QATAR UNIVERSITY

COLLEGE OF ENGINEERING

LIFE CYCLE SUSTAINABILITY ASSESSMENT FOR THE CONSTRUCTION OF DIW AND IMPROVEMENT SUGGESTIONS – CRADLE-TO-GATE APPROACH

BY

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A Thesis Submitted to

the College of Engineering

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering Management

June 2024

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ABSTRACT

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June: 2024, Masters of Science in Engineering Management

Title: Life Cycle Sustainability Assessment for The Construction of DIW And Improvement Suggestions – Cradle-to-Gate Approach

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Deep Injection Well systems (DIWS) are crucial for waste management, and they incorporate a deep injection well, deep monitoring well, and shallow monitoring well. This study conducts a cradle-to-gate Life Cycle Assessment (LCA) of constructing DIWS to quantify their environmental impacts. It sheds some light on improving the DIW system from a sustainability point of view.

Adopting a "cradle-to-gate" scope, the LCA evaluates all stages from material manufacturing through on-site construction. A standard 50,000 m3/day model system forms the baseline. Aligned with ISO standards, the study illustrates the four LCA phases; goal/scope definition, life cycle inventory analysis, impact assessment, and interpretation. We carefully collected data from different material, energy, and emission information sources and used extrapolation to estimate some machinery impacts.

The inventory part of our work follows ISO 14044, while the impact assessment part uses TRACI to evaluate environmental criteria including global warming potential, ozone depletion, and ecotoxicity.

DEDICATION

This thesis is dedicated to my family and my partner OBK who have always believed in me, inspired me, and encouraged me throughout my academic journey…

ACKNOWLEDGMENTS

I am deeply thankful to my mentor, Professor Kadir Ertogral, for his invaluable advice, encouragement, and backing in completing this thesis. My gratitude also extends to everyone who contributed to making this thesis feasible, particularly Professor Murat Kucukvar, Oumaima Benchekroun, and Mr. Vineeth. Moreover, words fall short to describe my appreciation for my family and friends, whose unwavering support has been pivotal throughout this academic endeavor.

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CHAPTER 1. INTRODUCTION

Nowadays the concept of sustainability plays a growing role in the construction industry because there are a lot of projects that show the ecological and societal consequences. Sustainable construction practices are known to offer benefits across three primary domains: environmental, economic, and societal health, as Bennett & Crudgington (2003) and Du Plessis (2002) pointed as well as numerous earlier debates which, exist already since the Earth Summit (RIO) conference. The environmental footprint of construction activities can be quite extensive, covering the use of any resources, materials, and energy in both direct production areas, as well as in industry. These actions do damage to the environment, the negative impact is in numerous ecological areas such as greenhouse gas emissions, huge energy use, pollution in air and water, disconnecting ecosystems, and inefficient waste management as indicated by Dong et al. (2015) and Shen & Tam (2002).

The attention of the world is directed toward the preservation of the environment because of which significant projects like the Kyoto Protocol were initiated which aimed to conserve energy by reducing the level of greenhouse gas emissions, but the project did not fully address the environmental concerns in all construction sectors. After that the creation of consequence assessment mechanisms such as the industry's Environmental Impact Assessments (EIA), the System of Economic and Environmental Accounting (SEEA), and tools like Environmental Auditing and Material Flow Analysis (MFA) were developed to represent and mitigate environmental impacts (Scheuer et al., 2003; Finnveden & Moberg, 2005). They entail specific tactics, strategies, and goals, nevertheless, Life Cycle Assessment (LCA) is preferred more proficiently characterized as systematic environmental impacts over the whole life cycle of any product or system (Singh et al., 2010; Rebitzer et al., 2004). The LCA approach is highly applicable to the construction industry and is composed of various stages right from design through to construction, and, eventually, its operation, paving the way for project-level scrutiny associated with the environmental impact of the industry.

1.1. Background and Context

The construction of Deep Injection Well Systems (DIWS) is recognized as a solution for managing treated sewage effluent (TSE) in areas where waste disposal presents considerable challenges. With the capacity to reach depths of around 400 meters and can go up to thousands, DIWs serve an indispensable function in the disposal of excess TSE, ensuring a dependable outlet for both routine and emergency disposal scenarios. The construction of these systems, which typically comprises three types of wells—deep injection wells (DIW), deep monitoring wells (DM), and shallow monitoring wells (DS)—entails a complex array of stages and processes. Commencing with site mobilization, this initial phase involves the assembly of equipment, materials, and personnel necessary to undertake the project. Pre-site activities then set the stage for construction, addressing preliminary tasks such as land clearing, site preparation, and the establishment of necessary infrastructure to support operations. Drilling of the wells follows, requiring substantial resource input and material usage, from the procurement of drilling rigs to the consumption of steel and concrete for well casing and structural integrity. This stage demands significant energy expenditure and bears the brunt of environmental impacts due to the intensive use of heavy, diesel-powered machinery. The construction process proceeds through several additional phases including casing, cementing, well completion, and development, each contributing to the overall environmental footprint of the project.

Introduction to Alternative Water Disposal Methods:

Other common methods for treating and disposing of treated sewage effluent (TSE) include surface water discharge, land application, and evaporation ponds. Each method has its own set of advantages, challenges, and suitability depending on geographical, environmental, and regulatory contexts.

1. **Surface Water Discharge**: Involves discharging treated effluent into rivers, lakes, or oceans. While this method can be cost-effective and straightforward, it poses risks of water contamination and ecological imbalance if not managed with stringent treatment standards.

2. **Land Application**: This method uses treated effluent for irrigation or as a soil conditioner in agriculture and reforestation. It supports water conservation and nutrient recycling but requires large areas of land and careful monitoring to prevent soil degradation and groundwater contamination.

3. **Evaporation Ponds**: Treated effluent is stored in large ponds where it evaporates, leaving behind solids for disposal. This method is suitable in arid regions but requires significant land area and can lead to air quality issues from aerosolized contaminants.

Based on the previous points there was noticed that there are several advantages such as:

1. **Environmental Safety**: DIWs minimize the risk of surface and groundwater contamination by disposing of effluent deep underground, well below groundwater levels. This method effectively isolates the effluent from the

biosphere, reducing the potential for environmental contamination compared to surface discharge and land application.

2. **Space Efficiency**: DIWs require considerably less land surface area than evaporation ponds and land application methods, making them ideal for areas where land is scarce or expensive.

3. **Regulatory Compliance**: Many regions with stringent environmental protection regulations find DIWs advantageous because they effectively mitigate the risk of pollutants reaching surface or shallow subsurface environments. This compliance with strict environmental standards helps in managing long-term liability and community relations.

4. **Reliability and Capacity**: DIWs can handle large volumes of effluent, offering a reliable solution for continuous and emergency disposal needs. Their capacity to manage significant inflows makes them particularly useful in urban or industrial areas with high wastewater outputs.

5. **Long-Term Effectiveness**: Once constructed, DIWs have a long operational lifespan with relatively low ongoing maintenance costs compared to the active management needed for land application and the monitoring required for evaporation ponds.

Given these points, DIWs present a more controlled and sustainable option for managing TSE, especially in densely populated or environmentally sensitive areas. The method’s ability to safely contain and dispose of large volumes of effluent deep underground provides a clear advantage in terms of environmental protection and space efficiency. Furthermore, the construction and operational standards for DIWs, which include rigorous monitoring wells and compliance with stringent environmental guidelines, ensure that they remain a safe and effective disposal method over the long term.

1.2. Significance of the Study

This research seeks to give detailed environmental impacts of the deep injection wells construction with the life cycle assessment methodology. Even though their importance, the impacts of DIW construction on the environment still lack exploration in practice and academia. This research intends to bridge this gap using the LCA approach, which contributes largely to the field in some key areas.

Firstly, this research shows the application of LCA methodologies specifically tailored to the construction phase of well systems, the study provides a detailed "cradle-to-gate" analysis, encompassing all activities from the initial drilling to the final well assembly. This approach ensures a thorough understanding of the environmental footprint, setting the ground for future LCA studies in this specialized area.

The shortage of previous research in this domain shows the novelty and importance of this study. By filling this void, the research not only adds to the academic knowledge base but also offers practical insights for industry stakeholders, policymakers, and environmental planners. These insights can guide the adoption of more sustainable practices and technologies in the construction of DIW systems, ultimately contributing to the broader goals of environmental protection and sustainability. Furthermore, this study's findings have the potential for emerging technologies and methodologies that could mitigate the environmental impacts of DIW system construction. By exploring these avenues, the research encourages innovation and technological advancement within the field.

1.3. Problem Statement and Objectives

While DIW systems are in widespread practice, a sustainability assessment is still not investigated. The objectives of this study are to:

- Define the materials and emissions involved throughout each stage of the construction process and quantify them.
- Use the OPENLCA software to determine the outputs, which will allow the building of a full life cycle inventory.
- Conduct an elaborate environmental life-cycle analysis of the DIW construction phase.
- Perform life cycle impact assessment according to the TRACI method.
- Explore potential alternative technologies, processes, and materials to improve the sustainability of DIWs.

To address the identified research problem, the following research questions were developed:

- How can the comprehensive LCA approach be employed to determine the environmental impacts across the construction phase of DIW?
- Which phases or processes in the construction of the wells present the most significant environmental impacts?
- Can alternative technologies or methodologies mitigate the environmental impacts identified during the LCA of the DIW system construction?

1.4. Thesis Structure

The chapters that are going to be discussed will provide a detailed literature review, detailed methodology, system boundary description, inventory analysis, a thorough environmental analysis of the current practice of the construction of DIWs, and try to find alternatives for each process to create a new/alternative system design, discussions, and implementations, ending with a conclusion and directions for the future research.

1.4.1. Chapter 1: Introduction

- Overview of sustainability in the construction industry and DIW systems
- Significance of DIWs for managing treated effluent
- Environmental impacts of construction
- Thesis structure

1.4.2. Chapter 2: Literature Review

- Principles of LCA and environmental impact assessment
- Prior research on DIW construction methods and materials
- Sustainability concepts and regulatory frameworks

1.4.3. Chapter 3: Methodology

- Approach for conducting environmental LCA of DIWs
- Case study selection, data collection methods
- Tools for analysis (OPENLCA, TRACI)

1.4.4. Chapter 4: Results and Discussion

- Environmental impacts by the construction phase
- Material sourcing, drilling, and assembly impacts
- Efficacy of sustainable practices and technologies

1.4.5. Chapter 5: Conclusion and Recommendations

- Synthesis of key findings and implications

- Suggested areas for future work to enhance sustainability.

CHAPTER 2. LITERATURE REVIEW

This chapter of the literature review looks specifically at the materials manufacturing and construction phase of the DIWs. The basic idea of LCA and the four main phases of such methodology are introduced and clarified in this chapter, where the methodological approach employed in the following paragraphs will be built. In the context of this study, no previous work has been done on this type of assessment related to DIWs. However, the analysis of recent LCA studies, focusing mainly on infrastructural projects related to the oil and gas industry, provides some insights into the approaches and methods used.

2.1. Deep Injection Wells Systems

A well is a bored, drilled, or driven hole whose depth is greater than the usual methods to drill a normal borehole of 25 or 35 meters below ground level (see Figure 1). They are typically several hundred to thousands of meters deep (Maliva et al., 2007).

DIWs originated in the early 1950s, born out of the need to safely manage and store wastewater and other water underground. This reduces environmental impact and protects groundwater. Since then, the methods have evolved dramatically from basic extraction methods to refined solutions, according to current research. These developments highlight the ongoing efforts across sectors to balance operational objectives with environmental protection principles over time. As disposal technologies and techniques continue to improve, they will discharge more wastewater further, and in a sustainable manner that protects the ecosystem and the health of communities (Shammas et al., 2009).

2.1.1. System Components

The system's main objective is to inject the liquid waste underground into deep rock formations for permanent disposal so that the disposals are isolated from shallow groundwater sources (Saripalli et al., 2000). The targeted geologic strata (layers of rock) must be sufficiently permeable to accept fluid injection and permeable enough to absorb and accept the waste without allowing vertical movement. These strata are predefined by doing something called a trial deep well (Qin et al., 2015).

The drilling involves as shown in Figure 1, constructing a series of protective steel casing strings that are set deeper into the ground with each successive section. Cement layers work to prevent contamination to the vertical sides while injecting. The innermost casing string called the injection tube, extends deepest into the accepted geologic formation. Mechanical devices called packers are used to seal between successive casing strings. Continuous pressure monitoring of the well annulus further ensures well integrity over time (Bolander, J., May 2011).

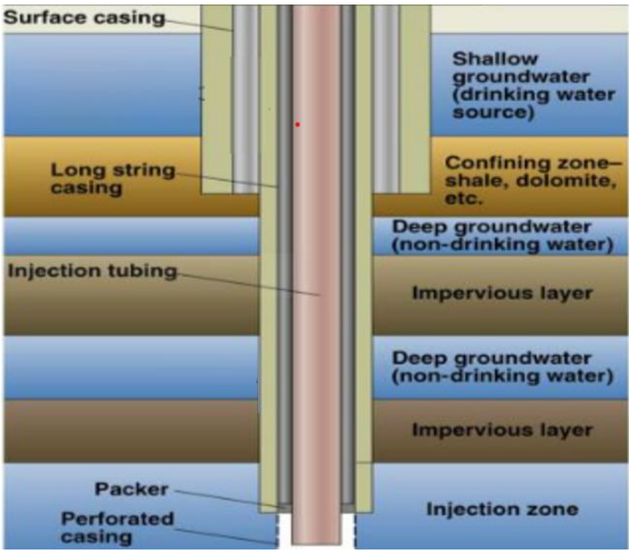

Figure 1: Typical design for The DIWs (Wright & Nebel, 2002).

In each system, there are mainly two missions, the first is to dispose of the waste far below the surface which is done by the deep injection well as it can be shown in Figure 2. The second is to check water quality at various underground depths and ensure compliance with regulatory standards set by the EPA and local regulations, and this is done by the deep and shallow monitoring wells (US EPA, 2023).

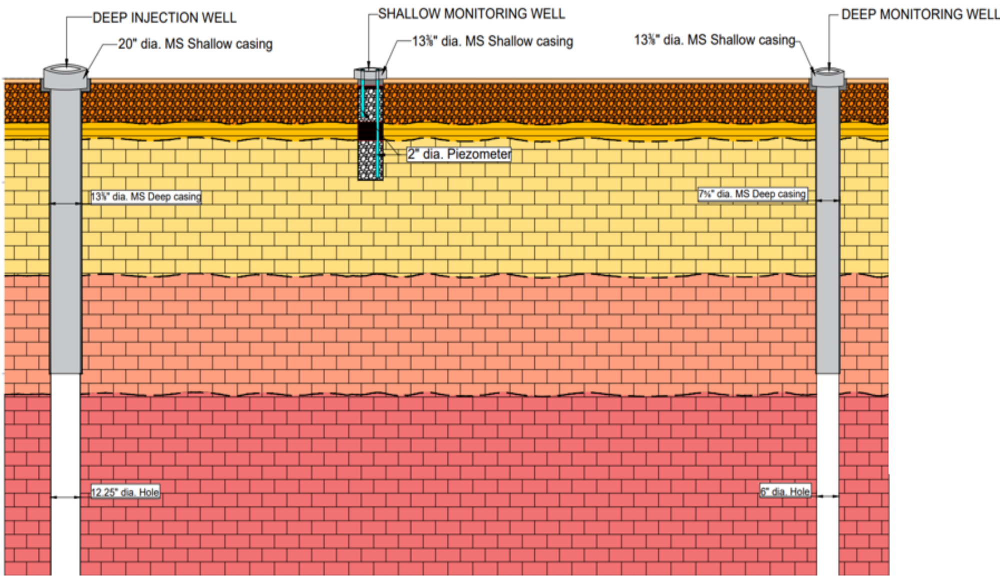

Figure 2. Well, system components.

2.1.2. Factors Affecting DIWs Construction Application Worldwide

The use of DIWs to dispose of water globally depends on many interconnected issues. One key factor is the regulations in each area, as rules can either support or slow projects. Countries have different environmental laws and standards, shaping what techniques can be used to construct the wells. With regulations varying so much in each location, those constructing wells must customize their methods according to the specific rules and hurdles presented in each location. Overall, many complex realities influence how DIW systems construction occurs worldwide (Water, 2022).

Land and geological considerations also stand out as key factors. The structure, permeability, and overall stability of the soil in the soil are also critical to a wellfunctioning, safe well. The geological characteristics of potential sites are of utmost importance in determining the feasibility of constructing dams that can safely intercept discharges and prevent unintended migration (Geoengineer.org, 2017).

The economic viability and technological capabilities of a region or industry also emerge as crucial determinants in the application of DIW systems. The ability to invest in, construct, and maintain such intricate systems is significantly influenced by economic strength and the availability of technological expertise and advanced methodologies. Additionally, the potential environmental and social impacts, as well as the public perception of such projects cannot be understated. Concerns regarding induced seismicity, contamination of freshwater sources, and overall environmental stewardship play a vital role in gaining social and regulatory approval (Hoskin & Heller, 2023).

2.1.3. The Extent of Injection Well Construction: A Global Overview

In 2018, the Environmental Protection Agency (EPA) conducted a study to specify how many deep wells are operational or regulated for construction, it was shown that more than 740,000 injection wells are all around the USA (EPA, 2020) as indicated below Figure 3.

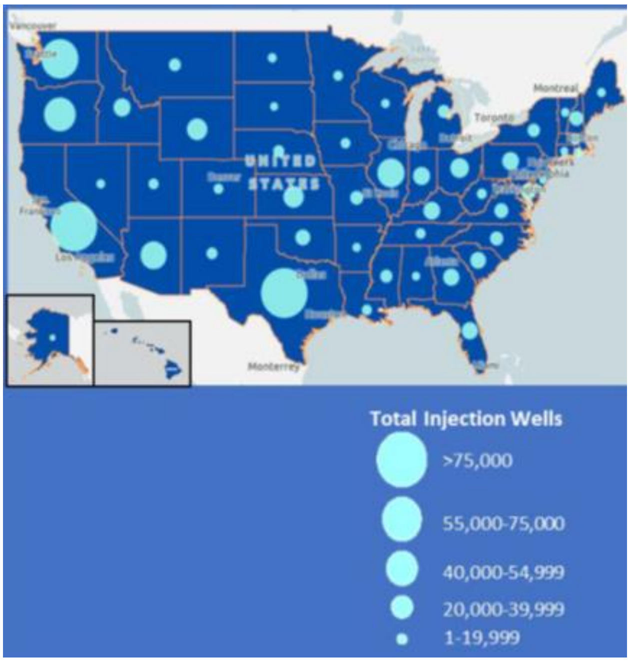

Figure 3. Injection wells as of 2018 that are constructed and operational or have been granted permits for operation (EPA, 2020).

EPA has categorized the deep wells based on what is injected into this well. As of the data from 2018, here is an overview:

- Class I: Wells inject hazardous and non-hazardous municipal, industrial, or radioactive wastes (EPA, 2024).
- Class II: Wells inject fluids associated with oil and gas production, primarily for enhancing recovery (EPA, 2024).
- Class III: Wells inject fluids to assist in mining minerals like uranium, salt, copper, and sulfur (EPA, 2024).
- Class IV: Wells, limited in use, inject treated groundwater from hazardous and radioactive wastes (EPA, 2024).
- Class V: The most varied, inject non-specific fluids including stormwater (EPA, 2024).

• Class VI: Wells are designated for deep underground carbon dioxide injection for long-term storage (EPA, 2024).

Figure 4 demonstrates the number of wells by class, and Class V (Deep injection wells for water disposal) is around 70% (531,000) of the total wells. These figures highlight the role that water disposal wells play in the management of wastewater.

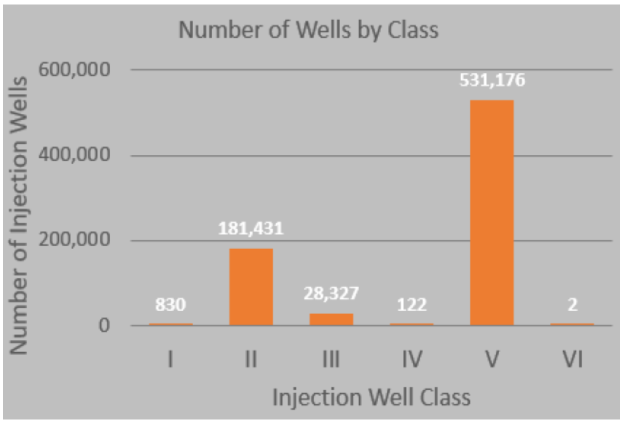

Figure 4 Quantity of wells by class (EPA, 2020).

2.2. Life Cycle Assessment (LCA)

LCA stands as the globally acknowledged methodology for environmental analysis, in line with ISO 14040 standards. This method entails a thorough gathering and assessment of all the inputs, outputs, and prospective environmental consequences associated with a product's lifecycle (ISO, 2006). Often referred to as the 'cradle to grave' approach, it encompasses the environmental implications from the extraction phase of raw materials to the disposal stage. As depicted in Figure 5, the LCA process is segmented into four critical phases: (1) Establishing the goal and scope, (2) Conducting the Life Cycle Inventory (LCI), (3) Performing the Life Cycle Impact Assessment (LCIA), and (4) Engaging in the Interpretation phase.

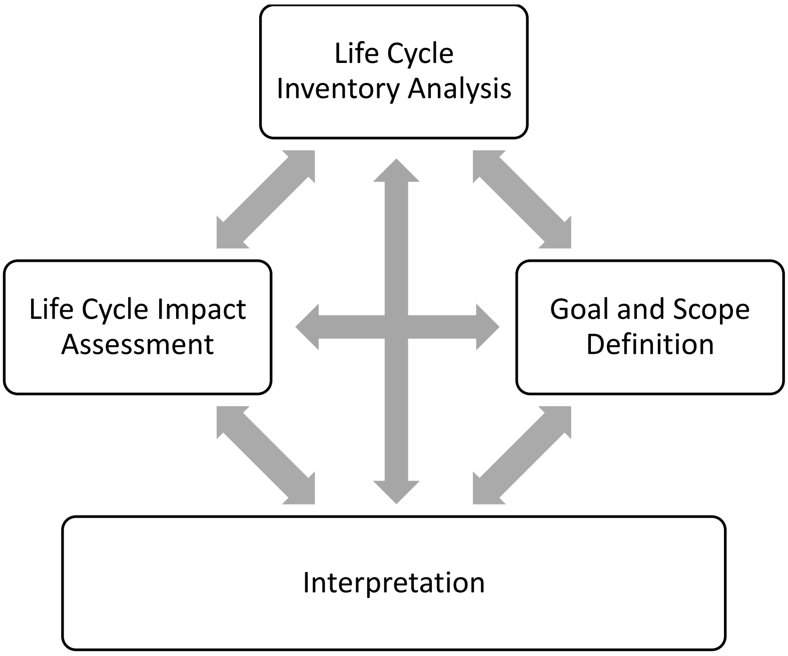

Figure 5. LCA framework (modified from ISO14040, 2006).

2.2.1. Goal and scope definition

The goal and scope definition are critical in research, especially for understanding the LCA of construction, the focus of this study. This involves identifying functional units and system boundaries, including life span, data requirements, assumptions, and limitations. It also highlights the study's rationale, applicability, and target audience (Marceau et al., 2012).

2.2.1.1. Functional unit

The functional unit represents the measurable performance of a product unit used as a basis for analysis in the LCA. This is the main parameter being used for comparisons of the products or systems having similar purposes with equal treatment and relevance. In a nutshell, it serves as a basis for the LCA by having the different functions of each system under examination expressed in the same measurable unit, thus making the latter easy to compare.

2.2.1.2. Life Span Consideration

The lifespan of any structure is important in LCA as it outlines the period of operation and environmental impacts over time. For DIWS, durability depends not just on construction quality but also on geological conditions, potential erosion from wastewater, and maintenance. Whereas residential buildings may last for decades, wells may have different lifespans. It is important to account for these unique factors in deep well systems to conduct an accurate and comprehensive LCA analysis of their full life cycle impacts. Prescribing an inappropriate lifespan could misrepresent results.

The functional unit is the study area that determines the system inputs and outputs. The system boundary, which links the product system to the environment, selectively includes unit processes in the LCA and addresses the material and energy flows at the boundary or elementary flows (Morrison Hershfield & the Athena Institute, 2010; Suh et al., 2004).

These boundaries as shown in Figure 6 and in line with ISO 14040 and ISO 14041, start with an initial definition and refine it according to the study's scope. The process involves raw material extraction, transportation, manufacturing, and on-site construction, use, and demolition.

The choice of LCA system boundary approach—cradle-to-grave, cradle-to-gate, or cradle-to-site—depends on the analysis phases, significantly affecting LCA outcomes, particularly in terms of cumulative energy consumption across a product or system’s life span (Rashid & Yusoff, 2015).

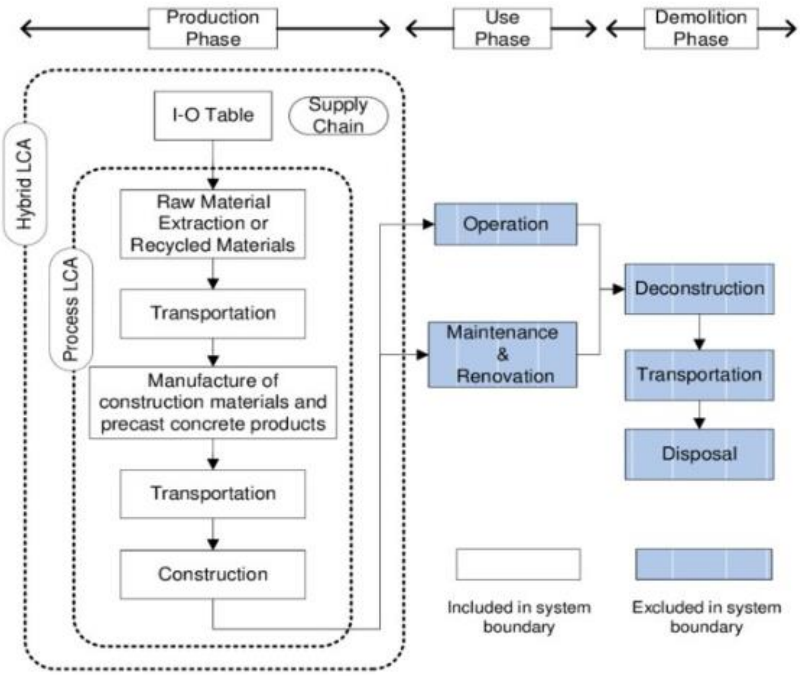

Figure 6. System boundary in typical construction projects (Omar et al., 2014).

2.2.1.3. System Boundaries

Determining system boundaries in LCA establishes the scope and limitations of the analysis (Rashid & Yusoff, 2015; Ye et al., 2011). For buildings and infrastructure, boundaries can vary. Some LCA studies only consider the construction stage (cradle to gate), while others encompass the entire lifespan from material sourcing through demolition (cradle to grave) the naming of each type of analysis is shown below Figure 7. Properly defining boundaries ensures the full scale of environmental impacts falls within the analysis. This helps provide an accurate understanding of a structure's life cycle effects.

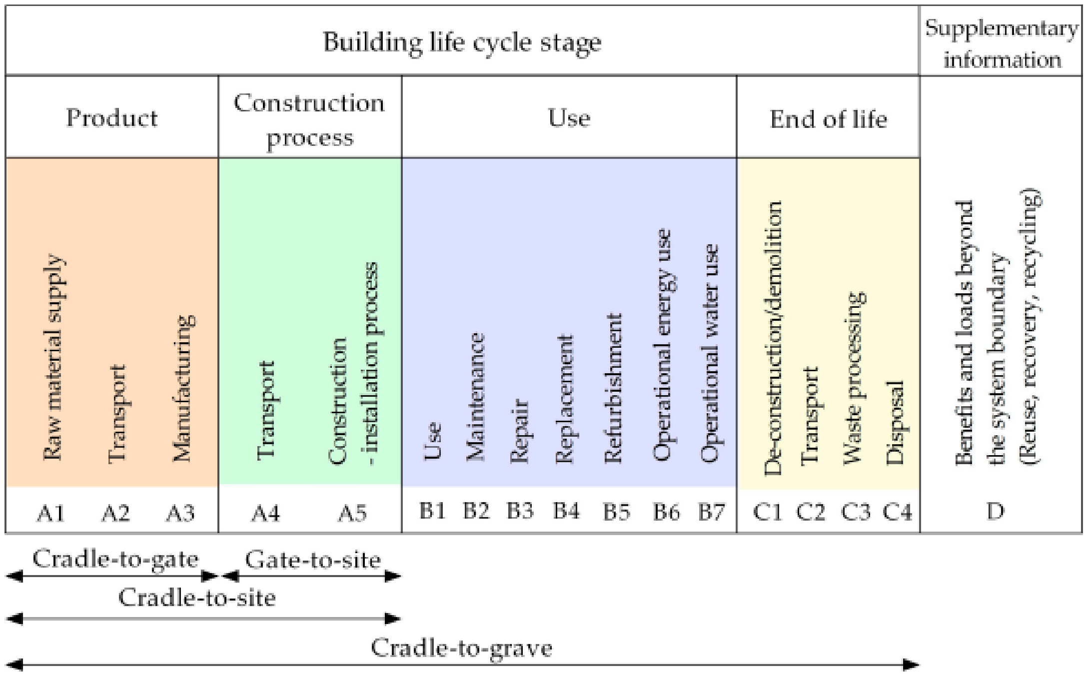

Figure 7. Stages in a building's life cycle and LCA-related system boundaries (Modified From EN 15978:2011).

2.2.2. Life Cycle Inventory (LCI)

LCI is referred to be the most important part of LCA wherein the inputs are collected and quantified through data measurement. There are times when you do not have the complete inventory of data which may force you to investigate the system boundary, refining and thus stretching the study's parameters. LCI compilation can be conducted through different methods: process-oriented approach, input-oriented approach, or a combination thereof, each of them providing information (Finnveden et al., 2009; Atmaca, 2016).

2.2.2.1. Process-Based Analysis

Process-based analysis, a traditional technique used in LCI, meticulously measures the consumption of resources, materials, and energy, along with their environmental repercussions, within a specific system boundary. This method tends to treat inputs beyond the boundary as negligible, concentrating solely on the delineated area. Nonetheless, this focus may inadvertently ignore effects and contributions outside the boundary, leading to potential omissions and a lack of completeness in the analysis (Aye et al., 2012; Lenzen, 2000).

Heijungs (1994) delineated two distinct methodologies within process-based analysis: the process flow and the matrix approaches. The process flow method utilizes consolidated data from the targeted system, downplaying the significance of upstream inputs. Alternatively, the matrix method systematically organizes each input and output within a technology matrix, spanning the entire lifecycle from production to disposal. To compute the LCI, this matrix is inverted and then applied to an environmental matrix. Although the matrix method is capable of accounting for an unlimited number of upstream processes in theory, in practice, it confines its analysis to those within the established system boundary (Suh et al., 2004).

2.2.2.2. Input-Output (IO) Analysis

Lenzen presents the IO approach as the holistic, macro-level methodology that takes into consideration complex, sector-based interdependencies of the modern economy through the input-output tables of the national and regional scales (Lenzen, 2002). The evaluation approach for environmental impacts the IO framework relies on goes back to the 1970s. This approach is based on the contributions of scholars, including Hendrickson, Horvath, Joshi, Lave (1998), Isard et al. (1968), and Proops (1977).

The IO analysis generates intricate flow charts that disclose the economic links between sectors based on tables and graphs. Take for instance the use case of analyzing greenhouse gas emissions caused by using fuel-consuming heavy equipment in construction projects. This methodology allows the tracking of raw materials with the use of input-output tables specific to a particular industry, as well as for the recording of direct and indirect ecological traces. Both production and consumption of goods and services involve standardized IO accounts that consist of payments such as salaries, taxes, and profits in the transactions across different sectors of production (Hendrickson et al., 1998; Leontief, 1990).

While the model based on the interactions of individuals promotes a holistic perspective on the economy and the comprehensive analysis of countless transactions and the whole energy environment, it is not free of weakness. The data represented by the IO tables may have gaps of information on geared commodities that make the interpretations inaccurate and may lead to nonconsistency, especially in the fluctuating pricing. On top of that, the model's breadth of coverage may fall short of identifying precise activities in a production process, and the use of old IO tables as input can constrain the model's practical implementation (Hong et al., 2016; Suh et al., 2004; Suh & Nakamura, 2007; Treloar, Love, & Crawford, 2 Process-based LCA is shown in Table 1, stand along with IO LCA with its specific strengths and weaknesses.

Table 1. Comparison Of The Benefits And Drawbacks Associated With Process-Based Analysis and Input-Output (I-O) analysis (Atmaca, 2016)

	Process-based LCA	**I-O based LCA**
Advantages	• More Accurate • specific comparisons • identifies areas for improvement. • provides information for future product development	• Economy-wide assessments • systems-level comparisons • raw data and workflow are openly accessible in the form of original articles and processed by peer-reviewed journals. • It makes provision for the improvement of their existing products and the production of new ones. • detail on all products in the economy.
Disadvantages	• Subjective system boundaries • time-intensive and costly. • applying the theory to the new processes is a challenge. • uses proprietary data. • This feature will not make the algorithms more generalized as they would inherently rely on the accessibility of confidential data. • uncertain data	• Product assessment averages are extremely significant. • setting up the questionnaires is a hard task. The respective money factor should be related to an existing physical unit. • nations shall not be considered foreign regions and as such their export goods shall be viewed as local ones to citizens of the respective nation. • uncertain data

As can be determined, processed LCA is more accurate and allows for more specific comparisons, but it is also more time-consuming and costlier. I-O-based LCA is less accurate and less specific, but it is also quicker and cheaper. The best choice depends on the specific needs of the study.

2.2.2.3. Hybrid Analysis

The hybrid tool is developed to deal with the shortfalls well known in both the input-output and process-based methods endorsing the need for detailed and precise designs of environmental impact assessment. Within this analytical framework, three unique models are employed: (1) the Tiered hybrid, (2) the INPUT-OUTPUT hybrid, and (3) the Integrated hybrid, which appeared in the article from Hong and co-authors in 2016. Here the approach synthesizes the data-driven fine detail analysis of the precision-based approach with the economic breadth of the input-output technique. It focuses on analyzing easy up-stream and down-stream elements of the lower complexity sequences within the scope of the set of more complicated high-order processes upon the integration of data. A notable difficulty in implementing this method is the duplication of the flows that happen either in process-based or input-output statistics without a clear source. The problem has been identified in several writings including by Crawford and Pullen in 2011 and by Treloar and his colleagues in 2004 among many others. The hybrid model of an integrated use of monetary and physical units presents an innovative approach, which is the first of its kind in the field of environmental assessments.

2.2.2.4. Used Analysis in Study

First, the applicable method for this study would be a hybrid approach which is likely to understand the scenario deeply on process-specific levels as well as on macro-economic level captured by input-output analysis. This choice is driven by several key factors:

In this case, a process-based technique is combined with an input-output type of analysis which is efficient to do this—window by a way of metaphor, constructing a

DIW system equal to solving a complicated puzzle. Process-specific analysis continues to focus on each jigsaw but rather than the environmental influence, it pays a closer view to specific materials like steel casing or diesel fuel. While it probably sidesteps the actual picture of the environment being destroyed by steel or diesel production, it might equally miss some other aspects. Here, input-output analysis plays the role of a fixed-winged aircraft providing an aerial view of the economy and targeting the impacts among sectors.

2.2.3. Life Cycle Impact Assessment (LCIA)

The LCIA is the subsequent step in the LCA, which allocates possible environmental impacts based on the flow inventory data (ISO, 2006). Even though ISO standards outline the structural frame of LCA, no standard method is defined for achieving environmental impact evaluation, leaving this step to the analyst who selects the impact assessment methods and categories according to the goal and scope (Sharma, 2019). Environmental performance categories or environmental indicators such as, but not limited to, GHG emissions, eco-toxicity, resource usage, eutrophication, acidification, land and water use, oxygen depletion, and use of renewable and non-renewable resources are identified and linked to the LCI outcomes through an environmental mechanism, LCIA can be conducted via two main approaches, which can also be combined: It has two methods e.g., Problem-oriented method (midpoints) and the Damage-oriented method (endpoints) (Buyle et al., 2013). While it may commonly be the preference for LCA researchers to employ pre-existing modeling platforms rather than start from zero (Goedkoop M, 2010), some of the platforms that can be leveraged here include CML 2002, Eco-Indicator 99, Impact 2002+, Recipe, TRACI, and LIME.

2.2.3.1. Selection of Environmental Impact Category Tool

In this case, data collection was done from vital LCA studies in the literature. As an example, an analysis of the environmental impacts of iron and concrete production involved the utilization of the information provided by Renzulli et al., and (2016) and Stafford et al., (2016), correspondingly. As a result, the LCIA was conducted under the framework of TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts). Within this system, the inventory data was distributed within predefined environmental and human health impact categories.

Selecting appropriate impact categories is important for accurately assessing the environmental ramifications of constructing and operating DIW wells. Historically, LCA research has prioritized metrics such as primary energy use and greenhouse gas (GHG) emissions, reflecting their significant environmental relevance, as noted by Heinonen et al. (2016). Various methodologies and tools, including the TRACI framework developed by the U.S. Environmental Protection Agency (EPA), have been applied in these studies. TRACI facilitates the evaluation of several midpoint impact indicators, including but not limited to global warming potential, acidification, respiratory effects, eutrophication, potential for photochemical smog, and impact on the ozone layer (PCI, 2009).

The TRACI methodology will be used in this study by the OpenLCA software. As shown in Table 2, Gabi, SimaPro, Athena, and BEES are some of the software options, but OpenLCA is appropriate as it has been used to assess construction systems in the past. In the following paragraphs, the results of the TRACI approach will be discussed.

Table 2. Generic LCIA Tools are Used for LCA Studies (Anand & Amor, 2017)

Name	Indicators Included	Website
GaBi	C, E, GHG	"http://www.gabi-software.com/Canada/index"
SimaPro	C, E, GHG	"https://simapro.com/about"
Umberto NXT LCA software	C, E, GHG	"Umberto NXT LCA software"
OpenLCA	C, E	"http://www.openlca.org/products"
TEAMTM 5.2	E, C	"http://ecobilan.pwc.fr/en/boite-a-outils/team.html"
EIO-LCA (Economic Input-Output Life Cycle Assessment)	C, E, GHG	"http://www.eiolca.net/"
Boustead Model	E, GHG	"Model: http://www.bousteadconsulting.co.uk/products.html"

(C-Cost, E-Environmental impacts, Green House Gases - GHG)

2.2.3.1.1. Environmental impact: global warming potential (GWP)

GWP measures the impact of greenhouse gas emissions in terms of carbon dioxide equivalents, assessing their contribution to global warming. (Bare, 2011).

2.2.3.1.2. Environmental impact: ozone layer depletion

This category assesses the impact of substances that can deplete the ozone layer, which is crucial for blocking harmful ultraviolet radiation. (Steven, 2022).

2.2.3.1.3. Environmental impact: respiratory effects (non-carcinogenic)

This impact refers to the potential non-carcinogenic effects on human respiratory health, measured in kilograms of toluene equivalent. (Steven, 2022).

2.2.3.1.4. Environmental impact: photochemical oxidation

Photochemical oxidation, leading to issues like smog, is quantified in terms of nitric oxide equivalents. (Steven, 2022).

2.2.3.1.5. Environmental impact: eutrophication

Eutrophication is the process where excessive nutrients lead to oxygen depletion in water bodies, affecting aquatic life. (Steven, 2022).

2.2.3.1.6. Environmental impact: resource depletion

This category evaluates the depletion of non-living resources, highlighting the environmental and societal impacts of reduced resource availability (Jolliet et al., 2003).

2.2.3.1.7. Environmental impact: water use

Water, an indispensable resource, was used extensively during the construction of the DIW system. Usage was quantified in cubic meters (m3) (Steven, 2022).

2.2.3.1.8. Environmental impact: acidification potential

Acidification potential, measured in sulfur dioxide equivalents, evaluates emissions that can lower pH levels in soil and water (Steven, 2022).

2.2.3.1.9. Environmental impact: land use

Land use impact is considered in terms of soil organic carbon loss, reflecting soil health and ecological impacts (Steven, 2022).

2.3. Interpretation

The LCIA and LCI results are merged in a recursive approach in this phase. Both methodological techniques, such as attribution analysis and impact analysis (Morrison Hershfield & the Athena Institute, 2010), but also other operational approaches have been used. The essence of that phase can be summarized as the interpretation of the results, drawing of conclusions, limitation sketching, and proposals rooted in the LCA earlier stage data results (Khasreen et al., 2009).

CHAPTER 3. APPLIED METHODOLOGY

This section aims to examine the effects of the DIW construction using a quantitative approach. The scope includes all processes of manufacturing and construction from start to finish, such as material manufacturing, transportation, and on-site activities.

For this study, a model DIW system representing standard wastewater disposal practices was selected as the baseline. This system, capable of disposing up to 50,000 m^3/day of treated water, was evaluated based on real-world data and that one system is divided into three types on site, a deep injection well 400m deep, a deep monitoring well 400m deep, and a shallow monitoring well 50m deep. To ensure consistency, these three types were carefully quantified, allowing for an in-depth analysis of their effects. The methodology of comparing alternative system configurations throughout the full life cycle draws inspiration from the previous academic work on sustainability, though no past research has specifically focused on the LCA of DIW system construction.

The research methodology not only encompasses a comprehensive assessment of the construction of DIW systems but also adopts innovative approaches to address some data gaps. Specifically, the study utilizes extrapolation methods for estimating the environmental impacts of machinery where specific LCA data is unavailable, ensuring a robust and comprehensive environmental assessment despite data limitations.

3.1. Life Cycle Framework

Figure 8 illustrates the research methodology framework, adhering to the four-step structure outlined by the ISO standard for Life Cycle Assessment (ISO, 2006). These steps include: (1) establishing the goal and scope; (2) compiling the life cycle inventory; (3) conducting the impact assessment; and (4) interpreting.

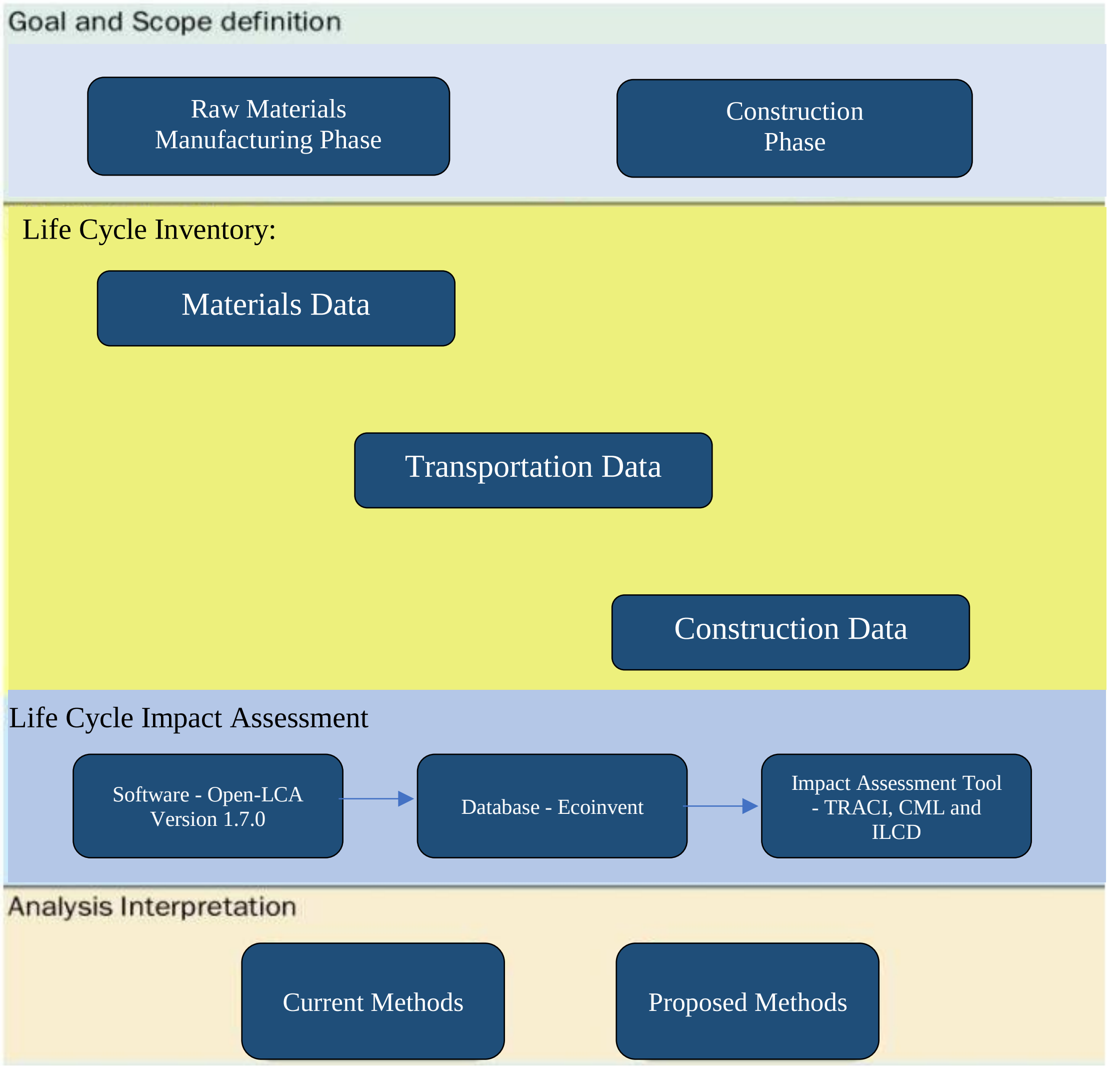

Figure 8. Methodology map modified (ISO, 2006).

3.1.1. Goal and Scope Definition

DIW system presents an innovative approach to disposal, addressing the challenges of environmentally sound waste management through the injection of waste into deep subsurface formations.

Table 3. Goals, objectives, and scope of the research.

Category	Description
Goals	Environmental implications and sustainable practices associated with the construction of DIW systems.
Objectives	**Environmental and Sustainability Evaluation:** To study and evaluate the environmental and sustainability aspects of DIW systems for waste management. **Innovative Alternatives Proposal:** Propose alternative methods that could reduce the environmental impact associated with the manufacturing and construction phases, while taking into consideration the cost.
Scope	**Construction and Environmental Outcomes:** The research focuses on the assessment of the construction of DIW systems and their environmental outcomes. **Alternatives for Environmental Impact Reduction:** Studying alternatives for the reduction of the environmental impacts.

3.1.1.1. Functional Unit

For this research study, the functional unit was defined as "the construction of a single system." Given the unique nature and specialized purpose of these systems, this unit was chosen to represent the infrastructure's objective and function for wastewater disposal. The functional unit accounts for important aspects like depth, diameter, and other key components.

This choice aims to provide a consistent and comprehensive basis for evaluating environmental impacts across different stages of the well's construction lifecycle.

3.1.1.2. System Boundary

The life cycle of the DIW system construction process was assessed using a “cradle-to-gate” approach, as shown in Figure 9. The scope begins with the initial raw material manufacturing phase ("Cradle Start") and ends with the completion of well assembly ("Site").

The environmental impacts start with identifying the key construction materials needed for the well, such as cement, steel, and drilling fluids. Since injection well construction requires extensive use of these materials, all production and procurement processes associated with their manufacture were considered.

Manufacturing cement, steel reinforcements, casing materials, and drilling fluids are the primary processes (inputs) for constructing the well. Other processes unrelated to construction were excluded from the system boundary.

All resources used during these processes, including diesel and water are included within the system boundary.

The LCA for a DIW well system requires consideration of distinct factors due to the specialized nature of the infrastructure. Whereas typical system LCAs may evaluate material sourcing, transport, and emissions, an assessment of this system must incorporate:

- Material procurement and manufacturing for construction elements such as steel casing, cement grout, and bentonite polymer.
- Construction processes involve rotary drilling, installation of casings, cement grouting, and well development.

- Transportation of workers, materials, and equipment to and from the site.
- Air emissions like carbon dioxide, sulfur dioxide, and carbon monoxide especially during drilling and development.

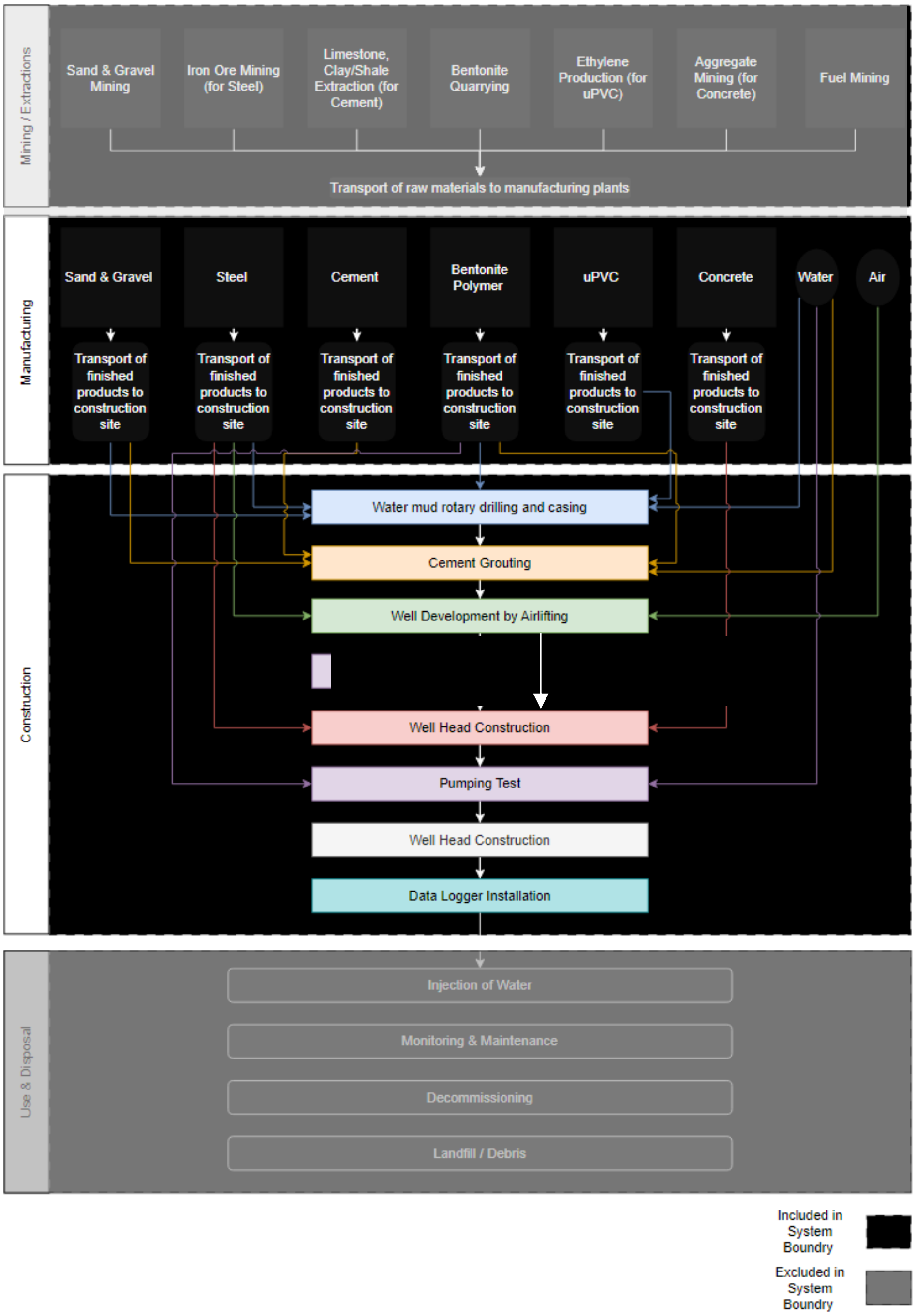

Figure 9. System boundary for deep water injection wells projects.

When evaluating the environmental impact of building DIWs, the use and demolition stages were not considered. The reasons for this exclusion are.

- DIW systems are built to last. When they're eventually demolished, the impact is usually small compared to the construction and operation stages. The materials used, like steel and concrete, aren't easily recycled or reused. So, focusing on the construction and operation stages allows us to better identify ways to reduce the environmental footprint of DIW systems.
- The current study establishes a foundational understanding of the environmental impacts during the construction phase, which is critical for any further comprehensive LCA. Future studies could build on this groundwork to include the operational and decommissioning phases, thereby creating a complete life cycle perspective.
- The current study establishes a foundational understanding of the environmental impacts during the construction phase, which is critical for any further comprehensive LCA. Future studies could build on this groundwork to include the operational and decommissioning phases, thereby creating a complete life cycle perspective.
- Data Reliability and Availability: Reliable data is crucial for an accurate LCA. The construction phase has more readily available and quantifiable data compared to the operational and decommissioning phases, which can involve speculative estimates and uncertain long-term data. Focusing on the construction phase ensures the reliability and accuracy of the LCA findings
- Policy and Practice Implications: Immediate changes in construction practices based on the LCA findings can influence policy and industry standards more quickly than

changes based on the operational or decommissioning phases. This can lead to faster implementation of best practices in environmental management within the industry.

3.1.2. Life Cycle Inventory (LCI)

Inputs accounted for include raw material extraction and processing, energy sources, and water. Outputs captured encompass air, water, and soil emissions, solid waste, and other releases at each life cycle stage within our scope. Foreground and background data were delineated clearly.

3.1.2.1. Data Collection Strategy

Data collection was carefully planned to capture essential information types like materials, energy use, and emissions as per Table 4. The focus was on collecting timely, project-relevant data directly related to the DIW construction processes under study. Data sources include detailed project estimates as well as well-known environmental databases and industry reports known for reliability and comprehensive scope. This strategy helped ensure a robust collection representing current construction practices for the analysis.

3.1.2.2. Data Quality and Reliability

To ensure the highest quality, reliable data, data were primarily sourced from peer-reviewed studies and reputable industry reports. The Ecoinvent database was extensively used due to its extensiveness of recognized environmental data, providing a confident basis for the LCI analysis. Verification and validation processes were applied to confirm data accuracy and applicability to the study context. This emphasis on sourcing from peer-reviewed materials, along with verification of data parameters, helped deliver trustworthy insights for sustainability improvements.

3.1.2.3. Handling Data Variability and Gaps

Data variability and gaps were addressed by selectively using proxy data where needed. This involved choosing comparable data sources from similar studies to ensure relevance and consistency with the study context. For example, emissions data for a specific 200 kW drilling rig engine were extrapolated from a 168-kW diesel excavator model studied by Khan and Huang (2023) due to similarities in engine type and size. This strategic use of related proxy data allowed us to fill in the gaps while maintaining accuracy appropriate to the system analyzed.

3.1.2.4. Alignment With LCA Standards

LCI methodology followed the ISO 14044 standards for life cycle assessment (LCA), adhering to core principles of transparency, consistency, and reproducibility. Aligning with these rigorous scientific standards ensured that the inventory analysis met demands for robust, reliable, and repeatable methods and outcomes. This approach provided a strong methodological foundation for the overall study and its ability to inform sustainable construction practices.

3.1.2.5. Environmental Impacts for Materials LCA Data

In the life cycle inventory phase, data was collected from various sources to represent the DIW system construction. This included drilling materials and equipment data, primarily sourced from actual project estimates and specialized equipment suppliers. Additionally, previous LCA studies focused specifically on construction materials like cement and steel were incorporated (Stafford et al., 2016; Renzulli et al., 2016). This allowed for an understanding of their respective environmental impacts. The multi-faceted data collection approach captured relevant information to construct the system inventory in line with LCA methodological best practices. Table 4 Below are the sources for data used.

Table 4. Data Sources Used.

Life-Cycle Phases	Data Sources	Data Type
Raw Materials Processing	Project Estimate, Ecoinvent Database.	Direct
Construction (Well Drilling & Assembly)	Main Contractor, Ecoinvent Database.	Direct
Machinery Environmental Impact Estimation	Extrapolated from Asmat Ullah Khan and Lizhen Huang's (2023) study on diesel, hybrid, and electric excavators.	Extrapolate
Environmental Impact of Combustion Engine – Heavy Equipment	Data from the research were considered when Eckard Helmers, Johannes Dietz, and Martin Weiss (2020) compared EVs with combustion engine vehicles in real-life situations.	Extrapolated
Environmental Impact of Combustion Engine – Light Equipment	The analysis originates from "Life Cycle Assessment in the Automotive Sector: A Comparative Case Study of Internal Combustion Engine (ICE) and Electric Car," authored by Francesco Del Pero and Delogu (2018).	Direct
Steel Production	Life Cycle Assessment of Steel Produced in Poland by D. Burchart-Korol, 2013.	Direct
Environmental Impact of Cement Production	The referenced work is a life cycle assessment focused on Portland cement production, specifically within the context of Southern Europe, conducted by Fernanda N. Stafford and her team in 2016.	Direct

Life-Cycle Phases	Data Sources	Data Type
Environmental Impact of Concrete	The referenced research, "Study and Use of Geopolymer Mixtures for Oil and Gas Well Cementing Applications," conducted by Saeed Salehi and colleagues in 2018, explores the potential of geopolymer mixtures in the context of cementing applications within the oil and gas industry.	Direct

3.1.2.5.1. Methodological framework for the calculation of the diesel engine equipment.

The quantification of environmental impacts for the proposed well construction practices is based on empirical data drawn from relevant academic literature. The main point of this analysis is to establish a baseline for equipment operations, focusing specifically on an excavator as a primary machine. This baseline, derived from literature sources, considers an excavator with a 168-kW combustion engine operating for 9,200 hours along with a 300-kWh electric engine (full electric engine). Table 5 shows the values for different scenarios of the used excavator and its impact category values in Table 6.

From this foundational dataset, a scaled approach was taken to calculate the emissions per hour of operation kilowatt of engine power capacity and electric storage capacity. This scaling methodology allows impacts to be estimated for the specific equipment capacities involved in DIW construction.

Relying on published data provides a standardized, evidence-based foundation for environmental assessment. Applying scaled calculations derived from this baseline facilitates a systematic evaluation of the machinery inputs and associated impacts. This approach aims to provide a realistic appraisal of the construction activities.

Table 5. Scenarios For Diesel, Hybrid, and Electric Construction Equipment (Asmat & Lizhen, 2023).

Scenarios	Diesel (%)	Electric (%)	Details	Battery (kWh)
1	100	0	Fully diesel powered	-
2	75	25	Hybrid	75
3	50	50	Hybrid	150
4	25	75	Hybrid	225
5	0	100	Fully electric	300

Table 6. Impact Of Manufacturing, Maintenance, Operation, And End-of-Life Stages For Diesel, Hybrid, and Electric Machines (Asmat & Lizhen, 2023).

Impact Category	Unit	Total	Manufacturing	Maintenance	Operation	End of Life	Scenarios
Global Warming (GWP)	ton CO2 eq	5191.61	1	0.3	98	0.7	1
		3914.09	1.3	0.5	97.7	0.5	2
		2662.83	2	0.8	97	0.2	3
		1405.15	4	1.8	93.8	0.4	4
		145.39	42.3	19.3	34.5	3.9	5
Terrestrial ecotoxicity (TE)	ton 1,4-DCB	574.99	73.9	9.1	15.5	1.5	1
		845.79	58.2	27.3	13.3	1.2	2
		1261.93	54	33.4	11.6	1	3
		1661.18	52	37	10	1	4
		2609.51	40.7	30.8	27.8	0.7	5
Stratospheric ozone depletion (ODP)	ton CFC11 eq	0.00143	1.5	0.46	97.99	0.05	1
		0.00111	1.3	0.7	97.6	0.1	2
		0.0008	2.4	1.3	96.1	0.2	3
		0.00069	3	1.8	95	0.2	4
		0.00016	15	9	75	1	5
Human carcinogenic toxicity (HT)	ton 1,4-DCB	32.86	88.7	6.9	4.2	0.2	1
		29.3	83	10.4	6.3	0.3	2
		31.21	80	11.7	8	0.3	3
		322.85	78	13	8.6	0.4	4
		39.52	66.4	12.4	20.8	0.4	5

Impact Category	Unit	Total	Manufacturing	Maintenance	Operation	End of Life	Scenarios
Terrestrial acidification (AP)	ton SO2 eq	1.58	15.3	4.5	80	0.2	1
		1.3	17	8.6	73.9	0.5	2
		1.15	23	13.1	63.1	0.8	3
		0.9	34	21	44	1	4
		0.78	44.3	29.7	24	2	5
Freshwater eutrophication (EP)	ton P eq	0.06	72.9	13.3	13.5	0.3	1
		0.07	60.13	25.37	14	0.5	2
		0.09	56.2	30	13.2	0.6	3
		0.11	54.6	33	11.7	0.7	4
		0.16	46	30.2	23.2	0.6	5
Marine ecotoxicity (ME)	ton 1,4-DCB	16.46	49	6	6	39	1
		21.13	40	16	14	30	2
		28.21	38.6	21	17.4	23	3
		35.09	38.3	24	19.2	18.5	4
		81.55	19.6	13.4	59	8	5

3.1.2.5.2. Methodological framework for transportation impact calculation.

The evaluation of environmental impacts from worker transportation to and from the DIW construction site is based on empirical data from academic literature. This analysis comparatively assesses the impacts of daily commutes using internal combustion engine (ICE) vehicles versus electric cars.

A standardized assumption was applied that each vehicle travels 40 km per day (20 km each way between the site and the office).

Table 7. Impact of Manufacturing, Maintenance, Operation, and End-of-Life Stages For Diesel and Electric Cars. (Francesco Del Pero et al., 2018).

	ICEV				BEV			
	Production	Use	EoL	Total LC	Production	Use	EoL	Total LC
Acid Levels Indicator	42	49	-1	91	104	33	-1	136

	ICEV				BEV			
	Production	Use	EoL	Total LC	Production	Use	EoL	Total LC
Greenhouse Gas Impact without Bio-Carbon	4970	25400	-95	30200	8960	10400	-87	19300
Greenhouse Gas Impact with Bio-Carbon	4970	25600	-95	30500	8970	10400	-87	19300
Freshwater Life Toxicity Potential	218000	3430	-13	222000	639000	315	-13	639000
Freshwater Nutrient Enrichment Indicator	3	0	0	3	16	0	0	16
Marine Water Nutrient Enrichment Indicator	4	12	0	16	12	7	0	19
Soil Nutrient Enrichment Indicator	44	181	-2	223	113	66	-1	177
Carcinogenic Toxicity Potential for Humans	0	0	0	0	0	0	0	0
Non-Carcinogenic Toxicity Potential for Humans	0	0	0	0	0	0	0	0
Radiation Exposure Indicator for Human Health	349	95	-8	436	862	5100	-7	5960
Land Occupation Impact	2730	9260	-49	11900	9720	5420	-49	15100
Stratospheric Ozone Depletion Potential	0	0	0	0	0	0	0	0

	ICEV				BEV			
	Production	Use	EoL	Total LC	Production	Use	EoL	Total LC
Particulate Matter Formation Impact [Fine Particulate Matter Kilogram Equivalent]	3	2	0	5	9	2	0	11
Ground-level Ozone Creation Potential, Human Health	15	28	0	43	36	17	0	53
Water Use Impact	44	41	-7	78	103	698	-7	794
Depletion of Minerals, Fossil Fuels, and Renewable Resources	2	0	0	2	3	0	0	3

3.1.2.5.3. Methodological framework for the calculation of steel casing.

The foundation of the calculations is anchored in the comprehensive study "Life Cycle Assessment of Steel Production in Poland: A Case Study" by D. Burchart-Korol (2013). This paper examines the emissions associated with steel production, employing the Basic Oxygen Furnace (BOF) method. The BOF method, prevalent in steel manufacturing, is known for its significant environmental footprint, primarily due to high energy consumption and resultant emissions.

The outcomes of these calculations are visually represented in Table 8, which illustrates the environmental impact assessment of steel production using the BOF method, as per the findings of Burchart-Korol (2013). This graphical representation aids in comprehending the significant role of steel production in the overall environmental impact of DIW construction and underscores the potential benefits of material optimization strategies.

Table 8. Results Of The Environmental Impact Assessment of Steel Production Using The BOF Method (Burchart-Korol, 2013).

Impact Category	Unit	BOF steel	BOF slag	BOF slag	EAF crude steel	EAF slag
Global Warming Potential	kg CO2	1703.00	516.00	240.00	766.00	147.00
Soil Acidification	kg SO2	4.81	1.46	0.68	2.48	0.48
Nutrient Overload in Freshwater	kg P	0.81	0.25	0.11	0.46	0.09
Nutrient Enrichment in Oceans	kg N	0.30	0.09	0.04	0.14	0.03
Toxic Effects on Humans	kg 1.4-DB	643.00	195.00	91.00	347.00	65.00
Formation of Ozone in the Lower Atmosphere	kg NMVOC	4.89	1.48	0.69	1.39	0.27
Emission of Fine Particulates	kg PM10	4.61	1.40	0.65	0.78	0.15
Toxicity to Land Ecosystems	kg 1.4-DB	0.17	0.05	0.02	0.06	0.01
Toxicity to Freshwater Ecosystems	kg 1.4-DB	12.77	3.87	1.80	6.96	1.34
Toxicity to Marine Ecosystems	kg 1.4-DB	13.32	4.04	1.88	7.10	1.36
Emission of Radioactive Substances	kg U235	82.83	25.11	11.69	24.13	4.64
Use of Farmable Land	m^2a	45.55	13.81	6.43	13.57	2.61
Use of Urban Land	m^2a	12.21	3.70	1.72	4.13	0.79
Change in Natural Landscapes	m^2	0.20	0.06	0.03	0.06	0.01
Consumption of Water Resources	m^3	87.44	26.51	12.34	1.88	0.36
Utilization of Metallic Resources	kg Fe eq	850.00	258.00	120.00	13.00	2.00
Fossil depletion	kg oil eq	529.00	160.00	75.00	143.00	28.00

3.1.2.6. Analysis

This phase involved collecting and calculating the energy input/output data needed to quantify the construction of DIW systems. All stages were captured, from initial material manufacturing through final construction. Calculations prioritized accurate, process-relevant quantification of energy and material usage, emissions, and other environmental loadings shown in Figure 10. Care was taken to ensure the impact assessment reflected the construction activities under evaluation, meeting scientific standards for the LCA methodology. The results provided insight into where to focus efforts to enhance sustainability performance. As pointed out earlier, our study was limited to a "cradle-to-gate" approach, and the operational phase post-construction was not included.

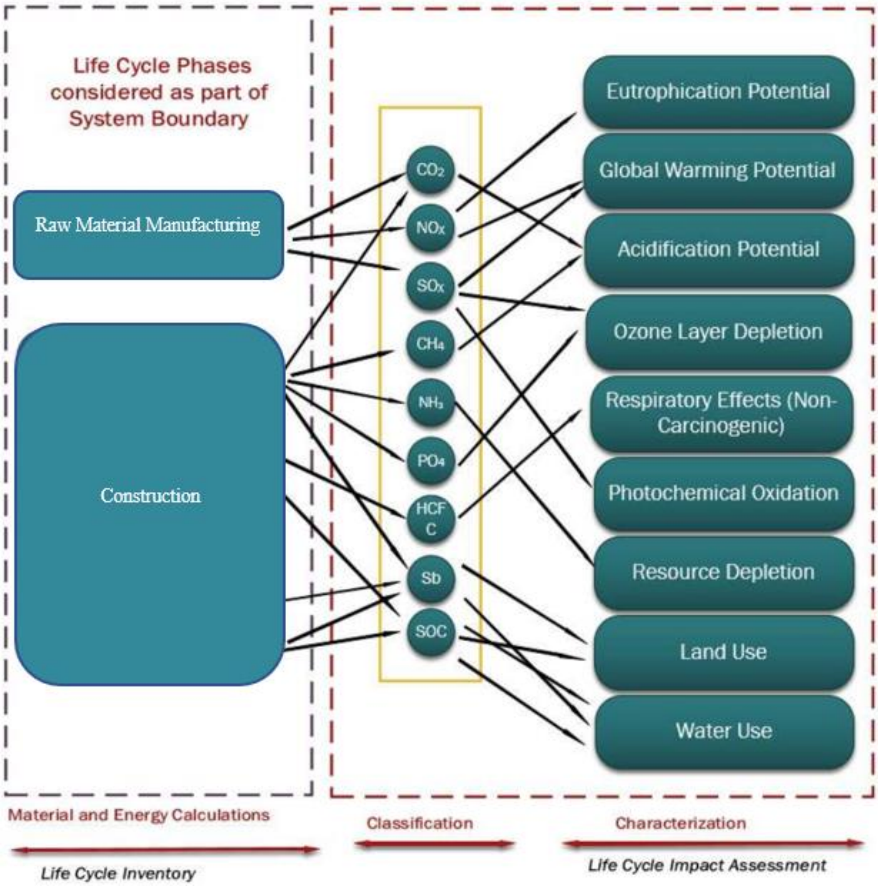

Figure 10. Life cycle impact assessment (LCIA) model.

3.2. Utilization of OpenLCA Software

The OpenLCA software was implemented for its comprehensive life cycle assessment modeling capabilities. It verified integral to representing complex construction processes based on different studies such as a study made by G. Sanoop, Sobha Cyrus, and G. Madhu (2024). OpenLCA enabled analysis across multiple impact categories including Global Warming Potential and eutrophication, deepening understanding of the environmental footprint. Its compatibility with databases such as Ecoinvent facilitated accurate, efficient data integration into the LCA model.

3.2.1. Selection of Environmental Impact Category Tool

Assessing the environmental impacts of construction projects, such as DIWS, requires robust and reliable tools that can provide a detailed analysis of potential effects. Several methodologies are prominent in environmental impact assessments, each with specific focuses and strengths:

1. **CML (Institute of Environmental Sciences, Leiden University)**: This method focuses on midpoint impact categories such as global warming, ozone layer depletion, human toxicity, ecotoxicity, and resource depletion. It provides detailed mechanisms to trace environmental impacts to specific chemical emissions.

2. **ReCiPe**: A method that offers a harmonized approach to impact assessment in LCA. It provides results at both the midpoint level, such as climate change, ozone depletion, and terrestrial acidification, and at the endpoint level, which includes damage to human health, ecosystems, and resource availability.

3. **IMPACT 2002+**: This method combines midpoint and endpoint impact categories into a single framework. It covers a wide range of environmental impacts, including human toxicity, ecotoxicity, global warming potential, and resource

depletion.

4. **Eco-indicator 99**: Primarily focused on Europe, this method evaluates the effects of emissions and resource extraction in terms of endpoint impacts, grouped into three damage categories: human health, ecosystem quality, and resource depletion.

For the environmental impact assessment of DIWS construction, the TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) method has been selected. Developed by the U.S. Environmental Protection Agency, TRACI is particularly suited for assessing environmental impacts within the U.S. context. Reasons for selecting TRACI include:

- **Relevance to U.S. Regulations**: TRACI is designed with the U.S. environmental regulatory framework in mind.
- **Comprehensive Impact Categories**: TRACI provides robust analysis across several critical impact categories relevant to DIWS, including global warming potential, acidification, respiratory effects, eutrophication, photochemical smog potential, and ozone depletion.
- **Integration with LCA Software**: TRACI's compatibility with OpenLCA software facilitates seamless integration into the broader life cycle assessment of the project, allowing for a streamlined and efficient analysis process.
- **Focus on Practical Implementation**: TRACI's methodology supports practical decision-making for environmental management and policy development, providing actionable insights that are directly applicable to reducing environmental impacts.

The selection of TRACI for this study is driven by its alignment with regional regulatory requirements and its capability to address specific environmental concerns associated with DIWS. The upcoming sections will detail the application of TRACI using OpenLCA software and discuss the results, highlighting how this tool helps quantify and mitigate the environmental impacts of constructing and operating DIW systems. This choice ensures that the environmental assessments are relevant, comprehensive, and supportive of sustainable development goals specific to the geographical context of the project.

3.2.1.1. Environmental Impact: Global Warming Potential (GWP)

Our study identified significant contributors to GWP from emissions associated with constructing the wells.

- Drilling operations: This includes emissions from the machinery used for drilling deep into the earth. It covers the energy-intensive drilling process as well as emissions from machinery and vehicles employed.
- Materials for DIW construction: Emissions associated with producing essential materials like concrete and steel casings. Concrete production typically involves extracting raw materials, grinding, and mixing as well as rotary kiln processes. Steel casing production involves blending, mixing, and sintering operations in furnaces.
- Transportation and logistics: Capture emissions from transporting materials to the construction site and associated logistics.

Given the specialized nature of the DIW system and lack of prior research on their LCA, this study provides novel insights into GWP from their construction. Understanding these primary contributors can help identify more sustainable construction methodologies to reduce the environmental impacts of these important wastewater management systems.

3.2.1.2. Environmental Impact: Ozone Layer Depletion

Given the importance of the ozone layer, it is important to assess the contribution of DIW system construction.

Ozone layer depletion was quantified in terms of CFC-11 (trichlorofluoromethane) equivalent. This measures degradation due to emissions of trichlorofluoromethane or CFC-11, a powerful greenhouse gas with far greater potential impact than carbon dioxide and a long atmospheric presence (Steven, 2022)

While traditional sources of depletion mainly come from sectors like petroleum and gas production, this study aims to explore the potential impacts of constructing a DIW system. The construction process encompassing drilling operations, machinery emissions, and materials used could all contribute to ozone layer depletion.

3.2.1.3. Environmental Impact: Respiratory Effects (Non-Carcinogenic)

We elaborate below on the potential contributors to non-carcinogenic respiratory impacts during construction:

- Drilling and machinery emissions: The operation of heavy machinery, especially for drilling and construction, may emit particulates and gases that can impact respiration. Their scale and duration warrant assessment.
- Material production: Materials used (certain metals or chemicals) may originate from processes that contribute to respiratory impacts. For example, extracting and processing metals or producing some chemicals could release emissions affecting respiration.

- Transportation and logistics: Vehicles transporting materials or involved in logistics may emit pollutants impacting respiration, including combustion emissions and potential particulate matter.

3.2.1.4. Environmental Impact: Photochemical Oxidation

For constructing the DIW system, key processes identified as potential contributors to photochemical oxidation include:

- Drilling and equipment operations: Machinery used in drilling can release significant NOx emissions from diesel engines, contributing to overall photochemical oxidation.
- Material production: Materials like certain metals, chemicals, or cement used may originate from processes emitting NOx, so their production needs accounting, even if off-site.
- Transportation and logistics: Vehicle movement of equipment and materials to/from the construction site can emit NOx, especially from diesel engines.
- Energy use during construction: Any on-site combustion energy generation or use can contribute to NOx emissions, including temporary power units during construction.

3.2.1.5. Environmental Impact: Eutrophication

For constructing DIW system, potential sources contributing to eutrophication include:

- Drilling fluids and additives: Fluids and additives used during drilling sometimes contain nitrogen and phosphorus compounds. Improper management could allow seepage into local water systems.

- Site runoff: Construction sites can produce runoff from rain or other water sources. Runoff containing high-nutrient materials or residues could introduce nutrients into water bodies.
- Waste disposal: Improper waste disposal or management, especially of nutrient-rich materials, may contribute to eutrophication.
- Transportation and equipment emissions: While a lesser factor, vehicle, and equipment emissions could deposit nitrogen compounds on the ground that later enter water systems.

3.2.1.6. Environmental Impact: Resource Depletion

For constructing the DIW system for wastewater disposal, potential sources contributing to resource depletion include:

- Drilling equipment and infrastructure: Specialized equipment and materials made from metals/alloys required for deep drilling. Their production leads to depletion.
- Construction materials: Materials needed for physical infrastructure like steel casings often have resource-intensive production processes, contributing to depletion.
- Drilling fluids and chemicals: Some chemicals and fluids used in drilling may originate from non-renewable sources, adding to their depletion.
- Energy consumption: Energy required for drilling and construction is possibly sourced from non-renewable sources, leading to their depletion.

3.2.1.7. Environmental Impact: Water Use

Specific activities that contribute to water consumption during construction were identified to evaluate associated environmental impacts:

- Drilling Fluids Preparation: An integral phase where water is used to formulate drilling fluids/muds. These fluids serve important functions in drilling by reducing friction and stabilizing the wellbore.
- Pumping Test: Conducted after construction, this test requires pumping water out of the well to analyze recovery/aquifer properties, leading to major water usage.

3.2.1.8. Environmental Impact: Acidification Potential

Specific activities that contribute to acidifying emissions during construction:

- Drilling Fluids and Materials: Chemicals and materials used for drilling could emit compounds exacerbating acidification.
- Equipment Emissions: Machinery for drilling and construction may emit gases during operation potentially contributing to acidification, notably from high-sulfur fuels.
- Material Processing: Processes involved in producing or incorporating materials into the well structure, such as metals or construction compounds, may release sulfur emissions with acidifying potential.

3.2.1.9. Environmental Impact: Land Use

Construction activities risk increased SOC losses:

- Drilling Site Preparation: Clearing land removes vegetation and disturbs the soil, contributing to SOC loss.
- Infrastructure Development: Establishing roads, facilities, etc. may require additional land clearance and the loss of SOC.
- Waste Management Pits: Pits created for drilling waste disposal can also result in substantial SOC depletion.

- Materials Extraction Sites: While not direct construction, extraction sites for materials like gravel and sand used could experience SOC losses if newly created or expanded to supply the project.

3.3. Interpretation

This final phase of the methodology involved synthesizing data from varied sources to interpret the life cycle impacts of well construction. This process involved integrating direct data from contractors and project estimates with extrapolated data from academic literature. A key challenge in this phase was aligning the diverse data sets to ensure a coherent and accurate interpretation of the environmental impacts. For instance, the environmental impact data from heavy machinery was contextualized using research from Khan & Huang (2023) and was critically compared to the baseline data from project estimates.

The full process in Figure 11 shows the current method used for DIW construction was studied and analyzed.

Figure 11. Construction full process.

The initial phase of constructing a DIW system is mobilization. This stage involves preparing and transporting essential equipment and materials to the construction site. Key items delivered include the drilling rig, excavator, drilling materials, generators, mud pump, and water tankers. site facilities like rest shelters and storage areas are also set up.

Next, pre-site works prepare the ground. Excavators create mud pits needed for drilling operations. Transportation for workers and safety inspections of pits are conducted.

The drilling phase involves circulating drilling mud using the mud pump and generators. The drilling rig is used to drill wells. Drill samples are periodically collected and sent for laboratory analysis. Transportation for workers continues. Once drilling is complete, casing installation secures the well structure. A mobile crane handles and installs steel casing materials.

Grouting then secures the well integrity. A cement mixer prepares grout which is pumped into the well. Transportation supports continue.

In the final well development phase, processes like airlifting and pumping tests ready the well for operations. Water usage and geophysical surveys conclude construction activities while considering transportation needs.

Overall, the key phases involve preparing and operating various equipment and machinery powered by sources like diesel, electricity, and compressed air. Coordinated transportation supports workers throughout construction.

The case study was guided by a system boundary that followed the sequence of previously outlined process steps where the environmental performance was evaluated over the product lifecycle. These operations were structured in seven states including the production of materials, mobilization, pre-site activities, drilling, grouting, casing, and well development. Each step was subject to an independent comparative analysis to identify the specific indicators of environmental impact applicable to every process. The findings were then combined to get a broad picture of the environmental impact. The study went to a detailed assessment of every phase and finally considered all the phase's sum environmental impacts to produce a total view of the life cycle's environmental impact.

After the results were analyzed, we also suggested alternatives for each phase to show the most sustainable practice for improving DIW system construction.

3.3.1. *Current Practice for the DIW Construction*

As discussed, the following will be the showing the results of the environmental impact indicators for each phase.

3.3.1.1. Mobilization

Mobilization is the initial phase that transitions the project from planning to execution. This phase involves logistical coordination to gather and transport all essential resources to the site. Diesel-powered vehicles are key in delivering specialized equipment and materials. As Figure 12 shows, the drilling rig, central to operations, along with an excavator for site preparation, is the first to arrive. Following are the continuous deliveries of drilling materials, site facilities, generators, mud pumps, and water tankers. Careful orchestration ensures that all necessary components are on-site, allowing construction activities to begin safely and efficiently.

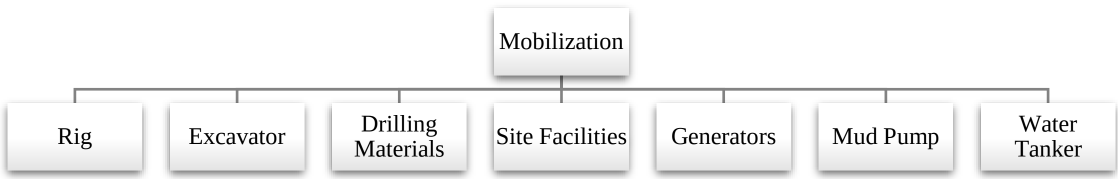

Figure 12. Mobilization activities.

3.3.1.2. Pre-Site Works

Pre-site work is the subsequent phase in the construction of a DIW well, involving preliminary groundwork. Notably, a diesel-powered excavator operates for 108 minutes to create the mud pit. Transportation is twofold: workers are shuttled to and from the site, totaling 40 km each day, and additionally make a 10 km daily round trip for lunch. Similarly, the supervisor engineer follows the same travel routine.

Manual tools such as shovels, pickaxes, and hoes are employed for initial inspections and site preparations.

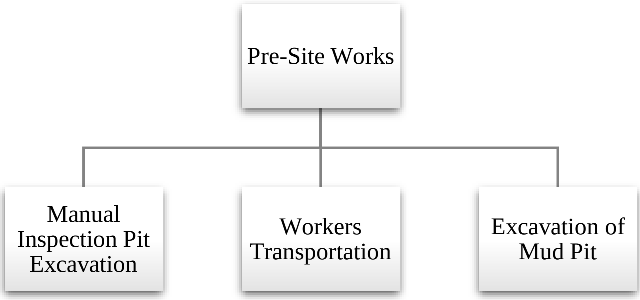

Figure 13. Pre-site work activities.

This phase has a specific environmental footprint associated with diesel usage, as evidenced in the upcoming LCIA results. The LCIA data will provide insights into the environmental impacts of diesel consumption for excavator operation, worker transportation, and tool usage, highlighting the importance of these activities in the overall environmental profile of well construction.

3.3.1.3. Drilling Works

The drilling phase, the main aspect of constructing the DIW system, contains various activities. It includes powering the mud pump and the drilling rig, both using diesel, to maintain fluid circulation and facilitate drilling. The preparation of drilling mud, involving a mud pump powered by a generator and using materials like water and bentonite, is another key component. Additionally, this phase involves the transportation of drill samples to laboratories and the daily commuting of workers, both vehicles fueled by diesel.

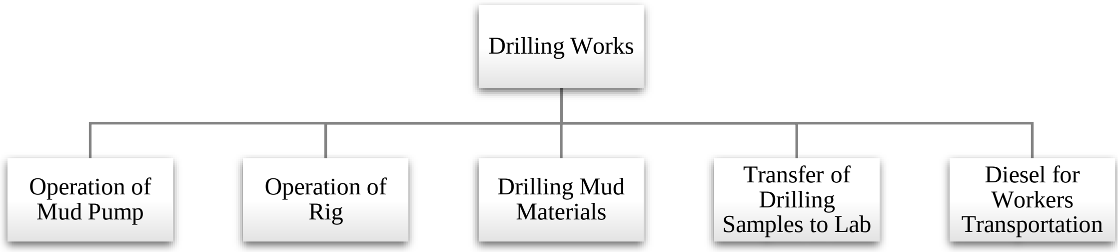

Figure 14. Drilling works activities.

3.3.1.4. Steel Casing

The steel casing is an important phase of this process. This phase includes several activities:

Firstly, installing the steel casings that were made by the Basic Oxygen Furnace (BOF) method then it goes to the site and requires using a mobile crane, which relies on a diesel engine to perform the intricate task. This process is integral to ensuring the well's stability and structural integrity. Additionally, transporting workers and supervisors to the site each day utilizing diesel-powered vehicles is also a notable part of this phase. The amount of steel needed for the casings represents a major material input for the project. Not only does this impact the structural aspects, but the quantity of steel used also influences the overall environmental impact given steel production requirements. Proper installation of the casings helps achieve the structural objectives while managing impacts. Figure 15 visually illustrates the activities, providing a clear graphical representation of the phase.

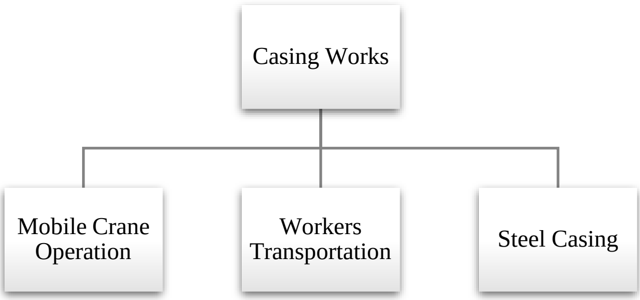

Figure 15. Casing works activities.

3.3.1.5. Grouting Works

The grouting phase is a parallel step with the drilling construction, ensuring the stability of the well by filling the fractures that have been made from the drilling. It involves as can be seen in Figure 16. mixing and injecting a cement, water, and bentonite mixture using equipment (Pump and Cement mixer) powered by diesel. The process requires coordination and precision to ensure the well's integrity. Additionally, the transportation of workers primarily uses diesel vehicles. The environmental impact of this stage, particularly in terms of material usage and fuel consumption.

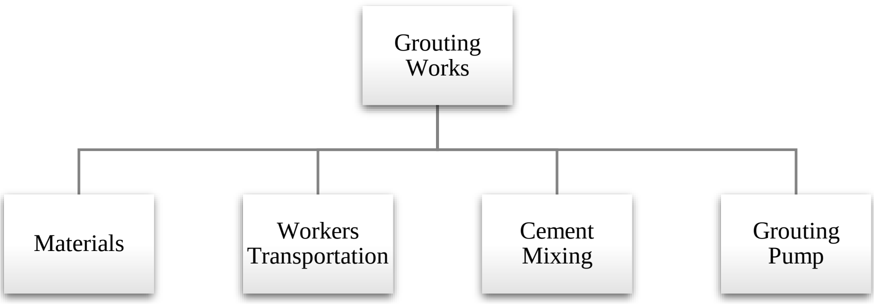

Figure 16. Grouting works activities.

3.3.1.6. Well Development Works

This phase is directly after drilling, grouting, and casing are finished, and several activities are carried out. As can be seen from Figure 17 it includes using diesel-powered air compressors for airlifting, which is important for cleaning the well. Pumping tests are also conducted, requiring diesel for the pumps. Additionally, this phase includes the transportation of workers to and from the site, mainly using diesel vehicles.

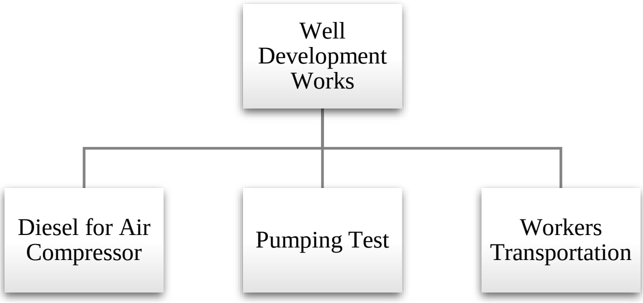

Figure 17. Well-development works activities.

3.3.1.7. Aggregated Results

The section will synthesize the findings from the previous construction stage analyses to provide a holistic view of DIW system implementation.

3.3.2. Analysis Interpretation

In the final step of the study, the LCA approach to evaluate the environmental impacts of constructing a DIWS was applied. By examining each phase of construction, a comprehensive insight into the process was gained. By standardizing the impacts of a single well system, we were able to assess the environmental effects more clearly. Key environmental concerns such as greenhouse gas emissions, land use, and water consumption were quantified using methods consistent with EPA guidelines, ensuring a thorough and reliable evaluation of the construction process.

3.3.3. Addressing Uncertainties and Assumptions

This study acknowledges the uncertainties and assumptions involved, particularly in the extrapolation of environmental impacts for specific machinery. The approach of scaling LCA results from similar machinery introduces potential variability in the results.

CHAPTER 4. RESULTS AND DISCUSSION

The system boundary framework was applied to the case study using the process sequence that is discussed above to evaluate the life cycle environmental impacts. Individual comparative assessments of the six phases mentioned in the methodology (Mobilization, Pre-Site Works, Drilling, Grouting, Casing, and Well Development) were performed and the results were compiled to quantify the environmental impact indicators in the process. Each phase will be discussed in detail. Then after evaluating all the environmental impacts of all the phases separately, the system for a complete life cycle is also analyzed to give a full view of the total result.

After the results were analyzed, we also suggested alternatives to show the most sustainable practice for improving DIW system construction.

4.1. Current Practice for the DIW Construction

As discussed, the following will be the showing the results of the environmental impact indicators for each phase.

4.1.1. Mobilization

Table 9 presents the LCIA for the mobilization activities. It details the environmental impacts associated with the delivery of each piece of equipment, from the drilling rig to the water tankers, across various impact categories such as Acidification, Ecotoxicity, Eutrophication, Global Warming, Ozone Depletion, Photochemical Oxidation, and Carcinogenic and Non-Carcinogenic effects on Human Health. Each category quantifies the impacts, providing a comprehensive view of the mobilization phase's environmental footprint.

Table 9. LCIA Results – Mobilization.

Impact Category	Reference Unit	Site Facilities	Generator	Mud Pump
Acidification	moles of H+	3.98E+01	2.65E+01	2.65E+01
Ecotoxicity	kg 2,4-D	5.65E+01	3.77E+01	3.77E+01
Eutrophication	kg N	1.23E-02	8.21E-03	8.21E-03
Global Warming	kg CO2	3.83E+00	2.55E+00	2.55E+00
Ozone Depletion	kg CFC-11	2.47E-06	1.64E-06	1.64E-06
Photochemical Oxidation	kg NOx	7.06E-02	4.71E-02	4.71E-02
Carcinogenic	kg benzene	8.74E-01	5.82E-01	5.82E-01
Non-Carcinogenic	kg toluene	2.57E+04	1.72E+04	1.72E+04
Respiratory Effects, Average	kg PM2.5	1.39E-01	9.26E-02	9.26E-02

Impact Category	Reference Unit	Rig	Excavator	Drilling Materials
Acidification	moles of H+	7.96E+01	7.96E+01	3.98E+01
Ecotoxicity	kg 2,4-D	1.13E+02	1.13E+02	5.65E+01
Eutrophication	kg N	2.46E-02	2.46E-02	1.23E-02
Global Warming	kg CO2	7.65E+00	7.65E+00	3.83E+00
Ozone Depletion	kg CFC-11	4.93E-06	4.93E-06	2.47E-06
Photochemical Oxidation	kg NOx	1.41E-01	1.41E-01	7.06E-02
Carcinogenic	kg benzene	1.75E+00	1.75E+00	8.74E-01
Non-Carcinogenic	kg toluene	5.15E+04	5.15E+04	2.57E+04
Respiratory Effects, Average	kg PM2.5	2.78E-01	2.78E-01	1.39E-01

Impact Category	Reference Unit	Water Tankers	Total Mobilization
Acidification	moles of H+	2.65E+01	**3.18E+02**
Ecotoxicity	kg 2,4-D	3.77E+01	**4.52E+02**
Eutrophication	kg N	8.21E-03	**9.86E-02**
Global Warming	kg CO2	2.55E+00	**3.06E+01**
Ozone Depletion	kg CFC-11	1.64E-06	**1.97E-05**
Photochemical Oxidation	kg NOx	4.71E-02	**5.65E-01**
Carcinogenic	kg benzene	5.82E-01	**6.99E+00**
Non-Carcinogenic	kg toluene	1.72E+04	**2.06E+05**
Respiratory Effects, Average	kg PM2.5	9.26E-02	**1.11E+00**

The LCIA results are integral in understanding the broader environmental consequences of deep-well construction, specifically highlighting the significant role of diesel consumption during the mobilization phase. These findings pave the way for discussions on potential improvements and the identification of areas where environmental performance can be optimized. Besides the table, Figure 18 presents a bar chart that illustrates the LCIA results graphically.

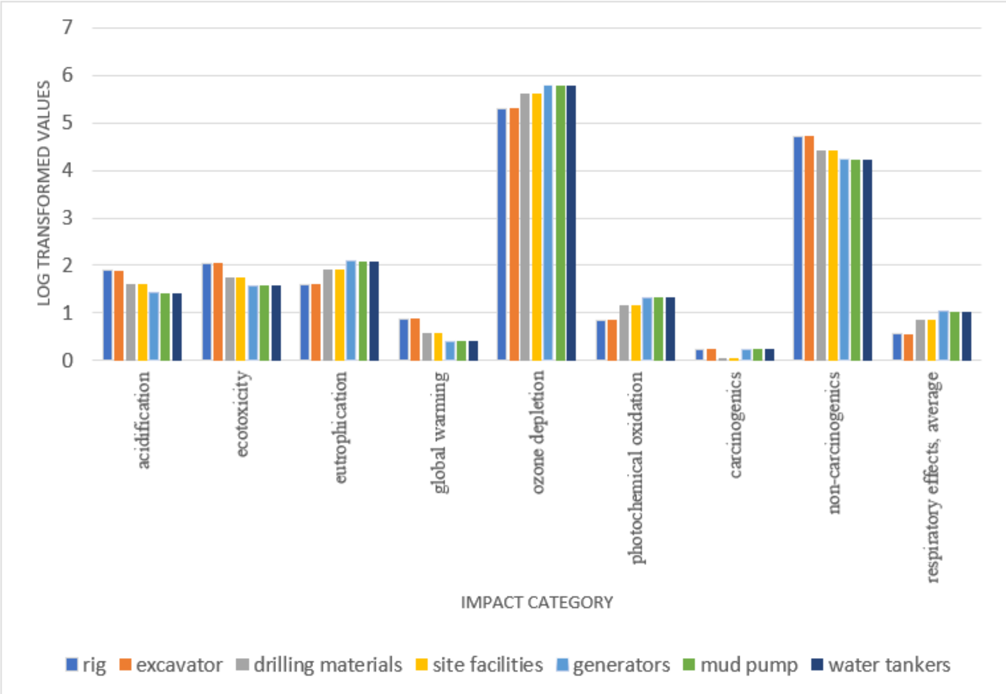

Figure 18. LCIA results – mobilization works.

4.1.2. Pre-Site Works

This phase has a specific environmental footprint associated with diesel usage, as evidenced in the upcoming LCIA results. The LCIA data will provide insights into the environmental impacts of diesel consumption for excavator operation, worker transportation, and tool usage, highlighting the importance of these activities in the overall environmental profile of well construction.

Table 10. LCIA Results – Pre-Site Works.

Impact category	Reference unit	Diesel for Excavator	Transportation Vehicle
acidification	moles of H+	5.49E+02	1.76E+02
ecotoxicity	kg 2,4-D	1.15E+03	2.50E+02
eutrophication	kg N	2.47E-01	5.45E-02
global warming	kg CO2	5.01E+01	1.69E+01
ozone depletion	kg CFC-11	7.75E-05	1.09E-05
photochemical oxidation	kg NOx	1.66E+00	3.13E-01
Carcinogenic	kg benzene	1.81E+01	3.87E+00
non-Carcinogenic	kg toluene	5.24E+05	1.14E+05
respiratory effects, average	kg PM2.5	1.43E+00	6.14E-01

Impact category	Reference unit	Materials of Manual Inspection Pit	Total
acidification	moles of H+	1.17E+01	**1.27E+03**
ecotoxicity	kg 2,4-D	1.66E+01	**2.55E+03**
eutrophication	kg N	3.61E-03	**5.49E-01**
global warming	kg CO2	1.12E+00	**1.17E+02**
ozone depletion	kg CFC-11	7.22E-07	**1.66E-04**
photochemical oxidation	kg NOx	2.07E-02	**3.64E+00**
Carcinogenic	kg benzene	2.56E-01	**4.00E+01**
non-Carcinogenic	kg toluene	7.54E+03	**1.16E+06**
respiratory effects, average	kg PM2.5	4.07E-02	**3.47E+00**

Adjacent to the table, Figure 19 presents a bar chart that illustrates the LCIA results graphically. This visualization effectively highlights the environmental impacts linked to each specific task in the phase, offering a visual comprehension of the data.

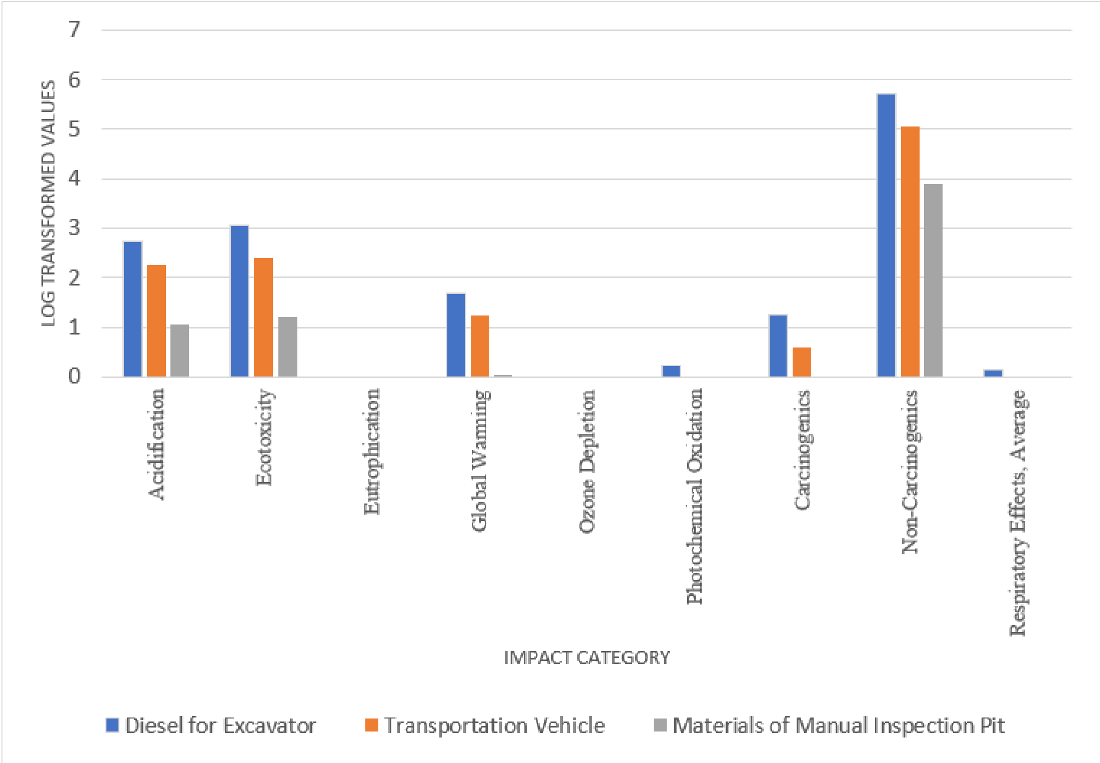

Figure 19. LCIA results – pre-site works.

4.1.3. Drilling Works

What is shown in Table 11 contributes to the environmental footprint of the drilling phase, specifically through their fuel and energy consumption, as will be analyzed in the forthcoming LCIA results.

Table 11. LCIA Results – Drilling Works.

Impact Category	Reference Unit	Mud Pump	Rig Operation	Water Mud
acidification	moles of H+	7.23E+01	2.22E+03	1.30E+03
ecotoxicity	kg 2,4-D	1.03E+02	3.16E+03	3.81E+02
eutrophication	kg N	2.24E-02	6.88E-01	9.33E-02
global warming	kg CO2	6.95E+00	2.14E+02	1.28E+02
ozone depletion	kg CFC-11	4.48E-06	1.38E-04	3.13E-05
photochemical oxidation	kg NOx	1.28E-01	3.94E+00	3.51E-01
Carcinogenic	kg benzene	1.59E+00	4.88E+01	5.30E+00
non-Carcinogenic	kg toluene	4.67E+04	1.44E+06	1.70E+05

Impact Category	Reference Unit	Transportation of Samples	Vehicle	Total
acidification	moles of H+	7.05E+01	1.76E+02	**3.84E+03**
ecotoxicity	kg 2,4-D	1.00E+02	2.50E+02	**3.99E+03**
eutrophication	kg N	2.18E-02	5.45E-02	**8.80E-01**
global warming	kg CO2	6.77E+00	1.69E+01	**3.72E+02**
ozone depletion	kg CFC-11	4.37E-06	1.09E-05	**1.89E-04**
photochemical oxidation	kg NOx	1.25E-01	3.13E-01	**4.86E+00**
Carcinogenic	kg benzene	1.55E+00	3.87E+00	**6.11E+01**
non-Carcinogenic	kg toluene	4.56E+04	1.14E+05	**1.81E+06**
respiratory effects, average	kg PM2.5	2.46E-01	6.14E-01	**1.53E+01**

Accompanying the table is a bar chart in Figure 20, visually depicting the LCIA results. This chart provides a clear graphical representation of the environmental impacts associated with each activity during the drilling phase.

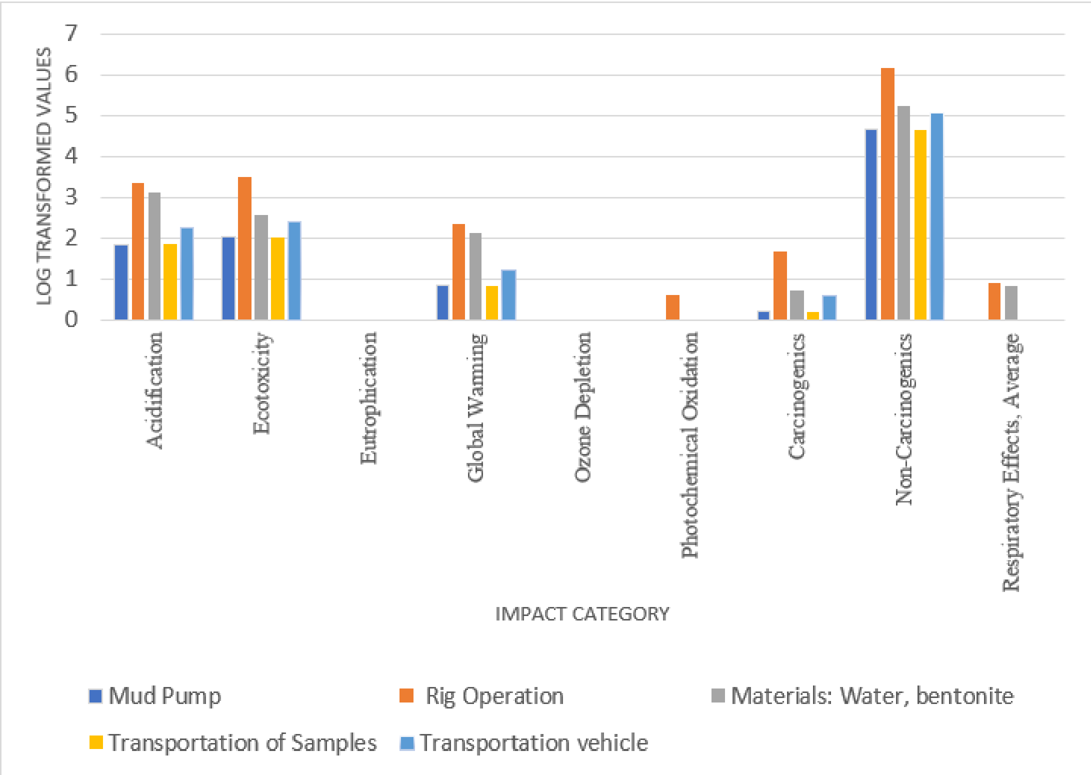

Figure 20. LCIA results – drilling works.

4.1.4. Steel Casing

The environmental impacts of the activities, particularly focusing on diesel consumption and steel usage, are detailed in the subsequent LCIA results.

Table 12. LCIA Results – Casing Works.

Impact Category	**Reference Unit**	**Mobile Crane**	**Vehicle**
acidification	moles of H+	8.96E+01	1.76E+02
ecotoxicity	kg 2,4-D	1.27E+02	2.50E+02
eutrophication	kg N	2.77E-02	5.45E-02
global warming	kg CO2	8.61E+00	1.69E+01
ozone depletion	kg CFC-11	5.55E-06	1.09E-05
photochemical oxidation	kg NOx	1.59E-01	3.13E-01
Carcinogenic	kg benzene	1.97E+00	3.87E+00
non-Carcinogenic	kg toluene	5.79E+04	1.14E+05
respiratory effects, average	kg PM2.5	3.12E-01	6.14E-01

Impact Category	Reference Unit	Steel	Total
acidification	moles of H+	2.69E+04	**2.72E+04**
ecotoxicity	kg 2,4-D	5.61E+04	**5.65E+04**
eutrophication	kg N	1.21E+01	**1.22E+01**
global warming	kg CO2	2.46E+03	**2.48E+03**
ozone depletion	kg CFC-11	3.76E-03	**3.78E-03**
photochemical oxidation	kg NOx	8.12E+01	**8.16E+01**
Carcinogenic	kg benzene	8.82E+02	**8.87E+02**
non-Carcinogenic	kg toluene	2.56E+07	**2.58E+07**
respiratory effects, average	kg PM2.5	7.02E+01	**7.11E+01**

Along with the table is a bar chart in Figure 21, visually depicting the results that provide a graphical representation of the impacts associated with each activity during the phase, allowing for an intuitive understanding of the data.

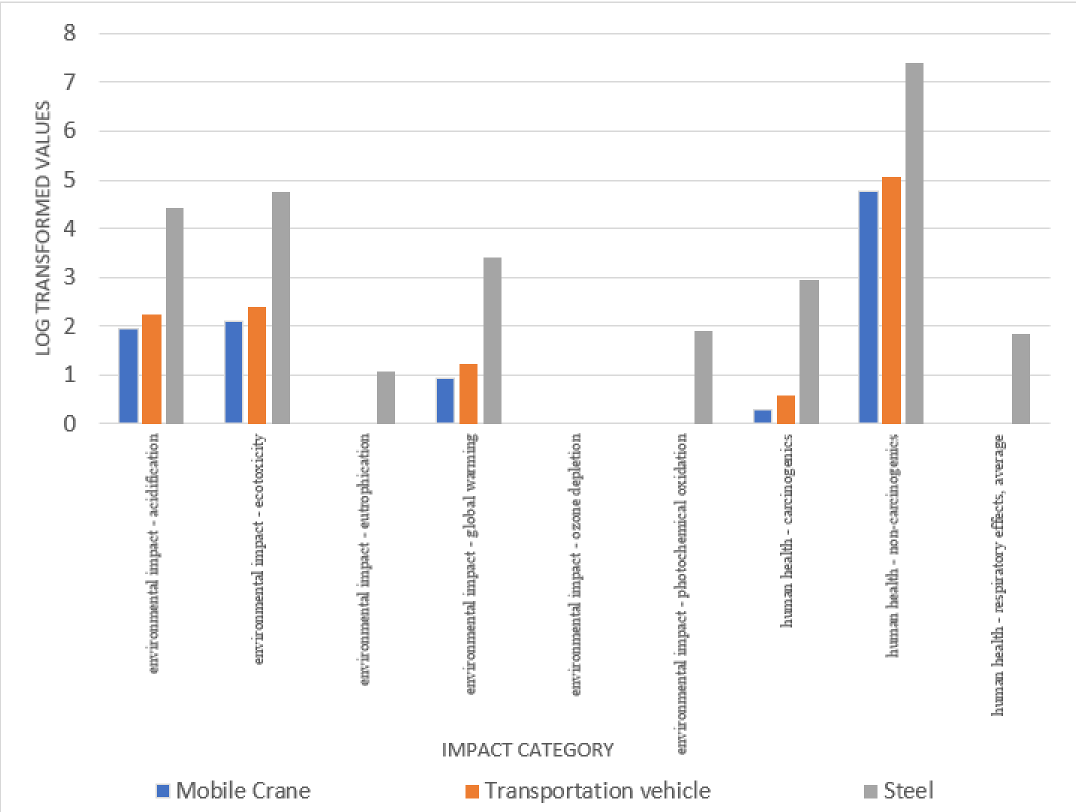

Figure 21. LCIA results – casing works.

4.1.5. Grouting Works

Table 13 presents these environmental impacts, and Figure 22 will provide a graphical representation of the data, offering a visual insight into the environmental footprint associated with the grouting activities.

Table 13. LCIA Results – Grouting Works.

Impact Category	Reference Unit	Materials	Cement Mixer Operation	Grouting Pump
acidification	moles of H+	1.38E+05	1.93E+02	7.23E+01
ecotoxicity	kg 2,4-D	4.10E+04	2.74E+02	1.03E+02
eutrophication	kg N	1.00E+01	5.97E-02	2.24E-02
global warming	kg CO2	1.36E+04	1.85E+01	6.95E+00
ozone depletion	kg CFC-11	3.29E-03	1.20E-05	4.48E-06
photochemical oxidation	kg NOx	3.64E+01	3.42E-01	1.28E-01
Carcinogenic	kg benzene	5.72E+02	4.23E+00	1.59E+00
non-Carcinogenic	kg toluene	1.83E+07	1.25E+05	4.67E+04
respiratory effects, average	kg PM2.5	6.86E+02	6.73E-01	2.52E-01

Impact Category	Reference Unit	Transportation Vehicle	Total
acidification	moles of H+	1.76E+02	**1.39E+05**
ecotoxicity	kg 2,4-D	2.50E+02	**4.17E+04**
eutrophication	kg N	5.45E-02	**1.02E+01**
global warming	kg CO2	1.69E+01	**1.37E+04**
ozone depletion	kg CFC-11	1.09E-05	**3.31E-03**
photochemical oxidation	kg NOx	3.13E-01	**3.72E+01**
Carcinogenic	kg benzene	3.87E+00	**5.82E+02**
non-Carcinogenic	kg toluene	1.14E+05	**1.86E+07**
respiratory effects, average	kg PM2.5	6.14E-01	**6.87E+02**

Along with the table above, a bar chart in Figure 22 gives a visual representation.

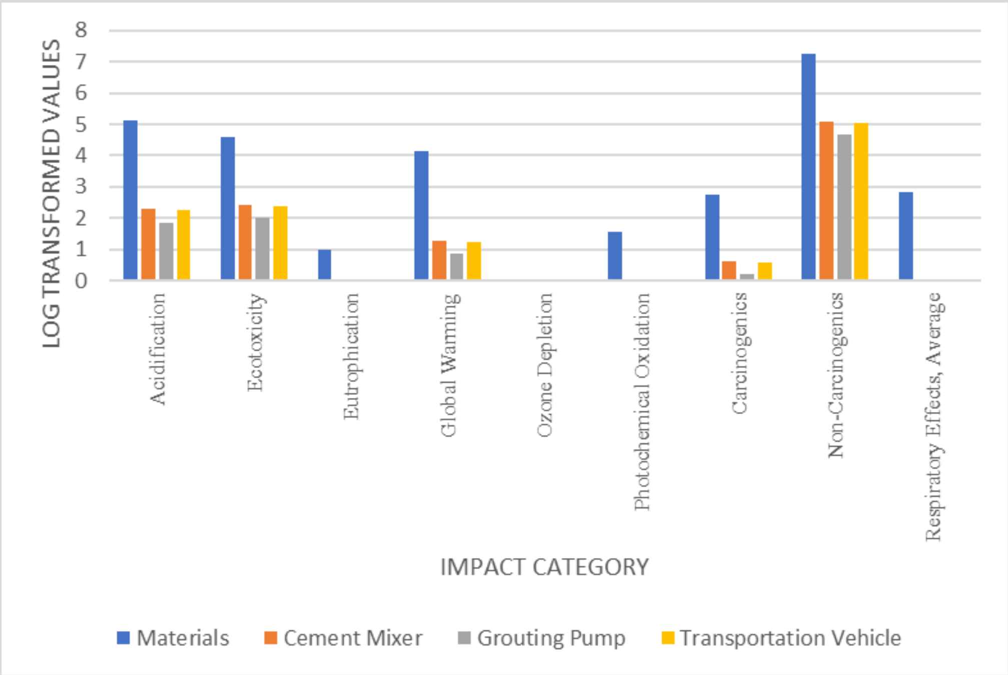

Figure 22. LCIA results – grouting works.

4.1.6. Well Development Works

The activities for this phase are crucial for ensuring the operational efficiency and safety of the well, but as with most of the phases, it has specific environmental impacts, particularly in terms of diesel and water usage. These impacts will be quantified and presented in the LCIA results in Table 14 below.

Table 14. LCIA Results – Well Assembly Works.

Impact Category	**Reference Unit**	**Air Compressor Operation**	**Transportation Vehicle**
acidification	moles of H+	7.05E+00	1.76E+02
ecotoxicity	kg 2,4-D	1.00E+01	2.50E+02
eutrophication	kg N	2.18E-03	5.45E-02
global warming	kg CO2	6.77E-01	1.69E+01
ozone depletion	kg CFC-11	4.36E-07	1.09E-05
photochemical oxidation	kg NOx	1.25E-02	3.13E-01
Carcinogenic	kg benzene	1.55E-01	3.87E+00
non-Carcinogenic	kg toluene	4.55E+03	1.14E+05
respiratory effects, average	kg PM2.5	2.46E-02	6.14E-01

Impact Category	Reference Unit	Pumping Tests Pump	Total
acidification	moles of H+	4.33E+01	**2.27E+02**
ecotoxicity	kg 2,4-D	6.15E+01	**3.22E+02**
eutrophication	kg N	1.34E-02	**7.01E-02**
global warming	kg CO2	4.16E+00	**2.18E+01**
ozone depletion	kg CFC-11	2.68E-06	**1.40E-05**
photochemical oxidation	kg NOx	7.68E-02	**4.02E-01**
Carcinogenic	kg benzene	9.50E-01	**4.97E+00**
non-Carcinogenic	kg toluene	2.80E+04	**1.46E+05**
respiratory effects, average	kg PM2.5	1.51E-01	**7.90E-01**

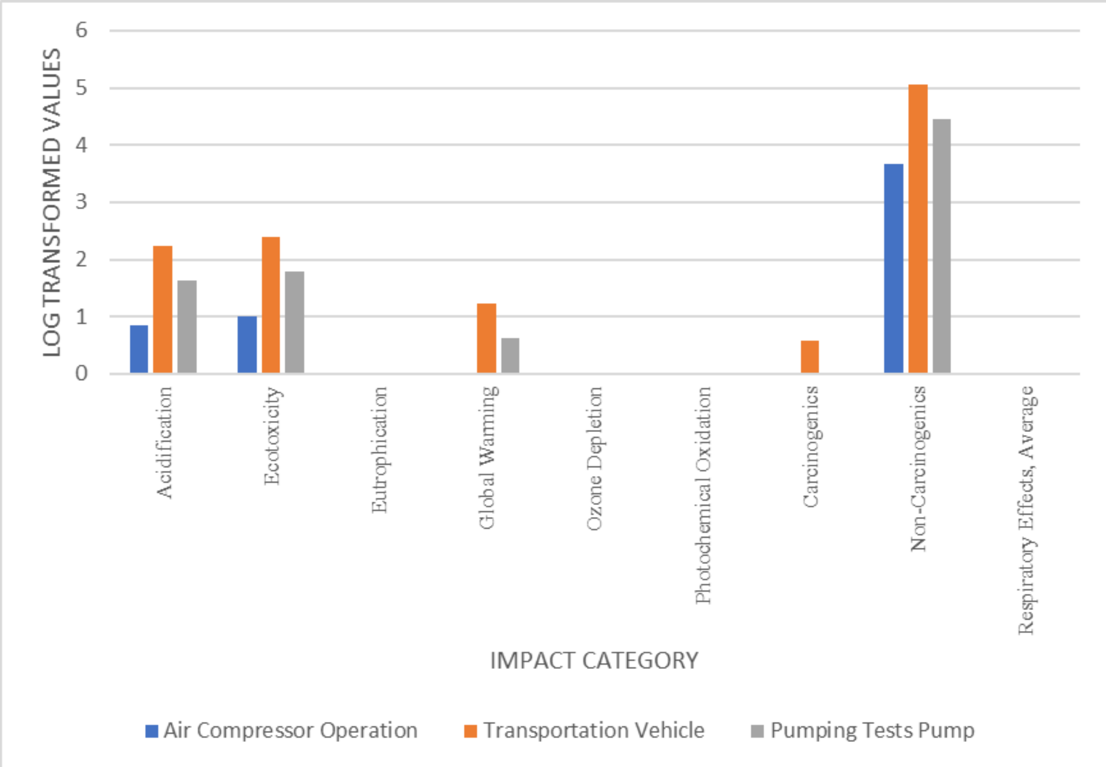

Figure 23. LCIA results – well assembly works.

4.1.7. Aggregated Results

The total aggregated results are shown in the following Table 15 and the visual representation is in Figure 24.

Table 15. LCIA Results – Aggregated Results.

Impact Category	Reference Unit	Mobilization	Pre-Site Works	Casing Works
acidification	moles of H+	3.18E+02	1.27E+03	2.72E+04
ecotoxicity	kg 2,4-D	4.52E+02	2.55E+03	5.65E+04
eutrophication	kg N	9.86E-02	5.49E-01	1.22E+01
global warming	kg CO2	3.06E+01	1.17E+02	2.48E+03
ozone depletion	kg CFC-11	1.97E-05	1.66E-04	3.78E-03
photochemical oxidation	kg NOx	5.65E-01	3.64E+00	8.16E+01
Carcinogenic	kg benzene	6.99E+00	4.00E+01	8.87E+02
non-Carcinogenic	kg toluene	2.06E+05	1.16E+06	2.58E+07
respiratory effects, average	kg PM2.5	1.11E+00	3.47E+00	7.11E+01

Impact Category	Reference Unit	Grouting Works	Drilling Works	Well Assembly Works
acidification	moles of H+	1.39E+04	3.84E+03	2.27E+02
ecotoxicity	kg 2,4-D	4.17E+03	3.99E+03	3.22E+02
eutrophication	kg N	1.02E+01	8.80E-01	7.01E-02
global warming	kg CO2	1.37E+04	3.72E+02	2.18E+01
ozone depletion	kg CFC-11	3.31E-03	1.89E-04	1.40E-05
photochemical oxidation	kg NOx	3.72E+01	4.86E+00	4.02E-01
Carcinogenic	kg benzene	5.82E+02	6.11E+01	4.97E+00
non-Carcinogenic	kg toluene	1.86E+07	1.81E+06	1.46E+05
respiratory effects, average	kg PM2.5	6.87E+02	1.53E+01	7.90E-01

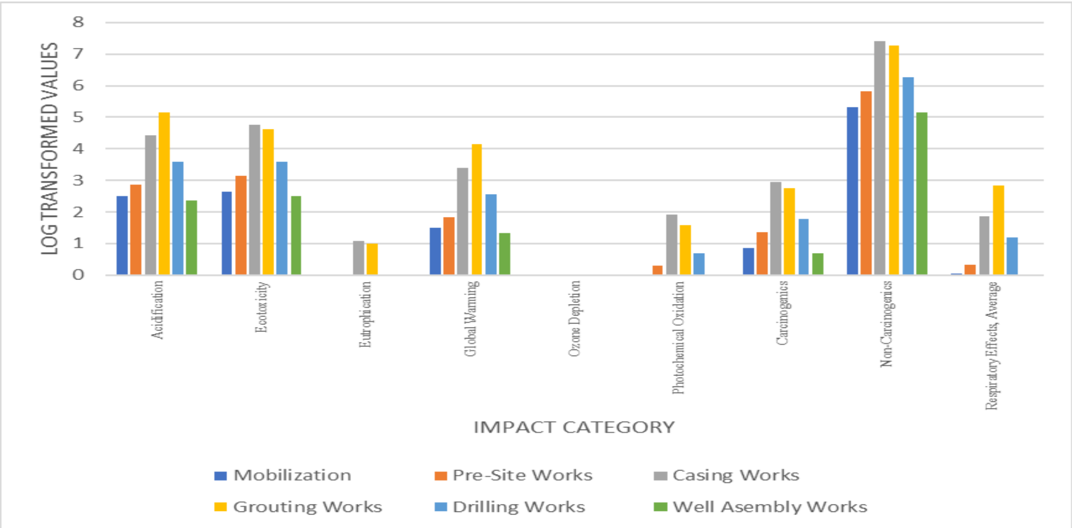

Figure 24. LCIA results – Aggregated results.

The following Table 16 will represent the aggregated results as a percentage of the total of each category.

Table 16. LCIA Results – Aggregated Results.

Impact Category	**Reference Unit**	**Mobilization**	**Pre-Site Works**	**Casing Works**
acidification	moles of H+	0.19%	0.43%	15.89%
ecotoxicity	kg 2,4-D	0.43%	1.36%	54.13%
eutrophication	kg N	0.42%	1.29%	51.34%
global warming	kg CO2	0.18%	0.41%	14.93%
ozone depletion	kg CFC-11	0.27%	1.20%	51.04%
photochemical oxidation	kg NOx	0.45%	1.58%	64.46%
Carcinogenic	kg benzene	0.45%	1.42%	56.73%
non-Carcinogenic	kg toluene	0.44%	1.37%	54.59%
respiratory effects, average	kg PM2.5	0.14%	0.27%	9.15%

Impact Category	**Reference Unit**	**Grouting Works**	**Drilling Works**	**Well Assembly Works**
acidification	moles of H+	81.11%	2.25%	0.13%
ecotoxicity	kg 2,4-D	39.94%	3.83%	0.31%
eutrophication	kg N	42.94%	3.71%	0.30%
global warming	kg CO2	82.11%	2.24%	0.13%
ozone depletion	kg CFC-11	44.75%	2.55%	0.19%
photochemical oxidation	kg NOx	29.36%	3.84%	0.32%
Carcinogenic	kg benzene	37.19%	3.91%	0.32%
non-Carcinogenic	kg toluene	39.45%	3.84%	0.31%
respiratory effects, average	kg PM2.5	88.37%	1.97%	0.10%

4.1.7.1. Contribution Of Each Phase Per Environmental Impact Category (EIC)

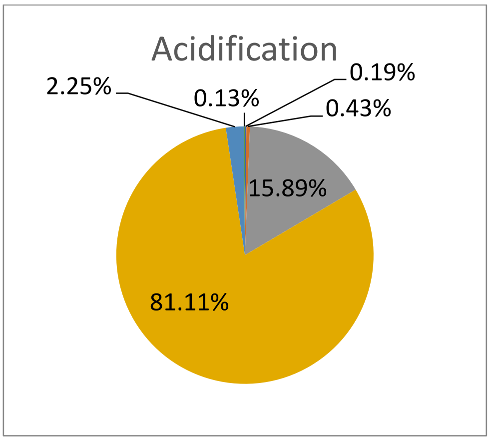

Figure 25. Acidification percentages.

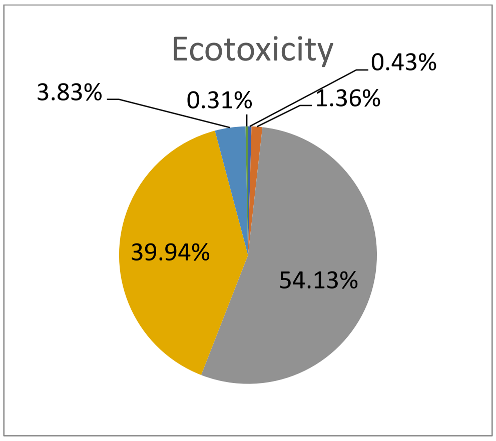

Figure 26. Ecotoxicity percentages.

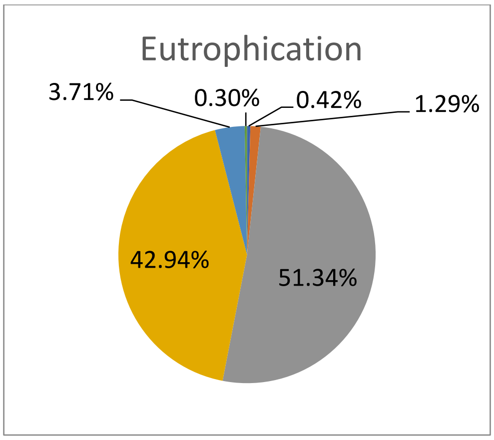

Figure 27. Eutrophication percentages.

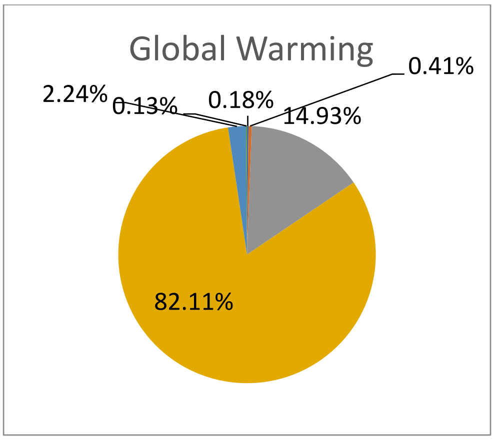

Figure 28. Global warming percentages.

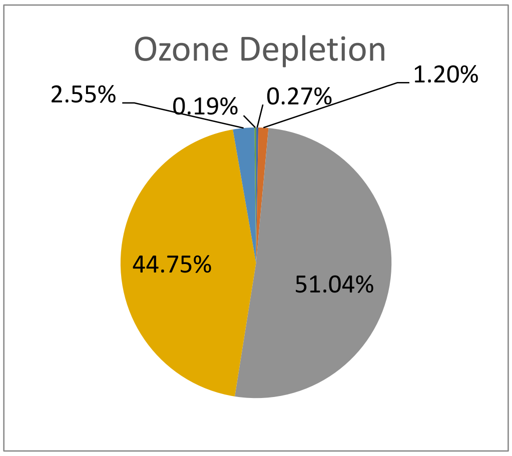

Figure 29. Ozone depletion percentages.

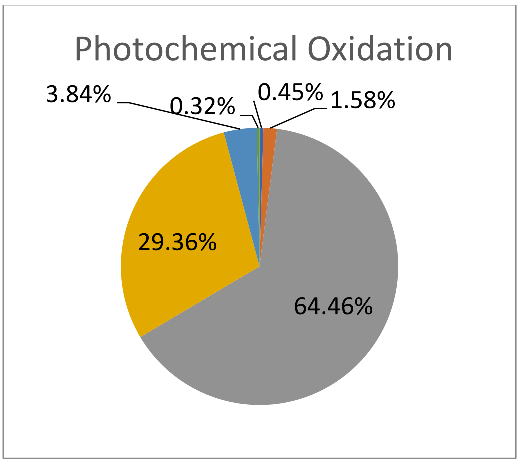

Figure 30. Photochemical oxidation- percentages.

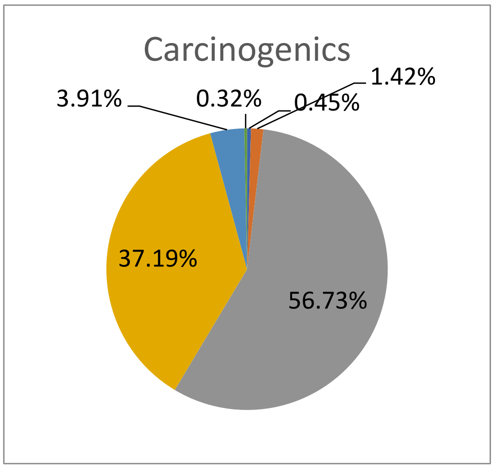

Figure 31. Carcinogenics percentages.

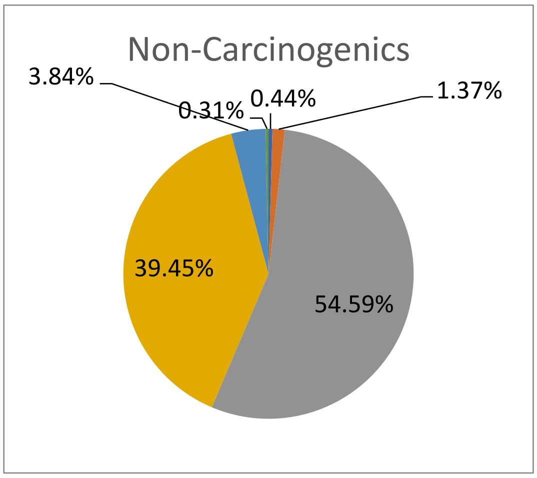

Figure 32. Non-Carcinogenics percentages.

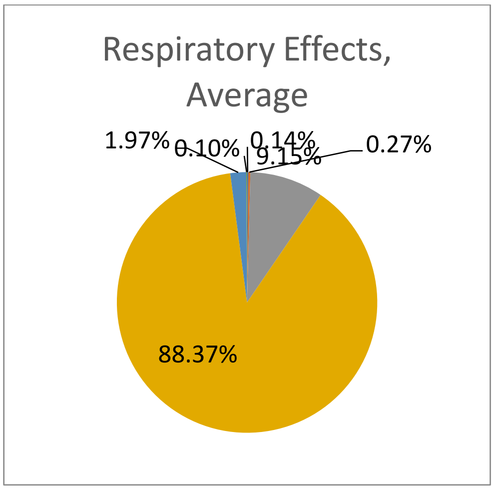

Figure 33. Respiratory effects percentages.

In assessing the environmental repercussions that come up in different stages of construction phases, it is crucial to identify crucial environmental and health impact categories to which each stage contributes. Besides, such a study provides a tool for identifying the most critical stages and strategizing a mitigating plan to deal with the environmental crises in a better way.

The map shown in Figure 25 indicates acidification contributions dominated by the Grouting Works part, i.e., (81.11%) of the impact from this category. The growing share of mobilizing in this mode of traffic brings to the fore the urgent need to implement more sustainable practices that can contribute to reducing the acidification effects.

Concerning ecotoxicity impacts in Figure 26, drill casing operations account for (54.13%) of the overall ecotoxicity which exceeds all the other operation phases. The speak-up period percentage is quite significant, meaning there are a lot of toxins being emitted during Casing Works, which gives us the eyebrow to look at the materials and methods used.

Eutrophication, one of the major sources of environmental problems, has been analyzed lastly in Figure 27. In percentage, we note that the Casing Works and Grouting Works categories rank number one (51.34%) and number two (42.94%), yet the latter is most relevant. Not only do we notice that the basic figures demonstrate the truly significant role that nutrient runoff, attached to these processes, has in eutrophication, but also this investigates the true reason for the affected organizations to ensure a runoff and waste material's good management.

The construction phases play a quantifying role in global warming potential (%GWP) which is demonstrated in the diagram below. Figure 28 shows that the GWP of the Grouting stage is (82.11%) which is the biggest one in the phases of the greenhouse gas. Such a thing involves a thorough review of how energy is used and how many emissions are generated in the Grouting Works phase to identify possibilities for the emission footprint reduction in this phase.

The Ozone depletion in Figure 29 is a dangerous environmental issue Casing and Grout Works were the big drivers that provided (51.04%) and (44.75%) contributions respectively. This shows that ozone-depleting substances are released in these steps, restrictions and explicit adoption of ozone harmless practices and materials should be placed, therefore.

The fact that the data on Photochemical Oxidation Figure 30 shows the largest portion of the Casing Works (64.46%) and Grouting Works (29.36%) underlines the significance of the operations. These important impacts include the release of ground-level ozone and smoke resulting in the necessity of regulation of emissions and VOCs and NOx in such activities.

Simultaneously Figure 31 and 30 above show that Casing Works mainly spoils the environment through carcinogenic effects (56.73%) and non-carcinogenic effects (54.59%). This is an issue of direct exposure to hazardous materials, making the safety measures for the workers and surrounding population more important than ever. Likewise, those companies working with such dangerous materials and processes should seriously reflect on possible alternatives that would be less harmful.

Also, Respiratory Effects shown in Figure 33, being the most predominant effect (88.37%) in Grouting Works, demonstrates the considerable release of fine particle matter, such as PM2.5, that occurs during this phase of pipe relining. It can be concluded that the establishment of dust control measures and the implementation of air quality management programs could be a solution to get rid of the poor state of respiratory health.

4.2. Proposed Practice for the DIW Construction

Considering the assessment of the environmental impacts associated with traditional methods of DIW construction, this section outlines a series of proposed improvements aimed at enhancing the sustainability of the construction process. These recommendations, derived from the detailed analysis presented in previous sections, focus on pivotal changes in equipment and materials, as well as operational modifications, to significantly reduce the environmental footprint of the construction.

4.2.1. New Cement Type Suggestion for Grouting

The environmental impact values associated with the Grouting Works phase, as indicated in Table 15, are significant and serve as a crucial reason for investigating alternatives to traditional cement. The high percentages attributed to this phase in various environmental impact categories highlight the need for a more sustainable option.

There is a recommendation for the adoption of geopolymers as an alternative to traditional cement in the construction of DIWs. This recommendation is grounded in the significant environmental benefits highlighted by geopolymers, as detailed in several studies, one of the studies is "An environmental evaluation of geopolymer based concrete production: reviewing current research trends" (Habert et al., 2011).

4.2.1.1. Why Geopolymers Stand Out

- **Lower Carbon Footprint:** Geopolymers are celebrated for their notably lower carbon footprint, with research suggesting that they can cut CO2 emissions by up to half when compared to traditional cement (Gomez et al., 2019).
- **Durability and Mechanical Properties:** Geopolymers meet and even surpass the specifications in civil engineering, where they exhibit excellent resistance to

carbonation, acid, and high temperatures. Their robustness in extreme environmental conditions makes them suitable for rehabilitation and demanding construction scenarios (Dai et al., 2023; Dufka et al., 2013).

- **Water and Chemical Resistance:** The geopolymer binders, are dependent on both permeability and durability through the distribution of pores, unreacted particles, and cross-linked regions. These are the key features by which service life can be predicted in aggressive environments (Provis and Deventer, 2010).
- **Performance in Severe Environments:** Geopolymers have been proven to perform very well in severe environmental conditions, implying their use in restoration for reinforced concrete structures, among other severe applications. Their capability to manage severe environmental stress makes them advantageous for special applications in construction (Dufka et al., 2014).
- **Flexibility:** The inherent ductility of geopolymers provides advantages, allowing them to adapt effectively to the dynamic pressures and temperatures encountered underground (Dufka et al., 2014).

4.2.1.2. Operational Considerations for Geopolymer

- **Adaptations in technical nature:** Geopolymers hold particular challenges and advantages that call for changes in construction technology. An example is the design of the mixture, application, and curing procedures, which are far from equivalent in the case of traditional Portland cement. Special care should be addressed to the chemical composition and the activation of geopolymerization reactions for the optimal performance of geopolymer products in the intended application (Devarajan et al., 2023).

- Operational Protocols Use of geopolymers will require adjustment of operational protocols. In this regard, adjustments will have to be made in terms of materials preparation and handling, as well as the timing of the various phases of construction. Realizing the environmental benefits and improvement in durability the geopolymers may offer, such adjustments could be very critical (Obonyo et al., 2011).
- **Environmental and Economic Aspects:** The new geopolymer formulations promise better mechanical and durability characteristics and, at the same time, provide critical ecological advantages such as the reduction of CO2 emissions and the potential for accommodating industrial by-products. A complete training and development course is being called for construction professionals so that the maximum potential of geopolymers can be unlocked (Sbahieh et al., 2023).

4.2.1.3. Associated Cost for Applying Geopolymer

Analysis shows that proposed material costs would increase. Conventional cement costs $10-20 per bag on average, while geopolymer concrete ranges from $20-50 per bag. This suggests costs could nearly double (Indexbox.io, 2024).

However, environmental impacts would substantially decrease by around half. Adopting geopolymer concrete provides long-term advantages like enhanced durability and a reduced carbon footprint. Thus, it helps us achieve sustainability goals.

4.2.2. Transition To Electric-Powered Equipment

A central element of the proposed approach involves the transition from diesel-powered to electric-powered machinery. This shift includes replacing diesel engines in drilling rigs, excavators, vehicles, and pumps with their electric counterparts. Electric machinery offers a dual advantage: it significantly reduces the reliance on diesel fuel, thus curtailing emissions related to its combustion, and it supports a transition towards cleaner energy sources.

4.2.2.1. Carbon Emissions Calculation

The calculations revealed that operating the referenced excavator powered by diesel fuel for one hour emits 88.81 kg of CO_2, while one hour powered by an electric engine emits 67.18 kg of CO_2. This foundational information allows extending the analysis to other equipment and operational scenarios involved in DIW construction.

For example, the drilling rig, which utilizes a 200-kW combustion engine, was evaluated for its environmental impact over 320 hours of operation. By applying the scaled emission calculation methodology derived from the excavator baseline data, CO_2 emissions from the drilling rig during this period were estimated to be approximately 250 kg. Quantifying emissions in this way sheds light on how operational parameters of various machinery translate to potential impacts. The approach aims to provide decision-relevant insights about lowering carbon footprints by assessing alternatives to combustion engines or optimizing equipment usage.

4.2.2.2. Electric Engine Capacity and Emissions

The study employed a methodology to estimate the motor capacity needed for electric equipment to match the operational performance of diesel-powered machines. Based on baseline excavator data showing a 168-kW diesel engine paired with a 300-kWh electric engine, it was extrapolated that a 200-kW diesel engine would require a 400-kWh motor using a scaling approach.

This conversion methodology, grounded in analyzing the relationship between diesel engines and electric engine specifications, provided a framework to quantify CO_2 emissions from electric-driven equipment. Applying this scaling logic, operating a drilling rig powered by a 400-kWh electric engine instead of the standard 200-kW diesel engine configuration was estimated to result in approximately 6 kg CO2 over the same operational period.

By systematically correlating technical parameters between diesel and electric options, this approach aimed to facilitate objective, quantitative comparisons that could offer insights toward transitioning to lower-carbon alternatives. The goal was to holistically evaluate sustainability impacts from different equipment in a standardized, data-driven manner.

Table 17 below presents calculated emissions from using diesel engines versus electric motors to power the construction machinery considered in this study. The values were derived following the methodology outlined above.

Table 17. CO2 Emissions – Diesel And Electric Batteries.

Equipment	Diesel - Kwh	Electric Engine - Kwh	Unit (Hours Operational)	Global Warming (Kg CO2/Unit)	
				Diesel Engine	Electric Engine
Drilling Rig	200	400	320	213	6
Water Pump	6.5	10	320	7	0.2
Crane	75	130	34.6	9	0.23
Cement Mixer	340	600	16.4	20	0.5
Compressor	17	30	11.6	1	0
Pumping Test Pump	26	45	48	5	0.1
Total				**255**	**7**

The calculations indicate that this shift would result in an overall reduction from 255 Kg to 7 Kg of CO2 emissions. This figure not only highlights the effectiveness of the proposed modifications but also underscores the potential for substantial environmental benefits in adopting cleaner energy solutions within DIW construction practices.

To reduce the environmental impact of DIW construction, we are taking a strategic approach to replacing diesel-powered equipment with electric alternatives.

Instead of replacing all equipment at once, which would be expensive, we suggest prioritizing the machinery that produces the most emissions – specifically, the drilling rig. This focused approach allows us to:

- Reduce emissions significantly.
- Keep costs manageable.

By targeting the equipment with the biggest impact, we can make a meaningful difference in the environmental footprint of DIW construction while still being cost-effective.

4.2.2.3. Associated Cost for Electric Drilling Rig

Analysis shows that proposed investment costs for the drilling rig would increase. Conventional rig costs $200,000-400,000 on average (schramm.com, 2022), while electric rig ranges from $500,000-750,000. This suggests costs could nearly double (schramm.com, 2022).

However, environmental impacts would substantially decrease by around 97% (the reduction for the rig in Table 17 from 213 to 6 kg Co2). Adopting the electric engine technology provides long-term advantages like enhanced durability and a reduced carbon footprint. These benefits better achieve sustainability goals.

The calculations indicate that this shift would result in an overall reduction of 97% in CO2 emissions. This figure not only highlights the effectiveness of the proposed modifications but also underscores the potential for substantial environmental benefits in adopting cleaner energy solutions within DIW construction practices.

4.2.3. Material optimization - steel

One proposal considered to enhance the sustainability of DIW construction practices is transitioning steel production methods. Existing research indicates the Electric Arc Furnace (EAF) method has environmental advantages compared to the currently used Basic Oxygen Furnace (BOF) method.

As previously discussed in the section 3.1.2.5, the BOF process is energy-intensive with significant emissions. In contrast, the EAF method has a relatively lower environmental impact primarily due to a higher recycled material input ratio and improved energy efficiency.

Adopting EAF steel production could help reduce the project's carbon footprint while supporting sustainable resource use and environmental protection. This methodology shift reflects a commitment within the construction sector to incorporate best practices that minimize impacts.

As shown in Table 18, preliminary estimates suggest transitioning to EAF could lower CO_2 emissions by approximately 37.13% compared to BOF-produced steel. Overall, given its performance benefits demonstrated in existing studies, further exploring EAF adoption aims to evaluate opportunities to optimize DIW construction sustainability. Additional considerations may include technical and economic feasibility factors relevant to project planning and implementation.

Table 18. CO_2 emissions – Steel production

Impact Category	**Unit**	**BOF (Current)**	**EAF (Proposed)**
Climate Change	kg CO2 / 240 Kg	590.16	219.12

4.2.4. Analytical Overview

The adoption of these proposed practices offers a significant reduction in the environmental footprint of DIW construction. This approach aligns with the broader objectives of sustainable development and environmental stewardship. Further, it sets a guide for future construction projects, emphasizing the importance of integrating environmental considerations into every phase of construction. The subsequent Tables and figures will quantify and represent the impacts of these improvements, providing a view of the potential benefits of these modifications.

4.2.4.1. Expected Results from Proposed Improvements

The implementation of proposed sustainable practices in the construction of DIWs promises a considerable enhancement in environmental performance. The following Figure 34 captures the anticipated outcomes stemming from the adoption of geopolymer concrete as an alternative to traditional cement in grouting works, and the transition to electric-powered equipment, supplanting diesel-powered machinery, and also the steel manufacturing.

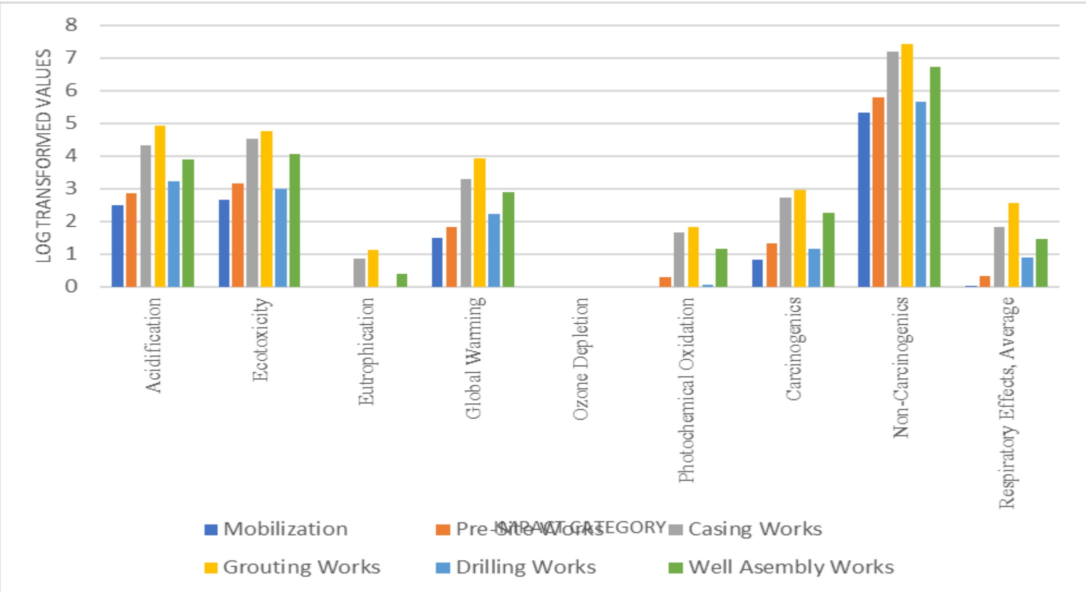

Figure 34. LCIA results – proposed aggregated results.

Table 19. Reduction Rate After Proposed Strategies.

Impact category	Reduction Rate
Acidification	32%
Ecotoxicity	0%
Eutrophication	0%
Global Warming	32%
Ozone Depletion	23%
Photochemical Oxidation	0%
Carcinogenic	0%
Non-Carcinogenic	0%
Respiratory Effects, Average	38%

In evaluating the life cycle sustainability of constructing Deep Injection Wells, we identified key areas where our proposed methods significantly after the environmental impacts compared to the current practices. The comparative analysis presents a picture as shown in Table 19 of how those proposed strategies may affect the environment and what are the challenges:

- **Acidification**: Our proposed approach yields a substantial decrease in acidification potential, cutting down the impact by 31.58%. This improvement demonstrates the effectiveness of our measures in reducing emissions that contribute to acid rain.
- **Global Warming**: We achieved a notable decline in contributions to global warming, with a 31.88% reduction in impact. This aligns with global efforts to mitigate climate change and underscores our commitment to sustainability.
- **Respiratory Effects**: The proposed methods lead to a 37.92% reduction in respiratory effect impacts, a significant health benefit contributing to less air pollution and improved air quality.

Conversely, the analysis also revealed increases in some environmental impacts, signaling areas for further improvement:

- **Ecotoxicity**: There's a slight increase of 3.85%, indicating that while our methods reduce overall toxicity, some aspects of the construction process still pose environmental challenges.

- **Eutrophication**: A marginal rise of 1.27% was observed, suggesting that nutrient runoff needs more stringent management strategies.
- **Photochemical Oxidation**: The increase of 3.94% prompts a review of our processes to lower emissions that contribute to smog formation.
- **Carcinogenic Impacts**: An increase of 5.77% calls for a reassessment of material choices and construction practices to minimize exposure to carcinogenic substances.
- **Non-Carcinogenic Impacts**: The slight rise of 4.03% in non-carcinogenic impacts highlights the necessity for continuous monitoring and evaluation of the non-carcinogenic risks associated with construction activities.

Overall, our proposed construction methods for DIWs illustrate a strong orientation towards reducing the carbon footprint and environmental impact, particularly in the key areas of acidification, global warming, and respiratory health effects, which are crucial for sustainable development and ecological conservation.

CHAPTER 5. CONCLUSION

The LCA of DIWs has cast a spotlight on the noticeable environmental effects essential in traditional construction methods. A comprehensive review from the initial mobilization to the final stages of well development has highlighted the pressing need for eco-friendly practices in the face of substantial emissions and intensive resource consumption. Drilling operations have been identified as major contributors to global warming potential and ecotoxicity, largely due to the prevalent use of diesel-powered equipment. The extensive use of materials like steel and concrete only amplifies the environmental burden, signaling an imperative for sustainable evolution in construction methodologies.

5.1. Evaluation of Alternative Technologies

The exploration of alternative technologies and practices, such as the transition to electric-powered equipment and the adoption of geopolymers to replace the traditional cement used, presented a promising path for reducing the environmental impacts of DIW construction. These alternatives not only offer a reduction in carbon emissions but also align with the principles of sustainable development by leveraging cleaner energy sources and more efficient material production methods.

5.2. Practical Implications and Recommendations

The study's findings support a model shift in DIW construction towards more sustainable practices. Adopting electric-powered machinery and alternative cement could significantly mitigate environmental impacts. Policymakers and industry stakeholders should consider revising construction standards and guidelines to incorporate these sustainable practices, promoting their widespread adoption.

Implementing sustainable practices in the construction of Deep Injection Well Systems requires a multi-faceted approach. This section outlines detailed policy recommendations and industry adoption strategies to facilitate the transition to environmentally friendly construction methodologies.

5.2.1. Policy Recommendations

5.2.1.1. Regulatory Support

Revise Construction Guidelines: To foster the adoption of sustainable practices, it is essential to revise existing construction guidelines. Policymakers should integrate specific provisions that mandate the use of eco-friendly materials and technologies. For instance, guidelines could require the utilization of geopolymer concrete instead of traditional Portland cement, given its lower carbon footprint and superior durability in aggressive environments. Additionally, construction codes should stipulate the use of electric-powered machinery where feasible, promoting a shift away from diesel-dependent equipment.

Develop and Enforce Standards: The development of new standards tailored to sustainable construction practices is critical. These standards should outline clear performance metrics for new materials and technologies, ensuring that they meet stringent environmental and safety criteria. Enforcement mechanisms, such as regular inspections and compliance audits, should be established to ensure adherence to these standards.

5.2.1.2. Incentives for Innovation

Financial Incentives: To motivate the construction industry to adopt sustainable technologies, policymakers should introduce financial incentives. These could include tax credits, subsidies, and grants for companies that invest in green technologies and materials. For example, tax reductions could be offered to firms that purchase electric machinery or use geopolymer concrete, offsetting the initial higher costs associated with these sustainable alternatives.

Regulatory Incentives: Regulatory incentives can also play a significant role in encouraging sustainable practices. Fast-track approvals for projects that incorporate green technologies and materials can reduce project timelines and costs, making sustainable construction more attractive. Furthermore, preferential treatment in public procurement processes for companies demonstrating a commitment to sustainability can drive broader industry adoption.

5.2.1.3. Support for Research and Development

Funding for Innovation: Government and industry stakeholders should collaborate to fund research and development in sustainable construction technologies. Allocating resources to universities and research institutions to explore advanced materials and construction methods can yield significant long-term benefits. For instance, continued research into the properties and applications of geopolymer concrete can lead to optimized formulations and wider industry acceptance.

Pilot Programs: Policymakers should also support pilot programs that test and demonstrate the efficacy of sustainable construction technologies in real-world projects. These pilot programs can provide valuable data and insights, helping to refine practices and build confidence among industry practitioners.

5.2.2. 5.2 Industry Adoption

5.2.2.1. Training and Development

Comprehensive Training Programs: To facilitate the adoption of sustainable construction practices, it is crucial to develop comprehensive training programs for construction professionals. These programs should cover the technical aspects of new materials and technologies, such as the properties and applications of geopolymer concrete and the operation of electric-powered machinery. Training should also address the environmental and economic benefits of sustainable practices, fostering a culture of sustainability within the industry.

Certification and Accreditation: Establishing certification and accreditation programs for professionals who complete training in sustainable construction practices can further incentivize participation. Recognized credentials can enhance career prospects and demonstrate a commitment to sustainability, encouraging more professionals to seek out and complete training programs.

5.2.2.2. Collaboration and Partnerships

Industry-Academia-Government Partnerships: Strengthening partnerships between industry, academia, and government is essential for accelerating research and development in sustainable construction technologies. Collaborative efforts can pool resources and expertise, leading to innovative solutions and faster implementation. Joint research projects, funded by public and private sectors, can explore new materials and methods, while government-backed initiatives can promote widespread dissemination of findings and best practices.

Knowledge Sharing Platforms: Creating platforms for knowledge sharing and collaboration can also drive industry adoption of sustainable practices. Conferences, workshops, and online forums can facilitate the exchange of ideas and experiences, helping to build a community of practice around sustainable construction. Case studies and success stories can inspire others to follow suit, showcasing the tangible benefits of adopting green technologies and materials.

5.2.2.3. Addressing Economic and Operational Challenges

Cost-Benefit Analysis: While sustainable materials and technologies often entail higher upfront costs, it is important to highlight the long-term economic benefits. Conducting and disseminating comprehensive cost-benefit analyses can demonstrate the return on investment for sustainable practices. For instance, although geopolymer concrete may be more expensive initially, its enhanced durability and reduced maintenance needs can lead to significant cost savings over the lifecycle of a project.

Overcoming Operational Barriers: Adopting new technologies and materials may pose operational challenges, such as the need for specialized equipment or adjustments to construction schedules. To address these barriers, companies should conduct pilot projects and phased implementations to gradually integrate sustainable practices into their workflows. Providing technical support and troubleshooting assistance can also help mitigate initial difficulties and build confidence among practitioners.

5.2.2.4. Long-Term Commitment to Sustainability

Sustainability Reporting: Encouraging companies to adopt sustainability reporting practices can promote transparency and accountability. Regular reporting on environmental performance, including metrics on emissions, resource use, and waste generation, can highlight progress and identify areas for improvement. Sustainability reports can also serve as valuable marketing tools, demonstrating a company's commitment to environmental stewardship to clients and stakeholders.

Continual Improvement: Finally, fostering a culture of continual improvement is key to long-term sustainability. Companies should regularly review and update their practices in light of new technologies and emerging best practices.

Engaging employees at all levels in sustainability initiatives can drive innovation and ensure that the entire organization is aligned with sustainability goals.

5.3. Environmental Impact Reduction Analysis

In assessing the environmental impact of DIW construction, it's essential to quantify the potential reductions that can be achieved through the proposed sustainable practices. This section provides a comparative analysis, presenting the environmental benefits as percentages, to illustrate the effectiveness of the adjustments recommended.

5.3.1. Current Environmental Impacts

The LCA of the current DIW construction practices identified significant environmental impacts across various categories, primarily attributed to high reliance on diesel-powered machinery and substantial use of materials like steel and cement.

5.3.2. Impact Reduction Through Proposed Adjustments

Anticipated reductions in environmental impacts are encouraging, with a transition to electric-powered equipment expected to reduce Global Warming Potential by 24.36%, and a projected reduction of over 50% in CO2 emissions with the introduction of geopolymer.

5.3.3. Comparative Analysis (% Reduction)

The analysis reveals that the proposed sustainable practices could significantly mitigate the environmental impacts of DIW construction, underscoring the potential for substantial improvements in sustainability within the construction sector.

5.3.4. Recommendations For Future Research

Future research should delve deeper into the life cycle impacts of DIW construction by expanding the scope to include operational and decommissioning phases. Investigating the long-term sustainability of alternative materials, such as geopolymer concrete, and the feasibility of integrating renewable energy sources into construction practices could provide further insights. Additionally, developing a comprehensive framework for assessing the environmental impacts of new technologies in the construction sector would be invaluable.

5.4. Final Thoughts

The current study on the environmental impacts associated with the construction of DIWs through detailed LCA has revealed a significant environmental footprint across various impact categories. The dependence on diesel-powered machinery and the increased use of materials such as steel and cement contribute significantly to these effects, emphasizing the need to shift towards more sustainable construction practices constantly emphasized.

In response to these findings, the proposed shift to electrically driven equipment and the adoption of geopolymers as alternatives to conventional cement offer suitable options to reduce the environmental footprint of DIW-use materials and production processes consistent with the broader objectives for sustainable development. The practical implications of these findings are far-reaching. The adoption of such sustainable practices can serve as a model for future construction projects, not only in the DIWs sector but also in the construction industry. Policymakers and industry stakeholders are encouraged to consider these findings in the development of building standards and guidelines, thereby promoting greater adoption of these environmentally friendly practices.

A comparative analysis of current and proposed practices in the study highlights the effectiveness of the recommended changes, showing a clear path toward reducing the environmental impacts associated with DIW construction. These proposed changes, based on sustainability principles, provide an opportunity to make a positive contribution to the construction industry.

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