 eq)	Scenario 1	1/100
	Scenario 2	1/500
Ecotoxicity (CTUe)	Scenario 1	7/10,000
	Scenario 2	1/10,000
Eutrophication (kg N eq)	Scenario 1	3/1,000
	Scenario 2	1/2,500
Global Warming (kg CO2 eq)	Scenario 1	1/100
	Scenario 2	1/500
Carcinogenics (CTUh)	Scenario 1	9/10,000
	Scenario 2	1/10,000
Non Carcinogenics (CTUh)	Scenario 1	7/10,000
	Scenario 2	1/10,000
Ozone Depletion (kg CFC-11 eq)	Scenario 1	3/100
	Scenario 2	1/250
Smog (kg O3 eq)	Scenario 1	1/25
	Scenario 2	7/1,000
Fossil Fuel Depletion (MJ surplus)	Scenario 1	1/50
	Scenario 2	1/250
Respiratory Effects (kg PM2.5 eq)	Scenario 1	1/200
	Scenario 2	1/1,250

APPENDIX D Supplemental Information: Treated Wastewater Reuse for Non-Direct Food Consumption Crops in Nebraska: Barriers and Benefits of Municipal Irrigation Lagoons Video Script

The short video will feature informative narration about irrigation lagoons, as well as testimonials and experiences from wastewater operators, agricultural producers and community leaders that currently work with irrigation lagoons. Agricultural producers and landowners that have questions about irrigation lagoons and want to learn more about them can use this video as a resource, in addition to the NebGuide developed. The video script is provided below.

Section	Audio	Visual	Narrator
Introduction	(hold a few seconds). Wastewater treatment plants help protect and maintain public health.	Introduction/Title Slide. Fade out.	Sussan
	Although the main function of a wastewater treatment plant is to treat wastewater, these systems also recover valuable resources such as energy, nutrients, biosolids, and water.	Flash picture of energy, nutrients, biosolids, and water.	Sussan
	Many areas of the world, especially deveoping and arid regions, have long been recovering and reusing wastewater, particularly for irrigation purposes.	Film a system in operation that is irrigating (if possible).	Sussan
	Researchers from the University of Nebraska - Lincoln have found that reusing treated wastewater for agricultural purposes in small, rural communities in the United States can have many local advantages, such as reduced costs, and lower labor and maintenance requirements.	Flash logos for UNL & Water for Food.	Sussan
	Irrigation lagoons are a specific type of wastewater treatment technology. These systems have the capability to apply treated wastewater onto cropland, instead of discharging the treated wastewater to a nearby water body or indefinitely storing the treated wastewater until it evaporates.	Flash title slide for "irrigation lagoons." Fade out.	Sussan
	In Nebraska, irrigation lagoons apply treated wastewater onto non-direct food consumption crops, which means that the crops irrigated with the treated wastewater are not directly consumed by humans.	Video of cropland.	Sussan
	The treatment process for irrigation lagoons begins with influent wastewater flowing by gravity or being pumped from the municipality to the lagoon site where it can undergo preliminary treatment, if applicable. The wastewater then enters the lagoon cells, where it remains for a specified detention time based on design factors, treatment requirements, and amount of wastewater. The lagoon is able to treat wastewater naturally by using bacteria to metabolize organic matter. The wastewater exits the lagoon cells in three major ways: evaporation, seepage through the liner, and in the case of irrigation lagoons, land application onto nearby agricultural land.	Walk through this process at one of the sites. A quick "tour" of the system. Sussan voiceover while system is shown.	Sussan
	Lagoon wastewater treatment systems are generally implemented in small, rural communities. Major reasons for implementing irrigation lagoons include converting from a mechanical wastewater treatment system, avoiding expansion of an existing discharge or complete retention lagoon wastewater treatment system, reducing operator labor requirements, and avoiding discharge permits.	"Reasons for implementation" title slide. Fade out to Sussan introducing the topic.	Sussan
Testimonials	Question: Why did you implement an irrigation lagoon?	Sussan asks questions. Operator responds to question. For this question, an example response is: "The existing lagoon was expanded in 1980 to add irrigation. Our town was growing, so to avoid permitting requirements, we increased the capacity by adding irrigation capabilities."	Sussan & Operator
	There are many barriers that can limit the success of irrigation lagoons in small communities. These include climate/seasonal variability, nearby land availability, finding willing landowners and agricultural producers, public perceptions of odors and groundwater contamination, and a community's optimism for growth.	"Barriers to implementation" title slide. Fade out to Sussan introducing the topic.	Sussan
	Question: What do you see as the biggest barriest to implementation?	Sussan asks questions. Operator responds to question. For this question, an example response is: "Buying the land for the lagoons can be difficult. Finding willing farmers to work with can be difficult because they have concerns with the effects on their crops."	Sussan & Operator
	Ownership structures for these systems are important to both the community and agricultural producer/landowner. In general, the city pays for piping to cropland, center pivot and maintenance, pumping electricity, and soil and water monitoring. The agricultural producer receives free water. These structures are set in place in one of three ways: most commonly agreements between landowner and city, landowner sells to city, or rarely eminent domain	"Ownership structures" title slide. Fade out to Sussan introducing the topic.	Sussan
	Questions: What is the ownership/financial structure for your system, or in other words, who pays for what?	Sussan asks questions. Operator responds to question. Farmer responds to question. For this question, an example response is: "The cropland is owned by a private landowner, and there is a long-term lease agreement between the city and landowner for the city to be able to irrigate onto the cropland. The city pays for maintenance on the infrastructure, and the farmer receives free water."	Sussan, Operator, Farmer
	Although irrigation lagoons essentially provide free water to agricultural producers, agricultural practices and cropland can still be affected. Major agricultural concerns include crop yields, potential salinity issues, and land valuations.	"Agricultural issues" title slide. Fade out to Sussan introducing the topic.	Sussan
	Question: What are the major agricultural concerns with these systems? What are the benefits to you as an agricultural producer?	Sussan asks questions. Farmer responds to question. For this question, an example response is: "Salinity is the biggest agricultural issue. It has started to show up in soil tests after about 10 years of the system operating. As long as we monitor it, it's okay. The benfit to me as an agricultural producer is free water."	Sussan, Farmer
Conclusion	Even though irrigation lagoons have vast environmental, economic, and social benefits, it is oftentimes difficult to implement these systems in the US because of limited agricultural producer and landowner cooperation. A better understanding of the reasoning behind implementation, barriers to implementation, ownership and financial structures, and agricultural impacts can help alleviate some concerns.	Flash "irrigation lagoons: a summary." Fade out.	Sussan
	Additional information on this topic may be found online in NebGuide (#) titled, "Treated wastewater reuse for non-direct food consumption crops in Nebraska: barriers and benefits of municipal irrigation lagoons."	Provide QR code/link for NebGuide (will provide at a later date once published).	Sussan
	-	Acknowledgements flash on screen.	-

APPENDIX E Supplemental Information: Treated Wastewater Reuse for Non-Direct Food Consumption Crops in Nebraska: Barriers and Benefits of Municipal Irrigation Lagoons NebGuide

This NebGuide discusses barriers and benefits of reusing treated wastewater from municipal lagoon systems for agricultural irrigation onto crops that are not directly consumed by humans. These systems have many benefits for small Nebraska communities. This NebGuide provides information and guidance for agricultural producers and cropland owners.

Introduction to Wastewater Reuse

The US Environmental Protection Agency (EPA) defines water reuse as "the practice of reclaiming water from a variety of sources, treating it, and reusing it for beneficial purposes." Agricultural water reuse specifically, is defined by the US EPA as treated wastewater that is applied to cropland. Reusing treated wastewater for agricultural purposes in small, rural communities provides local benefits such as reduced wastewater treatment costs and lower operations and maintenance requirements. Wastewater treatment plants (WWTP) help protect and maintain public health. Although the main function of a WWTP is to treat wastewater, these systems can also recover valuable resources such as water, energy, nutrients, and biosolids. Many countries, especially developing and arid countries, have long been recovering and reusing wastewater for irrigation purposes. In the US, there are no regulations for wastewater reuse at the federal level, although guidelines have been developed and made available to states. Therefore, each individual state can implement regulations or guidelines for wastewater reuse, as desired. Furthermore, there is a need for more federal funding of reuse projects, to continue encouraging wastewater reuse.

Irrigation Lagoons

Lagoon wastewater treatment systems are one of the most common technologies used for wastewater treatment worldwide. Lagoons treat wastewater naturally by using bacteria to metabolize organic matter. Lagoons are commonly used in small, rural communities of less than 3,000 people, where limited funding and resources are available for constructing and operating wastewater infrastructure. These smaller communities often struggle with maintaining qualified staff to operate WWTPs. Additionally, these systems tend to be implemented in areas where land is commonly and readily available, and where evaporation exceeds precipitation on an annual basis. Furthermore, small, rural communities often struggle with aging and inadequate WWTPs, and many of these systems will require improvements or replacements in the coming years to meet evolving treatment requirements and permit limits. It is important to clarify that municipal lagoon wastewater treatment systems, which are the focus of this guide, are regulated, designed, and operated differently than residential onsite wastewater treatment lagoons (i.e., decentralized systems that are not connected to a municipal system). Irrigating with water from a residential onsite wastewater treatment lagoon is currently not allowed in Nebraska. Further information regarding residential onsite wastewater treatment lagoons is covered in the NebGuides Residential Onsite Wastewater Treatment: Lagoon Design and Construction (G1441) and Residential Onsite Wastewater Treatment: Lagoon Maintenance (G1423).

Irrigation lagoons are a specific type of complete retention lagoon wastewater treatment technology. Irrigation lagoons have the capability to apply treated wastewater, which is considered to be the final discharge of the wastewater treatment lagoon, onto

cropland rather than discharging the treated wastewater to a nearby water body (i.e., controlled or continuous discharge lagoons) or indefinitely storing the treated wastewater until it evaporates (i.e., complete retention lagoons without irrigation capabilities). Irrigation lagoons, as referred to in this guide and in Nebraska, apply the treated wastewater onto crops that are not directly consumed by humans, such as feed crops, fiber crops, and industrial crops. There are two main ways that irrigation lagoons are used in Nebraska. First, cities or agricultural producers may use the treated wastewater alone to irrigate their cropland. This is most common when a city is irrigating nearby pasture or grassland. Second, agricultural producers may use a hybrid irrigation system, where the treated wastewater is applied to the cropland, but additional irrigation sources (e.g., groundwater wells) are available for supplemental irrigation purposes. This hybrid irrigation system is more common in Nebraska, as the treated wastewater alone generally does not meet all of the agronomic needs, which depend on factors such as seasonal variability.

Generally, when faced with the challenge of meeting updated treatment requirements, small, rural communities with existing wastewater treatment systems have two options: convert to a more advanced mechanical system or expand an existing lagoon system. However, irrigation lagoons can provide a third alternative that can be cheaper to construct and operate, have lower operational and labor requirements, and have less environmental impacts, compared to mechanical systems and expanded lagoons. Detailed requirements for land applying treated domestic wastewater in Nebraska are available through the Nebraska Department of Environment and Energy (NDEE) in the Guidance for Land Application Discharges of Treated Domestic Wastewater.

Understanding the Underutilization

Wastewater reuse systems for irrigation are not common in the US due to limited guidance and regulations, public acceptance, and system knowledge. Small, rural communities are often limited in terms of funding and resources available to help identify wastewater treatment best practices. Additionally, engineers working with communities typically do not have the time or funding to analyze case studies and educate every curious stakeholder about projects.

Another major implementation challenge for small, rural communities is obtaining agricultural producer and landowner cooperation. Although eminent domain (i.e., the power of the government to take private property) is an option available to communities looking to implement irrigation lagoons, many communities consider this a last resort to avoid community disruption. This NebGuide provides information that addresses common questions and concerns about irrigation lagoons to help agricultural producers and landowners feel more comfortable with the system and become more engaged in the initial decision-making process.

Reasons for Implementation

Irrigation lagoons are implemented in small, rural communities for various reasons and typically involve, to some extent, multiple stakeholders in the decision-making process as shown in Figure E1. The main reasons for implementing an irrigation lagoon system are to convert from a mechanical system or to avoid or limit the expansion of an existing lagoon system to move away from National Pollutant Discharge Elimination System (NPDES) permit requirements. Converting a mechanical WWTP to a lagoon system can be a result of old infrastructure and equipment, labor and operational

costs, challenges with discharge compliance, shrinking populations, inflow and infiltration, and funding eligibility. Communities may consider expanding an existing lagoon if their population is growing. However, avoiding the expansion of an existing lagoon by adding irrigation capabilities can reduce land requirements and construction impacts.

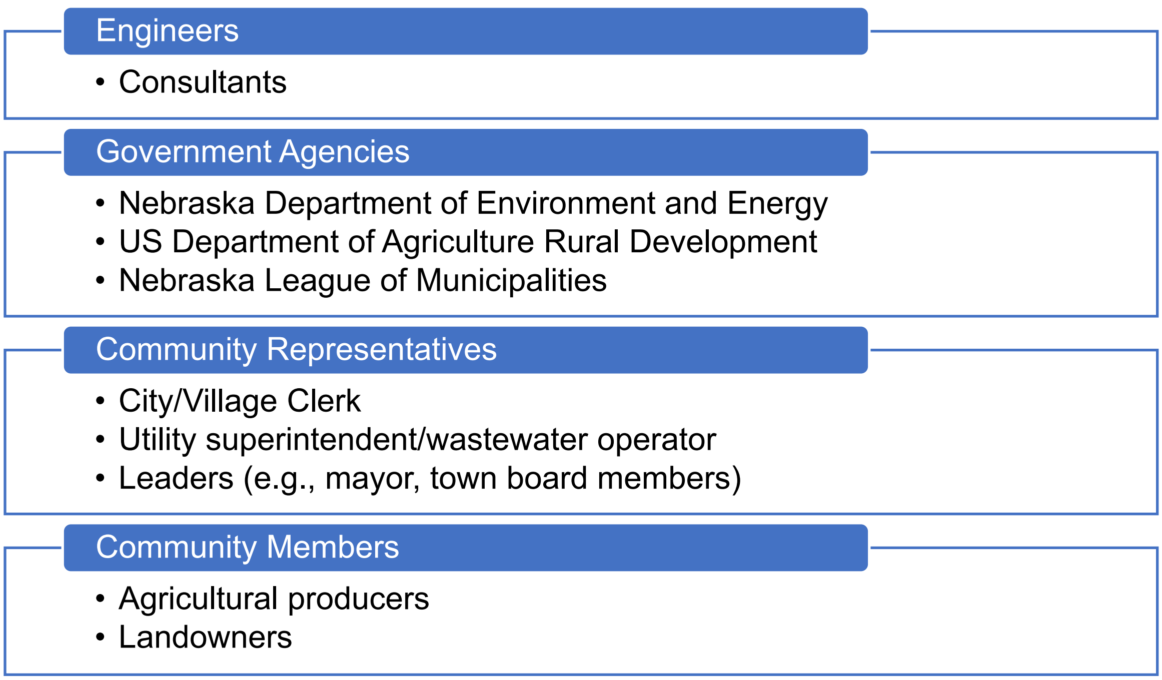


Figure E1 Major stakeholders involved with irrigation lagoons as observed in Nebraska

Many impacts can be avoided by implementing irrigation lagoons, including operator time and labor requirements, as well as discharge permit requirements. In Nebraska, there is no need to obtain an NPDES permit for an irrigation lagoon, as it is considered to be non-discharge and Authorized by Rule (Nebraska Administrative Code Title 119 Chapter 12). There is also a reduced land footprint for irrigation lagoons compared to some other lagoon systems, which results in lower construction and

materials costs, and thus lower environmental impacts of construction. Table E1 summarizes the reasons for implementation and avoided impacts associated with irrigation lagoons.

Table E1 Reasons for implementation and avoided impacts of irrigation lagoons

Reasons for Implementation	• Convert from mechanical system o Old infrastructure o High operational costs o Evolving permitting requirements o Shrinking populations o Inflow & infiltration o Funding constraints • Avoid expanding an existing lagoon o Growing populations
Avoided Impacts	• Operator time and labor o Reduced requirements compared to a mechanical plant • Discharge permits • Land footprint o Reduced land area requirements for lagoon o Lower economic and environmental impacts of construction

Barriers to Implementation

There are many barriers that can hinder irrigation lagoon success in small communities. The most common barriers to implementation include variability of the climate, availability of land nearby, and willingness of potential landowners and tenant agricultural producers. Climate (or seasonal) variability is a significant and common barrier amongst communities considering irrigation lagoons because it is difficult to meet the needs of both the city and the agricultural producer simultaneously. Agricultural producers prefer to receive water during dry times when their crops need water, whereas cities must dispose of water from the lagoons during wet times to avoid overflow. However, during dry years when the demand for irrigation is highest, the availability of

treated wastewater may be lower due to high evaporation rates and limited inflow. Therefore, irrigation lagoons are a good alternative under the right climatic conditions.

Economic costs can also be a major implementation barrier. The economic costs of purchasing cropland to irrigate onto and installing piping, a pump, and a pivot to pump water to the cropland can become substantial when having to pump long distances. However, if ideally located, irrigation lagoons have been found to have reduced treatment costs compared to mechanical systems because they do not have to meet the rigorous discharge treatment requirements that mechanical systems must. Additionally, if the irrigation lagoon is located near the receiving cropland, lower energy usage is required to operate the system, leading to reduced energy costs and environmental impacts associated with energy usage.

Additional implementation barriers include public perception, odor concerns, groundwater contamination, and a town's potential optimism for growth. The public is generally most concerned with odors when converting from a mechanical system to a lagoon system, but these concerns tend to subside once the lagoon becomes operational. The public may also be concerned about the potential for groundwater contamination due to seepage. However, geography and soil types are major considerations in the design and planning stages of irrigation lagoons to ensure groundwater is protected. Lastly, communities may feel that implementing an irrigation lagoon limits their ability to grow in population. Regarding public perception, acceptance of wastewater reuse increases if non-food crops are irrigated, and in areas with high crop demands and low water supplies.

Engineers have expressed concerns with potential water rights challenges. For example, a mechanical WWTP discharges effluent into nearby water bodies. If a community converts their mechanical WWTP to an irrigation lagoon, there will no longer be a discharge. However, the amount of effluent being added to the water body from a small mechanical WWTP is often a small component of the stream flow. It is recommended that communities in water scarce regions consider potential water rights challenges. In dry regions, a number of water rights feuds may actually be resolved, as surface water and groundwater irrigation withdrawals can be replaced or supplemented with treated wastewater.

There is also a lack of knowledge regarding these systems, which has led to underutilization in Nebraska and the US compared to the rest of the world. This is partially due to the exclusion of landowners and agricultural producers in the decision-making process for irrigation lagoons, which limits their knowledge and acceptance of such systems due to safety concerns and fear of risk. Agricultural producers and landowners should be included in the initial decision making, along with the city officials, engineers, the public, and wastewater operators. To help with inclusion, this guide aims to ensure that landowners and agricultural producers have a reliable way to gather information about these systems so that they may feel comfortable having a more active role in public meetings and decision-making.

In addition to helping identify implementation barriers, suggestions for overcoming these barriers are provided. These suggestions include explaining the details of these systems to the public during public meetings to help resolve concerns, researching the system and talking with agricultural producers currently using the system,

and building and maintaining trust between stakeholders within a community. Table E2 summarizes the implementation barriers and concerns for irrigation lagoons.

Table E2 Implementation barriers for irrigation lagoons

<table>
<tr><td>Barriers</td><td>

Climate/seasonal variability

Dry years

Agricultural producers have a high irrigation water demand
Municipal wastewater lagoon has a low water supply

Wet years

Municipal wastewater lagoon has a high water supply
Agricultural producers have a low irrigation water demand

Nearby land availability

Purchasing cropland can become expensive if there are few landowners willing to accept the system
Piping and pumping costs increase as the distance between the lagoon and receiving cropland increases

Nearby land reduces energy usage and costs

Reduced energy usage results in less environmental and economic impact from energy use

Willing landowners/agricultural producers

Lack of system knowledge
Limited access to streamlined information
Limited involvement in decision making process

</td></tr>
<tr><td>Concerns</td><td>

Odors
Groundwater contamination
Optimism for town growth
Public acceptance

Non-food crops (acceptance increases if non-food crops are irrigated rather than food crops)
Crop and water security (acceptance increases in areas with high crop demands and low water supply)

Water rights

Eliminate a discharge to a nearby water body

</td></tr>
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Lagoon and Irrigation System Ownership Structures

Ownership structures for each element of this system are important to both the community and the agricultural producer/landowner. The ownership and financial management structure of irrigation lagoons are similar across communities in Nebraska. Typically, the city pays for piping to the cropland, the center pivot (unless the agricultural

producer owns one), center pivot maintenance, pumping, and soil and water monitoring. In some communities, agricultural producers pay for their own pumping electricity and center pivot maintenance. However, in general, the treated wastewater is essentially free water for the agricultural producer.

Cropland for the application of reused wastewater is generally obtained in one of three ways: 1) most commonly through a long-term agreement between a willing landowner and the city, 2) through a city purchase, or 3) very rarely through eminent domain. Long-term agreements are required by the NDEE funding agency. In these agreements, landowners and/or agricultural producers operate the pivot according to crop needs. In contrast, if the land is acquired by the city, then the city operates the system with the main objective being to keep from discharging to surface waters. Landowners are generally more hesitant to accept the water compared to the tenant agricultural producers. This is because agricultural producers generally accept that free water is a valuable commodity. In general, agricultural producers are willing to irrigate with treated wastewater as long as it is economically beneficial. Funding opportunities may be available to communities interested in reuse. For example, the US Department of Agriculture Rural Development provides funding to states and local government entities for the acquisition, construction, or improvement of wastewater treatment systems, and the NDEE Clean Water State Revolving Fund provides funding to small communities for wastewater improvements, which can be combined with other federal and state funds.

Once the land is obtained, agreements related to system benefits between a landowner, city, and tenant agricultural producer, as applicable, are made, emphasizing the importance of building and maintaining trust within communities. Typically, long-

term (duration of funding) lease agreements are made between the city and the landowner. Landowners and tenant agricultural producers oftentimes have a verbal and/or informal agreement. This is to avoid overpromising the unknown, such as nutrient benefits, water availability, and maintenance support. By creating informal/verbal agreements, landowners and tenant agricultural producers can realize the uncertainty and variability of these systems, so as to not create false hope. Table E3 summarizes the common ownership and financial management structures related to irrigation lagoons.

Table E3 Common ownership structures of irrigation lagoons

Payment	• City pays for:
	  ○ Piping to cropland
	  ○ Center pivot and maintenance (unless agricultural producer already owns one)
	  ○ Pumping electricity
	  ○ Soil and water monitoring
	• Agricultural producer receives:
	  ○ Free water

Leasing or Acquiring Land	• Long-term (duration of funding) lease of the property to the city
	  ○ Required by NDEE funding agency
	  ○ Landowner/agricultural producer operates pivot
	• Landowner sells to city
	  ○ City operates pivot
	• Eminent domain (rare)

Issues Related to Agricultural Practices and Cropland

Agriculture practices and cropland can be affected by irrigation lagoon implementation. Agricultural producers have noticed that treated wastewater has little nutrient value due to effective wastewater treatment processes. Thus, similar crop yields can generally be observed between cropland irrigated with treated wastewater and cropland irrigated with traditional irrigation water sources. However, if the cropland was previously dryland/rainfed, then increased crop yields can be expected from applying the treated wastewater, although the increase in yield relies heavily on the climate dependent

supply and demand of treated wastewater. It should be noted that other regions in the world may find yield benefits when applying treated wastewater to their cropland. For example, agricultural producers in Italy, Spain, Tunisia, and Brazil all experienced higher crop yields when irrigating with treated wastewater.

Another common agricultural concern is long term sodium build up in soils, which may lead to additional costs incurred from having to neutralize cropland with chemicals. Some studies have found that there are generally no long-term salinity or nutrient related consequences due to the low amount of both in the treated wastewater used for irrigation, whereas others have found that wastewater irrigation can lead to long-term salinization. To avoid long term consequences of salinity, engineers should ensure that irrigation lagoons are sized properly to limit evaporation and maximize salt-free rainfall capture, as freshwater blending can reduce salinity. Additionally, agricultural producers should consider alternative irrigation methods such as cyclical irrigation or blending interventions. Cyclical irrigation methods use treated wastewater in conjunction with freshwater sources. Blending interventions could be done if multiple willing landowners rotated between receiving treated wastewater and using traditional water sources for irrigation. Alternative crop selections that are more resistant to salinity consequences may also be of interest to agricultural producers. Lastly, it is crucial that agricultural producers monitor and analyze the soils and crops to adequately manage any salt build up. Further information about water quality criteria for irrigation is covered in the NebGuide Water Quality Criteria for Irrigation (EC782).

Cropland value is an important consideration for landowners and tenant agricultural producers. Agricultural producers generally consider cropland where treated

wastewater is applied, although irrigated, to be less valuable compared to a system with surface or groundwater rights. This is because the agricultural producers do not have the ability to control their irrigation water usage or have a continuous source of water with only the treated wastewater supply. Thus, many agricultural producers choose to supplement their existing irrigation source with the treated wastewater to account for seasonable variabilities.

Irrigated cropland is known to be more valuable economically compared to dryland cropland. The state of Nebraska generally views cropland irrigated with treated wastewater as irrigated cropland for assessment purposes, which increases the value of the land. However, there may be an opportunity for lower assessment values for landowners converting from dryland to semi-irrigated land (i.e., land that is irrigated solely with treated wastewater), as this may not be considered a continuous water source because supplemental irrigation is not used. In addition, semi-irrigated land does not receive the same agronomic benefit as fully irrigated cropland due to it not having the full agronomic application of water. This information may be useful to landowners and tenant agricultural producers who wish to explore their current assessment values. Table E4 summarizes the agricultural impacts of irrigation lagoons.

Table E4 Agricultural impacts of irrigation lagoons

<table>
<tr><td>Agricultural Impacts</td><td>

Crop yields

Low nutrient values in treated wastewater
Yield can increase if converting from dryland/rainfed to irrigated (with treated wastewater) cropland
Larger treated wastewater supply results in larger yield increase

Salinity

Limited long-term consequences
Proper lagoon sizing
Maximize rainfall capture
Limit evaporation
Encourage freshwater mixing
Cyclical irrigation practices
Combine treated wastewater and freshwater sources
Blended irrigation practices
Multiple landowners rotate between receiving treated wastewater and using traditional water sources
Alternative crop selection
Monitor and analyze soils, crops, and water

Free water for agricultural producers

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<tr><td>Land Value</td><td>

Non-continuous water supply

Difficult to align supply and demand of treated wastewater with seasonal variability
Supplemental freshwater resources are generally needed

Higher economic value compared to dryland cropland
Opportunity to explore assessment values

Non-continuous water supply
Potential to classify as non-irrigated cropland

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</table>

Summary

This NebGuide provides streamlined information for those curious about irrigation lagoons. Although irrigation lagoons are known to have vast benefits in terms of environmental, economic, and social impacts, it is oftentimes difficult to implement these systems due to limited agricultural producer and landowner cooperation. A better understanding of the reasoning behind implementation, barriers to implementation,

ownership and financial structures, and agricultural impacts can help alleviate some concerns.

APPENDIX F Supplemental Information: Sustainability Assessments of Critical Civil Infrastructure Systems: A Mini-Review and Project Synthesis

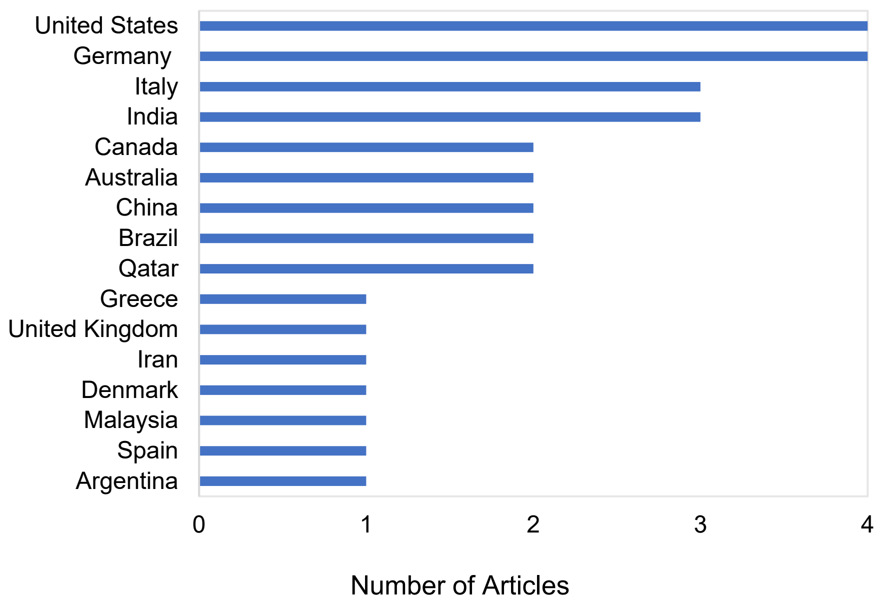

Figure F1 Location distribution of articles reviewed

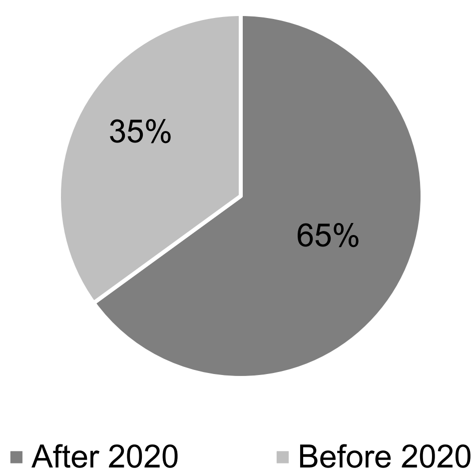

Figure F2 Time distribution of articles reviewed

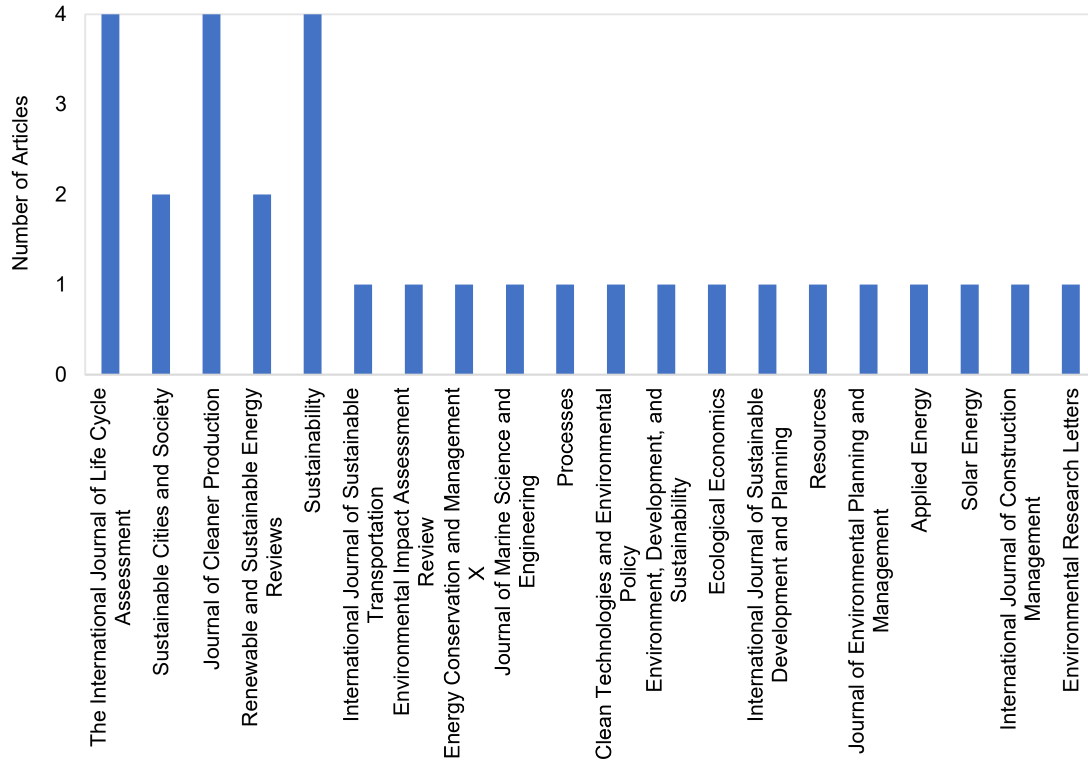

Figure F3 Journal distribution of articles reviewed

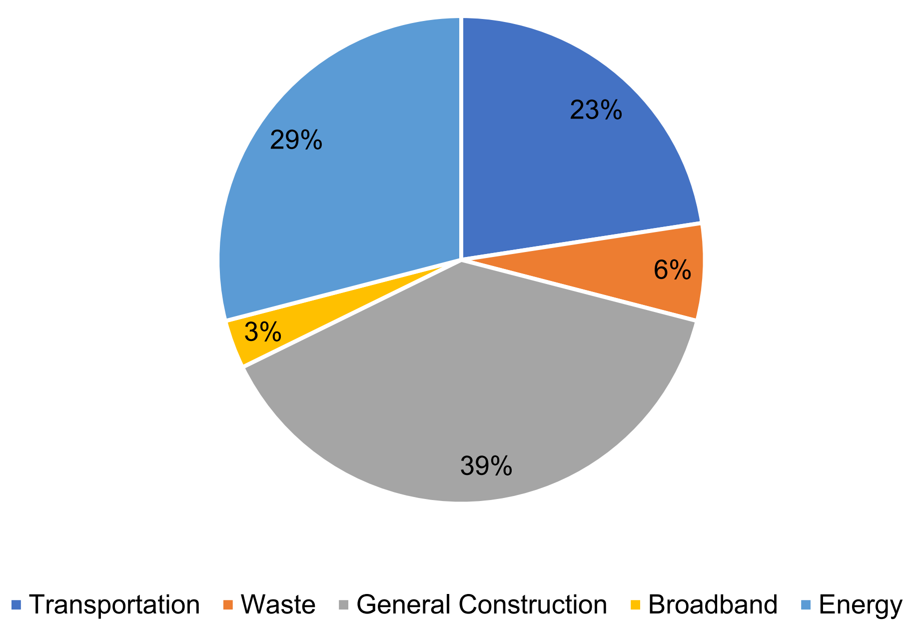

Figure F4 Critical civil infrastructure system distribution of articles reviewed

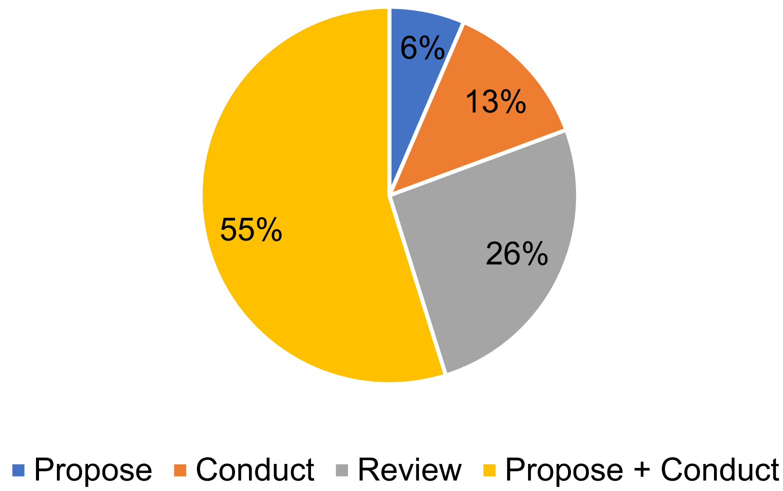

Figure F5 Goal distribution of articles reviewed

Table F1 Literature Review of life cycle sustainability assessments focused on critical civil infrastructure systems

Citation	Environmental Sustainability Methods	Economic Sustainability Methods	Social Sustainability Methods	Holistic Sustainability Methods	Study Location	Infrastructure System Studied	Article Goal	Journal
Aboushaqrah et al., 2022	LCA	LCC	SLCA	Hybrid LCSA, MCDM	Qatar	Transportation	Propose, case study	International Journal of Sustainable Transportation
Aleisa and Al-Jarallah, 2018	LCA		indicators	AHP TBL approach, weighting, composite sustainability index	Germany	Waste	Propose, case study	The International Journal of Life Cycle Assessment
Alejandrino et al., 2021	LCA	LCC	SLCA	LCSA, AHP, weighted average	Argentina	General Construction, Energy, Transportation, Waste	Review	Environmental Impact Assessment Review
Alramadhan et al., 2022	LCA	net present value	SLCA, stakeholder perspectives of indicators	weighting, composite sustainability index	Germany	Transportation	Propose, case study	The International Journal of Life Cycle Assessment
Al-Yafei et al., 2022	LCA	LCC	SLCA	LCSA, TBL	Qatar	Energy	Propose, case study	Energy Conservation and Management X
Amerson et al., 2022	LCA	LCC	indicators	N/A	United States	Energy	Review	Journal of Marine Science and Engineering
Backes and Traverso, 2021	LCA	LCC	SLCA	LCSA, AHP, weighting	Germany	General Construction	Propose	Processes
Batuecas et al., 2021	LCA	LCC	N/A	N/A	Spain	Energy	Case study	Clean Technologies and Environmental Policy
Bhyan et al., 2022	LCA	LCC	SLCA	MCDM	India	General Construction	Review	Environment, Development, and Sustainability
Costa et al., 2022	LCA	LCC	SLCA	LCSA, MCDM, AHP	Brazil	Waste	Review	The International Journal of Life Cycle Assessment
D'Adamo et al., 2020	N/A	N/A	N/A	AHP-MCDA	Italy	Energy	Propose, case study	Ecological Economics
Dinh and Götze, 2020	LCA	LCC	SLCA	LCSA, AHP, Likert Scale	Germany	General Construction	Propose, case study	International Journal of Sustainable Development and Planning
Dong et al., 2023	LCA, indicators	LCC	SLCA, indicators, risk and performance assessment	LCSA, MCDA	China	General Construction	Review	Sustainable Cities and Society
Ferrari et al., 2019	LCA	LCC	SLCA	LCSA	Italy	General Construction	Propose, case study	Resources
Francis and Thomas, 2022	indicators	LCC	indicators	dynamic LCSA	India	General Construction	Propose, case study	Sustainable Cities and Society
Goh et al., 2020	LCA	LCC	SLCA	N/A	Malaysia	General Construction	Review	Journal of Cleaner Production
Govindan et al., 2016	indicators	indicators	indicators	hybrid MCDM	Denmark	General Construction	Propose, case study	Renewable and Sustainable Energy Reviews
Hashemi et al., 2021	indicators	indicators	indicators	ranking, MCDM	Iran	Transportation, General Construction	Propose, case study	Sustainability
Hoque et al., 2020	LCA	LCC	SLCA	LCSA	Australia	Energy, Transportation	Case study	Sustainability
Hossaini et al., 2015	LCA	LCC	SLCA	AHP	Canada	General Construction	Propose, case study	Journal of Environmental Planning and Management
Khan et al., 2022	indicators	indicators	indicators	AHP, weighting	Italy	General Construction	Case study	Sustainability
Li et al., 2018	LCA	LCC	SLCA	Weighting, ranking	United Kingdom	Energy	Propose, case study	Applied Energy
Naves et al., 2019	N/A	LCC	N/A	N/A	Brazil	Energy	Review	Solar Energy
Onat et al., 2014	LCA	LCC	SLCA	LCSA	United States	Transportation	Propose, case study	Sustainability
Onat et al., 2016a	LCA	LCC	SLCA	LCSA, MCDM	United States	Transportation	Propose	Journal of Cleaner Production
Onat et al., 2016b	indicators	indicators	indicators	LCSA	United States	Transportation	Propose, case study	The International Journal of Life Cycle Assessment
Patel and Ruparathna, 2021	LCA	LCC	SLCA	BIM based LCSA	Canada	Transportation	Propose, case study	International Journal of Construction Management
Ren and Lützen, 2017	N/A	N/A	N/A	MCDM	China	Energy, Transportation	Propose, case study	Renewable and Sustainable Energy Reviews
Romanovska et al., 2023	LCA	CBA	indicators	life cycle thinking approach	Australia	General Construction	Review	Environmental Research Letters
Shrivastava and Unnikrishnan, 2021	LCA	LCC	SLCA	LCSA	India	Energy	Case study	Journal of Cleaner Production
Tsalis et al., 2017	N/A	N/A	SLCA, indicators	benchmarking, LCSA	Greece	Broadband	Propose, case study	Journal of Cleaner Production

Table F2 Examples of generalized topics/questions researchers can ask to applicable stakeholders, in addition to the social indicators available in the existing literature, during semi-structured interviews and/or stakeholder discussions to capture the difficult to quantify, additional impacts of a case study related to critical civil infrastructure projects. It is important to encourage discussion and allow the interviewee to expand upon the questions asked.

- **System overview**
    - How does the current infrastructure system work?
    - How familiar are you with the current infrastructure system?
    - What are the key benefits of the infrastructure system for the users?
    - What are the disadvantages of the infrastructure system, if any, for the users?
        - What solutions would you propose to improve the infrastructure system?
- **System implementation (ask for each alternative infrastructure system, if applicable)**
    - What are the reasons for implementation?
    - What are the reasons against implementation?
    - How easy is the implementation?
        - How important is the ease of implementation in the selection between alternatives?
        - Would easier or more difficult installation alter your decision to implement?
- **Stakeholder involvement**
    - Which stakeholders are involved in the decision-making process for the infrastructure system?
        - What role do each of these stakeholders play in the decision-making process?
        - How involved is the public (e.g., local community members) in the decision-making process?
            - How does the public influence decision making for the infrastructure system?
    - What policies influence system decisions, if any?
    - What are the legal and regulatory constraints (or benefits) associated with this system?
- **Operations**
    - Once operational, what is the management structure of the system?
        - Do stakeholders receive any benefits from the operational system? If so, please identify the stakeholder and the benefit received.
    - Have safety preferences altered decision making during the planning and design stage of the infrastructure?
        - If so, please explain how.
    - What are the safety concerns with this system, if any?
    - Do you feel that you value safety more, less, or about the same as other operators of similar infrastructure systems?
    - If disaster strikes, what guidance is currently available for system operators?

        - Do you feel this is enough guidance? If not, what additional support is needed?
- **Employment**
    - Do the employees working with the infrastructure system have responsibilities beyond this infrastructure system (e.g., shared with another infrastructure system)?
        - If so, please identify which employees have additional responsibilities.
            - What positions do these employees hold?
            - What is the time allocation for each employee's responsibilities?
        - If work time were reduced for the infrastructure system, could the employee's time be used to address other responsibilities or tasks? If so, please explain how.
    - How frequently is there operator turnover?
        - What are the common reasons for operator turnover?
    - Is there currently automation at the facility?
        - If so, which equipment processes are automated?
        - Is there more opportunity for automation?
        - Would increased automation encourage or discourage people from working with the system, and why?
    - How often are employees on-call?
        - How do disasters affect employee hours? For example, are employees on-call 24/7 during floods, tornados, fires, hurricanes, etc.?
    - Would you say employees are satisfied?
        - Are there factors that have altered their satisfaction? This could include factors like working hours, ease of operation, and disaster guidance.
- **Perceptions of risk and resilience**
    - How important is resilience of the infrastructure?
    - What could be done to improve the resilience of the infrastructure?
    - How important is the certainty that the infrastructure will function properly, if disrupted?
        - What is your threshold (i.e., how much risk are you willing to take) and why?
        - What factors would prevent you from investing in resilience measures?
        - What factors would encourage you to invest in resilience measures?

Table F3 Summary of author's success in using stakeholder discussions to identify social impacts of critical civil infrastructure systems

Study	Critical Civil Infrastructure Sector	Stakeholders	Identified Additional (i.e., social) Impacts

Moussavi et al., 2021	Wastewater	• Engineers
		• Wastewater operators
		• Government agencies
			• Operator preference accommodations
			  ○ efficiency improvements
			  ○ automation of equipment
			  ○ safety
			• Operator turnover
			• Land topography impacts
			• Modern technology opportunities
			  ○ renewable energy acceptance

Moussavi et al., 2023a	Wastewater	• Engineers
		• Wastewater operators
			• Treatment process impacts
			  ○ bypass treatment processes
			  ○ community and industry shutdowns/restrictions
			  ○ restricted facility access
			  ○ downstream water supply changes
			• Worker impacts
			  ○ psychological affects
			  ○ limited disaster guidance
			  ○ increased working hours
			• Community impacts
			  ○ daily life disruptions
			  ○ community growth implications
			• Facility impacts
			  ○ loss of records
			  ○ undersized facilities

Moussavi et al., 2023b	Energy	• Engineers • Government agencies	• Increased installation speeds • Domestic job opportunities • Reduced reliance on foreign supply chains • Ability for expansion into deeper and disaster-prone waters globally • Support of current political goals

Moussavi et al., 2023c	Wastewater	• Engineers
		• Wastewater operators
		• Government agencies
		• Community representatives
		• Community members
			• Reduced operator time and labor
			• Compliance with evolving regulations
			• Community growth implications
			• Producer/landowner acceptance
			• Public perception
			  ○ odors
			  ○ groundwater contamination
			• Financial and ownership structures
			• Land valuation opportunities