Master Thesis

Environmental Sustainability Assessment of Water Pumping Stations

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2025

Environmental Sustainability of Water Pumping Stations

to obtain the degree of
Master of Science in Civil Engineering and Management
at the University of Twente,

to be presented on July 24, 2025

Colophon

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Version
Final version

Date
17 July 2025

Colloquium date
24 July 2025

Education
Faculty of Engineering Technology
Civil Engineering and Management (CEM)
Track: Sustainability

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Preface

This document presents my Master's thesis entitled: *"Environmental Sustainability Assessment of Water Pumping Stations"*. This research marks the final requirement for the completion of the Master of Science in Civil Engineering and Management at the University of Twente, with a specialisation in Sustainability.

The research was conducted over a period of six months and focuses on the application of Life Cycle Assessment (LCA) for evaluating the environmental performance of water pumping stations in the Netherlands. The study was carried out using DuBoCalc, a tool developed for sustainability assessment in Dutch civil engineering projects. The research was performed individually, but in collaboration with Aveco de Bondt.

Throughout my academic journey, I developed a growing interest in the field of sustainability, particularly in relation to infrastructure, construction and water systems. Courses such as Sustainable Engineering deepened my understanding of environmental evaluation methods and sparked my enthusiasm for incorporating sustainability into engineering practice. This thesis represents an opportunity to apply that knowledge to a real-world context and contribute to more sustainable decision-making within the water sector.

I would like to take this opportunity to express my sincere gratitude to everyone who supported me during this process. First and foremost, I wish to thank my university supervisors, Rosalie Arendt and Markus Berger, for their critical feedback, clear guidance, and continuous support. Your expertise and encouragement have been invaluable throughout this project. I am also really thankful to Willeke van de Wardt and Dirk van Hout, whose input and collaboration greatly enriched the practical relevance of this research. Furthermore, I would like to thank the whole 'gemalen'-team and other colleagues at Aveco de Bondt, for really treating me as a colleague and helping me in general with all my questions and requests, even during busy projects.

A special thanks goes to my family, friends, housemates, and most importantly, my girlfriend Annika, for their patience, interest, lovely support, and humour during the more challenging moments of this thesis. Your encouragement helped me to stay motivated and maintain perspective. I would also like to thank my fellow students and colleagues for the insightful discussions and enjoyable company during this period.

I hope this thesis provides valuable insights into the potential of life cycle-based sustainability assessment and supports further efforts towards more environmentally responsible civil engineering practices.

I hope you enjoy reading this thesis as much as I did working on it!

Niek Pouwels

Enschede

July 17, 2025

Summary

This master thesis investigates how sustainability assessment methods and circular economy (CE) principles can be applied to evaluate and improve the environmental and circular performance of water pumping stations in the Netherlands. Conducted in collaboration with engineering consultancy Aveco de Bondt, the research responds to national challenges such as climate change, sea level rise, ageing infrastructure, and growing policy ambitions for circular and climate-resilient public works. With over 7,800 pumping stations—many constructed between 1920 and 1960—the Netherlands faces a major infrastructure replacement challenge (vervangingsopgave), particularly given that approximately 40% of the country lies below sea level.

Framed by the central research question—*"How can sustainability assessment methods and circular principles be applied to evaluate and improve the circularity and environmental performance of water pumping stations?"*—the thesis follows a mixed-methods approach: literature review, expert interviews, development of material passports, and quantitative Life Cycle Assessment (LCA) modelling using DuboCalc and Nationale Milieudatabase (NMD) data. The Environmental Cost Indicator (MKI/ECI) is used as the primary metric to quantify life cycle environmental impact.

Two case studies provide contrasting perspectives: the large boezem station De Drie Delfzijlen, and the small, newly built polder station Noordeinde- en Geerpolder. These serve as empirical testbeds for 11 design variants per site, exploring interventions such as renewable energy integration, geopolymer concrete, reused or alternative sheet piles, prefabrication, and extended equipment life spans.

The results confirm that operational energy use is the dominant contributor to environmental impact, accounting for up to 90% of total MKI in larger stations like De Drie Delfzijlen. In smaller stations, however, material choices—particularly for foundations and concrete works—play a comparatively greater role. Across both cases, the application of circular design strategies and sustainable material choices enables MKI reductions of up to 50%, demonstrating that meaningful gains are feasible without compromising functionality.

Beyond MKI totals, analysis of life cycle phases reveals that the Use and Maintenance phase—dominated by electricity consumption—has the highest impact, followed by the Production phase, particularly concrete production. Scenario modelling shows that prefabrication and geopolymer concrete reduce the concrete-related impact by up to 37%. Similarly, circular alternatives like PVC sheet piles and EcoSheetPiles offer substantial reductions in the foundation component, with marginal differences between the steel-based variants. Moreover, comparing shorter (25-year) and longer (75-year) design lifespans shows that sustainability performance becomes increasingly dependent on material choices over time, particularly when using updated MKI datasets. This longer-term perspective highlights that certain low-impact materials—such as geopolymer concrete and Combar reinforcement—offer both environmental and financial advantages, especially when lifecycle performance is accounted for in design decisions.

A key innovation in the study is the operationalisation of Material Passports, which digitally document material composition, origin, and reuse potential. Their integration into asset management allows for long-term circularity tracking. The thesis combines this with CE frameworks such as Het Nieuwe Normaal and the Material Circularity Indicator to holistically evaluate disassemblability and reuse scenarios. Simpler systems like Noordeinde- en Geerpolder score higher in circularity metrics, reflecting the feasibility of low-impact design through reuse and transparency.

Nonetheless, the research also highlights limitations in current assessment tools. DuboCalc's reliance on outdated or non-transparent data, lack of profiles for innovative materials, and the MKI's static assumptions (e.g. fixed lifespan, shadow pricing) constrain the accuracy and usability of results. While an update to DuboCalc in 2026 promises improved, EU-compliant and inflation-corrected data, the current version lacks sufficient granularity and responsiveness for advanced CE assessments.

The thesis recommends embedding sustainability and circularity assessments in the early design phase, not post-procurement. It advocates for broader adoption of Material Passports, harmonised circularity indicators across water boards, and improved data governance in national LCA tools. Additionally, it emphasises design flexibility, modularity, and the strategic pairing of material efficiency with smart energy strategies (e.g. predictive maintenance, renewable integration).

In conclusion, this thesis contributes practical insights and applied methods for enhancing the sustainability and circularity of water infrastructure. It bridges theory and practice by integrating LCA, circular design principles, and qualitative expertise, and positions water pumping stations not just as functional assets, but as opportunities to lead in climate-neutral, future-proof infrastructure development.

Samenvatting

Deze masterscriptie onderzoekt hoe duurzaamheidsbeoordelingsmethoden en principes uit de circulaire economie (CE) kunnen worden toegepast om de milieuprestaties en circulariteit van Nederlandse watergemalen te evalueren en te verbeteren. Het onderzoek, uitgevoerd in samenwerking met ingenieursadviesbureau Aveco de Bondt, speelt in op nationale uitdagingen zoals klimaatverandering, zeespiegelstijging, verouderende infrastructuur en toenemende beleidsambities voor circulaire en klimaatbestendige publieke werken. Met meer dan 7.800 operationele gemalen—waarvan vele gebouwd tussen 1920 en 1960—staat Nederland voor een grote vervangingsopgave, zeker gezien het feit dat circa 40% van het land onder zeeniveau ligt.

De centrale onderzoeksvraag—*"Hoe kunnen duurzaamheidsbeoordelingsmethoden en circulaire principes worden toegepast om de circulariteit en milieuprestaties van gemalen te evalueren en verbeteren?"*—wordt beantwoord via een mixed-methods benadering, bestaande uit literatuurstudie, expertinterviews, de ontwikkeling van materialenpaspoorten, en kwantitatieve Levenscyclusanalyse (LCA)-modellering met behulp van DuboCalc en data uit de Nationale Milieudatabase (NMD). De Milieukostenindicator (MKI/ECI) wordt als primaire maatstaf gehanteerd om de milieubelasting over de gehele levenscyclus te kwantificeren.

Twee casestudies bieden contrasterende perspectieven: het grootschalige boezemgemaal De Drie Delfzijlen en het kleinschalige, nieuw gebouwde poldergemaal Noordeinde- en Geerpolder. Beide projecten dienen als empirisch kader voor het testen van 11 ontwerpvarianten per locatie, waarbij ontwerpmaatregelen worden onderzocht zoals de integratie van hernieuwbare energie, toepassing van geopolymere betonmengsels, hergebruik van damwanden, prefabricage en verlengde levensduur van technische installaties.

De resultaten bevestigen dat het energieverbruik in de gebruiksfase de grootste bijdrage levert aan de milieubelasting, met tot wel 90% van de totale MKI bij grotere gemalen zoals De Drie Delfzijlen. Bij kleinere gemalen speelt de materiaalkeuze—vooral in funderingen en betonconstructies—een relatief grotere rol. In beide gevallen tonen de scenarioanalyses aan dat toepassing van circulaire ontwerpstrategieën en duurzame materiaalalternatieven de MKI tot 50% kan reduceren, zonder concessies te doen aan functionele prestaties.

Naast de totaalscores biedt de analyse per levenscyclusfase aanvullende inzichten. De gebruiks- en onderhoudsfase, gedomineerd door elektriciteitsverbruik, veroorzaakt de hoogste impact, gevolgd door de productiefase, met name de betonproductie. Variantscenario's tonen aan dat prefabricage en geopolymere betonmengsels de impact op de betonnen onderdelen tot 37% kunnen reduceren. Ook circulaire alternatieven zoals PVC-damwanden en EcoSheetPiles leiden tot aanzienlijke reducties in de funderingscomponent, met beperkte verschillen tussen stalen varianten. Bovendien blijkt uit de vergelijking van kortere (25 jaar) en langere (75 jaar) ontwerplevensduren dat de milieuprestatie op lange termijn steeds meer afhangt van materiaalkeuzes, zeker bij gebruik van geactualiseerde MKI-datasets. Dit langetermijnperspectief onderstreept dat bepaalde materialen met een lage milieu-impact—zoals geopolymere beton en Combar-wapening—zowel ecologische als economische voordelen bieden, vooral wanneer de prestaties over de gehele levensduur worden meegewogen.

Een belangrijke innovatie binnen het onderzoek is de implementatie van materialenpaspoorten, digitale documenten die informatie bevatten over de samenstelling, herkomst en hergebruikspotentie van materialen. De integratie hiervan in assetmanagementsystemen maakt het mogelijk om circulariteit gedurende de hele levensduur van het gemaal te volgen. In combinatie met CE-raamwerken zoals Het Nieuwe Normaal en de Material

Circularity Indicator, bieden deze tools een holistische evaluatie van herbruikbaarheid en losmaakbaarheid. Eenvoudigere systemen zoals Noordeinde- en Geerpolder scoren hoger op circulariteitsindicatoren, wat wijst op de haalbaarheid van laag-impactontwerpen via hergebruik en transparantie.

Toch legt het onderzoek ook beperkingen bloot van bestaande beoordelingsinstrumenten. DuboCalc is sterk afhankelijk van verouderde of niet-transparante data, en de MKI hanteert statische aannames (zoals vaste levensduur en schaduwprijzen), wat de nauwkeurigheid en toepasbaarheid van de resultaten beperkt. Hoewel een update van DuboCalc in 2026 betere, gecertificeerde en EU-conforme data belooft, voldoet de huidige versie nog niet aan de eisen voor geavanceerde duurzaamheidsbeoordelingen.

De scriptie adviseert dan ook om duurzaamheid en circulariteit al in de vroege ontwerpfase te integreren, in plaats van pas bij aanbesteding of gunning. Daarnaast wordt gepleit voor bredere toepassing van materialenpaspoorten, harmonisatie van circulariteitsindicatoren tussen waterschappen, en verbeterd databeheer binnen nationale LCA-instrumenten. Flexibel ontwerpen, modulair bouwen en het combineren van materiaalefficiëntie met slimme energieoplossingen (zoals voorspellend onderhoud en variabele pompregelingen) worden aanbevolen als effectieve strategieën.

Concluderend levert deze scriptie waardevolle inzichten en toegepaste methodieken voor het verduurzamen en circulair maken van waterinfrastructuur. Door theorie, kwantitatieve analyses en praktijkervaring te combineren, biedt het concrete aanknopingspunten voor beleidsmakers, ontwerpers en beheerders. Gemalen worden hierbij niet alleen benaderd als technische assets, maar als kansrijke voorbeelden van klimaatneutrale, toekomstbestendige infrastructuur.

Contents

1 Introduction **3**

1.1 Background and Context . . . 3

1.2 Problem Context . . . 4

1.2.1 Impact of Climate Change . . . 5

1.2.2 Lifespan of Pumping Station Components . . . 5

1.2.3 Sustainability Assessments and MKI in Practice . . . 6

1.3 Chosen Case Studies to Evaluate . . . 6

1.3.1 Selection Rationale . . . 7

1.3.2 Characteristics of the Pumping Stations . . . 8

2 Literature Review **12**

2.1 Literature Questions . . . 12

2.2 Current State of Sustainability in Water Pumping Stations . . . 13

2.2.1 Policy and Guideline Frameworks . . . 13

2.2.2 Ecological Sustainability and Fish Migration . . . 13

2.2.3 Procurement and Governance . . . 13

2.2.4 Circular Asset Management and Data Challenges . . . 13

2.2.5 Overarching Challenges, Opportunities, and the Path Forward . . . 14

2.3 Lifecycle Environmental Impacts . . . 14

2.4 Sustainable Design Choices and Energy Efficiency . . . 15

2.4.1 Renewable Energy Integration . . . 15

2.4.2 Smart Technologies and Simulation Models . . . 15

2.4.3 Challenges and Future Research . . . 17

2.5 Circular Economy Principles . . . 17

2.5.1 Historical Development and Core Principles . . . 17

2.5.2 Circular Economy in Water Infrastructure . . . 17

2.5.3 Circular Economy Integration in Assessments . . . 18

2.6 International Standards and Certification Schemes . . . 18

2.6.1 Life Cycle Analysis (LCA) ISO Standard . . . 18

2.6.2 Sustainability Assessment Schemes . . . 18

2.6.3 Limitations and Future Directions . . . 20

2.7 Conclusion and Identified Research Gaps . . . 21

3 Research Objectives & Questions **22**

4 Methodology **24**
4.1 Research Design . . . 24
4.2 Life Cycle Assessment (LCA) Methodology . . . 26
4.2.1 Goal and Scope Definition . . . 26
4.2.2 Life Cycle Inventory (LCI) . . . 27
4.2.3 Impact Assessment . . . 28
4.2.4 Life Cycle Interpretation . . . 30

5 Assessment of Current Sustainability Evaluation Practices in Water Pumping Stations **31**
5.1 Systematic Review of Assessment Frameworks and Case Applications . . . 31
5.2 Expert Interview Synthesis and Workshop Insights . . . 33
5.3 Circularity Assessment in Water Pumping Stations . . . 35
5.3.1 Material Passport 'Noordeinde- en Geerpolder' . . . 37
5.3.2 Material Passport 'De Drie Delfzijlen' . . . 37

6 Environmental Impact Assessment of Water Pumping Stations using the MKI/ECI (LCA) method **40**
6.1 Goal and scope definition . . . 40
6.1.1 Function and Functional Unit . . . 40
6.1.2 System Boundaries . . . 41
6.1.3 Cut-off Criteria . . . 42
6.1.4 Allocation Procedure . . . 42
6.1.5 Data Requirements . . . 43
6.1.6 Assumptions . . . 43
6.2 Life Cycle Inventory (LCI) Analysis . . . 43
6.2.1 LCI for the Noordeinde- en Geerpolder water pumping station . . . 43
6.2.2 LCI for the De Drie Delfzijlen water pumping station . . . 47
6.3 Modelling Variants in DuboCalc for Sustainable Design Comparison . . . 50
6.3.1 Overview of Energy Consumption Estimates . . . 51
6.3.2 Energy Estimation for Noordeinde- en Geerpolder . . . 52
6.3.3 Energy Estimation for De Drie Delfzijlen . . . 53

7 Results: Environmental Impact Assessment from DuboCalc **55**
7.1 DuboCalc Results: Noordeinde- en Geerpolder . . . 55
7.1.1 MKI/ECI Results . . . 57
7.1.2 Climate Change GWP Results . . . 59
7.1.3 MKI/ECI Results per Life Cycle Phase . . . 61
7.2 DuboCalc Results: De Drie Delfzijlen . . . 62

7.2.1 MKI/ECI Results . . . 64
7.2.2 Climate Change GWP Results . . . 67
7.3 MKI/ECI Results 25 and 75 years lifespan . . . 69
7.4 Interpretation Phase . . . 73
7.4.1 Identification of Significant Issues . . . 73
7.4.2 Completeness Check . . . 74
7.4.3 Consistency Check . . . 74
7.4.4 Sensitivity Analysis . . . 74
7.4.5 Comparison between the two pumping stations in capacity terms . . . 75

8 Evaluation of LCA Challenges and Cost-Analysis of Sustainable Design Choices 76
8.1 Challenges in the Application and Interpretation of DuboCalc for Life Cycle Assessment in Dutch Civil Engineering . . . 76
8.2 Critical Review of DuboCalc and LCA Practice in Dutch Civil Engineering . . . 77
8.3 Cost Analysis of Sustainable Design Choices . . . 78

9 Development of Practical Design and Implementation Strategies 81

10 Discussion 84
10.1 Methodological Reflections on LCA and MKI/ECI . . . 84
10.2 Interpretation of Comparative Results and Scale Effects . . . 85
10.3 Circularity in Practice: Barriers and Opportunities . . . 86
10.4 Expert Insights and Institutional Dynamics . . . 86

11 Conclusions and Recommendations 88
11.1 Revisiting the Research Questions . . . 88
11.2 Key Lessons from the Case Studies . . . 90
11.3 Strategic and Practical Recommendations . . . 90
11.4 Broader Implications and Outlook . . . 91
11.5 Final Reflection . . . 92

Appendix A Modelling Assumptions 98

Appendix B Material Passports 100

Reader Guidance: Structure of This Thesis

This thesis investigates how sustainability assessment methods and circular economy principles can be applied to improve the environmental performance of water pumping stations in the Netherlands. The research follows a structured approach that integrates theoretical grounding, empirical case study analysis, and practical design recommendations. This section provides an overview of the contents and purpose of each chapter to guide the reader through the study's development.

Chapter 1 – Introduction

The opening chapter introduces the research context, emphasising the increasing importance of sustainable and resilient water management in the face of ageing infrastructure and climate change. It outlines the historical background of Dutch water pumping stations, the sustainability challenges they face, and the rationale for focusing on two specific case studies. The chapter concludes with an explanation of the study's relevance and the characteristics of the chosen water pumping stations.

Chapter 2 – Literature Review

This chapter provides the theoretical foundation for the research. It explores sustainability challenges in water infrastructure, focusing on Dutch policy frameworks, ecological concerns, and procurement practices. It then reviews the application of Life Cycle Assessment (LCA) and circular economy (CE) principles in infrastructure, followed by an overview of international standards and certification schemes. The chapter concludes by identifying research gaps that inform the remainder of the thesis.

Chapter 3 – Research Objectives & Questions

This chapter formulates the main research objective and the central research question. Four sub-objectives are developed to structure the analysis, each accompanied by a corresponding sub-question. These guide the study's exploration of current sustainability practices, environmental impact quantification, methodological evaluation, and the development of design strategies. The chapter also maps how each question is addressed in the subsequent chapters.

Chapter 4 – Methodology

Here, the research design and methodological framework are detailed. The chapter outlines the four-phase mixed-methods approach employed in the study, combining qualitative expert interviews and policy review with quantitative LCA modelling. It describes the data sources, case selection, and analytical tools used—including DuboCalc and the MKI/ECI method—to ensure transparency and reproducibility.

Chapter 5 – Assessment of Current Sustainability Evaluation Practices

This chapter assesses how sustainability and circularity are currently evaluated in water pumping stations. It includes a review of case study documentation, insights from expert interviews, and application of the Material Passport method. The findings reveal both emerging best practices and persistent limitations in how sustainability goals are translated into asset-level outcomes.

Chapter 6 – Environmental Impact Assessment using the MKI/ECI Method

This chapter applies the Dutch MKI/ECI (LCA) methodology to assess the environmental impacts of the two case study pumping stations. It describes the LCA scope, system boundaries, and assumptions, followed by the compilation of life cycle inventories. It then explores design alternatives by modelling multiple material and energy variants to examine their impact on total environmental costs.

Chapter 7 – Results of the Environmental Impact Assessment

Building on Chapter 6, this chapter presents the results of the LCA simulations for both pumping stations. It compares the MKI/ECI scores of various design variants, identifies environmental hotspots, and highlights trade-offs between performance, material choice, and operational energy use. Sensitivity analyses and comparative capacity assessments provide further context to interpret the findings.

Chapter 8 – Evaluation of Methodological Challenges and Cost Analysis

This chapter critically reflects on the limitations of the MKI/ECI method in infrastructure projects. It identifies methodological, practical, and policy-related challenges in applying LCA tools to civil engineering contexts. A cost-benefit analysis compares the financial investment required for sustainable alternatives with their environmental gains, providing valuable insights for decision-makers.

Chapter 9 – Development of Practical Design and Implementation Strategies

Synthesising findings from earlier chapters, this section outlines concrete design and implementation strategies for improving sustainability in water pumping stations. It focuses on early-stage integration of circular principles, modular construction, resource recovery, and digital tools such as Material Passports. It also discusses organisational and procurement strategies to facilitate adoption.

Chapter 10 – Discussion

This chapter reflects on the broader implications of the research. It discusses the scalability and generalisability of the findings, evaluates the robustness of the applied methods, and considers socio-institutional barriers to implementation. It also revisits the interplay between design scale, data quality, and policy integration, and proposes avenues for future research.

Chapter 11 – Conclusions and Recommendations

The final chapter answers the main research question and synthesises key insights from the study. It revisits the four sub-questions, formulates practical recommendations for stakeholders in the water sector, and considers how this research contributes to advancing sustainability in civil engineering. The chapter concludes with reflections on the research process and its implications for future infrastructure planning and design.

1 Introduction

In this introductory chapter, a comprehensive overview of the context, objectives, and structure of this thesis is provided. Section 1.1 discusses the background and context of the research, highlighting the importance of sustainability assessments in the Water Boards and Aveco de Bondt. The problem context, which details the specific challenges and context faced by Aveco de Bondt, is presented in Section 1.2. Thereafter in Section 1.3 the chosen case studies will be introduced and elaborated on.

1.1 Background and Context

Aveco de Bondt is an independent consultancy and engineering firm that provides solutions for national challenges as well as specific environmental and organisational issues. With a focus on sustainability, the company aims to contribute to a well-balanced living environment by considering key elements such as water, land, air, and people (Aveco de Bondt, 2021). Their efforts include reducing CO_2 emissions, promoting responsible resource use, and fostering sustainable development and innovation (Aveco de Bondt, 2024).

In the field of water management, Aveco de Bondt works on projects related to water purification, water safety, and water systems. They have particular expertise in enhancing the sustainability of water pumping stations by improving capacity and reducing CO_2 emissions, as demonstrated in their work on the De Drie Delfzijlen Pumping Station (Staman, 2023).

More broadly, in civil engineering and water infrastructure, the company tries to integrate innovative sustainable practices to minimise environmental impact while ensuring long-term functionality and resilience. Their approach includes reducing CO_2 emissions, optimising resource use through circular construction methods, and incorporating nature-based solutions where feasible. In water infrastructure, this extends to improving energy efficiency, integrating renewable energy into operations such as pumping stations, and designing systems that align with climate adaptation goals to address challenges like rising sea levels and extreme weather events. Through these efforts, Aveco de Bondt aims to combine technical expertise with environmental responsibility to develop infrastructure that supports a sustainable and resilient future (Aveco de Bondt, 2024).

Before delving into a sustainability assessment for water pumping stations, it is crucial to establish an understanding of what a water pumping station is (known as 'gemaal' in Dutch) and its importance within the water management infrastructure of the Netherlands. A water pumping station is defined as 'a facility primarily used to move water from a lower elevation to a higher one, either to remove excess water from low-lying areas (discharge) or to supply water to higher areas (supply)' ((NEN), 2021). The main functions of these stations include pumping out excess water, maintaining water levels, and improving water quality through the distribution of fresh water. In figure 1.1 the schematic working of 'polder' pumping stations and 'boezem' pumping stations can be seen.

Water pumping stations are instrumental in controlling water levels to ensure safe living conditions and productive agricultural land. By managing water levels proactively, these stations make it possible to drain swampy areas and maintain balance within the system. Water pumping stations vary in size, from large, prominent structures that define the boezem landscape to smaller, less noticeable facilities that are equally essential for effective water regulation.

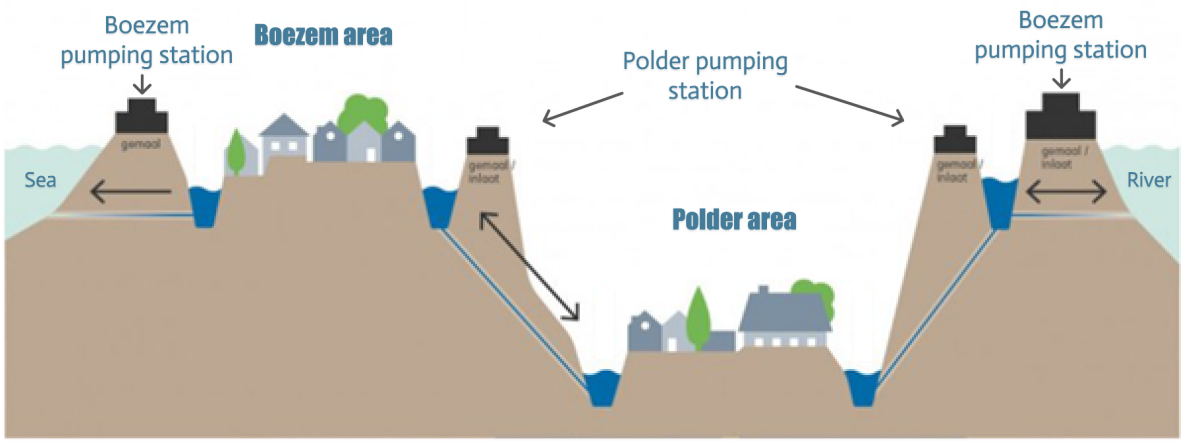


Figure 1.1: Schematisation of 'boezem' and 'polder' water pumping stations (Source: Hoogheemraadschap van Rijnland)

1.2 Problem Context

The Netherlands is widely known as a flat country with minimal elevation differences. However, a closer look reveals notable variations in height. Approximately 40% of the country lies below sea level, making water management a fundamental part of Dutch identity (Al et al., 2012). Starting in the 15th century, the Dutch used wind-powered pumps to drain land, and by the 1700s, they began utilizing alternative energy sources for this purpose. These innovations led to the creation of polders, where drained land was converted into fertile farmland and, later, land for habitation (Stichting, 2023). Today, the Flevopolder, drained between 1950 and 1968, remains the largest polder in the world, covering over 2,000 square kilometers (Loman, 2021).

Currently, the Dutch Water Boards together operate around 7,800 pumping stations, with an estimated replacement value of €448 million (Bleijenberg, 2021). Despite centuries of expertise, the challenges of water management persist due to climate change. Rising sea levels, intense rainfall, and increasing droughts necessitate a revised approach to water management infrastructure (Mol, 2021). Pumping stations, along with levees and dunes, continue to play a vital role in ensuring the Netherlands remains habitable.

Historically, significant investments were made in pumping stations to create arable and liveable land. However, as these structures age and are subjected to intensive use, their functionality tends to decline over time due to two primary factors. First, mechanical wear and tear—particularly in the pumps—leads to reduced efficiency. As the components age, the pump may deliver a lower flow rate, require more energy to maintain the same output, or exhibit both effects simultaneously. In addition to reduced performance, the likelihood of technical failures increases over time if key components (mechanical, electrical, or control systems) are not replaced. This rising failure risk negatively impacts the overall reliability of the pumping station. Second, external environmental changes—particularly those driven by climate change—also contribute to the decline in functional adequacy. Increasing weather extremes, such as prolonged droughts or heavy rainfall, can alter the demands placed on the pumping station. As a result, existing systems may no longer meet the requirements of the water system, either due to capacity limitations or the need for different operational control strategies. Together, these factors form the basis for the need to replace or upgrade ageing water pumping stations. With an average lifespan of 50 years, much of the hydraulic infrastructure built between 1920 and 1960 is nearing the end of its operational life, requiring substantial replacement efforts, known in the Netherlands as the "vervangingsopgave", translated to the 'replacement task' (KCAO-gemalen, 2023).

1.2.1 Impact of Climate Change

Climate change increasingly affects the performance and design requirements of water pumping stations. In the Netherlands, more frequent and intense weather extremes are already challenging existing infrastructure. These climate-driven trends include:

- **Higher Peak Flows:** Intense rainfall events cause sudden surges in water levels, often exceeding the design capacity of older pumping stations (Platform, 2021).
- **Prolonged Droughts:** Extended periods of low precipitation place additional strain on water systems, requiring stations to manage both water surplus and scarcity (Bruin, 2022).
- **Rising Sea Levels:** Coastal pumping stations face increased challenges in preventing saltwater intrusion and managing inflows.

These developments highlight the need for future-proofing measures in both new and existing pumping stations. Additionally, national policy frameworks such as the *Climate Agreement* and the *Raw Materials Agreement* set long-term sustainability goals: a 95% reduction in CO_2 emissions by 2050 and fully circular construction practices by the same year (KCAO-gemalen, 2023).

To ensure climate resilience and regulatory alignment, several design and operational strategies can be adopted:

- **Design Flexibility:** Incorporate modular and adaptable system architectures that can be expanded or modified to meet future capacity demands without full system replacement.
- **Flexible Water Level Management & Smart Pumping:** In the operational phase, flexible water level management and smart pumping involve adjusting pumping operations based on real-time data and system needs. This includes adaptive schedules, buffering extreme conditions, and using sensors and predictive models to optimise performance.
- **Enhanced Capacity:** Upgrade pump and storage capacities to manage increased water volumes due to extreme rainfall events (Timmermans et al., 2022).
- **Energy Efficiency:** Implement energy-efficient technologies and explore renewable energy sources to reduce both operational emissions and long-term energy costs (Xylem, 2015).
- **Regular Maintenance and Upgrades:** Establish proactive maintenance and replacement schedules, especially for mechanical and electrical systems, to extend operational reliability under shifting environmental conditions.

By anticipating the impact of climate change water pumping stations can maintain their performance over time while contributing to broader sustainability objectives.

1.2.2 Lifespan of Pumping Station Components

Understanding the lifespan of pumping station components is essential for sustainable design, maintenance planning, and investment in infrastructure renewal. With an average overall lifespan of around 50 years, many Dutch pumping stations are reaching the end of their design life—resulting in a growing national replacement challenge, or *'vervangingsopgave'*.

Typical Lifespan Estimates:

- **Civil In- & Outlet Structures:** Components such as steel or concrete wells and foundations typically have a lifespan of approximately 50 years, depending on factors such as environmental exposure, material quality, and maintenance practices.
- **Mechanical, Electrical, and Control Systems:** Pumps, valves, electric motors and its controlling system generally last about 15 years, although simpler systems may function reliably for up to 50 years with adequate maintenance (Wieland, 2010). Control Systems, including SCADA and other control technologies typically require updates or replacements every 10 to 15 years to ensure continued compatibility and performance in light of evolving technological standards.

Recognising the varying lifespans of these components is crucial for aligning replacement schedules with future-proofing efforts. This ensures both cost-efficiency and operational continuity, particularly in the context of changing environmental and regulatory demands.

1.2.3 Sustainability Assessments and MKI in Practice

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle, from raw material extraction to end-of-life disposal or recycling. In construction and engineering, LCA helps assess sustainability and guide improvements in project design and execution. A key metric derived from LCA is the Environmental Cost Indicator (ECI), known in Dutch as the Milieu Kosten Indicator (MKI). The MKI translates environmental impacts into monetary terms using "shadow prices," which reflect the highest cost acceptable for governments to mitigate environmental harm (Hillege, 2024). This provides a tangible way to incorporate environmental costs into financial and planning decisions.

Despite its widespread use, particularly in the construction and housing sectors, the MKI has notable limitations. Developed around 2000, its parameters are increasingly outdated and may not reflect contemporary sustainability priorities such as CO_2 emission weighting which nowadays have a much higher focus and MKI score. Aside from the data, and whether or not the most recent shadow prices are being used in the LCA calculations, the MKI does not seem to be inflation corrected in a total way.

Opportunities for Improvement

The Duurzaam GWW (Sustainable Ground, Road, and Waterworks) approach emphasises integrating sustainability throughout project planning and execution (Infrastructuur et al., 2016). While the Environmental Cost Indicator (MKI) is a valuable tool for assessing environmental impact, it is not sufficient on its own to achieve circularity and emission reduction targets. To maximise its effectiveness, MKI calculations should be incorporated early in the design phase rather than being confined to procurement. Experts emphasise that simply determining an MKI value is not enough to drive meaningful sustainability. A holistic approach, encompassing environmental, economic, and social dimensions, must be embedded from the outset—when decisions on materials, construction methods, and system designs have the greatest potential for long-term impact (Kranendonk, 2022). By integrating sustainability early in the process, the GWW sector can more effectively address evolving environmental challenges.

1.3 Chosen Case Studies to Evaluate

For conducting a Life Cycle Assessment (LCA) on water pumping stations ('water pumping stations'), two specific cases have been selected: the large-scale De Drie Delfzijlen pumping station ($> 250\ m^3/min.$) and the smaller Noordeinde- en Geerpolder pumping station (< 50



Figure 1.2: Map of the Netherlands with the locations of the two water pumping stations (Source: Rijkswaterstaat)

m^3/min.). These were chosen due to the significant availability of data within Aveco de Bondt, which is necessary for a well-informed and detailed analysis. In figure 1.2 , the exact locations of the two water pumping stations chosen for this study to evaluate can be seen. The large-scale De Drie Delfzijlen is located in Delfzijl, in the North of the Netherlands and the small-scale Noordeinde- en Geerpolder is located near Nieuwveen, in the polder area between Amsterdam, The Hague and Utrecht.

1.3.1 Selection Rationale

Comparing only one type of water pumping station with an average capacity would provide limited insight into the variability in environmental impact. Instead, by selecting two stations of common vastly different scales and contexts, the study can better illustrate the range of impacts within water management infrastructure. De Drie Delfzijlen pumping station is a major installation, whereas the Noordeinde- en Geerpolder station represents a much smaller-scale operation. This selection allows for a more nuanced understanding of how factors such as the number of pumps, construction materials, and operational requirements affect sustainability.

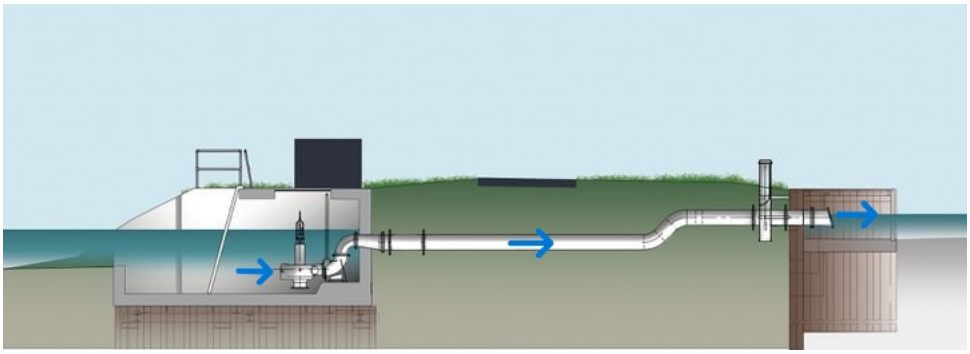


Figure 1.3: Schematic example of a small polder water pumping station and its flow direction (Source: Wetterskip Fryslan)

Standard example schematisation of cross-sections of a small water pumping station (figure 1.3) and a large water pumping station (figure 1.4) and its flow direction from left to right, from low to high water levels can be seen.

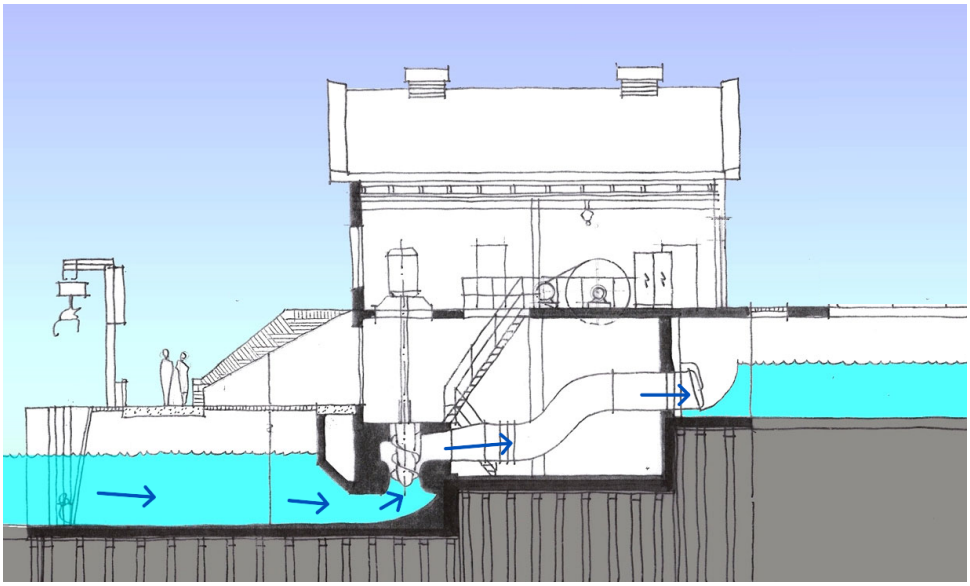


Figure 1.4: Schematic example of a large boezem water pumping station and its flow direction (Source: GGH Architecten)

1.3.2 Characteristics of the Pumping Stations

Large-Scale Boezem Pumping Station: *De Drie Delfzijlen*

De Drie Delfzijlen is a large-scale *boezem* water pumping station currently undergoing a major renovation aimed at full electrification. A photo of the existing structure is presented in Figure 1.5, while Figure 1.6 shows a 3D rendering of the facility, in which the high-capacity pumps are indicated in yellow. The transition involves replacing the original 1974 Brons diesel engines with two new electric motors, updating the electrical infrastructure, and expanding the station's operational capacity. This renovation project is being carried out collaboratively by Waterschap Noorderzijlvest, Stork, and Aveco de Bondt (Staman, 2023).



Figure 1.5: Photo of current water pumping station 'De Drie Delfzijlen' (Source: RTV Noord)

Designed for substantial hydraulic performance, the station currently delivers a discharge capacity of 1,500 m^3/min, which will be upgraded to 1,800 m^3/min upon project completion. This increase is necessitated by intensifying climate pressures, including rising sea levels, land subsidence, and more frequent extreme rainfall events that pose flood risks to Delfzijl and the surrounding areas.

From a functional standpoint, De Drie Delfzijlen exemplifies a *boezem* water pumping station, which is specifically tasked with draining excess water from the *boezem*—a storage basin that buffers and manages regional water levels. These stations typically serve as the final link in a broader hydrological chain, moving water from inland storage to external bodies of water such as rivers, seas, or lakes when gravitational flow is no longer sufficient.

Post-renovation, the station will operate autonomously and be remotely controlled, integrating intelligent monitoring systems into its design. This digital transformation is paired with a strong emphasis on sustainability. Where feasible, materials are being reused, contributing to a circular construction process. Additionally, significant environmental gains are anticipated. The elimination of combustion engines—despite the previous use of low-emission HVO100 biofuel—reduces both CO_2 output and dependence on maintenance-heavy mechanical systems. The station's electrification also lowers lubricant needs and minimizes noise emissions, benefiting the surrounding community.

The project partners were specifically chosen based on their commitment to sustainable innovation. Examples of circular measures under consideration include reusing a large fuel tank as a thermal buffer for a future heat pump and finding new applications for the Brons engines, which hold historical and technical significance. The renovation is scheduled for completion in autumn 2025.

Small-Scale Polder Pumping Station: *Noordeinde- en Geerpolder*

In contrast to this large-scale facility, the Noordeinde- en Geerpolder pumping station offers a small-scale, recently constructed reference point, as illustrated in Figure 1.7. This station is part of a group of five polder water pumping stations renewed between 2021 and 2023 through a partnership between AHCO Weg- en Waterbouw and Water board Hoogheemraadschap van Rijnland. A technical drawing of the station is shown in Figure 1.8.

As a polder water pumping station, Noordeinde- en Geerpolder is designed to transfer water from low-lying polder areas to the higher-level *boezem* system. Among the five stations in the renewal program, this facility is the most substantial in terms of newly constructed infrastructure

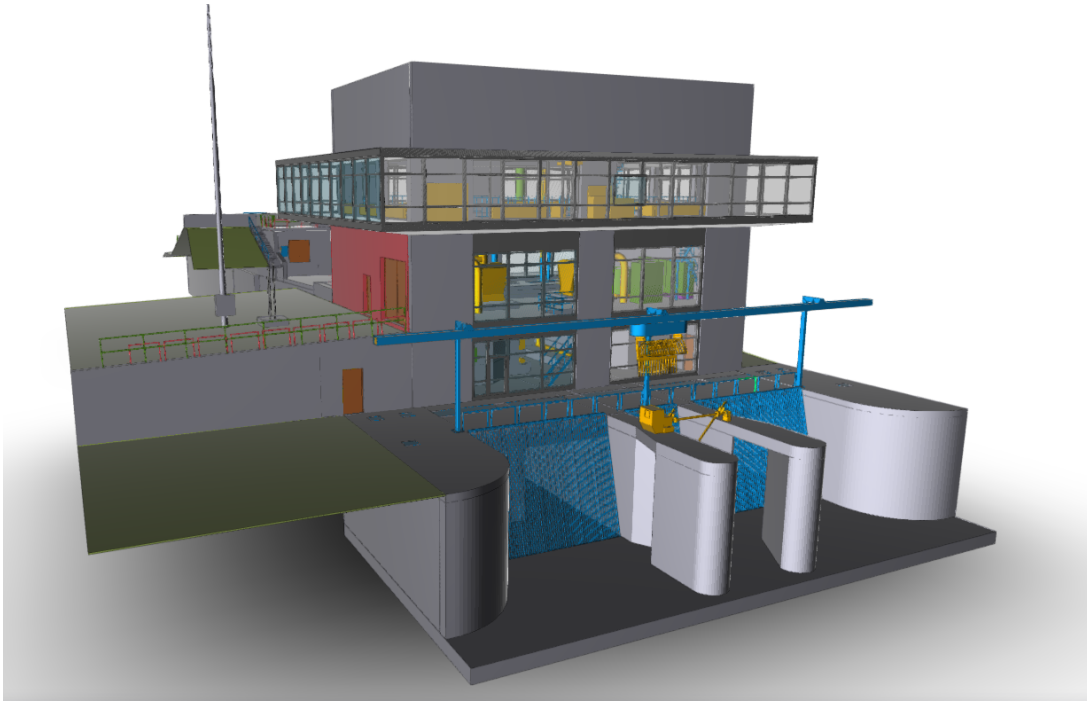


Figure 1.6: Image of 3D model of 'De Drie Delfzijlen' (Source: Aveco de Bondt)

and possesses the highest design discharge capacity at 12 m^3/min. Despite this, it remains modest in scale compared to De Drie Delfzijlen and requires less complex engineering and operational resources.

The design of Noordeinde- en Geerpolder incorporates ecological considerations, most notably the inclusion of fish-safe pumps and a fish passage system, visible as the lower conduit in the technical schematic. This reflects an integrated approach to environmental stewardship, aligning with contemporary water management goals.

To ensure long-term operational integrity, water board Hoogheemraadschap Rijnland has defined minimum life span requirements for each system component. Civil and structural works must last at least 50 years, while mechanical, electrical, and process automation systems are each expected to perform reliably for a minimum of 15 years.



(a) (b) (c)

Figure 1.7: Three images of Noordeinde- en Geerpolder: (a) From the road, (b) From the water, (c) 'Krooshek' and pump inside

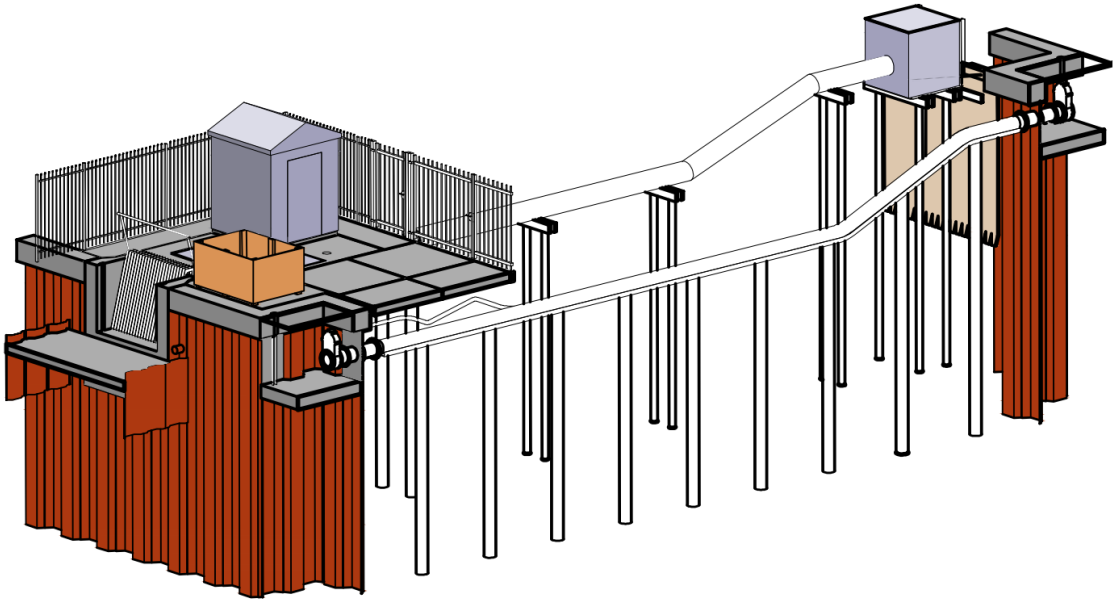


Figure 1.8: Technical drawing of water pumping station Noordeinde- en Geerpolder

2 Literature Review

This chapter explores the theoretical foundations underpinning this research. It begins with an introduction to the sustainability challenges and opportunities associated with water pumping stations, emphasizing their crucial role in water management and the increasing need for climate adaptation (Section 2.1). Section 2.2 presents the guiding research questions shaping the literature review. The subsequent sections examine the current state of sustainability in Dutch water pumping stations (Section 2.3), focusing on policy frameworks, ecological considerations, and procurement practices. Section 2.4 delves into the lifecycle environmental impacts of these infrastructures, highlighting the role of Life Cycle Assessment (LCA) and the existing research gaps. Section 2.5 discusses sustainable design choices and energy efficiency improvements, while Section 2.6 investigates the integration of circular economy principles into water infrastructure. Finally, Section 2.7 examines international standards and certification schemes that support sustainability assessments. Collectively, this chapter provides a comprehensive theoretical background to inform the research's approach.

2.1 Literature Questions

Water pumping stations, or "gemalen," are essential for water management in regions like the Netherlands, where maintaining water levels is crucial for flood prevention and land reclamation. Together the Dutch Water Boards operate 7,792 water pumping stations, with 2,663 having a capacity greater than 50 m^3/min. Many were built before 1970, necessitating significant replacements to meet modern sustainability standards. National initiatives such as the Climate Agreement and the Green Deal Energy (Unie van Waterschappen, 2018) have driven the development of programs like KCAO-water pumping stations (KCAO-gemalen, 2023), which focus on developing climate-neutral and circular polder pumping stations. However, challenges such as rising sea levels, intense rainfall, increasing droughts, ecological impacts, and the resilience of flood defences remain key concerns (Mol, 2021; Stijnen et al., 2014).

This literature review explores the current state of research on the sustainability assessment of water pumping stations, identifying challenges, opportunities, and best practices for achieving climate neutrality and circularity in their design, operation, and maintenance. Additionally, it examines innovative technologies and methodologies to improve sustainability while addressing technical, financial, and societal challenges. While adaptation costs for strengthening flood defences are expected to double by 2100, they remain affordable (€ 1 billion annually or 0.1% of GDP) (Stijnen et al., 2014). Nonetheless, spatial development, societal acceptance, and ecological considerations pose additional challenges. Ultimately, this research aims to inform policy and decision-making processes for water boards and engineering firms, supporting long-term flood protection and climate adaptation strategies.

This literature review aims to understand the sustainability challenges and opportunities associated with water infrastructures, specifically water pumping stations, throughout their lifecycle. The review explores environmental impacts, energy efficiency, circular economy principles, and the impact of standards and certifications. Key questions guiding the review include:

1. What is the current state of sustainability implementation in Dutch water pumping stations?
2. How are the lifecycle environmental impacts of water infrastructures evaluated, from construction to decommissioning?

3. What design choices and technologies can improve energy efficiency and sustainability in water pumping stations?
4. How can circular economy principles be effectively implemented in water infrastructures?
5. How do international standards and certification schemes support the sustainability assessment of water infrastructure?

2.2 Current State of Sustainability in Water Pumping Stations

Dutch water pumping stations show progress in sustainability through national policies, yet challenges remain in applying these frameworks at the asset level. The sustainability landscape reflects an evolving effort to integrate circularity, climate neutrality, and ecological performance within water infrastructure. However, translating national policies into practical outcomes at the asset level remains complex.

2.2.1 Policy and Guideline Frameworks

The *Handreiking: Aanpak Duurzaam GWW* (Infrastructuur et al., 2016) provides a structured approach to implementing sustainability in ground, road, and water (GWW) infrastructure projects. It incorporates tools like DuboCalc for life cycle assessments (LCA), the Ambition Web for visualizing sustainability goals, the CO_2 Performance Ladder for carbon footprint reduction, and the Environmental Compass for environmental management. The *KCAO-water pumping stations* (KCAO-gemalen, 2023) offers an asset-focused approach that bridges high-level policies with practical actions through stakeholder collaboration and area-specific planning. Despite these frameworks, their targeted application in pumping stations often lags behind broader ambitions.

2.2.2 Ecological Sustainability and Fish Migration

Ecological sustainability, particularly concerning fish migration, is an important consideration in pumping station operations. The STOWA report *water pumping stations of Vermalen Worden?* (Al et al., 2012) studied the fish-friendliness of 26 pump types, revealing significant variations in fish injury and mortality rates depending on pump design and fish size. Technologies such as Faunapumps and fish-friendly Hidrostal pumps demonstrate promising results, yet gaps remain in understanding the full ecological impacts, especially regarding delayed mortality and the performance of high-capacity systems. Tools like the *water pumping stationswijzer* aid water managers in selecting appropriate pump technologies, but further research and technological innovation are needed to fully mitigate the ecological impacts of pumping station operations.

2.2.3 Procurement and Governance

Sustainable Public Procurement (SPP) is pivotal in embedding sustainability into infrastructure projects, including water pumping stations. The RIVM report *Verkenning Monitor SPP Waterschappen* (Valk et al., 2020) highlighted that, while awareness of SPP is growing, its practical application across water boards is still in an early stage. Monitoring efforts remain inconsistent, with fewer procurement projects assessed than initially anticipated, limiting comprehensive conclusions. Organisational alignment and dedicated resources are essential to improving SPP's effectiveness. The report recommends utilizing flagship or pilot projects to generate enthusiasm and establishing long-term monitoring frameworks to track progress.

2.2.4 Circular Asset Management and Data Challenges

Circular asset management has emerged as a priority for Dutch water boards, aiming to translate national circular economy goals into concrete asset-level strategies. The reports *Circulair Assetmanagement Waterschappen* (B.M. Roelofs, Huinink, et al., 2022) and its background

study (B.M. Roelofs and Tauber, 2022) focus on developing methodologies to assess material stocks and environmental impacts. These reports underscore the importance of integrating LCA thinking into asset management, yet challenges persist due to incomplete datasets and inconsistent methodologies. MKI (Environmental Cost Indicator) values, while valuable for assessing environmental costs, are sensitive to data assumptions, limiting the precision of environmental assessments. Asset-specific applications, including those targeting polder water pumping stations, demonstrate that while circular methods are feasible, their full integration into design and maintenance strategies remains a work in progress.

2.2.5 Overarching Challenges, Opportunities, and the Path Forward

Despite strong policy frameworks and practical tools, several challenges hinder the full realisation of sustainability goals in water pumping station infrastructure. Data quality and consistency issues limit the accuracy of environmental assessments, while operational demands often conflict with long-term ambitions. Technological constraints, particularly in balancing high-capacity pumping with ecological safety, further complicate progress. Inconsistent procurement practices and varying levels of knowledge sharing among water boards slow the standardisation of best practices across the sector. Addressing these challenges requires improved data management, targeted research and development of fish-friendly and energy-efficient technologies, and consistent procurement guidelines that integrate circular principles. Strengthening the collaboration among water boards, engineering firms, and stakeholders will accelerate the adoption of best practices. While the Dutch water management sector has made notable progress, practical implementation remains uneven. Bridging the gap between ambitious policies and asset-level applications through innovation, data-driven decisions, and cooperation will enable water pumping stations to contribute meaningfully to the Netherlands' broader sustainability goals.

2.3 Lifecycle Environmental Impacts

Life Cycle Assessment (LCA) is a vital tool for evaluating the environmental impacts of water infrastructures throughout their lifecycle. While extensive research exists for water treatment plants and urban water systems, detailed assessments of water pumping stations remain scarce. Existing studies often lack detailed material flow analysis, operational efficiency assessments, and full lifecycle impacts. However, broader urban water system assessments provide valuable insights, identifying pumps as significant contributors to energy and environmental impacts.

LCA Studies in Water Systems and Infrastructure

Studies (Venkatesh et al., 2011; Slagstad et al., 2014; Remy et al., 2008; Barjoveanu et al., 2013; Friedrich et al., 2007) analyse urban water systems, highlighting that pumps contribute significantly to energy use and environmental impact. However, detailed LCA studies specifically for pumping stations are limited.

Table 2.1 summarises key studies, findings, and literature gaps.

These studies are also reviewed in Loubet et al. (2014), which highlights the importance of defining appropriate functional units and system boundaries in LCAs of urban water systems. The review calls for a more comprehensive approach, including the user's behaviour and the entire water system, to better evaluate impacts such as energy use, water quality, and emissions.

The current literature reveals a significant gap in LCAs or sustainability evaluations specifically for water pumping stations, despite their notable environmental impact and substantial energy and resource consumption. Future research must prioritise comprehensive data collection, improved data quality, refined methodologies, and system-wide approaches to fully tackle the sustainability challenges associated with water pumping stations.

Reference	Focus	Key Findings	Gaps
Venkatesh et al., 2011	Energy in Oslo's water system	240.7 kWh/capita/year; pumps contribute significantly.	Excludes construction/decommissioning data.
Slagstad et al., 2014	LCA of Trondheim's system	WWTPs cause 54% of impacts; eutrophication key.	Few regional studies; parameter uncertainties.
Remy et al., 2008	Conventional vs. source-separation sanitation	Source separation can lower GHG emissions by 15–30%.	Needs region-specific data and sensitivity analyses.
Barjoveanu et al., 2013	Iasi City's water system LCA	Pre-tap processes have high impacts.	Lacks local impact factors for certain pollutants.
Friedrich et al., 2007	LCA in South African systems	Energy use is the major burden.	Needs better local data and uncertainty analysis.

Table 2.1: Overview of LCA Studies on Water and Wastewater Systems

2.4 Sustainable Design Choices and Energy Efficiency

Sustainability in the design of pumping stations is crucial for reducing energy consumption and minimising ecological impact. Current research emphasises enhancing energy efficiency through technologies such as photovoltaic (PV) self-generation, smart pump systems, and advanced simulation models. Integrating renewable energy sources into water pumping infrastructure is a growing trend; however, sustainability trade-offs and regional feasibility remain under-explored.

2.4.1 Renewable Energy Integration

Integrating photovoltaic energy into pumping stations can significantly lower operational costs and maximise energy self-consumption. Naval et al. (2021) demonstrated a 21.56% reduction in costs and 99.41% energy self-consumption through PV integration. Figure 2.1 illustrates a schematic model of solar PV integration in a pumping station.

Other renewable energy sources, such as wind and biomass, require further investigation. Kougias et al. (2016) highlighted the potential of integrating hydropower plants and solar panels in water infrastructure, but noted the lack of specific case studies for pumping stations. Furthermore, Zakariazadeh et al. (2024) emphasised the importance of managing renewable power intermittency through stochastic modelling and energy storage solutions.

2.4.2 Smart Technologies and Simulation Models

Industry 4.0 smart pump systems offer advanced supervision and control mechanisms that enhance energy efficiency and real-time monitoring. Souza et al. (2022) analysed the application of such technologies in urban water supply and sewage systems, suggesting their potential benefits for pumping stations, including predictive water height monitoring.

Simulation models help in designing resilient infrastructure under future uncertainties such as climate change. Timmermans et al. (2022) developed a robust multi-objective simulation approach for polder pumping stations, providing valuable insights into their long-term performance. Figure 2.2 illustrates the simulation and testing model.

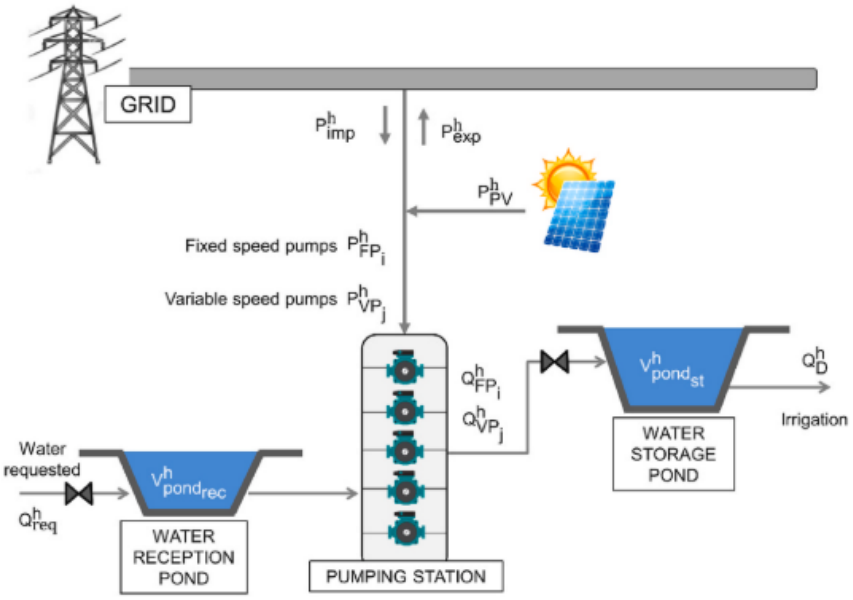


Figure 2.1: Diagram Model of Local Solar PV Integration

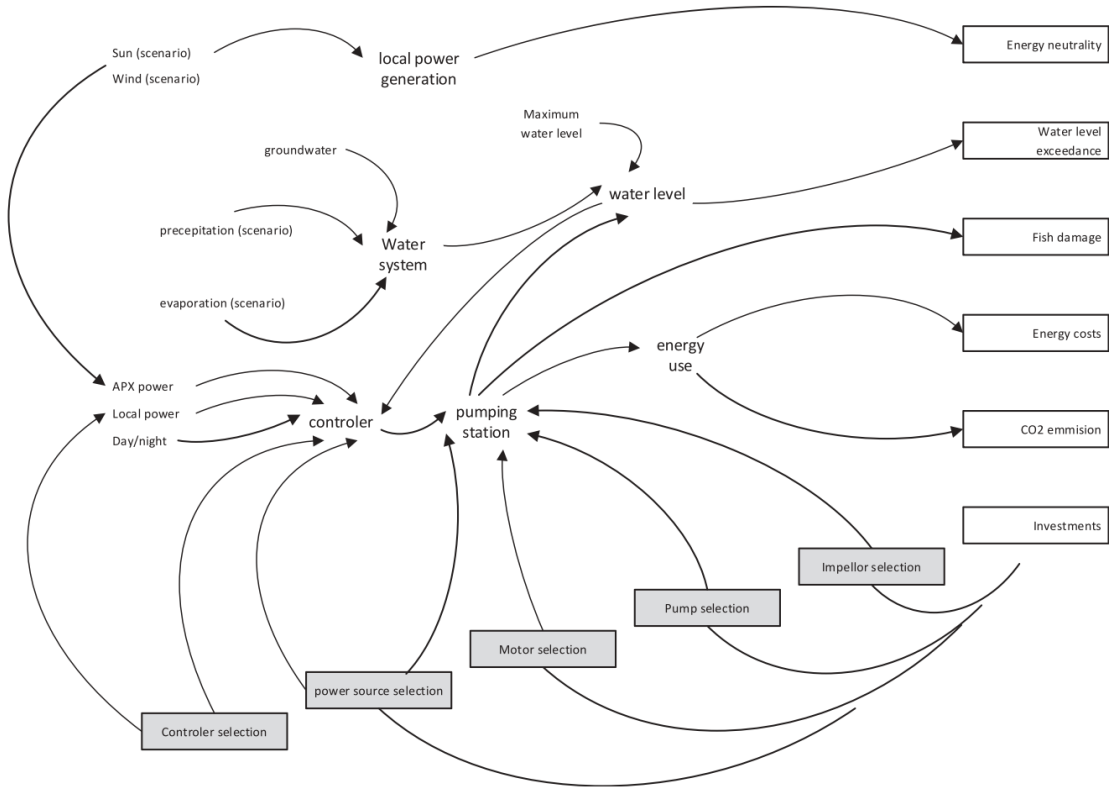


Figure 2.2: Causal Model of the Pumping Station Simulation and Testing Model

2.4.3 Challenges and Future Research

While innovative technologies offer significant potential for improving pumping station sustainability, practical applications remain limited. Studies often focus on theoretical models rather than real-world implementations, highlighting a gap between research and practice. Future work should prioritise comprehensive lifecycle assessments, regional feasibility analyses, and pilot projects to bridge this divide and ensure long-term, practical sustainability.

2.5 Circular Economy Principles

The transition from a linear "make-use-dispose" model to a circular economy (CE) presents significant opportunities for improving sustainability in water infrastructure. Although CE principles have gained traction in broader water and wastewater management, their implementation in water pumping stations remains limited. CE aims to promote sustainable resource and waste management practices, including reduction, reuse, recycling, and recovery.

2.5.1 Historical Development and Core Principles

CE's evolution—from natural cycles to industrial models—emphasises closed-loop systems (Stahel, 2020). A central framework within Dutch circular economy policy is the "R-ladder", which ranks strategies for resource efficiency and waste reduction in order of circular impact. This ladder begins with Refuse and Rethink—the most impactful strategies—and descends through Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, and finally Dispose—the least desirable option. It serves both as a conceptual tool and a policy guide, promoting actions that preserve the highest value of materials for as long as possible (Illankoon et al., 2023). The R-ladder aligns closely with the EU Waste Hierarchy, which also prioritises prevention and minimisation over recycling and disposal. These principles have expanded beyond the original 3Rs (Reduce, Reuse, Recycle) into broader frameworks like the 10R and 11R models. Figure 2.3 presents the EU Waste Hierarchy for comparison.



Figure 2.3: Waste Hierarchy according to the EU Waste Framework Directive

Additional frameworks such as Avoid-Shift-Improve and the mitigation hierarchy further support sustainable practices (TUMI et al., 2019; Moulherat et al., 2023).

2.5.2 Circular Economy in Water Infrastructure

CE principles in water management prioritise water conservation, pollutant removal, and the reuse and recycling of treated wastewater (Smol et al., 2020). Water reclamation techniques help remove harmful substances, ensuring treated water is safe for reuse and reducing dependency

on fresh water sources. The rethink element of the model stresses the importance of changing societal behaviours and reimagining the entire water and wastewater management process to build a more sustainable and waste-free economy.

Despite these efforts, CE implementation in water pumping stations is still in its infancy. Stumpf et al. (2021) identified key enablers and barriers to CE adoption, with eco-innovation, business models, and eco-design being frequently applied, while extended producer responsibility and product-service systems remain under used. Regulatory challenges, such as the lack of harmonised standards and enforcement, along with technical and logistical barriers, further hinder adoption.

2.5.3 Circular Economy Integration in Assessments

Integrating CE with Life Cycle Assessment (LCA) offers a powerful method for improving resource efficiency and reducing waste in water infrastructure (Nikolaou et al., 2021). Mohnish et al. (2024) highlight the importance of LCA in evaluating environmental impacts and minimising waste, resource depletion, and pollution. However, challenges such as data gaps and the need for standardised methodologies persist.

Although CE presents a comprehensive framework for enhancing sustainability in water infrastructures, its practical application in water pumping stations remains limited. Overcoming regulatory, technical, and standardisation barriers requires a holistic approach—combining innovative technologies, supportive policies, and multi-level cooperation to drive the transition towards sustainable and resilient water systems.

2.6 International Standards and Certification Schemes

International standards and certification schemes, such as ISO and BREEAM, play a pivotal role in the development of sustainability assessment frameworks for water infrastructure. ISO 14040:2006 and ISO 14044:2006 provide the principles and guidelines for conducting Life Cycle Assessments (LCAs), facilitating comparability and credibility of results. These standards help organisations identify opportunities to reduce environmental impacts and improve sustainability throughout the product lifecycle.

2.6.1 Life Cycle Analysis (LCA) ISO Standard

ISO 14040:2006 outlines the general requirements and guidelines for LCA, including goal and scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA), life cycle interpretation, reporting and critical review, and limitations and conditions for use (Subcommittee SC 5 LCA, 2006). ISO 14044:2006 builds on this framework, offering more specific instructions for each phase of the LCA process (Standardization, 2006). These standards ensure a structured approach to assessing environmental impacts with transparent reporting and robust assessments.

2.6.2 Sustainability Assessment Schemes

Several interdisciplinary sustainability frameworks provide structured assessment methodologies for water infrastructure:

1. **BREEAM Infrastructure (formerly CEEQUAL)** (BRE-Group, 2022)
   This scheme, developed by the Institution of Civil Engineers (ICE) in the United Kingdom, applies weighted ecological criteria in pre-design and design phases. It includes categories such as Management, Resilience, Communities and Stakeholders, Land Use and Ecology, Landscape and Historic Environment, Pollution, Resources, and Transport.

Category	Credits available, Projects (max.)	Credits available, Term Contracts (max.)	Credits available (after scoping)	Credits achieved	Credits achieved, %
Management	550	502	461	385	83.5%
Resilience	600	600	371	320	86.3%
Communities and stakeholders	550	478	416	385	92.5%
Land use and ecology	600	524	464	424	91.4%
Landscape and historic environment	450	381	209	209	100%
Pollution	400	330	266	245	92.1%
Resources					
Materials, including waste	800	772	729	707	97.0%
Energy and carbon (operational)	200	200	115	105	91.3%
Energy and carbon (construction)	250	250	250	230	92.0%
Water use	200	184	134	118	88.1%
Transport	400	328	286	224	78.3%
TOTAL	5000	4549	4122	3720	90.2%
Innovation	500		-	-	2.00%
BREEAM score					**92.2%**
Minimum standards achieved					Yes
BREEAM rating					**Outstanding**

Figure 2.4: BREEAM Infrastructure Scheme Output Scoring Example

2. **Envision** (Envision, 2018)
   Developed by the Institute for Sustainable Infrastructure (ISI), Envision assesses sustainability across all life cycle phases, balancing ecological, social, and economic factors.

CREDIT CATEGORY	AVAILABLE POINTS	AWARDED POINTS	INNOVATION POINTS	TOTAL POINTS	% OF AVAILABLE POINTS
QUALITY OF LIFE	181	67	0	67	37%
LEADERSHIP	121	81	1	82	67%
RESOURCE ALLOCATION	182	56	0	56	31%
NATURAL WORLD	164	84	0	84	51%
CLIMATE & RISK	122	35	0	35	29%
TOTAL PROJECT POINTS	**770**	**323**	**1**	**324**	**42%**

Figure 2.5: Envision Scheme Output Scoring Example

3. **Infrastructure Sustainability (IS) Rating Scheme**
   The IS Rating Scheme, developed by the Infrastructure Sustainability Council of Australia (ISCA), is the only comprehensive infrastructure sustainability assessment system in Australia and New Zealand. It evaluates multiple phases with flexible weighting criteria.

4. **SPeAR** (SPeAR-group, 2017)
   Developed by Arup, SPeAR assesses sustainability in both infrastructure and building construction, covering the entire project life cycle. Its rose diagram visualises performance across multiple sustainability dimensions.

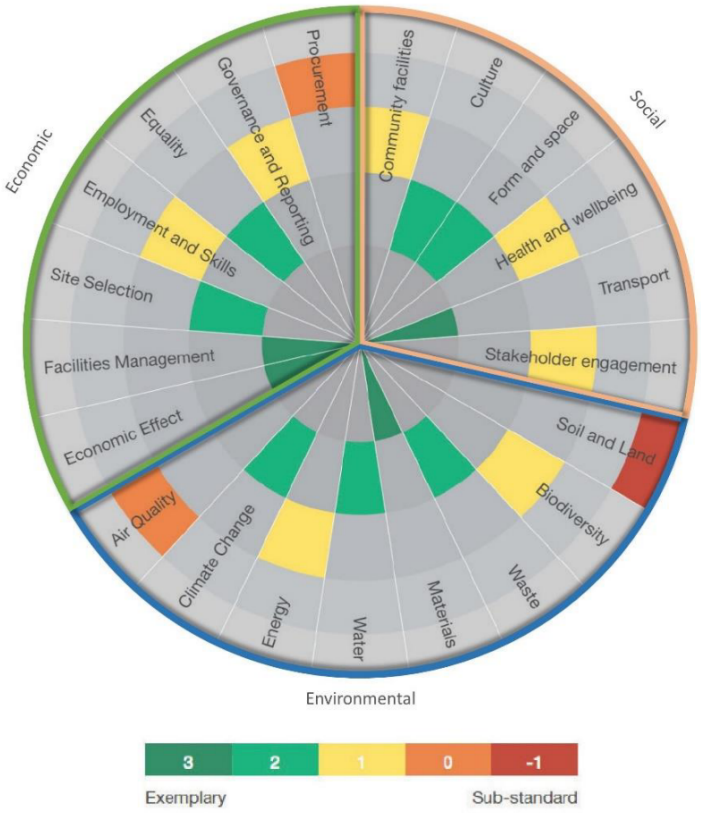


Figure 2.6: SPeAR Scheme Output Scoring Example Chart

2.6.3 Limitations and Future Directions

While international standards and certification schemes offer valuable frameworks for assessing sustainability in water infrastructure, they have notable limitations. Many existing schemes do not fully address operational efficiency, total lifecycle impacts, and climate resilience—factors that are particularly critical for water infrastructure. These standards are often broad and widely applicable, but significant modifications may be required to align them with the specific needs of water pumping stations. Future assessments should emphasise adaptability and a more holistic evaluation approach, incorporating water-specific operational benchmarks to enhance their relevance and effectiveness.

2.7 Conclusion and Identified Research Gaps

The literature review highlights the significant potential of innovative technologies and circular economy (CE) principles in enhancing the sustainability of water pumping stations. Dutch water pumping stations are at a crossroads—national policies and innovative guidelines exist, yet practical application is fragmented. While models and simulations offer valuable insights, they often assume ideal conditions that do not reflect real-world complexities. This disconnect is exacerbated by the scarcity of pilot projects and limited long-term data collection, hindering the understanding of both immediate and extended impacts. Future research should prioritise pilot studies across diverse environments, focus on real-world constraints, and develop frameworks to guide practical implementation.

Another major gap is the lack of comprehensive life cycle assessments (LCAs), essential for evaluating environmental impacts from construction to decommissioning. LCAs show that pumps are major energy consumers, but detailed, component-level studies are scarce. Existing studies often overlook full lifecycle stages and indirect impacts, such as supply chain emissions or end-of-life waste management. Incomplete or inconsistent data further weaken the robustness of LCAs. Future research should develop holistic assessments covering all lifecycle stages, incorporate dynamic elements to track evolving impacts, and create benchmarking tools for comparative analyses.

Regional feasibility is another under-explored area. Water pumping stations operate under varying local conditions, resources, regulations, and socio-economic contexts. Yet, many studies generalise solutions without addressing local nuances, risking impractical recommendations. Region-specific feasibility studies are needed to evaluate renewable energy integration, economic viability, and community acceptance tailored to local contexts.

Despite the sustainability benefits of CE principles, their integration into water pumping stations remains limited. Research often neglects aspects such as resource recovery, waste reduction, and sustainable materials use. Future studies should explore modular designs that extend component life, promote repairs and upgrades, and utilise recycled materials without compromising performance.

The lack of standardisation and the gaps in data availability in water infrastructures further hinder robust sustainability assessments. Variations in LCA methodologies and a lack of reliable, region-specific data—especially in developing regions—complicate comparative analyses. Addressing this requires internationally recognised standards, open access databases, and clear guidelines for systematic data collection.

In conclusion, while innovative technologies and CE principles offer significant sustainability potential, addressing gaps in practical implementation, comprehensive assessments, regional feasibility, CE integration, and standardisation is vital. Bridging these divides, aligning policy with asset-level applications through collaboration and pilot projects, will ensure solutions that are not only theoretically sound but also practically viable, environmentally beneficial, and adaptable to diverse real-world conditions.

3 Research Objectives & Questions

This chapter defines the central objectives and guiding questions of the study. It begins by presenting the main research question, which seeks to explore how sustainability assessment methods and circular principles can enhance the environmental performance of water pumping stations (Section 3.1). Section 3.2 elaborates on the four sub-objectives and corresponding sub-questions, each targeting a different facet of the main research goal. These include evaluating current sustainability assessment practices, quantifying environmental impacts through Life Cycle Assessment (LCA), identifying limitations within the MKI/ECI methodology, and developing design recommendations for more circular and sustainable pumping stations. Each sub-question is linked to specific chapters to follow, creating a roadmap that structures the thesis.

Following from the identified research gaps and in consultation with the internal supervisors at the University of Twente and the external supervisors at Aveco de Bondt, the research objectives and questions are formulated to define the exact focus of this study. The main goal or main research objective is stated as follows:

To get insights in practical and adaptable solutions helping to improve the environmental sustainability of water pumping stations by integrating innovative technologies and circular economy principles.

The broader aim of this research is to analyse the environmental impact of water pumping stations across their entire life cycle—from construction and operation to eventual decommissioning. By examining both a large-scale boezem pumping station and a smaller-scale polder pumping station, the study enables a comparative assessment of embodied carbon, energy use, and material efficiency. Assuming new construction scenarios for both cases ensures that the findings remain consistent and directly comparable. The two case studies serve as a solid foundation for a Life Cycle Assessment (LCA), helping to identify opportunities for improved sustainability and circularity in future water infrastructure developments.

To guide this research, following from the research objectives, the below-mentioned research questions are formulated:

Main Research Question

RQ: *"How can sustainability assessment methods and circular principles be applied to analyse, evaluate and improve the circularity and environmental performance of water pumping stations?"*

After establishing the sub-objectives below, the corresponding research questions that this thesis seeks to answer can be drawn up.

Sub-Questions

Out of the main research question, the following four sub-objectives and corresponding sub-questions could be formulated to fully address the main research question's premise from different angles.

The specific sub-objectives and sub-questions of this research are to:

1. **Assess current sustainability evaluation practices** for water pumping stations and identify opportunities to enhance these assessments.
    - **SQ1:** *How are circularity and sustainability currently assessed in water pumping stations?*
2. **Analyse the environmental impact of water pumping stations** by determining, quantifying, and monetising their effects under different material choices and design alternatives using the MKI/ECI (LCA) method, while improving the comprehensiveness and consistency of life cycle assessments.
    - **SQ2:** *What are the environmental impacts of water pumping stations, considering different materials and design alternatives, using the MKI/ECI (LCA) method?*
3. **Identify limitations and areas for improvement within the MKI/ECI (LCA) methodology** and explore the additional costs of more sustainable materials and designs in comparison to the environmental improvement (MKI/ECI reduction) gain.
    - **SQ3:** *What challenges exist within the MKI/ECI (LCA) method, how can they be improved, and how can environmental gains (MKI/ECI) be weighed against the additional costs of more sustainable materials and designs?*
4. **Develop concrete design recommendations** to improve the circularity and environmental performance of water pumping stations by integrating CE principles, resource recovery strategies, sustainable materials, and modular design concepts from the early design phase.
    - **SQ4:** *What concrete measures can be implemented in the (preliminary) design phase to enhance the circularity and environmental performance of water pumping stations?*

SQ1 will be answered in Chapter 5, SQ2 will be answered in Chapter 6 & 7, SQ3 will be answered in Chapter 8, and lastly SQ4 will be answered in Chapter 9. These objectives serve as a foundation for addressing the research questions and ensuring that the solutions developed are functionally effective, environmentally sustainable, and replicable across diverse contexts.

4 Methodology

This chapter outlines the mixed-methods approach underpinning this research. Section 4.1 introduces the four-phase research design, integrating both qualitative and quantitative methods to ensure a holistic analysis of sustainability in water pumping stations. Section 4.2 explains the LCA methodology used to quantify environmental impacts via the MKI/ECI approach, including goal and scope definition (4.2.1), life cycle inventory (LCI) data collection (4.2.2), and impact assessment procedures (4.2.3). Section 4.2.4 focuses on life cycle interpretation, including uncertainty and scenario analyses. Collectively, this chapter provides a robust methodological framework that supports the empirical analysis and practical recommendations that follow.

4.1 Research Design

This research follows a structured four-phase approach, aligning with the formulated research questions to systematically evaluate and improve the sustainability of water pumping stations. The research design integrates both qualitative and quantitative methods, leveraging lifecycle assessments, case studies, and expert consultations to ensure a comprehensive evaluation.

Phase 1: Assessment of Current Sustainability and Circularity Evaluation Practices (SQ1)

The first phase of this research is dedicated to evaluating the current approaches used to assess sustainability and circularity within the context of water pumping stations. This involves an in-depth analysis of two case studies—De Drie Delfzijlen and Noordeinde- en Geerpolder—to examine prevailing evaluation methodologies and determine the extent to which sustainability considerations were integrated into their design and implementation.

Primary data for this phase are collected through the detailed review of technical documentation and construction drawings of both case studies, enabling the accurate extraction of material quantities and specifications. Additionally, qualitative data are gathered through expert consultations and internal knowledge-sharing sessions conducted at the engineering consultancy Aveco de Bondt. As no formal interview protocol was established in advance, relevant experts were approached based on availability and project involvement. This included six engineers from the pumping station design team, who provided insights into sustainability considerations across both new-build and renovation projects, as well as four sustainability advisors, two of whom offered guidance on the use of DuBoCalc. Discussions focused on current practices, tool limitations, and opportunities for improving sustainability and circularity assessments. Notes were taken throughout these informal consultations to document key observations.

Further input was obtained through attendance at an internal presentation summarising the outcomes of a prior workshop on circular pumping stations (*circulaire gemalen*), jointly organised by Aveco de Bondt and water authority Wetterskip Fryslân. This session provided contextual information on the circularity ambitions of water boards, as well as the practical implementation strategies and challenges encountered in operational settings.

Moreover, the Material Passport method, a recognised circularity assessment tool, is applied to both case study stations to evaluate material flows and end-of-life reuse potential. Secondary data sources, such as academic literature and regulatory guidelines, are reviewed to contextualise the findings within the broader discourse on circularity and sustainability in infrastructure projects.

The outcome of this phase is the identification of critical gaps and opportunities for improving sustainability and circularity assessment methods tailored to water pumping stations.

Phase 2: MKI/ECI Results with Life Cycle Assessment of Water Pumping Stations (SQ2)

The second phase of the research seeks to quantify the environmental impact of water pumping stations through the application of a Life Cycle Assessment (LCA), utilising the MKI (Milieu Kosten Indicator) or ECI (Environmental Cost Indicator) methodology with the software DuboCalc (Duurzaam Bouwen Calculator, or 'Sustainable Building Calculator').

Primary data collection in this phase focuses on gathering detailed material and energy data derived from the technical documentation of the case study stations. These data include material quantities, construction techniques, operational parameters, and maintenance schedules, which are essential for robust LCA modelling. Pilot projects from Dutch water boards and engineering consultancies are also consulted to obtain operational data and examples of innovative technologies or circular design applications.

Secondary data for LCA modelling are sourced from standardised environmental databases, including the Nationale Milieudatabase, Ecoinvent, and DuboCalc's internal datasets. These sources provide validated environmental indicators for consistent assessment of environmental impacts across the life cycle stages of construction, operation, maintenance, and decommissioning. Additionally, scientific literature and technical reports are consulted to supplement and validate the modelling approach.

This phase also includes a comparative analysis of various design alternatives and material selections, facilitating the identification of design strategies that minimise environmental impacts. The outcome of this phase is a comprehensive understanding of the environmental implications of different design and material choices, offering crucial input for sustainable decision-making in water infrastructure projects.

Phase 3: Evaluation of MKI/ECI (LCA) Challenges and Cost-Analysis of Sustainable Design Choices (SQ3)

The third phase of the research critically investigates the limitations and opportunities for enhancement within the MKI/ECI-based life cycle assessment (LCA) framework as applied to water pumping stations, while simultaneously exploring the economic valuation of environmental improvements.

Primary data for this phase include expert interviews with stakeholders involved in sustainable infrastructure projects to identify methodological challenges, data gaps, and practical barriers related to the use of MKI/ECI methodologies in practice. These interviews also gather perspectives on the financial trade-offs between environmental benefits and additional construction costs associated with sustainable design choices.

Secondary data collection encompasses the review of LCA case studies, cost data from recent infrastructure projects, and relevant technical and academic publications addressing LCA challenges, economic assessments, and cost-benefit analyses in the infrastructure sector. Regulatory frameworks and sustainability policies at national and EU levels are also reviewed to ensure alignment with current policy environments.

The outcome of this phase is a critical evaluation of the robustness, limitations, and practical applicability of the MKI/ECI framework, alongside a cost-benefit analysis that elucidates the economic implications of integrating more sustainable design approaches into water pumping stations.

Phase 4: Development of Design and Implementation Strategies (SQ4)

The final phase of the research is dedicated to formulating actionable recommendations aimed at enhancing both the circularity and environmental performance of water pumping stations. Building upon the findings from the previous phases, this stage focuses on translating analytical insights into practical strategies for design, construction, and operation.

Primary data collection in this phase involves further stakeholder engagement through validation interviews and expert consultations with industry professionals, technical consultants, and policy experts. These consultations serve to verify the feasibility, scalability, and relevance of the proposed strategies, ensuring that the recommendations are grounded in operational realities.

Secondary data sources, such as best practice reports, policy guidelines, and technical manuals from leading industry bodies and government agencies, are reviewed to benchmark the proposed recommendations against existing standards and to incorporate widely accepted design principles.

The outcome of this phase is a comprehensive set of design and implementation guidelines that can be readily adopted by engineers, policymakers, and industry practitioners to advance sustainability and circularity in water infrastructure systems.

4.2 Life Cycle Assessment (LCA) Methodology

This study will perform a Life Cycle Assessment (LCA) using DuBoCalc, a standardised environmental impact assessment tool developed by Rijkswaterstaat for the Dutch civil engineering (GWW) sector. The assessment will apply the standard LCA framework to selected case studies to quantify environmental impacts and explore alternative designs and materials for water pumping stations.

4.2.1 Goal and Scope Definition

The primary goal of this LCA is to quantify and compare the environmental impacts of Dutch water pumping stations across their entire lifecycle—from construction to end-of-life—using the Environmental Cost Indicator (MKI/ECI) method in accordance with ISO standards. Two station sizes will be examined to investigate the influence of scale on environmental performance.

A functional unit will be defined to ensure comparability across different types and designs of water pumping stations.

The study will adhere to EN 15804 (3, 2019) and the Dutch 'Bepalingsmethode Milieuprestatie Bouwwerken' (N. Milieudatabase, 2025), ensuring a consistent and verifiable approach aligned with Dutch infrastructure assessment practices. The LCA will adopt a cradle-to-grave scope, encompassing all stages from raw material extraction to end-of-life processing.

The lifecycle is divided into four modules (A–D):

- **Module A**: raw material extraction, transport, and on-site construction, including pumps and electrical systems;
- **Module B**: operational energy use, maintenance, and component replacement;
- **Module C**: demolition, waste transport, and material recycling or disposal;
- **Module D**: impacts and benefits from material reuse beyond the system boundary.

System Boundaries Specific to Polder Pumping Stations

The assessment will focus on core components such as pumps, motors, control systems, foundations, pipelines, sluice gates, and operational energy consumption. Adjacent infrastructure—e.g., roads or buildings—will be excluded unless functionally integral to the station.

Allocation

In cases where pumping stations serve multiple functions or involve multi-output processes, allocation will be based on mass or economic value. For recycled materials, the Dutch NMD methodology will be used to share environmental burdens across lifecycles. Operational energy impacts will be allocated according to the total volume of water pumped over the design life.

Cut-off Criteria

In line with the Bepalingsmethode, components or processes may be excluded if they contribute less than 1% of the total mass or impact in each of three impact categories. Although the methodology allows a cumulative exclusion of up to 5%, this study will apply a stricter 1% threshold to enhance result reliability.

Data Requirements

Primary data will be prioritised where available, including material specifications, energy use, maintenance schedules, and demolition strategies from comparable projects. Secondary data will be sourced from the Nationale Milieudatabase (NMD), Ecoinvent, and default values in DuBoCalc. All operational data will be modelled over an assumed 50-year service life and adapted to Dutch or European conditions to ensure geographic relevance.

4.2.2 Life Cycle Inventory (LCI)

This section outlines the planned approach for performing the Life Cycle Inventory (LCI), which forms the foundation for the Environmental Impact Assessment using the MKI/ECI method. The LCI will systematically identify and quantify all relevant material and energy flows associated with the lifecycle of water pumping stations.

Two case studies will be selected to represent different scales of Dutch pumping stations: a small-scale polder station (*Noordeinde- en Geerpolder*) and a large-scale boezem station (*De Drie Delfzijlen*). For each case, data will be collected on material quantities, construction components, operational energy use, and maintenance interventions over a 50-year service life.

A hybrid data collection strategy will be used:

- **Primary data** will be derived from technical design documentation, 2D/3D drawings, and energy specifications;
- **Secondary data** will be drawn from environmental databases, sector-specific guidelines, and DuBoCalc default values where project-specific information is unavailable.

The LCI will include all relevant lifecycle stages—material production, construction, operation, maintenance, and demolition—within clearly defined system boundaries that account for both direct and indirect flows (e.g., transport and electricity generation). Opportunities for material reuse and recycling will be included in accordance with the Dutch LCA approach outlined in the NMD and DuBoCalc framework.

Collected data will be structured into flow models and material quantity tables, forming the basis for subsequent environmental modelling in DuBoCalc. This structured approach aims to ensure consistency, transparency, and comparability across case studies.

4.2.3 Impact Assessment

The environmental performance of each water pumping station will be evaluated using the MKI/ECI method. This method aggregates impacts across multiple environmental categories into a single score expressed in Euros (i.e., shadow prices). These shadow prices represent the societal cost of avoiding one unit of environmental damage and serve to monetise the total lifecycle impact.

Characterisation Methodology

Compliant with EN 15804 and the Dutch 'Bepalingsmethode Nationale Milieudatabase (B-NMD)', environmental impacts will be quantified using standardised characterisation models. These models convert inventory data into a set of impact indicators, enabling comparison across different environmental dimensions.

Overview of Characterisation Methods Table 4.1 outlines the characterisation methods to be used in line with the NMD.

Impact Category	Characterisation Method	Unit
Global Warming Potential (GWP)	IPCC 2021 (100-year horizon) (V. et al., 2023)	kg CO_2-equivalent
Ozone Depletion Potential (ODP)	World Meteorological Organisation (WMO, 2018)	kg CFC-11-equivalent
Acidification Potential (AP)	Accumulated Exceedance (Dincer et al., 2020)	mol H^+-equivalent
Eutrophication Potential (EP)	EUTREND model (Huijbregts et al., 2016)	mol N-equivalent
Photochemical Ozone Formation (POFP)	LOTOS-EUROS model (Manders-Groot et al., 2021)	kg NMVOC-equivalent
Abiotic Resource Depletion (Fossil fuels)	CML (2002) (Guinée et al., 2002)	MJ
Abiotic Resource Depletion (Minerals & metals)	CML (2002) (Guinée et al., 2002)	kg Sb-equivalent
Water Use	AWARE model (Boulay et al., 2018)	m^3 water-equivalent

Table 4.1: Characterisation methods used for LCA in compliance with the NMD

Application to Polder Pumping Stations The environmental impact of pumping stations will be evaluated across all lifecycle stages, with particular attention to energy consumption and material-related emissions. The MKI score will represent a weighted, monetary aggregation of all relevant impact categories.

Weighting of Environmental Impact Categories in Set A1

MKI scores within DuBoCalc are calculated based on a fixed weighting of 11 impact categories. Each category is multiplied by a predefined shadow price to produce an aggregated score. Table 4.2 lists the weighting factors used in Set A1.

Transition to Set A2: Methodological Changes

To align with EN15804+A2, the Dutch MKI methodology is transitioning to Set A2. This updated methodology expands the scope from 11 to 19 impact categories and introduces updated characterisation models. Table **??** provides an overview of the new categories and weightings.

Impact Category	Unit	Weighting Factor (€/ unit)
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16 €
Depletion of abiotic resources – elements	kg Sb-eq	0,16 €
Global warming	kg CO_2-eq	0,05 €
Ozone depletion	kg CFC-11-eq	30,00 €
Photochemical oxidant creation (Smog)	kg C_2H_4	2,00 €
Acidification of soil and water	kg SO_2-eq	4,00 €
Eutrophication	kg PO_4^{3-}-eq	9,00 €
Human toxicity	kg 1,4 DB-eq	0,09 €
Freshwater ecotoxicity	kg 1,4 DB-eq	0,03 €
Marine water ecotoxicity	kg 1,4 DB-eq	0,0001 €
Terrestrial ecotoxicity	kg 1,4 DB-eq	0,06 €

Table 4.2: Set A1: MKI/ECI weighting factors used in DuboCalc

The new EF3.1 characterisation model significantly expands emission coverage and improves regional accuracy. While scientifically more robust, it is expected to raise MKI scores due to broader scope and higher CO_2 shadow prices. Human toxicity, however, will be weighted less heavily (Schipper, 2024).

Sectoral Implications for Civil Engineering (GWW)

The transition from Set A1 to A2 will affect LCA outcomes across the civil engineering sector. MKI scores are expected to rise by a factor of 1.4 to 2.1, particularly for concrete- and steel-intensive projects. This may shift preferred design choices, especially during tenders where only Module A impacts are assessed.

A further challenge lies in the limited sample (50 EPDs) used to calibrate weighting factors, which may not represent the full material diversity of the GWW sector. Full implementation of Set A2 also hinges on the phased update of Category 3 data in the NMD.

Implications for LCAs of Water Pumping Stations

For water pumping stations, the following implications are anticipated under Set A2:

- Increased MKI scores, especially for conventional materials;
- Potential shifts in optimal material choices, impacting comparative assessments;
- Reduced emphasis on human toxicity for metals such as aluminium and stainless steel;
- Greater importance of assessing Modules A–D for biobased materials to realise environmental gains;
- Need for updated EPDs to ensure alignment with the revised methodology.

Environmental Impact	Unit	Weighting Factor	Core or Additional
Climate change (fossil, biogenic, land-use)	€/kg CO_2	0,116	Core
Ozone depletion	€/kg CFC11-eq	32	Core
Acidification	€/Mol H^+-eq	0,39	Core
Eutrophication (freshwater, marine, terrestrial)	€/kg or mol	0.36–3.28	Core
Photochemical ozone formation	€/kg NMVOC-eq	1.22	Core
Resource depletion (metals and fossil)	€/kg or MJ	0.00033–0.3	Core
Water scarcity	m^3 water-eq	0.00506	Core
Fine particulate matter formation	€/kg disease cases	549,750	Additional
Ionising radiation	€/kg kBq U235-eq	0.049	Additional
Ecotoxicity and human toxicity	€/CTU	Varies	Additional
Land use	Pt/m^2·year	0.000087	Additional

Table 4.3: Environmental Impact Categories and Weighting Factors (A2 Set)

This evolution in methodology enhances scientific credibility but also requires practitioners to interpret legacy A1-based results with caution. While Set A1 will remain the basis for this study, anticipated shifts under A2 will be acknowledged in the conclusions.

4.2.4 Life Cycle Interpretation

The interpretation phase will synthesise the LCA results and identify key contributors to environmental impact. This phase will also assess data quality, evaluate result robustness, and inform recommendations for more sustainable design and operation of pumping stations.

Uncertainty analysis will include sensitivity testing for variables such as electricity mix, transport distances, and material substitutions. Scenario analysis will explore different end-of-life options (e.g., recycling versus landfill) for major components.

Based on these analyses, practical strategies for sustainability improvement will be formulated.

The study will also reflect on limitations including data availability (particularly reliance on secondary data), geographical scope (Dutch context), and the inherent constraints of the MKI/ECI framework, which does not account for social or economic sustainability dimensions.

The following chapters will present the results obtained through this methodological approach.

5 Assessment of Current Sustainability Evaluation Practices in Water Pumping Stations

This chapter investigates how sustainability and circularity are currently assessed in the design and realisation of water pumping stations. Section 5.1 introduces the chapter's qualitative focus, while Section 5.2 presents a systematic review of existing sustainability frameworks and case study applications. Section 5.3 synthesises insights from expert interviews and workshops with practitioners and water authorities. Section 5.4 then applies circularity assessment tools—such as the Material Passport—to two case studies: Noordeinde- en Geerpolder and De Drie Delfzijlen. Through this multi-source approach, the chapter identifies current gaps, best practices, and opportunities for improving sustainability assessments in practice.

While Chapter 2 provided a theoretical foundation by reviewing academic literature on sustainability and circularity in infrastructure, this chapter shifts focus to the practical application of these concepts in the Dutch water sector. This chapter explores how sustainability is currently evaluated in water pumping station projects through a systematic review of Dutch policy documents, sector guidelines, and assessment tools. This is complemented by expert interviews and a workshop to capture practical insights. Additionally, the Material Passport method is applied to the case studies to assess how circularity is addressed in practice. By moving from a conceptual to an applied perspective, this chapter highlights implementation challenges and identifies opportunities to strengthen sustainability assessments at the asset level, forming a critical link to the environmental modelling in the following chapters.

The primary objective is to analyse how sustainability is currently operationalised, identify existing limitations in these practices, and contribute towards more comprehensive evaluation strategies aligned with national circularity ambitions.

5.1 Systematic Review of Assessment Frameworks and Case Applications

A range of sustainability assessment frameworks are commonly employed in Dutch water infrastructure projects, each offering distinct methods for evaluating environmental and operational performance. Among the most widely used is the CO_2 Performance Ladder, a tool designed to assess and stimulate carbon emission reductions among organizations (OECD, 2015). As of 2021, this framework had issued over 1,140 certificates—an increase of 20% compared to the previous year—and had been adopted by around 200 public procurement agencies as part of their tendering criteria. Its increasing popularity reflects growing institutional alignment with climate goals, particularly in the water management sector.

In parallel, Total Cost of Ownership (TCO) frameworks have gained traction by emphasizing long-term financial planning, accounting for both energy use and maintenance (Stork, 2020). The pumping station upgrade at water pumping station Krimpenerwaard serves as a notable example. There, TCO-based decision-making led to the implementation of a design that enables energy generation during water release, offsetting approximately one-third of the station's electricity consumption, this is the first polder pumping station in the Netherlands to do so. This illustrates how financial sustainability can be aligned with ecological performance, provided that tools are applied beyond upfront cost considerations.

Another emerging approach is Model Predictive Control (MPC), used by water boards such as Noorderzijlvest. MPC leverages predictive algorithms to anticipate variables like rainfall patterns, energy prices, and storage capacities in low-lying areas, enabling more energy-efficient pump operations while simultaneously improving flood resilience (Heeringen et al., 2015). By dynamically adjusting pumping schedules based on forecasted data, MPC has demonstrated considerable potential in reducing operational emissions and lowering energy costs, positioning it as a promising innovation for data-driven water infrastructure (WIN, 2020).

Despite their benefits, these frameworks collectively reveal several limitations. Most critically, they offer limited insight into the circularity of infrastructure systems. Indicators related to material reuse, design for disassembly, or end-of-life recovery are largely absent. Moreover, the predominant focus on carbon dioxide (CO_2) emissions—although important—leaves broader ecological dimensions, such as biodiversity impacts, pollution risks, and ecosystem service disruptions, largely unexamined. Additionally, advanced sustainability tools such as full Life Cycle Assessments (LCAs) and Material Passports remain underutilized and are rarely integrated into mainstream project workflows, which diminishes their potential influence during the critical design and procurement stages.

To explore how these challenges are addressed in practice, the study examined recent Dutch case studies that explicitly incorporated circular principles. For instance, Waterschap Drents Overijsselse Delta (WDODelta) has initiated several projects integrating circular strategies across both new builds and renovations. These efforts include forming long-term partnerships with contractors to align construction practices with sustainability targets—although the current standard duration of four years may be insufficient to fully realize impactful systemic change. WDODelta also employs modular prefabricated components that facilitate reuse and simplify future maintenance activities. Early-stage engagement through sustainability workshops and circular design charrettes further ensures that circularity is considered from the outset. Additionally, Material Passports are used to document material types and quantities, recyclability, and potential for future disassembly, supporting long-term resource traceability.

The De Drie Delfzijlen pumping station project, developed by Waterschap Noorderzijlvest in collaboration with Aveco de Bondt, further illustrates how Material Passports can be systematically implemented. The passports used in this project catalogue detailed information about material specifications, toxicity, recyclability, and maintenance guidelines. This data facilitates lifecycle tracking and can inform reuse scenarios at the end of the station's service life. However, the use of such passports remains largely limited to pilot projects, and their sector-wide adoption has not yet materialized.

Innovative materials were also explored in several other projects. For example, the Vilsteren pumping station became the first in the Netherlands to use 100% circular concrete, incorporating aggregates sourced entirely from demolished structures (Actueel, 2021a). The Coehoorn station advanced this innovation further by constructing a relocatable facility made from 100% cement-free geo-polymer concrete (Actueel, 2021b). This design achieved a significant 50% reduction in CO_2 emissions compared to conventional mixes. Nonetheless, the environmental benefits were partially offset by concerns over the use of chemical activators such as sodium hydroxide, which introduce trade-off's in toxicity and material handling, as noted in previous research (Salas et al., 2018; Munir et al., 2023).

In summary, while Dutch water boards are beginning to incorporate circular design strategies into infrastructure development, implementation remains inconsistent. Existing frameworks provide valuable foundations, yet they often fail to capture the full environmental and material lifecycle impacts necessary for genuinely sustainable infrastructure.

The case studies reveal both the potential and limitations of current practices, highlighting the need for standardized circularity metrics, deeper integration of lifecycle tools into design workflows, and long-term institutional commitment.

Summary of Findings

The qualitative analysis reveals several emerging practices aimed at enhancing sustainability and circularity in Dutch water pumping stations. However, these developments remain fragmented and inconsistently adopted across the sector. Table 5.1 provides an overview of the key innovations identified and the associated barriers to wider implementation.

Table 5.1: Summary of emerging sustainability and circularity practices in Dutch water pumping stations

Focus Area	Observed Innovations	Challenges and Limitations
Material Innovation	Use of 100% circular concrete (e.g., Vilsteren); geopolymer concrete (e.g., Coehoorn); biobased materials in pilot studies	Toxicity concerns with chemical activators; limited EPD availability; lack of long-term performance data
Modular Design and Disassembly	Prefabricated components to facilitate future reuse (e.g., WDODelta projects)	Design for disassembly not yet a procurement standard; integration limited to specific contractors
Lifecycle Documentation	Implementation of Material Passports (e.g., De Drie Delfzijlen) documenting recyclability, maintenance, and toxicity	Limited adoption beyond pilot projects; lack of digital infrastructure for sector-wide data sharing
Predictive Control Strategies	Use of Model Predictive Control (e.g., Noorderzijlvest) to optimize pump scheduling and reduce emissions	High data requirements; applicability limited to digitally equipped stations
Carbon Assessment Tools	Adoption of CO_2 Performance Ladder across public tenders; increasing institutional alignment with carbon reduction targets	Narrow focus on carbon; neglects broader circularity and ecological metrics
Lifecycle Costing Approaches	Use of Total Cost of Ownership (TCO) in procurement decisions (e.g., Krimpenerwaard) aligning cost and energy savings	Often excluded in early design phases; limited transparency in long-term cost modelling

These findings indicate a clear movement towards integrating sustainability and circularity into water infrastructure projects, yet systemic adoption remains limited. A more consistent application of lifecycle tools, broader circularity metrics, and stronger institutional frameworks are required to transition from pilot innovations to standardised practice.

5.2 Expert Interview Synthesis and Workshop Insights

Interviews with engineers and sustainability advisors revealed both promising opportunities and persistent challenges in advancing circularity within Dutch water infrastructure projects. Experts consistently observed an increasing awareness of circularity principles among clients, contractors, and institutional stakeholders. This growing consciousness is not only reflected in strategic dialogues but also in a greater willingness to experiment and innovate within pilot projects. Especially within water boards, knowledge exchange is accelerating, as lessons from ongoing experiments are more frequently shared across institutional boundaries.

These developments signal a cultural shift in the sector towards more sustainable and circular thinking.

Nonetheless, several barriers continue to impede meaningful implementation. Experts pointed out that existing tools predominantly quantify benefits related to energy savings and carbon reductions, while falling short in capturing broader circular or ecological gains. This limitation hampers the ability to justify circular interventions that may offer long-term or systemic benefits, such as improved material retention or reduced resource dependency. A further obstacle lies in the absence of standardised definitions and metrics for circularity. Without a shared language or agreed-upon indicators, stakeholders often interpret circularity differently, leading to fragmented approaches and inconsistent evaluations. In addition, there remains a notable disconnect between policy ambitions and operational practice. While circularity is prominently featured in strategic plans, it is not always effectively translated into project requirements or measurable outcomes on the ground.

Insights from two internal workshops—organised by engineering firm Aveco de Bondt and water authority Wetterskip Fryslân—offered further contextualisation of these institutional dynamics. Water boards in particular have committed to ambitious national sustainability goals, including a 50% reduction in the use of primary raw materials by 2030 and achieving full circularity by 2050. These goals are reflected in the adoption of specific implementation themes that aim to embed circular principles in daily practice.

One of the core themes that emerged from the workshops is the emphasis on circular design, where prefabrication, modularity, and reversibility are actively explored as means to extend the lifespan and adaptability of infrastructure. Complementing this is a renovation-first approach, which prioritises the reuse of components and retrofitting of existing assets over complete replacement. Sustainable procurement practices are also evolving, with increasing use of circular key performance indicators (KPIs) and material recovery clauses in contracts to stimulate market innovation and accountability. Moreover, the importance of robust data management was widely acknowledged, particularly in relation to tracking material flows and benchmarking environmental performance over time. Capacity building through professional development and internal knowledge sharing was repeatedly highlighted as a prerequisite for embedding circularity in both policy and practice. Finally, innovation plays a central role, not only in the testing of alternative materials but also in the development of predictive models for environmental and lifecycle evaluation.

A recurring tension identified in both interviews and workshops concerns conflicting priorities in material selection. For example, stainless steel is often favoured for its recyclability and durability, yet it significantly increases embodied emissions during production, however it is also known for its long lifetime and durability. This case illustrates the need for decision-making tools that can balance multiple sustainability criteria simultaneously, or at least taking into account multiple focussed sustainability assessments next to each other, rather than focusing solely on circularity or carbon in isolation.

Overall, the qualitative assessment illustrates that while there is a growing institutional commitment to sustainability and circular economy goals in the Dutch water sector, current evaluation frameworks such as the CO_2 Performance Ladder and Total Cost of Ownership (TCO) are insufficient for capturing the full scope of ecological and circular performance. Case studies suggest that circular design is feasible—especially when supported by innovation in materials, procurement processes, and documentation practices. However, broad adoption across projects and organisations remains inconsistent and often limited to experimental initiatives.

Bridging the gap between strategic ambition and practical implementation will require the sector to adopt more holistic and transparent evaluation tools, enhance cross-institutional collaboration, and scale up pilot-based learning.

Through such integrative and system-wide strategies, the Netherlands can better align daily practices with its national circularity targets and contribute meaningfully to a sustainable future in infrastructure development.

5.3 Circularity Assessment in Water Pumping Stations

Circularity in civil infrastructure plays a key role in reducing material depletion, construction waste, and lifecycle emissions—aligning with the broader ambitions of the EU and the Netherlands toward a regenerative and climate-neutral economy. In the Dutch context, the concepts of reuse and detachability are particularly emphasized. These concepts are embedded in the *Bepalingsmethode* of the Nationale MilieuDatabase (NMD), which underpins environmental calculations in tools such as DuboCalc (S. N. Milieudatabase, 2025). This section examines the circularity of the two water pumping stations by building Material Passports, quantifying material flows, and assessing performance using two key frameworks: *Het Nieuwe Normaal* (HNN) and the *Material Circularity Indicator* (MCI).

The NMD's assessment method integrates circularity through metrics that capture product reuse and potential for disassembly. A key distinction is made between *unintended reuse*—where materials are recovered opportunistically after demolition—and *intended reuse*, which is embedded in the design strategy from the outset. Unintended reuse is quantified using the H-factor, typically set at 0.2, indicating that the environmental burden is reduced by 80% compared to new production, yet still accounts for processing and end-of-life impacts (Modules A1–A3, C3, C4, D). Intended reuse is more robustly rewarded in life cycle modelling via the K-factor, which varies from 1 to 100 based on three criteria: the technical quality of the reused element after first use, its expected residual service life, and its relative market value compared to a new equivalent. These factors modify the environmental benefits captured in Module D of the LCA.

At end-of-life, materials are classified based on their potential for reuse. Fully reusable products, such as demountable slabs, retain their function without further processing. Partially reusable components allow for selective recovery of materials, while non-reusable products are considered waste and routed through recycling, incineration, or landfill. These classifications influence environmental outcomes in Module D, with higher reuse potential translating to greater environmental credits.

Detachability is a crucial enabler for high-quality reuse. It refers to the ability to disassemble components without damaging them, thereby preserving their functional integrity for future applications. Though not yet explicitly included in NMD's quantitative framework, detachability is increasingly recognised through indices such as those developed by Alba Concepts and the Dutch Green Building Council (DGBC). In practical terms, manufacturers of detachable products are expected to provide verifiable documentation, including disassembly instructions, mounting methods, and structural substantiation. This is formally recognised under section 2.6.3.9 of the Assessment Method.

An emerging extension of this concept is the *take-back guarantee*, wherein manufacturers commit to reclaiming products at the end of their service life. This model supports circularity by shifting product responsibility back to the supplier, enabling reuse or high-quality recycling. Take-back schemes are particularly relevant for demountable components and contribute positively to the Module D credits in LCAs.

These strategies align with the life cycle structure of environmental assessments. Modules A1–A3 cover material production, C1–C4 address deconstruction and waste processing, while Module D accounts for benefits gained through reuse, recovery, and recycling beyond the system boundary. The H and K reuse factors adjust these outcomes based on the type and quality of reuse.

In summary, the Assessment Method offers a structured and operational framework for integrating circular principles into infrastructure LCAs. By capturing both unintended and intended reuse, incorporating design for detachability, and encouraging take-back models, it facilitates a more nuanced and performance-driven evaluation of environmental impact. These mechanisms offer a pathway to align environmental performance assessment with circular economy objectives in the Dutch built environment.

Frameworks and Methodology

Het Nieuwe Normaal (HNN) Infrastructure HNN provides nine indicators across three themes (environmental impact, material use, value retention) to standardize circular performance (Bas Roelofs et al., 2023). The *Infrastructure* guideline offers clear benchmarks for each indicator, allowing consistent evaluation across projects.

Theme	Indicator	Objective
Environmental Impact: Protecting the environment	Environmental and climate impact	Provides insight into the total environmental and climate impact over the full lifecycle of the project, expressed in the Environmental Cost Indicator (MKI) and greenhouse gas emissions (CO_2-eq).
	Material-related CO_2 emissions	Indicates the greenhouse gas emissions (CO_2-eq) from project implementation, caused by the production of materials, components, and equipment use.
	Material-related CO_2 storage	Reflects the amount of CO_2 stored in (biobased) building materials, thus removed from the atmosphere.
Material Use: Protecting material reserves and preventing depletion	Material origin	Assesses the total quantity of materials used in the project, distinguishing between primary (virgin), secondary (recycled, reused), and biobased sources.
	Healthy materials	Addresses the proportion of materials used in a project that are demonstrably non-toxic.
	Handling residual materials (construction phase)	Insight into the destination of leftovers, temporary structures, and packaging materials during construction.
	Handling residual materials (demolition phase)	Insight into the reuse of residual materials from demolition of existing structures (if applicable).
Value Retention: Protecting existing value for the future	Functional adaptability	Indicates the adaptability of a project's function during its lifecycle, e.g., functional expansion or conversion to other uses.
	Disassemblability	Insight into how easily products, components, and materials can be separated from each other.
	Reuse potential	Indicates the extent to which products, components, or materials can be reused or recycled (high or low value) at the end of their service life.

Table 5.2: Circularity Themes, Indicators, and Objectives (Translated) (Source: Het Nieuwe Normaal)

Material Circularity Indicator (MCI) Developed by the Ellen MacArthur Foundation, the MCI measures virgin material input, product lifetime extension, and end-of-life recovery efficiency. It offers a quantifiable, comparative circularity metric.

Material Passport and National Database To assess the circularity of a water pumping station, one can use a so-called Material Passport to structurally store and continuously update all the material data and its connections. A Material Passport lists all materials in a structure, detailing origin, reuse potential, recyclability, and detachable connections (Twillert, 2022). In the Netherlands, AMA and Madaster pilots use passports to enhance material traceability for reuse (Madaster, 2019). The NMD now supports LCA data including secondary material flows, reuse, and detachability (S. N. Milieudatabase, 2025). In light of this study the two cases, the two water pumping stations, will be analysed and given a in so far possible a Material Passport. First for the small one, 'Noordeinde- en Geerpolder', and later in this section a Material Passport for the large water pumping station 'De Drie Delfzijlen'.

A Material Passport is useful to get insights in multiple characteristics such as transparency in material flows, basis for reuse and detachability and it enhances circular design. It gives insight in the used (and reused or bio-based) materials, and to know what is constructed where exactly and it is documented well it could in the future be demounted easily instead of demolition.

The Dutch national database with GER-values and CO2 list will be used to obtain environmental product specific information. This is published by : 'De Rijksdienst voor Ondernemend Nederland (RVO)' is an agency of the Dutch Ministry of Economic Affairs and the Ministry of Agriculture, Nature and Food Quality. The database is freely available and updated with scientific supported LCA and emission data.

GER-value (Gross Energy Requirement) refers to the total primary energy content of a material or activity. It measures the amount of energy required to produce a product or perform an activity, including both direct energy use and the energy used in producing raw materials and semi-finished products. The GER-value is commonly applied in sustainability assessments and life cycle analyses (LCA).

CO_2 List (Emission Factors List) is a document that provides emission factors for various energy sources and activities (e.g., natural gas, electricity, gasoline). These factors indicate the amount of CO_2 or CO_2-equivalents emitted per unit of energy or activity. Some lists also include emissions of other greenhouse gases like methane and nitrous oxide, converted into CO_2-equivalents. These lists are essential for calculating the carbon footprint of products, activities, or organizations.

5.3.1 Material Passport 'Noordeinde- en Geerpolder'

In order to assess the circularity, it will be done according to project data and latest knowledge of the materials and its reusability etc. the complete Material Passport table of the first small water pumping station 'Noordeinde- en Geerpolder' can be found in appendix B in Table B.1. In this long table it has a lot of components as columns where a lot of data can be stored, such as the material properties, where it comes from, if its primary or secondary material use, and its lifespan and detachability types, and location of the components, its joint type, and then the percentage availability for reuse, recycling, incineration and landfill as end-of-life scenario's.

5.3.2 Material Passport 'De Drie Delfzijlen'

Next to the Material Passport of the small water pumping station case, another one of the large water pumping station 'De Drie Delfzijlen' is conducted, and can also be found in the appendix B in B.2. Also according to latest project data and knowledge of materials and well estimated calculations on life expectancy and end-of-life scenarios.

Material Passports Columns and Assumptions

The Material Passport table includes key indicators relevant to end-of-life and circularity considerations.

- **Detachability** refers to the ease of disassembly (Easy, Moderate, Difficult).
- **Joint Type** indicates the method of connection (e.g., Bolted, Welded, Interlocked).
- **Location** specifies the component's structural placement (e.g., Foundation, Perimeter, Pipeline), while
- **Accessibility** reflects the ease with which a component can be reached for maintenance.
- **End-of-Life (%)** presents estimated and currently common distributions across reuse, recycling, incineration, and landfill at the end of service life.

Key Assumptions: Steel and Azobé (red ironwood, tropical hardwood used in construction) elements are assumed to have a reuse potential of 20–30% due to their bolted joints, which facilitate disassembly. Next to that, the Azobé hardwood can be shaved and sawn again for use in different (construction) projects. Prefabricated concrete components, such as grass tiles, offer limited reuse (0–10%). Pumps and motors are estimated to have 10–30% reuse potential based on the possibility of refurbishment.

Regarding recyclability, metals achieve high recovery rates (80–95%), while concrete can be crushed and reused as aggregate at around 90%. Plastics like HDPE and EPS show lower rates (30–50%), primarily due to contamination issues.

Energy recovery via incineration is assumed for bio-based materials (e.g., Azobé hardwood, approx. 20%) and plastics (45–60%). Landfill disposal is limited to concrete fines and soil (5–10%), typically as cover material. Metals and glass are assumed to avoid landfill entirely.

Scoring Notes R-ladder The circularity scoring framework excludes R1 and R2 (related to reduction and reuse in design), as this assessment focuses on operational phase improvements of existing infrastructure. Reuse potential is influenced by connection type: bolted elements are favoured, followed by interlocked, then monolithic constructions.

End-of-life percentages are aligned with the 7R framework: components with more than 20% reuse potential are classified as R3 (Reuse); mechanical equipment with viable refurbishment options scores R4 (Repair/Refurbish); materials with over 70% recycling rates, such as metals and concrete, fall under R5 (Recycle); and incinerable plastics are assigned to R6 (Recover). Composite components, such as sandwich panels, are evaluated based on their dominant end-of-life route. All end-of-life percentages per material sum to 100%.

Discussion:

- *Renewable content* is currently nil; future projects should integrate bio-based alternatives (e.g., timber or bio-composite seals).
- Higher reuse and recycling percentages indicate stronger circular performance.
- Noordeinde- en Geerpolder facilitates more direct reuse potential, particularly for relatively a lot of steel—a valuable practice according to HNN indicator "value retention".

While the Material Passport provides valuable insights into the material composition of a structure, it does not offer a comprehensive assessment of circularity. Key design principles such as detachability, reuse potential, and adaptability over the lifecycle are not fully addressed. Although the sector often promotes the passport as a document that can be continuously updated, in practice it remains largely static and requires active management to reflect changes over time, particularly regarding use, maintenance, and renovation activities. Additionally, the Material Passport lacks an integrated assessment of environmental impacts, which limits its ability to evaluate circularity holistically. In subsequent chapters, a Life Cycle Assessment (LCA) will be conducted, after which the results will be linked to the Material Passport to provide a more complete understanding of material choices and their environmental implications.

Both cases could benefit from the early integration of detachable design features, in line with the detachability criterion of the Dutch National Environmental Database (NMD). More broadly, improving Material Passports enhances transparency, facilitates the development of secondary materials markets, and supports future tender evaluations—an impact already demonstrated by pilot projects in the Amsterdam Metropolitan Area. To further advance circular outcomes, it is recommended to integrate bio-based alternatives such as timber and mycelium-based sealing materials to increase the share of renewable content. Additionally, employing bolt connections and modular design strategies can improve disassembly and enable reuse. Linking Material Passports to digital tools such as Building Information Modelling (BIM) platforms or Madaster enhances traceability throughout the asset lifecycle. Finally, applying the Het Nieuw Normaal (HNN) scoring framework in procurement processes can help incentivise circular practices in civil infrastructure projects.

6 Environmental Impact Assessment of Water Pumping Stations using the MKI/ECI (LCA) method

This chapter quantifies the environmental impacts of water pumping stations using the DuboCalc software and the Dutch MKI/ECI method. Section 6.1 defines the goal and scope of the LCA, including system boundaries, assumptions, and cut-off criteria. Section 6.2 provides a detailed life cycle inventory for both case study pumping stations, supported by technical documentation and material quantities. Section 6.3 explores sustainable design alternatives by modelling different material and energy variants in DuboCalc. Together, these sections assess how material choices and system configurations influence total environmental performance across the full life cycle. Chapter 4 briefly introduced the LCA methodology. In this chapter, it will be elaborated in more detail, along with all the results obtained from applying the method.

6.1 Goal and scope definition

An LCA aims to quantify and compare the environmental impacts of water pumping stations throughout their entire lifecycle—from construction to decommissioning—following the ISO standard and focusing on the Environmental Cost Indicator (MKI/ECI) method. The study will assess two water pumping station sizes, the small water pumping station 'Noordeinde-en Geerpolder', and the large water pumping station 'De Drie Delfzijlen'. The goal is thus to quantify and evaluate the environmental impacts of water pumping stations throughout their entire lifecycle, to evaluate scalability and determine how proportions play a role. The method which will be used is according to Dutch standards and is called de 'Bepalingsmethode' or the assessment method from the Nationale Milieudatabase (NMD) (N. Milieudatabase, 2025; Berenschot, 2019).

First, a reference scenario or baseline variant is modelled in DuboCalc, after which a comparative analysis is conducted using more sustainable design variants and alternative material combinations. These are based on multiple adjustable parameters within the model. Initially, both water pumping station variants are modelled for a standard design life of 50 years, in line with common practice in life cycle assessments and the assumptions embedded in current environmental datasets. To gain deeper insight into the impact of lifespan assumptions on environmental performance, additional sensitivity analyses are conducted using 25-year and 75-year periods. These alternative lifespans are applied specifically to the MKI calculations to assess how shorter or longer operational durations influence environmental outcomes. Due to time constraints and data availability, the extended and shortened lifespans are not applied to full modelling but instead serve to highlight potential shifts in environmental impact across time, offering valuable guidance for long-term planning and policy development.

6.1.1 Function and Functional Unit

In a Life Cycle Assessment (LCA), the function refers to the intended service or operational role of the system, product, or service under investigation. In this study, the primary function of the system is the controlled pumping and flushing of water, aimed at maintaining and regulating water levels within the designated area. This function is central to the infrastructure's operational relevance and defines the scope of the environmental performance evaluation.

The functional unit (FU) is a key element in LCA methodology. It provides a quantified and standardised measure of the system's function, serving as a consistent reference point for

calculating and comparing environmental impacts across different system configurations. In this assessment, the initial modelling was conducted at the level of two complete water pumping stations, each assessed over a 50-year operational lifespan. Accordingly, the primary functional unit is defined as the operation of one functional water pumping station over 50 years.

To enable comparison between the two stations—one small-scale and one large-scale—the results were subsequently normalised based on their respective design pumping capacities. The smaller station operates at a capacity of 12 m^3/min, while the larger station is designed for 1,800 m^3/min. By dividing the total impact scores by the design capacity, a normalised measure was derived, expressed as environmental impact per 1 m^3/min of pumping capacity per operational year. This approach facilitates a capacity-adjusted comparison between infrastructure of differing scales, allowing for insights into relative efficiency and environmental intensity across projects. The reference flow—that is, the quantity of the service provided for which environmental exchanges are tracked—is accordingly set as 1 m^3 of water per minute.

6.1.2 System Boundaries

In line with the EN 15804 standard (3, 2019) and the Dutch *Bepalingsmethode Milieuprestatie Bouwwerken* (Method for Determining the Environmental Performance of Constructions) (N. Milieudatabase, 2025), a uniform and verifiable methodology is applied for assessing the environmental performance of the selected water infrastructure projects. Although adapted from European guidelines, this methodology is tailored to the Dutch regulatory and infrastructural context.

The system boundaries for this Life Cycle Assessment (LCA) follow a comprehensive *cradle-to-grave/cradle* approach, encompassing all life cycle stages from raw material extraction to end-of-life management. The life cycle is subdivided into four main modules (A–D), as illustrated in Figure 6.1:

- **Module A (Production and Construction Phase):** Includes the extraction and processing of raw materials (e.g. concrete, steel), manufacturing of pump components, transportation to the construction site, and installation of components such as pumps, electric motors, and control panels.
- **Module B (Use Phase):** Covers the operational phase including energy consumption, routine maintenance, and component replacements (e.g. lubrication systems and pump elements).
- **Module C (End-of-Life Phase):** Accounts for dismantling, transportation of decommissioned components, and final treatment such as disposal or recycling.
- **Module D (Benefits and Loads Beyond the System Boundary):** Considers potential benefits from material recovery and reuse, such as repurposing recycled steel or electrical parts in future applications.

Scope of Included and Excluded Elements

The scope of assessment for both the large-scale and small-scale pumping stations includes primary structural and operational components: pumps, electric motors, control panels, foundations, sheet pilings, sluice gates or in- and outlets, pipelines, operational energy consumption, and routine maintenance.

Secondary infrastructure, such as access roads, adjacent utility networks, or auxiliary buildings, is excluded unless its inclusion is explicitly required by the functional operation or construction logistics of the station. Minor components or negligible material flows may be excluded in accordance with defined cut-off criteria.

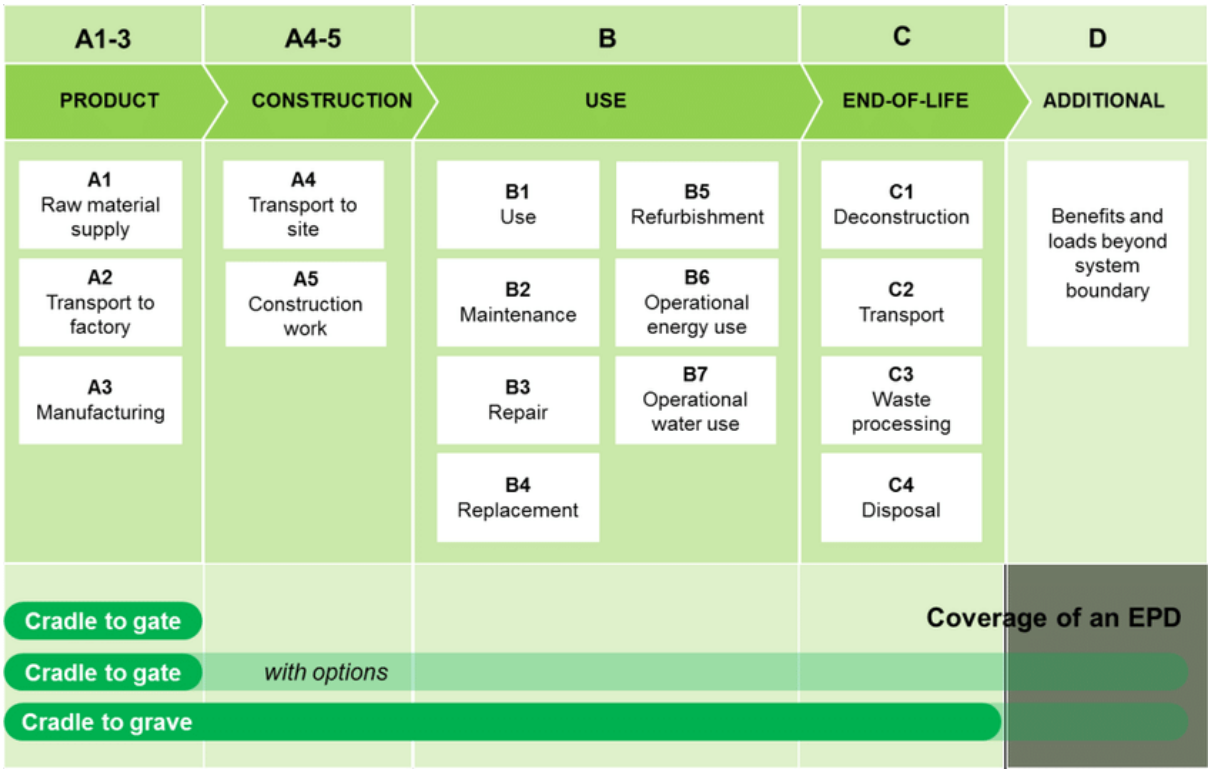


Figure 6.1: The Life Cycle Stages

6.1.3 Cut-off Criteria

When defining the scope of the analysis, certain aspects may be included or excluded:

- Physical cut-off: Small components (e.g., bolts, nuts) can be excluded if they account for$<$ 1 % of total mass and $<$ 1% of total impact.
- Energy cut-off: Equipment or processes with negligible energy use can be excluded ($<$ 1% of the total energy use).
- Environmental impact cut-off: If a process or material contributes $<$ 1% to the total impact in at least three impact categories, it can be excluded.

The Bepalingsmethode states that a maximum of 5% of environmental impacts may be excluded. However, for precision purposes, the 1% boundary will be maintained.

6.1.4 Allocation Procedure

Allocation in Life Cycle Assessment (LCA) involves distributing inputs and outputs of a multi-functional process among the products or services that share it. This can introduce bias and uncertainty, so avoiding allocation is recommended. One way to avoid allocation is to divide the process into distinct sub-processes, allowing data collection to focus on specific flows for each function. Another approach is to expand the system boundary to include all co-products, treating them as separate functional units. Physical partitioning of co-products is another method, measuring flows specific to each product. ISO 14044 (Standardization, 2006) advises prioritising these methods over allocation to achieve more accurate results.

Given that pumping stations may perform multiple functions and involve multi-output processes, allocation rules are defined according to established LCA conventions. For processes producing multiple outputs, such as concrete production with both primary and secondary

products, allocation will be based either on mass or economic value. When recycled materials are involved, the allocation of impacts follows the rules set by the Nationale Milieudatabase (NMD), wherein the environmental impact of a material is partly attributed to both its previous and subsequent life cycles. Energy consumption during the operational phase will be allocated based on the cumulative volume of water pumped over the station's defined service life.

6.1.5 Data Requirements

The LCA will rely primarily on accurate, project-specific data wherever possible. Preferred primary data include detailed specifications of materials used in the construction of the pumping stations, empirical energy consumption data during operation, documented maintenance schedules, and component replacement intervals. Where available, demolition and recycling data from analogous projects will be used to inform the end-of-life modelling. Secondary data will supplement primary sources when necessary, particularly in cases involving generic construction processes. These secondary datasets will be sourced from reputable LCA databases, including the Nationale Milieudatabase (NMD), Ecoinvent, and DuboCalc, offering standardised environmental performance values for materials and systems.

The operational phase of the LCA will be initially modelled over a service life of 50 years, reflecting standard practice for civil infrastructure. In terms of geographical relevance, all data will be selected to reflect Dutch or, where appropriate, European conditions, as environmental impacts are significantly influenced by regional variables such as energy generation mix, waste treatment technologies, and climatic conditions.

6.1.6 Assumptions

General assumptions and well estimated calculated values for all the materials and important processes within the water pumping stations which where not in DuboCalc as pre-defined can be found in the appendix A.

6.2 Life Cycle Inventory (LCI) Analysis

The Life Cycle Inventory (LCI) phase involves collecting data on all inputs and outputs throughout the lifecycle of a water pumping station, or 'water pumping station'. This includes quantifying resources such as raw materials and energy, as well as emissions to air, water, and soil. The objective is to systematically gather data on all flows associated with the pumping station, including construction, operation, maintenance, and end-of-life disposal with recyclability and re-use taken into account. Data collection methods include reviewing technical construction drawings, reviewing energy usage data, using data collection sheets, and applying secondary data from industry or construction averages when specific data is unavailable. Flow models are typically employed to clearly illustrate the system boundaries and flow relationships in a structured manner, as is to be seen for this research in figure 6.2.

6.2.1 LCI for the Noordeinde- en Geerpolder water pumping station

For the Noordeinde- en Geerpolder water pumping station, the scope of data collection typically involves lower resource consumption, fewer operational processes, and simpler infrastructure compared to a large water pumping station. Inputs include construction materials like concrete, steel, and pumps, as well as energy sources, primarily electricity for pump operation. Given the smaller scale, data collection may rely more on direct measurements and energy consumption, with limited secondary data inputs.

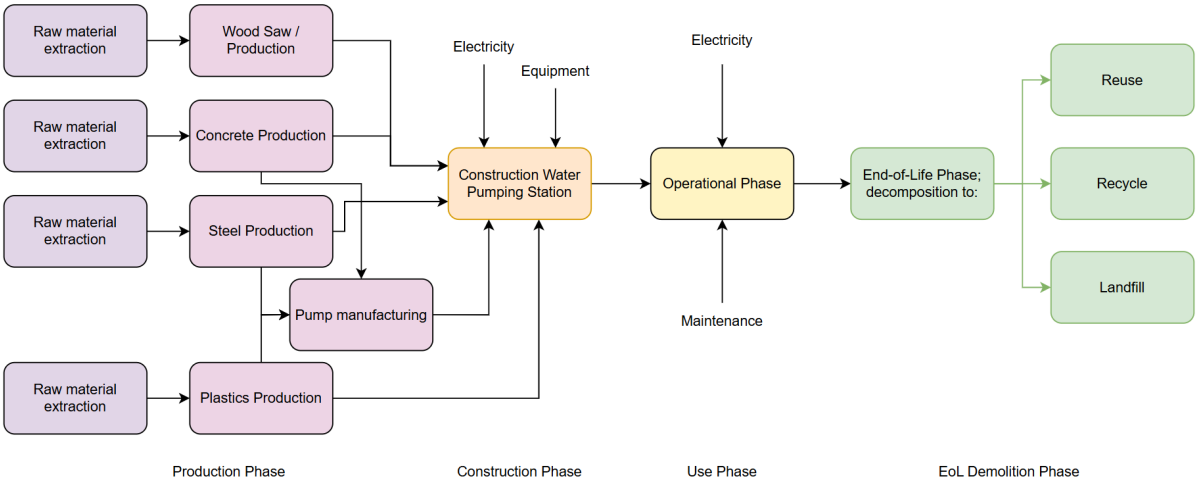


Figure 6.2: Flow Model Water Pumping Station

Geometric characteristics of 'water pumping station Noordeinde- en Geerpolder'

in table 6.1 all the input data categorized and sorted with its quantities and lifespans to get it in DuboCalc can be seen. Out of technical drawings and project data and documentation all the general quantities, numbers, processes, amounts and materials have been gathered and calculated.

Table 6.1: Material quantification list 'water pumping station Noordeinde- en Geerpolder'; source: Internal Aveco de Bondt

	Name	**Quantity**	**Unit**	**Lifespan (years)**
Preparatory Work	Excavation of construction pit	360	m3	
	Excavation of dredged material	12	m3	50
	Placement of temporary pump	480	m3/h	<5
	Operating hours of temporary pump (8 weeks)	8	KW	
	Installation of temporary sheet pile, az18, 10-week rental	177	m2	50
	Power supply cables dig and placement	70	m1	50
	Transport of material / equipment (150km)	27,000	ton*km	
Civil Work	Excavation for sewer trench	360	m3	50
	Transporting soil	360	m3	50
	Refilling with new sand	360	m3	50
	Transport of material and equipment (150km)	27,000	ton*km	
Foundation	Driving hardwood sheet piles, azobe 8m	48	m2	50
	Driving steel pipe piles, filled with concrete, Ø170x5mm ($\sim$ 10m deep)	15	pcs.	50
	Installing steel sheet piles front	158	m2	50
	Installing steel sheet pile corner needles	8	pcs.	50
	Installing hardwood Azobé sheet pile silt barrier	21	m2	50
	Installing steel sheet piles rear side	130	m2	50
Concrete Work	Placing concrete capping beam 50x50cm on steel sheet pile, incl. reinforcement	22	m1	50
	Delivery and installation of prefab concrete pumping pit	18	m3	50
	Crane for installation concrete pumping pit	15	hours	
	Pouring concrete for fish passage front and rear	3	m3	50
	Pouring concrete slab bottom protection	1	m3	50
Steel Work	Installation of steel trash rack and support beam (0,0408m3)	1	pcs.	50

	Name	Quantity	Unit	Lifespan (years)
	Installation of metal cover plate for pumping pipeline outlet	2	m2	50
	Installation of steel beam HEA frame for pumping pipeline	9	m1	50
	Steel UNP 380mm profile for fish pipeline support	20	m1	50
Masonry / Wall / Plate / Roof - Elements	Housing for electrical switch cabinet	25	m2	50
Mechanical Engineering	Installing new check valves (pumping and fish pipelines)	2	pcs.	50
	Installing large pumping station pump	1	pcs.	15
	Installing small fish passage pump	1	pcs.	15
Pipelines Pump	Installing cast iron pipelines, all $\sim$ 450mm	18	m1	50
Pipelines Fish Passage	Installing automatic butterfly valve Ø300mm	2	pcs.	50
	Installing air vent with ball valve	2	pcs.	50
	Installing HDPE pipelines fish passage, $\sim$ 315mm	21	m1	50
	Pressure pipeline Ø100mm	9	m1	50
	Slide valve for pressure pipeline	2	pcs.	50
Electrical	Process installation; pump, valves, lighting, heating, fan, electrical systems, powerage	25	kVA / kW	15
Site Layout	Installation of steel balustrade	6	m1	50
	Installation of coated fencing, 2m high incl. swing gate	24	m1	50
	Concrete grass tiles paving	100	m2	50

6.2.2 LCI for the De Drie Delfzijlen water pumping station

A large water pumping station typically involves more complex systems, higher throughput, and greater energy and material inputs. Inputs include significant quantities of structural materials (steel, concrete), high-capacity pumps, and advanced monitoring and control systems. Operational data encompasses extensive electricity use, maintenance activities, and potential backup power sources (e.g., diesel generators). Outputs involve greater volumes of emissions, waste, and potential discharges due to the larger operational scale. Data collection is more extensive and may include detailed process-level data, industry databases, and secondary data to account for larger and more complex flows. Flow models for large water pumping stations often require more detailed system mapping to accurately represent interconnected processes.

Geometric characteristics of 'water pumping station De Drie Delfzijlen'

in table 6.2 all the input data categorized and sorted with its quantities and lifespans to get it in DuboCalc can be seen. Out of technical drawings, the 3D-model and project data and documentation all the general quantities, numbers, processes, amounts and materials have been gathered and calculated.

Table 6.2: Material quantification list 'water pumping station De Drie Delfzijlen'; source: Internal Aveco de Bondt

	Name	Quantity	Unit	Lifespan (years)
Preparatory Work	Excavation of construction pit	13,650	m3	50
	Installation of temporary sheet pile, az18, 20-week rental	2.025	m2	50
Civil Work	Transporting soil	13,650	m3	50
	Refilling with new sand	13,650	m3	50
Foundation	Driving concrete foundation piles (0.4x0.4x10m deep)	309	pcs.	50
	Installing steel sheet piles (15m long)	660	m2	50
	Installing Azobé sheet piles	8	m2	50
Concrete Work	Installing floor foundation slabs incl. reinforcement	1,062	m3	50
	Installing cantilevered floors incl. reinforcement	977	m3	50
	Cellar walls incl. reinforcement	170	m3	50
	Retaining wall on dike	15	m1	50
	Installing solid load-bearing walls incl. reinforcement	2,632	m3	50
Steel Work	Installation of steel trash racks	6,728	kg	50
	Trash rack cleaner motor (cast iron and copper)	1	pcs.	50
	Steel grates front and inside combined	9,246	kg	50
	Trash rack cleaner steel incl. suspension system	18,060	kg	50
	Steel sluice gate door incl. suspension system	48,568	kg	50
	Sluice gate motor	150	kg	15
	Fish passage sluice gates (2 pcs.)	23,000	kg	50
	Steel stairs	6	pcs.	50
	Housing for electrical cabinets (steel sandwich panels)	113	m2	50
	Transport of material and equipment	3,450	ton*km	-
Mechanical Engineering	Installing large pumping station pump	2	pcs.	15
	Installing fish passage pump	1	pcs.	15

	Name	Quantity	Unit	Lifespan (years)
Pipelines	Installing cast iron water pipelines	50	m1	50
Electrical	Process installation; pump, valves, lighting, heating, fan, electrical systems, powerage per pump	450	kW	15
Building Finishes	Installing steel sandwich panels	200	m2	50
	Installing isolation layers EPS 100 floor and roof	1,113	m2	50
	Facade filling panels	35	m2	50
	Installing lighting fixtures	15	pcs.	50
	Installing frames and doors steel	36	m2	50
	Installing glazing, double glass	371	m2	50
	Installing steel frames for glass	265	m2	50
Site Layout	Installation of steel balustrade	210	m1	50
	Transport of material and equipment	2,500	ton*km	-
	Concrete grass tiles paving	40	m2	50

6.3 Modelling Variants in DuboCalc for Sustainable Design Comparison

To assess more sustainable alternatives within the DuboCalc environment, a series of parametrised variants were modelled across key life cycle categories. These variants explore material substitutions, energy source optimization, construction strategies, ecological integration, and circularity enhancements. The objective is to evaluate the environmental impact of feasible design alternatives and their respective influence on the overall MKI (Milieu Kosten Indicator) score.

Material Substitutions

Structural and mechanical elements offer opportunities for impactful material substitutions. In reinforced concrete structures, conventional concrete was replaced with low-carbon alternatives such as geo-polymer concrete. For reinforcement steel, variants using electric arc furnace (EAF)-produced or recycled-content rebar were modelled. In some elements, steel reinforcement was substituted with fibre-reinforced polymers (FRP), reducing embodied carbon. For sheet piling, recycled steel and PVC-based alternatives were considered where structurally and environmentally viable.

Mechanical and piping systems were adapted to incorporate HDPE piping in place of traditional PVC or metal-based piping where pressure and chemical compatibility permitted. Components such as housings and covers were evaluated for feasibility using recycled plastic composites.

Within building components, sustainable material choices included prefabricated timber or hybrid timber-concrete systems for technical buildings, alongside insulation replacements using bio-based materials such as hemp, flax, or cellulose, substituting conventional EPS or PUR-based insulation.

Energy Source and Operational Efficiency

The energy supply scenario for pump operations was modified from conventional Dutch grid electricity to a green energy variant reflecting renewable sources (NL-groen). Additionally, local photovoltaic (PV) panel integration—e.g., roof-mounted or adjacent field-based systems—was modelled to explore partial self-sufficiency.

Operational efficiency enhancements included upgrading motor types to IE4+ high-efficiency electric motors and integrating variable frequency drives (VFDs) for demand-responsive pumping. Hydraulic optimisation strategies were incorporated to reduce system head losses, improving both energy consumption and performance.

Construction Method and Transport Logistics

Sustainable construction logistics were introduced by minimising transport distances for heavy materials such as concrete and aggregates through local sourcing strategies. Modular and prefabricated construction methods were considered to reduce on-site construction duration, labour, and equipment usage. Additionally, alternatives involving electric or biofuel-powered construction machinery were introduced to lower indirect emissions during the realisation phase.

Ecological Integration and Waterside Elements

Environmental performance was further enhanced through nature-inclusive design strategies. Eco-concrete or textured surfaces were considered for revetments and culverts to promote biodiversity. The reuse of sheet piles, particularly for temporary works, was modelled to avoid primary material demand.

Excavated materials such as clay or peat were considered for reuse in landscaping or dike reinforcement, pending contamination assessments. An explicit comparison was made between scenarios with and without fish passage implementation. While the MKI slightly increases with fish passage inclusion, the ecological benefits, such as enhanced fish migration, lower mortality rates, and improved biodiversity, often outweigh the marginal environmental costs. However, these benefits are not fully captured by current LCA indicators, necessitating a complementary multi-criteria or ecosystem service assessment approach.

Design and System Optimisation

Design dimensioning was analysed to avoid over-sizing. Pumping capacity was better aligned with hydrological models of peak discharge, with consideration for climate change resilience over extended lifespans. Adaptive pumping strategies were also explored, including load-shifting to coincide with renewable energy availability ("slim malen"). Storage buffers and temporary retention basins were evaluated to mitigate peak loads and smooth demand profiles.

Circularity and End-of-Life Considerations

End-of-life strategies were integrated into the modelling via circularity-informed design. Material selections were guided by recyclability, second-life potential, and availability of environmental product declarations (EPDs). Material Passports and digital traceability systems (e.g., Madaster-like approaches) were assumed in variants, enabling component-level identification, maintenance logging, and disassembly planning.

The design of station housing and other above-ground components included demountable construction principles, facilitating future disassembly and reuse. These interventions improve Module D outcomes in the LCA by ensuring higher recoverability and reducing landfill dependency.

Modelling Strategy in DuboCalc

The variant modelling within DuboCalc followed a staged strategy. Priority was given to interventions with high environmental impact reductions and low complexity or cost—so-called "low-hanging fruit." These included renewable electricity sourcing, use of reused foundation piles, and application of recycled concrete or steel variants.

Combined variants were also evaluated, integrating measures such as low-carbon concrete, recycled steel, and renewable energy sources in a bundled approach. Sensitivity analysis was conducted to identify dominant impact drivers and inform prioritisation. Additionally, normative and legal feasibility of each option was assessed, with consideration for implementation under current Dutch tendering frameworks and policy standards.

This integrated variant modelling enables a robust assessment of sustainability trade-offs, offering evidence-based guidance for early design phase decisions in future water pumping station projects.

6.3.1 Overview of Energy Consumption Estimates

As indicated in Table 6.3, the estimated annual energy consumption of Dutch polder and boezem pumping stations varies substantially depending on their scale and capacity. For instance, the relatively small polder pumping station 'Noordeinde- en Geerpolder' with a flow capacity of 12 m^3/min is estimated to consume approximately 25,000 kWh per year. Conversely, a large-scale boezem pumping station 'De Drie Delfzijlen' with a flow capacity of 1,800 m^3/min may require up to 3,000,000 kWh annually.

Type of Pumping Station	Capacity	Energy Use [kWh/year]
Surface Water and Inlet Pumps		
Inlet, surface, and flushing pumps	1 – 10 m^3/min	100 – 20,000
Polder Pumps		
Small polder pumps	10 – 50 m^3/min	10,000 – 100,000
Medium polder pumps	50 – 500 m^3/min	50,000 – 1,000,000
Large polder or boezem pumps	500 – 3,500 m^3/min	500,000 – 5,000,000
Municipal Sewer Pumps		
Sewer lift pumps	10 – 30 m^3/hour	200 – 600
Small sewer pumping stations	20 – 50 m^3/hour	500 – 15,000
End or main sewer pumping stations	50 – 1,000 m^3/hour	3,000 – 35,000
Large municipal sewer pumping stations	500 – 4,000 m^3/hour	15,000 – 150,000
Water Board Sewer Pumps (with Pressure Line)		
Sewer pumping stations with pressure line	25 – 500 m^3/hour	5,000 – 65,000
Large sewer pumps with pressure line	500 – 2,000 m^3/hour	35,000 – 132,500

Table 6.3: Classification of pumping stations by type, capacity, and annual energy use. Source: Cijfers en tabellen 2007 (Agentschap NL).

Classification of Pumping Stations by Capacity and Energy Use

6.3.2 Energy Estimation for Noordeinde- en Geerpolder

The Noordeinde- en Geerpolder pumping station is representative of a small polder system. The technical specifications indicate a normal operating power of 7.47 kW, which includes not only the pumping power but also auxiliary demands such as lighting, heating, and control systems. The peak power demand is approximately 12.34 kW. For modelling purposes, an average operational power of 10 kW is assumed as a reasonable midpoint between normal and peak values.

Assuming continuous operation, the station would consume 10 kWh. However, actual daily operating hours can vary significantly due to influencing factors such as polder size, head difference, rainfall intensity, seasonal variability, flow rate, and the number of installed pumps.

According to operational benchmarks for polder systems of similar scale and head such pumps typically run between 4 and 5 hours per day on average. For a conservative estimation, an average of 5 operating hours per day is assumed. This leads to a daily consumption of:

$$E_{\text{daily}} = 10\ \text{kWh} \times 5\ \text{h} = 50\ \text{kWh}$$

and an annual consumption of:

$$E_{\text{yearly}} = 50\ \text{kWh/day} \times 365\ \text{days} = 18,250\ \text{kWh/year}$$

This value is slightly lower than the generalised estimate provided earlier but considered more accurate for the Noordeinde- en Geerpolder use case. Therefore, the model adopts this refined estimate of 18,250 kWh per year as the baseline energy demand.

It should be noted that over a 50-year lifecycle, future uncertainty remains substantial due to factors such as increased precipitation extremes, sea level rise, and continued peatland subsidence. These developments may result in increased pumping requirements, particularly in low-lying polder regions.

6.3.3 Energy Estimation for De Drie Delfzijlen

The De Drie Delfzijlen pumping station represents a large-scale boezem station. Initial rough estimates indicated a total energy demand of approximately 3,000,000 kWh/year. However, this value was considered an overestimation and was subsequently refined through a technical calculation based on installed capacity and expected operational hours.

This station operates with three pumps, each rated at 300 kW. From previous data and knowledge of the pumping station operator, an average of 3 operating hours per day per pump could be assumed, the annual consumption would be:

$$E_{\text{yearly, initial}} = 3 \times 300 \text{ kW} \times 3 \text{ h/day} \times 365 \text{ days} = 985,500 \text{ kWh/year}$$

To further improve the accuracy of this estimate, historical operational data from 1994 to 2020 were analysed. This period was chosen because it reflects the time after all three pumps, including the third (installed in 1994), were in operation. Note that the first two pumps were originally diesel-driven and may have exhibited lower efficiency than the current electric motors, but they still offer a valid baseline for long-term usage analysis.

	Pump 1	**Pump 2**	**Pump 3**	**Total**
Total Hours (1994–2020)	15.207,36	18.688,59	29.075,20	62.971,15
Average Hours per Day	1,56	1,92	2,99	6,48
With 20% Margin for Future Increase	–	–	–	7,77

Table 6.4: Historical operational hours for De Drie Delfzijlen pumping station (1994-2020)

As shown in Table 6.4, the average combined operating time for all three pumps is 6.48 hours per day. In anticipation of future intensification of pumping needs due to climate-related pressures (e.g. sea level rise, heavier precipitation, and land subsidence), a 20% increase is applied, resulting in an adjusted daily average of about 7 hours and 45 minutes.

Accordingly, the revised annual energy consumption is:

$$E_{\text{yearly, adjusted}} = 3 \times 300 \text{ kW} \times 7,77 \text{ h/day} \times 365 \text{ days} = 2,552,445 \text{ kWh/year}$$

This adjusted figure will be used in the model as a more realistic energy demand projection for the De Drie Delfzijlen pumping station over the 50-year evaluation period.

Pump selection criteria

There is a desire for a pumping station to pump as efficiently as possible. Most pumps are adjustable, whereby it is possible to switch between a nominal capacity and a design capacity (=maximum capacity). The nominal capacity (on average approx. 70% of the maximum capacity) is the capacity at which the pumping station starts and will operate >90% of the time that it is operating (Rijnland, 2021). The advantage of this lower capacity is that the pumping station will oscillate less and that a smaller gradient is created in a water system. In many cases, it is not necessary for a pump to operate at full capacity immediately, as doing so would result in unnecessary energy consumption. Additionally, it is desirable for a pump to have a controllable operating range, enabling the implementation of smart water management strategies and

reducing the frequency of start-stop cycles. The desire is to choose a pump that delivers the highest efficiency at nominal capacity.

Climate change causes higher burden on polders

Recent climate projections indicate not only more frequent and intense rainfall events, but also greater extremes in weather patterns—resulting in both wetter and drier conditions. This leads to a dual challenge: increased volumes of water to discharge during heavy rainfall, and the need to ensure sufficient water supply during prolonged dry periods. Consequently, water pumping stations must be capable of both drainage and water intake functions to maintain water balance under varying conditions.

Between 2014 and 2019, new insights into precipitation statistics have shown that the volume of rainfall associated with events having a recurrence interval of 10 to 100 years increased by approximately 50%. This rise in extreme precipitation places additional stress on polder systems (Rijnland, 2021).

Simultaneously, land use within many polders is becoming more intensive, increasing both the economic value and the vulnerability of these areas. As a result, the available space for water retention and storage is increasingly constrained. While drainage capacity is typically designed to remain constant in accordance with policy guidelines, this limits the adaptability of polders to evolving climate conditions.

Although from a hydraulic perspective the climate challenge in polders may appear resolved due to consistent drainage design, the burden is effectively transferred downstream to the boezem system. This can lead to localized surcharges, despite the boezem often having residual storage capacity during isolated rain events.

With a limited increase in capacity (10-20%), the additional costs are nil. With a larger increase in capacity, the additional costs are significant.

A determining factor in the construction costs of a in first hand designed single-pump pumping station is whether one or two pumps are installed when capacity should increase. With a single-pump pumping station, the additional costs of a 10-20% higher capacity are nil, since this can be easily handled by the existing pump with negligible cost. With a significant increase in capacity (>20%), it is usually necessary to switch to 2 pumps because of maintaining efficiency and reliability, resulting in significant additional investment if only 1 pump is kept (Rijnland, 2021). With 1 pump, the range between nominal and maximum capacity would otherwise become too large. This means that the water system can be overloaded in regular situations. A second pump means 30-50% higher direct construction costs for medium-sized and large pumping stations. For small pumping stations, the additional costs are limited (approx. 10%).

7 Results: Environmental Impact Assessment from DuboCalc

This chapter presents the outcomes of the LCA simulations. Section 7.1 reports the MKI/ECI scores of both reference and alternative design variants for each pumping station. Section 7.2 analyses the environmental impacts across life cycle phases—production, operation, and end-of-life. Section 7.3 compares the effects of sustainable substitutions, including bio-based materials, renewable energy integration, and modular design choices. The chapter concludes by identifying key environmental hotspots and design interventions with the highest sustainability potential.

The environmental performance of the two water pumping stations have been assessed using the DuboCalc software, which is based on LCA principles and expresses environmental impact primarily through the MKI/ECI (Milieu Kosten Indicator / Environmental Cost Indicator) in euros. In addition to this aggregated impact indicator, the category of Global Warming Potential (GWP), expressed in kilograms of CO_2-equivalents, was also considered separately to directly reflect contributions to climate change.

This chapter presents the results from the two case study pumping stations. The smaller Noordeinde- en Geerpolder is discussed first, followed by the larger De Drie Delfzijlen installation. For each case, the reference scenario is analysed, and several modelled variants are evaluated to assess their impact on sustainability outcomes.

7.1 DuboCalc Results: Noordeinde- en Geerpolder

The baseline configuration for Noordeinde- en Geerpolder represents a small polder water pumping station as currently built in the Netherlands. The design consists of a concrete foundation pit, steel sheet piles, a cast iron pump, HDPE and/or cast iron piping, and a fish passage with a separate pump. The reference case assumes conventional construction practices using standard materials, powered by the national grey electricity mix, and employing diesel-powered construction equipment. This configuration serves as the baseline for assessing the relative performance of alternative design variants.

The following eleven variants in table 7.1 were modelled in DuboCalc to investigate how specific material and design modifications influence the environmental impact. Each variant isolates or combines key interventions proposed in the sustainable design section, enabling comparative analysis. In the last column the modelled MKI/ECI value in Euros is given.

Variant	Description	MKI/ECI [€]	% vs Ref
1 – Reference Scenario	Reflects current standard practice, including traditional concrete, steel sheet piles, cast iron and HDPE pipelines, conventional reinforcement, diesel-fuelled equipment, and standard electricity supply (NL grey mix). This scenario forms the benchmark for evaluating all subsequent variants.	58,901	0%
2 – Renewable Energy	Identical to the reference case, but replacing the electricity source with a Dutch renewable mix. This isolates the effect of greening operational energy use during the service life.	41,246	–30.0%
3 – Reused Sheet Piles	Replaces new steel sheet piles with reused ones sourced from other projects. The reused components are assumed to meet structural requirements and offer a remaining service life of at least 50 years, accounting for material degradation. The reuse factor (H) is applied accordingly in the LCA model.	55,667	–5.5%
4 – Omission of Fish Passage	The fish passage and related components (pump, housing, piping) are excluded to examine the environmental burden associated with their inclusion. This facilitates a discussion on trade-offs between ecological functionality and lifecycle environmental cost.	56,985	–3.3%
5 – HDPE Pipelines	Substitutes cast iron pipes with HDPE equivalents. Given HDPE's lower embodied carbon and similar technical performance and service life, this scenario highlights the benefit of polymer-based piping alternatives.	57,224	–2.8%
6 – PVC Sheet Piles	Replaces conventional steel sheet piles with PVC composite sheet piles (e.g., from Rowat SPS), composed of recycled plastic and reinforced with glass fibre. This option represents a circular, lightweight alternative suitable for non-critical foundation applications.	50,920	–13.5%
7 – EcoSheetPiles	Incorporates steel sheet piles manufactured by ArcelorMittal under the EcoSheetPiles brand, made from recycled steel using conventional grid electricity. These products are verified by Environmental Product Declarations (EPDs) and are listed in the Nationale Milieudatabase (NMD).	51,779	–12.1%
8 – EcoSheetPiles Plus	Similar to Variant 7, but with 100% renewable electricity used in the manufacturing of the recycled steel sheet piles. This results in a significantly lower environmental footprint compared to traditional steel alternatives.	51,679	-12.3%
9 – Geo-polymer Concrete and Combar Reinforcement	Replaces standard cement-based concrete with geopolymer concrete and conventional reinforcement with Schöck Combar® glass fibre-reinforced polymer bars. These materials offer lower embodied environmental impact while maintaining required structural performance.	58,674	–0.4%
10 – Extended Pump Lifespan	Assumes that the main pumps, originally modelled with a 15-year service life, are maintained and used for 20 years instead. The scenario evaluates whether improved maintenance and monitoring to extend component life can contribute meaningfully to MKI reduction.	58,235	–1.1%
11 – Combined Measures (All-In-One)	Integrates all previous measures to assess the cumulative effect of multiple sustainability improvements. This variant represents a best-case scenario in terms of environmental performance under the modelled constraints.	31,267	–46.9%

Table 7.1: Overview of Modelled Variants and MKI/ECI values with percentual change for Noordeinde- en Geerpolder

7.1.1 MKI/ECI Results

Each of these variants was individually modelled using the DuboCalc platform, incorporating component-level adjustments to material types, sourcing strategies and energy inputs. The resulting MKI and GWP scores offer quantitative insights into which interventions yield the greatest environmental benefits for small-scale water pumping stations.

Subsequent sections will present the quantified MKI and GWP results of each variant, as well as comparative graphs and interpretation of trade-offs.

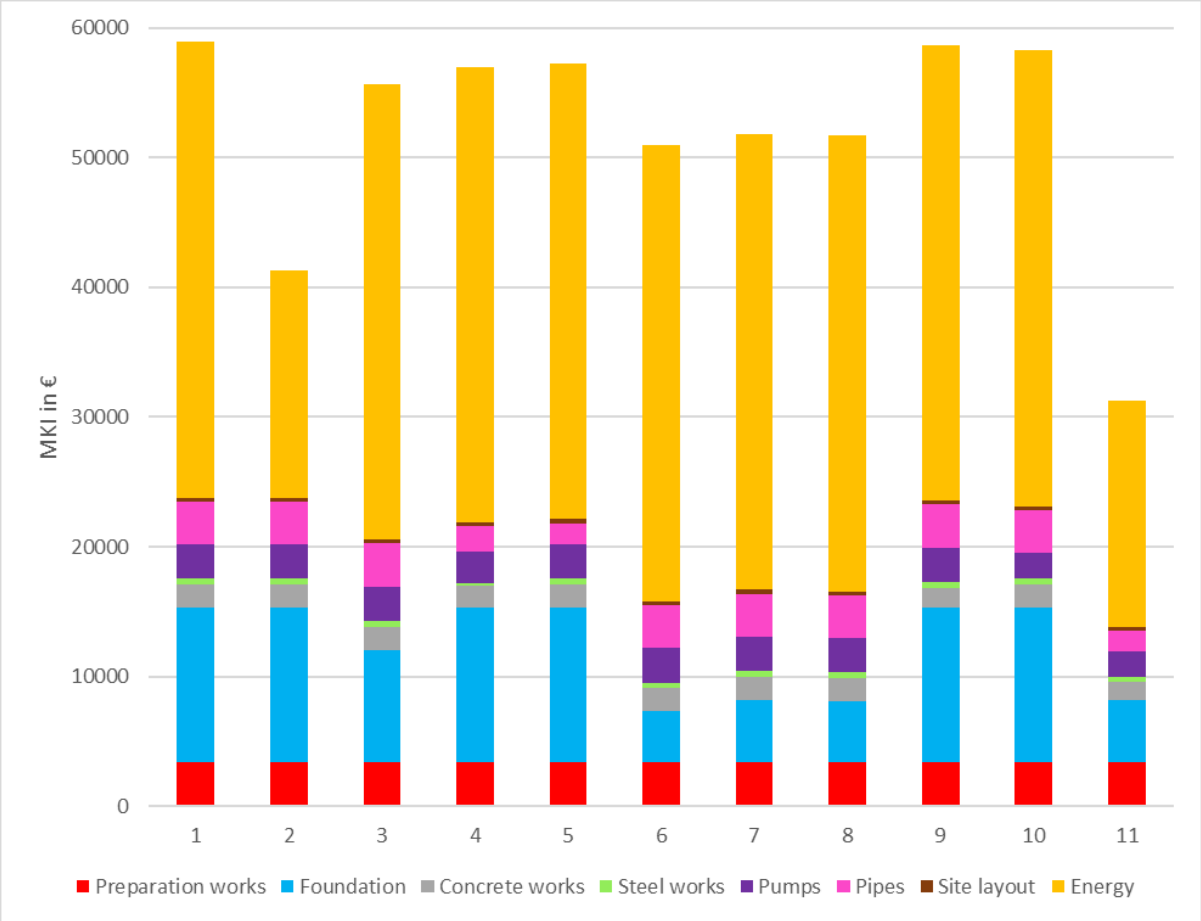


Figure 7.1: MKI/ECI results for Noordeinde- en Geerpolder for all Variants

Figure 7.1 presents the environmental impact results (expressed in MKI/ECI values) of all modelled variants for the Noordeinde- en Geerpolder pumping station. The reference variant, based on current standard practice, shows a total environmental cost of €58,900.47 over a 50-year lifespan. Within this baseline scenario, the dominant contributor is operational energy use (represented by the yellow segment in the figure), which accounts for approximately 60% of the total environmental burden. This is consistent with findings from prior LCA studies of water infrastructure assets, which consistently identify electricity consumption during the operational phase as the most significant factor in the overall life cycle impact.

The second largest contributor to environmental impact in the reference scenario is the foundation system (light blue segment), comprising steel sheet piles and foundation piles.

This component contributes approximately 20% of the total impact. Given the structural prominence and mass of these elements within the design—as observed in the technical drawings—this proportional impact is logically aligned with their material intensity and production footprint. By contrast, the remaining elements such as the concrete pit, pipelines, and mechanical components contribute comparatively minor shares.

The analysis of all other modelled variants builds upon this reference case to evaluate the relative impact of targeted sustainability interventions.

Variant 2, which substitutes the electricity supply with a Dutch renewable energy mix, demonstrates a substantial reduction in operational energy-related emissions. The overall MKI/ECI value drops to €41,245.93, translating to a 30% decrease in total environmental cost relative to the reference. The yellow segment is visibly halved, underscoring the critical importance of decarbonising electricity sources for infrastructure with high operational energy demands.

Variant 3, which employs reused sheet piles, results in a more modest reduction to €55,666.62 (a 5.5% decrease). As expected, the environmental burden associated with the foundation (light blue) decreases, reflecting the lower embodied impacts of reused steel. This highlights the potential of circular construction strategies in reducing material-related emissions, though the overall benefit is moderate due to the unchanged contribution from operational energy use.

Variant 4, in which the fish passage is omitted, shows an MKI/ECI value of €56,985.32—only a 3.2% reduction compared to the reference. This modest improvement is attributed to the elimination of components such as small pumps, foundation elements, and pipelines associated with the fish passage. While this measure reduces material use, the overall effect is limited due to the relatively small contribution of these components to total impact. The result illustrates the trade-off between ecological features and life cycle performance, and could inform prioritisation discussions during early design stages.

Variant 5, replacing cast iron pipelines with HDPE, slightly lowers the environmental burden to €57,224.48 (a 2.8% reduction). This is primarily reflected in a reduced contribution from the piping system (pink segment), consistent with the lower embodied carbon and processing energy associated with HDPE. However, since the pipelines are not the dominant component in the overall footprint, the net gain remains relatively small.

Variants 6, 7, and 8 explore the use of more sustainable alternatives for the foundation sheet piles, focusing on materials with lower embodied environmental impacts.

Variant 6 utilises PVC composite sheet piles produced from recycled plastic, leading to a total MKI/ECI value of €50,919.60—representing a 13.5% reduction compared to the reference variant.

Variant 7 employs ArcelorMittal's EcoSheetPiles, made from recycled steel but produced using conventional electricity. This results in a slightly higher MKI/ECI of €51,778.96, corresponding to a 12.1% reduction.

Variant 8 builds upon Variant 7 by incorporating 100% renewable electricity in the production process of the recycled steel sheet piles. This further improves the environmental performance, yielding a total MKI/ECI value of €51,679, equivalent to a 12.3% reduction.

The environmental benefit across these three variants is primarily visible in the reduction of the light blue segment of the graph, which corresponds to the foundation components. These reductions highlight the potential of circular material strategies in the structural design of pumping stations. Although PVC composite offers the largest absolute reduction, the use of EcoSheetPiles Plus balances both environmental performance and structural familiarity, making it a promising solution for practical implementation. These findings demonstrate that

material substitutions in foundation systems, particularly when paired with cleaner production processes, can yield substantial environmental gains without compromising structural integrity or feasibility.

Variant 9, featuring geo-polymer concrete and Combar® reinforcement, achieves an MKI/ECI of €58,674.18—a negligible reduction (0.4%). The minimal impact is attributable to the limited volume of concrete in the original design. Although geo-polymer alternatives possess significantly lower embodied emissions per unit, their overall influence remains small due to the minor share of concrete in the total material footprint.

Variant 10 models a scenario in which the mechanical pumps are assumed to operate for 20 years instead of the standard 15, thanks to enhanced maintenance strategies. This yields an MKI/ECI value of €58,235.14 (a 1.1% reduction). The improvement is minor but reflects the potential gains from extending component lifespans, which reduce the frequency of material replacement and associated impacts.

Finally, **Variant 11**, which integrates all previously modelled measures into a comprehensive sustainable design, results in a total MKI/ECI value of €31,266.77—representing a 47% reduction relative to the reference. This holistic scenario includes renewable electricity, PVC or EcoSheetPiles foundations, HDPE pipelines, geopolymer concrete with Combar reinforcement, and extended pump life. Furthermore, construction-phase impacts are minimised through the assumed use of HVO-fuelled or electric machinery. Although the PVC sheet piles yield slightly better environmental performance, EcoSheetPiles were selected in this variant to meet structural safety standards and existing regulations.

So, the analysis illustrates that while individual measures each offer varying degrees of environmental benefit, the most substantial reductions are achieved through systemic and integrated design approaches. The dominance of energy-related impacts reinforces the importance of clean electricity use, while circular materials and design-for-durability contribute meaningful but secondary benefits. Together, these findings provide a practical framework for prioritising interventions in future sustainable pumping station projects.

7.1.2 Climate Change GWP Results

In addition to the overall MKI/ECI comparisons, a more specific assessment was conducted on the impact category global warming potential (GWP), expressed in terms of CO_2-equivalent emissions. This enables a more targeted evaluation of the climate change-related effects associated with each variant. As with the MKI analysis, the results were generated using DuBoCalc, which models emissions based on material flows, construction processes, and operational energy use over the asset's 50-year lifespan.

For the small water pumping station Noordeinde- en Geerpolder, the CO_2-equivalent results largely mirrored the trends found in the MKI outcomes, with operational energy use once again dominating the total climate impact. In scenarios using the conventional Dutch grey electricity mix, the energy component accounted for an overwhelming 99.5% of the total CO_2-equivalent emissions. This disproportionately large share raises questions about the weighting or emission factors used in the model for grey electricity. While this finding aligns with expectations that operational energy dominates environmental impacts—especially in smaller pumping stations—the scale of dominance is unusually high, casting doubt on the reliability or representativeness of the emission factor used for the grey mix in the current database version of DuBoCalc. Despite this near-elimination of energy-related emissions, the overall MKI/ECI reduction in this variant remains moderate rather than transformative. This is because MKI encompasses a broader set of environmental indicators beyond GWP, such as human toxicity, resource depletion, and acidification, which are not affected equally by changes in the electricity mix.

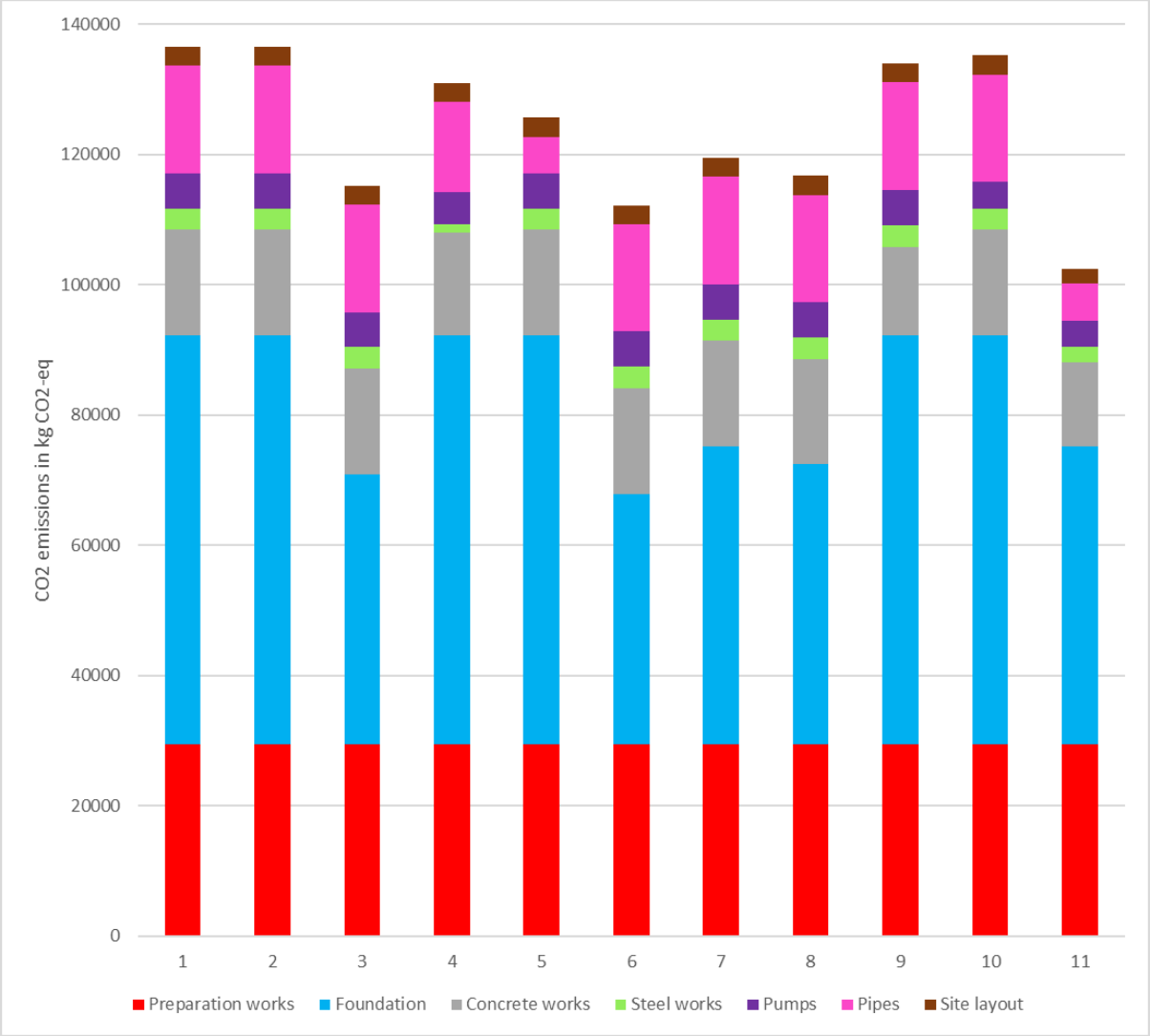


Figure 7.2: Global Warming Potential in CO2 emissions, for Noordeinde- en Geerpolder, without energy use

Due to this extreme dominance, visualising the total CO_2 emissions for all variants in a single graph would obscure the smaller—but still meaningful—differences between the construction-related interventions. Therefore, to improve readability and insight, the GWP results are shown excluding the energy component, thereby allowing for a clearer comparison of emissions attributable to material choices and construction techniques (see Figure 7.2).

So, the GWP analysis strongly confirms that energy use—particularly its carbon intensity—remains the dominant contributor to climate change impact in water pumping stations. However, it also reveals the importance of disaggregating impact categories: while a switch to renewable electricity has a profound effect on CO_2 emissions, it does not proportionally lower the total MKI score due to its multi-criteria nature. This reinforces the value of using both MKI and specific impact indicators such as GWP when evaluating sustainable design strategies.

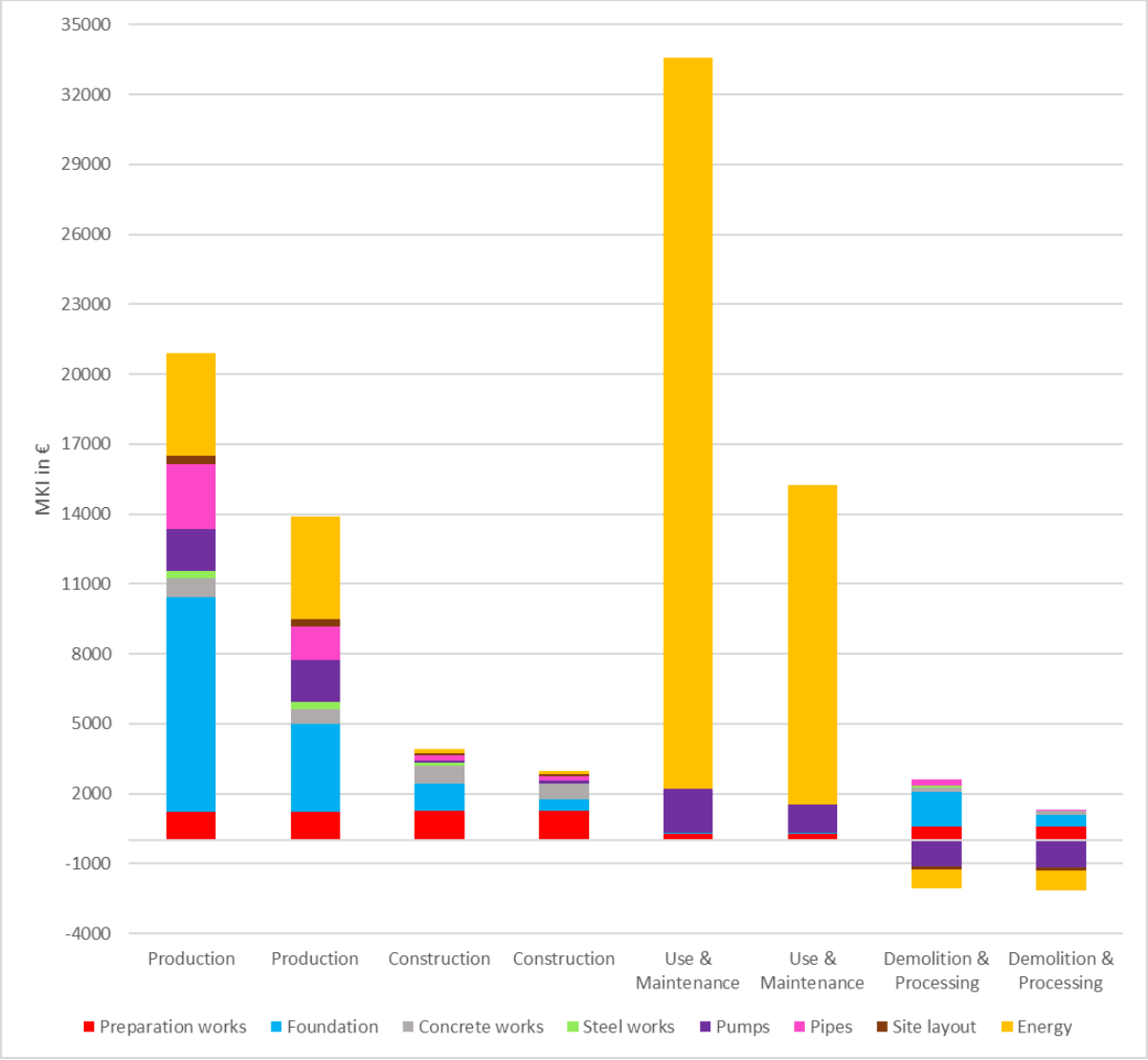


Figure 7.3: MKI/ECI per life cycle phase for Noordeinde- en Geerpolder for V1 (left bars) and V11 (right bars)

7.1.3 MKI/ECI Results per Life Cycle Phase

To provide a more detailed understanding of the environmental performance across the life cycle of the Noordeinde- en Geerpolder pumping station, the total MKI/ECI results have been disaggregated by life cycle phase: production (A1–A3), construction (A4–A5), use and maintenance (B1–B7), end-of-life processing (C1–C4), and benefits beyond the system boundary (D). Figure 7.3 compares these results for the reference variant (Variant 1, the left bars) and the fully optimised design including all sustainable measures (Variant 11, the right bars).

The use and maintenance phase accounts for the largest share of environmental costs over the 50-year lifespan, particularly in Variant 1. This is primarily driven by operational electricity consumption, which—as discussed previously—is the dominant contributor to impact in both the MKI and the global warming potential (GWP) assessments. The use of the conventional (grey) electricity mix leads to a high long-term burden, reaffirming the importance of decarbonising energy supply in water infrastructure.

In Variant 11, the total environmental costs are significantly reduced, with the largest improvements again observed in the use phase. This is the result of shifting to a renewable electricity mix, substantially lowering the operational impact over time. These results demonstrate the high mitigation potential associated with transitioning to sustainable energy sources in water sector assets.

A noticeable reduction also occurs in the production phase (A1–A3), which is largely attributed to the integration of more sustainable construction materials, such as EcoSheetPiles Plus, prefabricated geopolymer concrete, and alternative reinforcement materials. These materials not only reduce embodied environmental costs but also align with circular design principles without compromising structural integrity.

The end-of-life phase (C1–C4), combined with the benefits beyond the system boundary (Phase D), results in negative MKI values. This reflects the residual value and potential for reuse or recycling of materials at the end of the asset's life. In particular, high-value components such as steel elements or modular prefabricated units can displace virgin material production in future projects, thereby generating environmental credits. These values are included in Phase D to account for avoided impacts that occur outside the defined system boundary.

Summarising, the comparison between the reference scenario and the all-measures variant illustrates that strategic choices in both the operational energy mix and the use of low-impact, circular construction materials can substantially reduce environmental costs across all life cycle phases. While operational energy remains the dominant factor in absolute terms, the production phase and end-of-life benefits also provide significant opportunities for impact reduction in future water infrastructure projects.

7.2 DuboCalc Results: De Drie Delfzijlen

The De Drie Delfzijlen case study represents a large-scale, complex "boezem" water pumping station situated in a location-specific hydraulic and infrastructural context. Unlike standard polder pumping stations, this installation consists of multiple high-capacity pumps, extensive reinforced concrete works, steel sheet pile foundations, trash racks with mechanical cleaners, and a building enclosure. Additional components such as a flushing sluice and an integrated fish passage system add further material and energy intensity to its life cycle.

This section presents the results of environmental impact calculations conducted in DuboCalc. As in the previous case, the results are expressed in both the aggregated MKI (MilieuKostenIndicator) and the climate-specific Global Warming Potential (GWP, in kg CO_2-eq). A reference scenario was established to reflect the environmental performance of a newly constructed pumping station based on current Dutch practice, using traditional materials and standard construction approaches.

Following the baseline assessment, a set of eleven design and material variants were modelled to examine the effect of targeted sustainability interventions. These variants reflect the key options outlined in the previous methodology section and aim to assess feasible pathways for reducing the life cycle environmental burden of large pumping infrastructure.

Variant	Description	MKI/ECI [€]	% vs Ref
1 – Reference (In-Situ Concrete Pouring)	This baseline scenario models conventional construction methods, including on-site concrete pouring, use of diesel-powered machinery, standard steel sheet piles, cast iron water pipelines, and the standard Dutch electricity mix (NL grey).	4,804,623	0%
2 – Prefabricated Walls and Slabs	Cast-in-place concrete walls and slabs are replaced with prefabricated reinforced concrete elements, including cellar walls and solid floor components. The aim is to explore the impact of off-site production efficiencies and reduced construction-phase emissions.	4,740,364	–1.34%
3 – Renewable Electricity	Modifies the reference scenario by substituting the conventional electricity supply with the Dutch renewable mix. The objective is to isolate the contribution of cleaner energy sources to the overall environmental footprint, particularly during the operational phase.	2,335,459	–51.39%
4 – Geo-Polymer Concrete	Traditional cement-based concrete is substituted with geopolymer concrete. This alternative binder system is associated with lower embodied carbon due to the absence of Portland cement and has seen increased application in pilot projects within Dutch hydraulic engineering.	4,768,501	–0.75%
5 – Geo-Polymer Concrete with Combar Reinforcement	Combines geopolymer concrete with Schöck Combar® reinforcement bars made from glass fibre-reinforced polymer (GFRP). Combar offers reduced environmental impact, high tensile strength, and resistance to corrosion, making it a viable replacement for conventional steel reinforcement.	4,764,604	–0.83%
6 – Geo-Polymer Prefabricated Elements	Combines the benefits of prefabrication (Variant 2) with geopolymer concrete (Variant 4). Prefabricated cellar walls and slabs are modelled using the lower-impact binder and integrated reinforcement, representing a hybrid low-carbon construction approach.	4,712,530	–1.91%
7 – PVC Sheet Piles	Steel sheet piles are replaced by PVC composite sheet piles manufactured by Rowat SPS. Comprising recycled plastic and glass fibre reinforcement, these components represent a circular alternative, particularly suitable for low-load or non-critical foundation contexts.	4,790,032	–0.30%
8 – EcoSheetPiles (Steel)	Uses steel sheet piles from ArcelorMittal's EcoSheetPiles product line, made from recycled steel and produced using conventional electricity. These components have verified EPDs and are included in the NMD.	4,792,109	–0.26%
9 – EcoSheetPiles Plus	Similar to Variant 8, but with 100% renewable energy used during the production process. This results in lower embodied environmental impacts, especially with respect to carbon emissions and is suitable when steel is required.	4,791,892	–0.27%
10 – Extended Pump Lifespan (+5 Years)	This scenario does not alter materials but changes the replacement schedule for the mechanical pumps. Instead of replacing them every 15 years, a longer service life of 20 years is assumed, supported by proactive maintenance strategies.	4,793,822	–0.22%
11 – Integrated Sustainable Design (All Measures)	This scenario bundles all previous interventions into one comprehensive design variant. It includes PVC sheet piles, geopolymer concrete with Combar reinforcement, prefab structural components, renewable energy use, and extended pump lifespans. Construction is assumed to use electric or HVO-fuelled machinery to minimise realisation-phase impacts.	2,211,776	–53.98%

Table 7.2: Overview of Modelled Variants with MKI/ECI values and percentual change for De Drie Delfzijlen

7.2.1 MKI/ECI Results

Each of these variants was implemented and assessed within DuboCalc using consistent boundary conditions, functional units, and lifespan assumptions. The resulting MKI and GWP scores allow for quantitative comparison and help identify which measures deliver the greatest environmental returns for large-scale water pumping infrastructure.

The next section will visualise and interpret the findings, comparing all variants against the reference and drawing conclusions about key material, operational, and systemic levers for sustainable performance. First the most important MKI/ECI results comparison between the reference variant and the last 'All-in-one' variant for De Drie Delfzijlen can be seen in Figure 7.4. As can be seen the energy use contributes a lot, more than 90%, to the total environmental costs for the reference variant. For better visualisation the energy use part has been taken out in the next comparison graph, Figure 7.5 for all the variants.

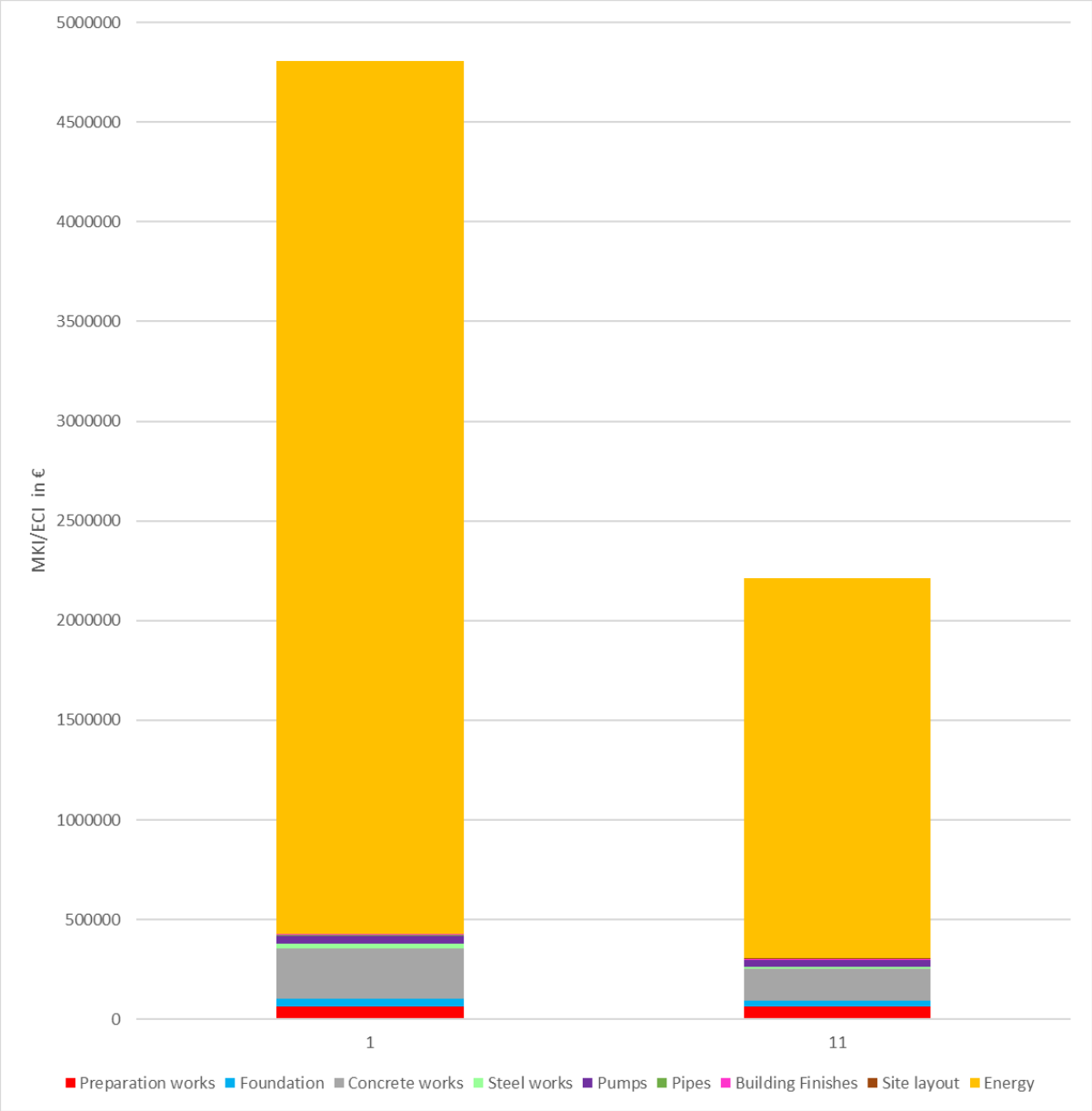


Figure 7.4: MKI/ECI Results for De Drie Delfzijlen for Variant 1 Reference and Variant 11 All-in-one

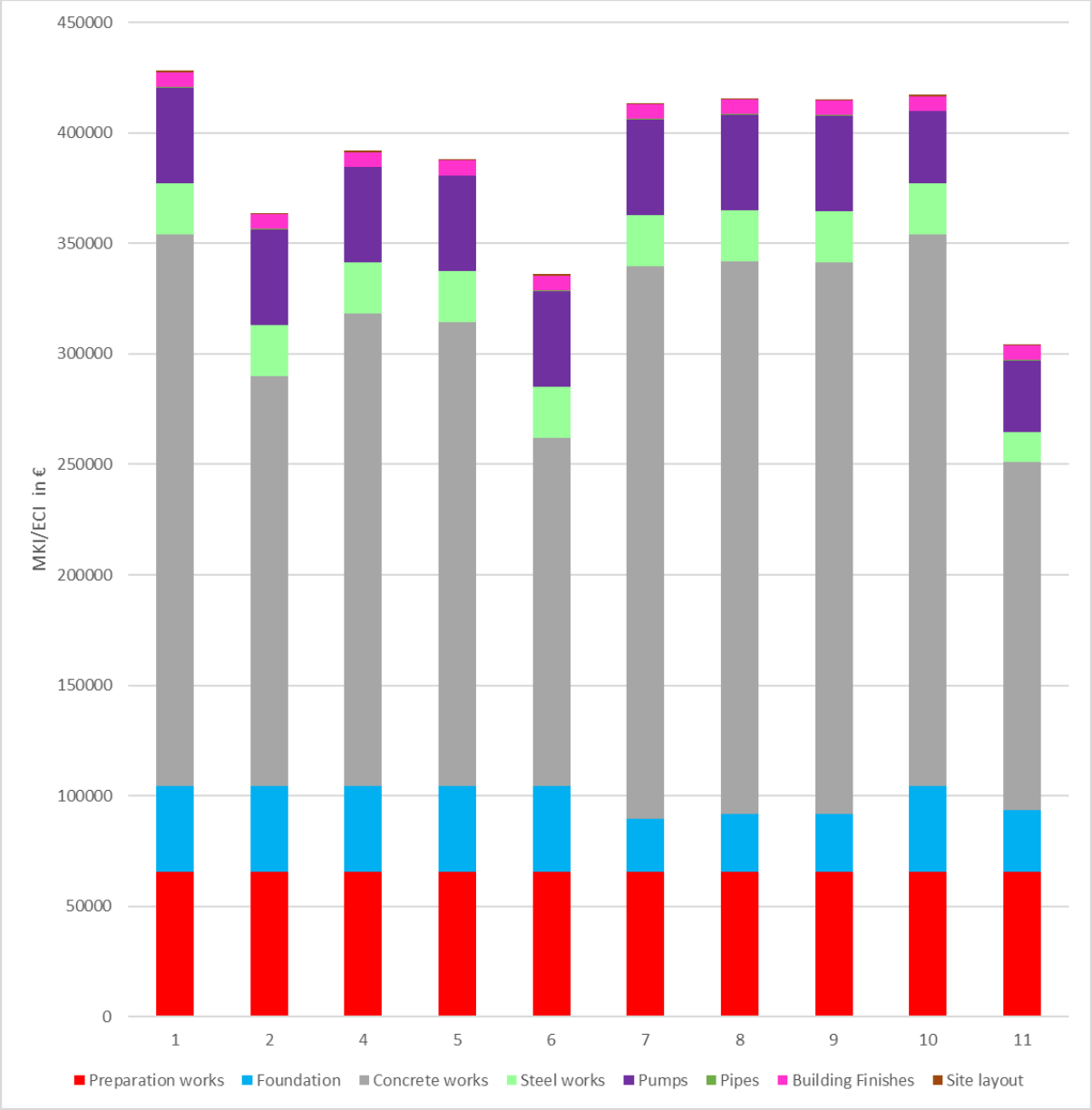


Figure 7.5: MKI/ECI Results for De Drie Delfzijlen for all Variants, without Energy Use

The modelled reference variant for the De Drie Delfzijlen pumping station yields a total environmental cost of €4,804,623 , as expressed in MKI/ECI terms over a 50-year design life. The largest contributor to this total is electricity consumption during operation, accounting for approximately 90% of the impact. This dominance of operational energy is in line or even surpassing the findings from other life cycle assessments (LCAs) of Dutch water infrastructure. Particularly in large-scale 'boezemgemalen'—which are equipped with multiple high-capacity pumps—the electricity demand over time is by far the most significant determinant of total environmental burden.

The second most impactful component is associated with the reinforced concrete works, which comprise the structural pit, floor slabs, and vertical walls. These elements are responsible for approximately 5% of the total environmental impact. This is consistent with their substantial material volume and mass, as is evident from both the 3D model and technical drawings. In contrast, other components such as sheet pile walls, foundation piles, piping, and mechanical components represent only minor shares of the overall footprint.

These observations confirm that the one main focus and the one sub focus for environmental performance improvement are (1) reducing electricity use and/or sourcing electricity from cleaner origins and (2) minimising the impact of heavy concrete structures—whether through material substitution, prefabrication, or structural optimisation.

The remainder of the analysis compares a series of targeted design variants against the reference case, each aimed at reducing environmental impact through a specific intervention or combination of measures.

Variant 2 explores the use of prefabricated concrete slabs and walls. Prefabrication offers environmental benefits due to production in controlled factory environments with more efficient material usage, reduced waste, and cleaner energy sources. Moreover, on-site assembly is typically faster and less energy-intensive than conventional in-situ construction. This variant reduces the environmental impact of the reinforced concrete component by approximately 25%, leading to a total MKI/ECI value of €4,740,364 .

Variant 3 substitutes the standard Dutch grey electricity mix with a predefined renewable electricity mix. Since operational electricity is the dominant contributor to the MKI score, this results in a substantial overall reduction. The total environmental cost decreases to €2,335,459 —representing a reduction of over 50% compared to the reference. This result underscores the critical role that green electricity sourcing plays in enhancing the sustainability performance of energy-intensive infrastructure.

Variant 4 introduces geopolymer concrete as a low-carbon alternative to conventional Portland cement-based concrete. Due to the large volume of concrete in the reference design, this substitution achieves a meaningful reduction in environmental impact, resulting in a total MKI/ECI of €4,768,501. Although geopolymer concrete offers substantial emission savings per kilogram, the effect on total MKI remains moderate due to the continuing dominance of electricity use in the overall lifecycle.

Variant 5 builds upon Variant 4 by also replacing conventional steel reinforcement bars with Combar® glass fibre-reinforced polymer bars. These alternatives offer lower embodied environmental impact while maintaining structural performance. The additional substitution leads to a marginal improvement over Variant 4, reducing the total MKI/ECI to €4,764,604.

Variant 6 combines the benefits of prefabrication (Variant 2) with those of geopolymer concrete (Variant 4), resulting in prefabricated geopolymer concrete structural elements. This integrated approach proves particularly effective, reducing the environmental impact of the concrete works by approximately 37% relative to the reference. The total MKI/ECI value for this variant is €4,712,530, indicating the value of synergistic design strategies that combine material substitution with industrialised construction methods.

Variants 7 to 9 evaluate alternative materials for the foundation sheet piles. Variant 7 replaces conventional steel sheet piles with PVC-based composites made from recycled plastic, while Variants 8 and 9 adopt ArcelorMittal's EcoSheetPiles, with the latter manufactured using 100% renewable electricity. Although the foundation contributes only a small fraction of the total environmental impact in the reference case, the reductions achieved within this specific component are substantial. The PVC sheet pile variant achieves a 37% reduction in foundation-related impact, while the EcoSheetPiles and EcoSheetPiles Plus options yield reductions of 32% and 33%, respectively. The PVC-based solution again emerges as the most environmentally effective, provided of course that structural requirements allow for its use.

Variant 10 examines the effect of extending the operational lifespan of the pumps from 15 to 20 years through improved maintenance and monitoring. This effectively reduces the frequency of pump replacement cycles over the 50-year time-frame. Although the pumps represent a minor share of the total environmental cost, the intervention still leads to a measurable reduction,

primarily within the mechanical components category. This highlights the value of durability and proactive asset management in mitigating environmental impacts over the infrastructure's lifecycle.

Variant 11 integrates all previously modelled interventions into a single holistic design. This "all-in-one" scenario includes renewable energy, prefabricated geopolymer concrete, Combar reinforcement, EcoSheetPiles foundation, and extended pump lifespan. The result is a substantial improvement in environmental performance, with total MKI/ECI costs falling to €2,211,776. This corresponds to a 54% reduction relative to the reference case, clearly demonstrating the compounded benefits of multi-faceted, integrated sustainability measures.

So, while individual interventions vary in their relative effectiveness, their cumulative impact is relatively high when implemented together. The results confirm that the greatest environmental gains are realised through decarbonising operational energy and optimising material-intensive components, particularly the concrete structure. Informed by this analysis, future pumping station designs can prioritise energy sourcing, industrialised low-carbon materials, and asset longevity to meet stringent sustainability goals in both design and operation.

7.2.2 Climate Change GWP Results

In addition to the MKI/ECI analysis, the climate change impact of the De Drie Delfzijlen pumping station variants was assessed through the Global Warming Potential (GWP) expressed in CO_2-equivalent emissions. This evaluation offers a focused view on greenhouse gas emissions, complementing the broader spectrum of environmental indicators captured in the MKI scores.

As observed previously in the Noordeinde- en Geerpolder pumping station analysis, a similar issue arises here: the GWP results are overwhelmingly dominated by operational energy use when the Dutch grey electricity mix is applied. This results in a highly skewed impact profile in which the electricity consumption eclipses nearly all other contributors. While this reflects the real significance of energy in long-term operations, it also complicates meaningful comparisons between material-based interventions, as the relative differences among variants become visually and numerically negligible.

To address this and allow for a more balanced comparison, the energy use component was excluded from the GWP analysis presented in Figure 7.6. This enables a clearer interpretation of the impact of construction materials and design strategies, independent of energy-related emissions that are heavily dependent on external grid characteristics and assumptions in the database.

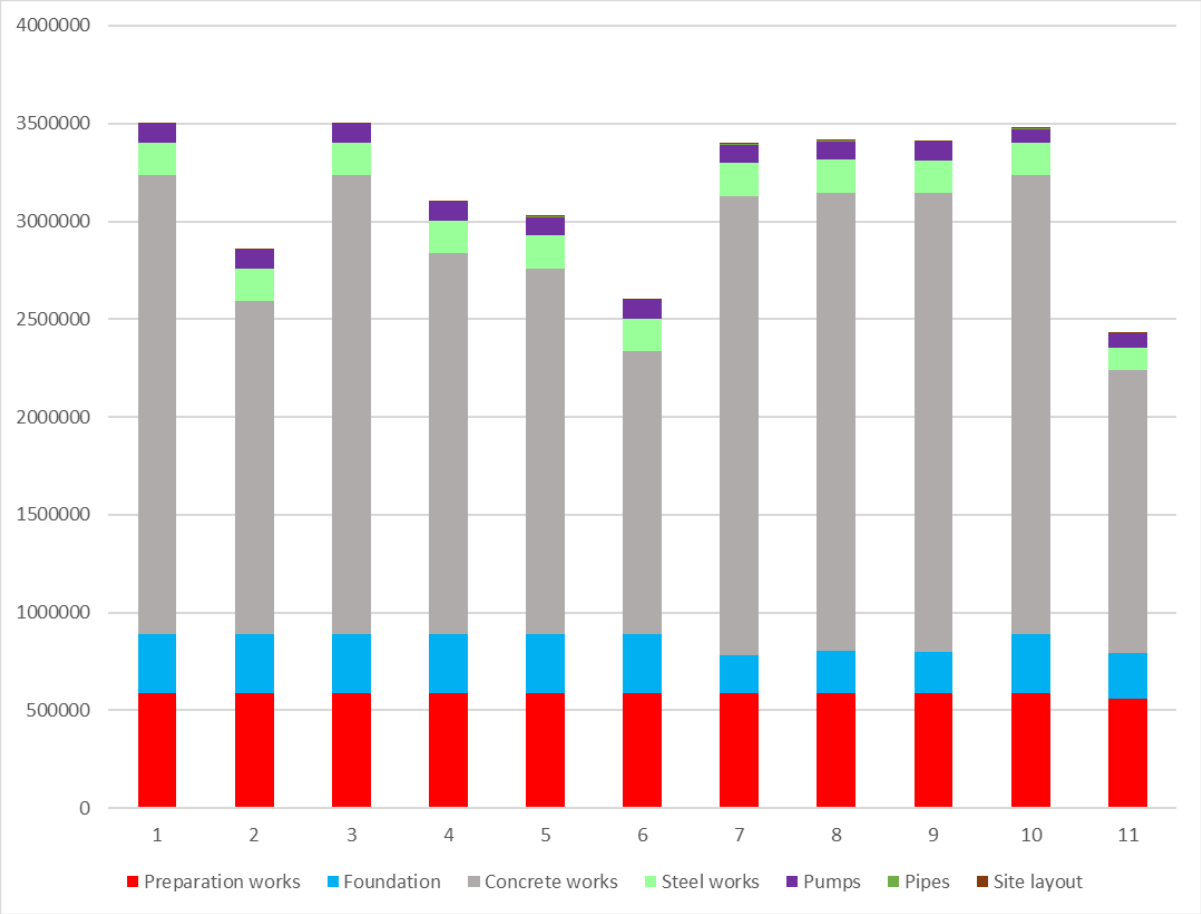


Figure 7.6: Global Warming Potential in kg CO2-eq. emissions for De Drie Delfzijlen, without energy use

Results per Life Cycle Phase De Drie Delfzijlen

Beyond assessing total environmental costs, a phase-by-phase analysis of the MKI/ECI values across the life cycle offers valuable insights into which project stages contribute most to the environmental burden—and therefore where targeted reductions are most effective. For the De Drie Delfzijlen pumping station, the breakdown of MKI per life cycle phase is presented in Figure 7.7. This figure compares the reference variant to Variant 11, which integrates all environmentally beneficial design measures.

In the reference scenario, the Use & Maintenance phase is by far the most dominant contributor to the total environmental impact. This is consistent with the earlier findings on total MKI values, and it underscores the critical influence of long-term energy consumption over the asset's 50-year lifespan. The Production phase follows as the second-largest contributor, primarily driven by the manufacture of concrete components, which have high embodied environmental impacts due to cement usage and associated emissions.

When examining the Variant 11 scenario, which includes multiple mitigation strategies (e.g., geopolymer concrete, prefabrication, Combar reinforcement, renewable electricity), a substantial overall reduction in MKI/ECI is observed. Nonetheless, the relative distribution of impacts across life cycle phases remains largely consistent: the Use & Maintenance phase still dominates, although at a significantly reduced scale, followed by the Production phase. This indicates that, while improvements in materials and design can yield measurable benefits, energy consumption during operation remains the primary driver of environmental costs.

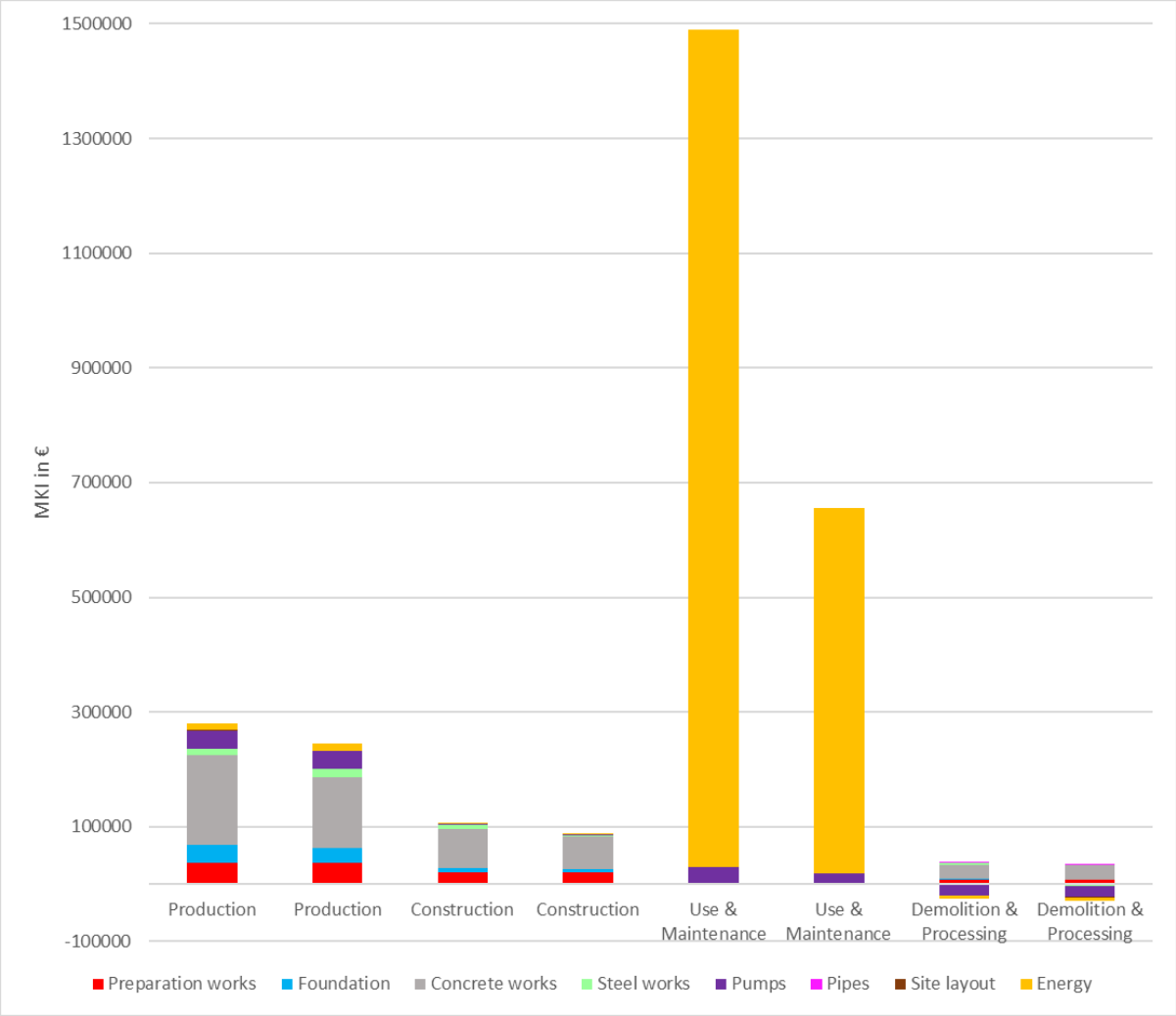


Figure 7.7: MKI/ECI per life cycle phase for De Drie Delfzijlen for V1 (left bars) and V11 (right bars)

7.3 MKI/ECI Results 25 and 75 years lifespan

All these results above from the two water pumping stations have been for a static period of 50 years, since that is normally considered and modelled as the lifespan of civil structures. However, since especially concrete and steel mostly have a service life span of way longer than 50 years, this is what will be modelled as well in the form of adding 25 years, so a lifespan of 75 years will be modelled and compared as well for all the components and materials. Next to this, wood is a great and sustainable renewable material, so this is also worth considering, but then changing the lifespan to 25 years, since then the most of the wooden elements will need replacement. The rest of the water pumping station will then be designed in terms of materials around this 25 years as well, or being doubled to 50 years such that maintenance practices are planned in a smart way.

Reduction and Extension of Design Life to 25 and 75 Years

To assess the environmental performance of water pumping stations across varying service life scenarios, a breakdown was made of the expected lifespan and replacement needs of the key components involved. This analysis distinguishes between components that can remain in place with little to no intervention, those that require midlife refurbishment or replacement,

and those that must be renewed multiple times over an extended operational period.

For the 25-year design scenario, it is assumed that all components will last the full operational period without replacement. To further optimise environmental performance within this timeframe, substituting conventional steel sheet piles with hardwood (e.g., Azobé) sheet piles is recommended wherever structurally feasible. This approach offers a lower environmental impact due to the renewable nature and favourable MKI score of sustainably sourced timber. Wooden sheet piles commonly exceed their typical design lifespan of 25 years, with modern standards often requiring 30 years. Research by the Ministry of LNV and Centrum Hout reports an average service life of 36.6 years for construction wood, supporting 30 years as a reasonable design assumption (CentrumHout, 2020). While timber sheet piles are particularly suited for projects with a shorter design life, such as 25 years, it is important to consider that they serve as part of the foundation. If the superstructure is expected to last significantly longer, replacement of these piles may become problematic. Therefore, aligning the service life of foundation elements with that of the overall structure is essential for long-term sustainability and maintainability.

In contrast, the 75-year scenario requires a deeper consideration of long-term durability, maintenance cycles, and component renewals. Key distinctions between passive, long-life elements and more maintenance-intensive or wear-prone parts have been identified and are summarised in Table 7.3.

In both service life scenarios, most passive and structural components—including earthworks, concrete works, and non-moving pipelines—are expected to perform reliably. Over a 25-year lifespan, all components can reasonably be assumed to meet their operational requirements without replacement. This enables a lower maintenance burden and simplifies inventory modelling.

Moreover, the 25-year scenario offers opportunities for material substitution to further reduce environmental impact. Specifically, the replacement of steel sheet piles with Azobé hardwood piles is recommended, provided that structural criteria are met. This option leverages the renewable nature and favourable MKI score of certified timber, aligning with sustainable construction principles.

Component Type	**Action by 25 Years**	**Action by 75 Years**	**Reason**
Earthworks	Retain	Retain	Passive, durable materials
Concrete structures	Retain	Retain / Minor maintenance	High durability
Pipelines (HDPE, cast iron)	Retain	Retain / Minor inspections	Long life, low wear
Pumps (main & fish)	Retain	Replace every 15–20 yrs	Mechanical wear, lifespan >20 yrs
Check valves, butterfly valves	Retain	Maintain / Replace (50 yrs)	Moving parts, but sufficient for 25 yrs
Electrical systems	Replace or maintain to reach 25yrs	Replace every 15–20 yrs	Obsolescence >20 yrs
Steel foundation structures	Replace with hardwood	Maintain / Replace coating	Sustainable timber (e.g., Azobé) if structurally feasible

Table 7.3: Expected Component Actions Over 25 and 75 Years

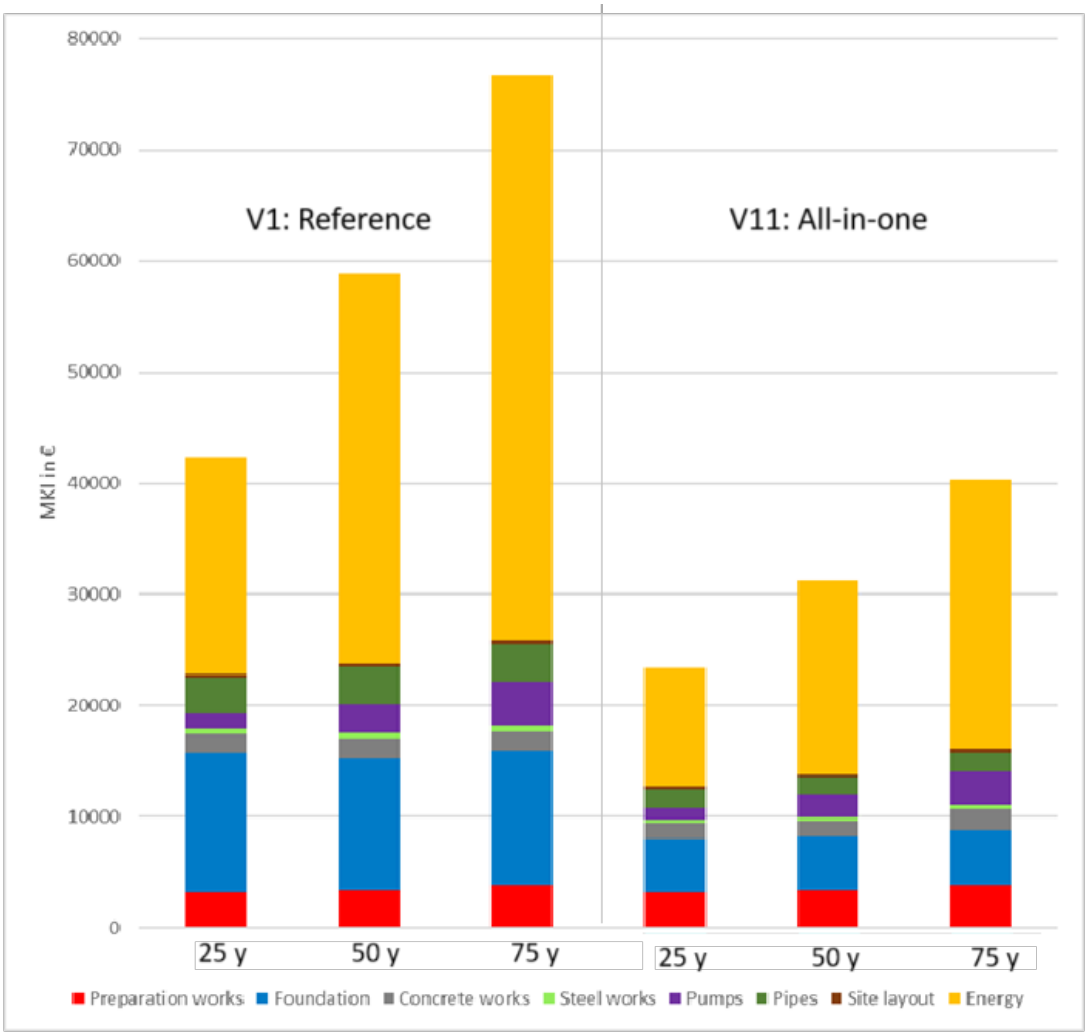


Figure 7.8: MKI/ECI Results Noordeinde- en Geerpolder for 25, 50 and 75 years, Variant 1: Reference and Variant 11: All-in-one compared

Conversely, the 75-year design life requires a more dynamic view, incorporating periodic replacements of pumps, coatings, and certain electromechanical components. Including these replacement cycles and maintenance assumptions in the LCA inventory will result in a more realistic footprint for long-term infrastructure planning.

One key insight from the small modelled polder pumping stations, 7.8 is that designing for longer lifespans can yield environmental benefits, but only if components are durable and well-maintained. Both variants show an increase in MKI over time, yet this increase is not linear. For example, MKI in the reference grows by 81% from 25 to 75 years, while in Variant 11 it grows by 72%, indicating that more sustainable materials and longer-lasting systems scale better environmentally.

High-impact categories like energy use and pumps grow disproportionately over time, suggesting these are critical areas for intervention. Lifespan extension of pumps in particular shows significant environmental savings. Meanwhile, structural elements such as foundations and concrete works grow more modestly in impact, underlining the long-term value of circular and prefabricated construction approaches.

So, the findings suggest that extending lifespan is beneficial, but only when paired with smart material choices and maintenance strategies. Instead of designing for maximum duration alone,

the optimal approach lies in creating flexible, maintainable, and circular systems that maintain low impact over their full lifecycle.

As can be seen in Figure 7.9, the energy use part is again really dominant in all variants over all the different years. So, for visualisation purposes here again the totals will be shown without the energy use part as well, see Figure 7.10.

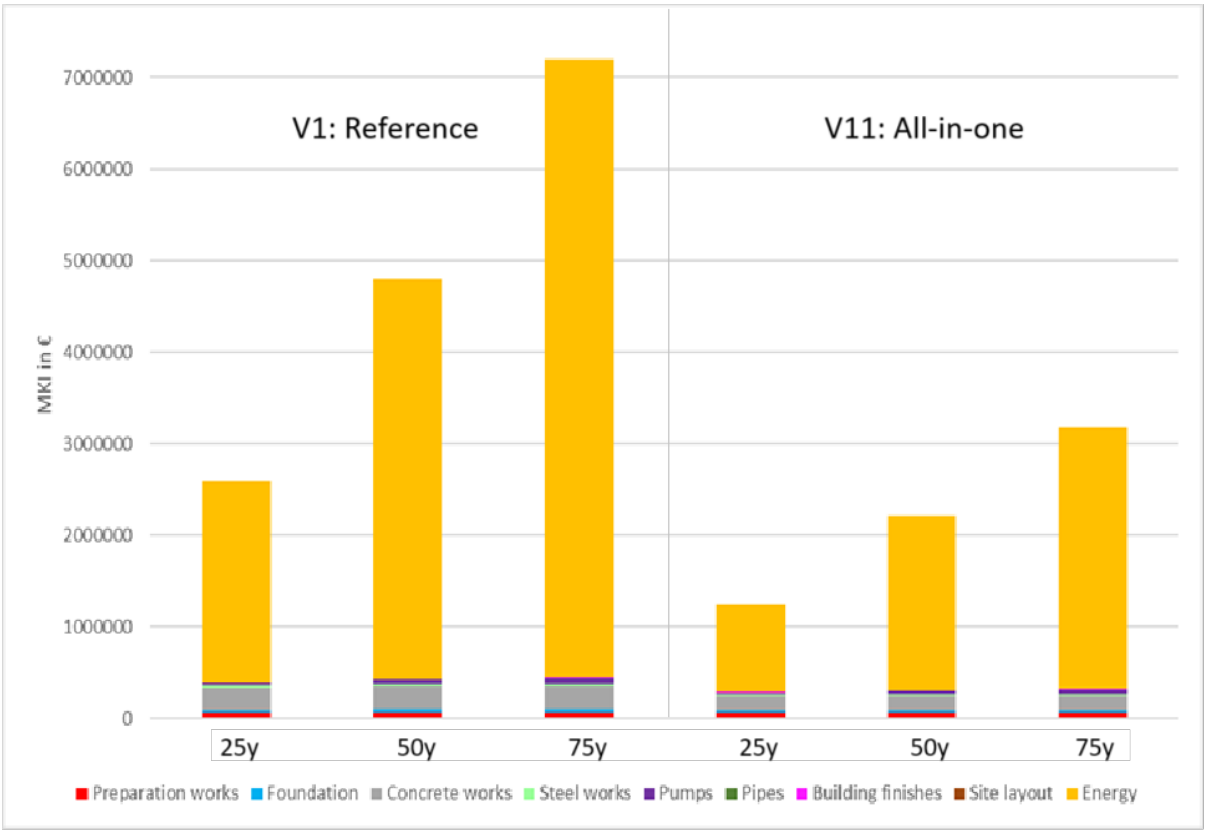


Figure 7.9: MKI/ECI Results De Drie Delfzijlen for 25, 50 and 75 years, Variant 1: Reference and Variant 11: All-in-one compared

The MKI results for the large water pumping station across 25, 50, and 75 years show that sustainable design (Variant 11) significantly outperforms the conventional reference design (Variant 1) in environmental terms. While total MKI in the reference scenario rises from €2.58 million (25 years) to €7.19 million (75 years), the all-in sustainable variant shows much lower values: €1.24 million to €3.18 million over the same period. This represents a 56% reduction at the 75-year mark.

Importantly, the increase in impact over time is less steep in the sustainable variant. V1 sees a 179% increase from 25 to 75 years, compared to 156% in V11. This indicates that circular and low-impact design choices—such as renewable electricity, geo-polymer concrete, and durable components—scale better over time.

Energy use remains the dominant contributor in both variants, especially in the reference case, where it accounts for over 90% of impact at 75 years. In V11, this is significantly reduced due to renewable energy use. Other high-impact elements like pumps and concrete also show substantial reductions in V11 thanks to lifespan extension and material substitution.

From a design strategy perspective, the data support designing for a longer lifespan, but only when combined with sustainable materials and operational strategies. A 75-year design horizon under conventional assumptions leads to high cumulative impacts, but when paired with

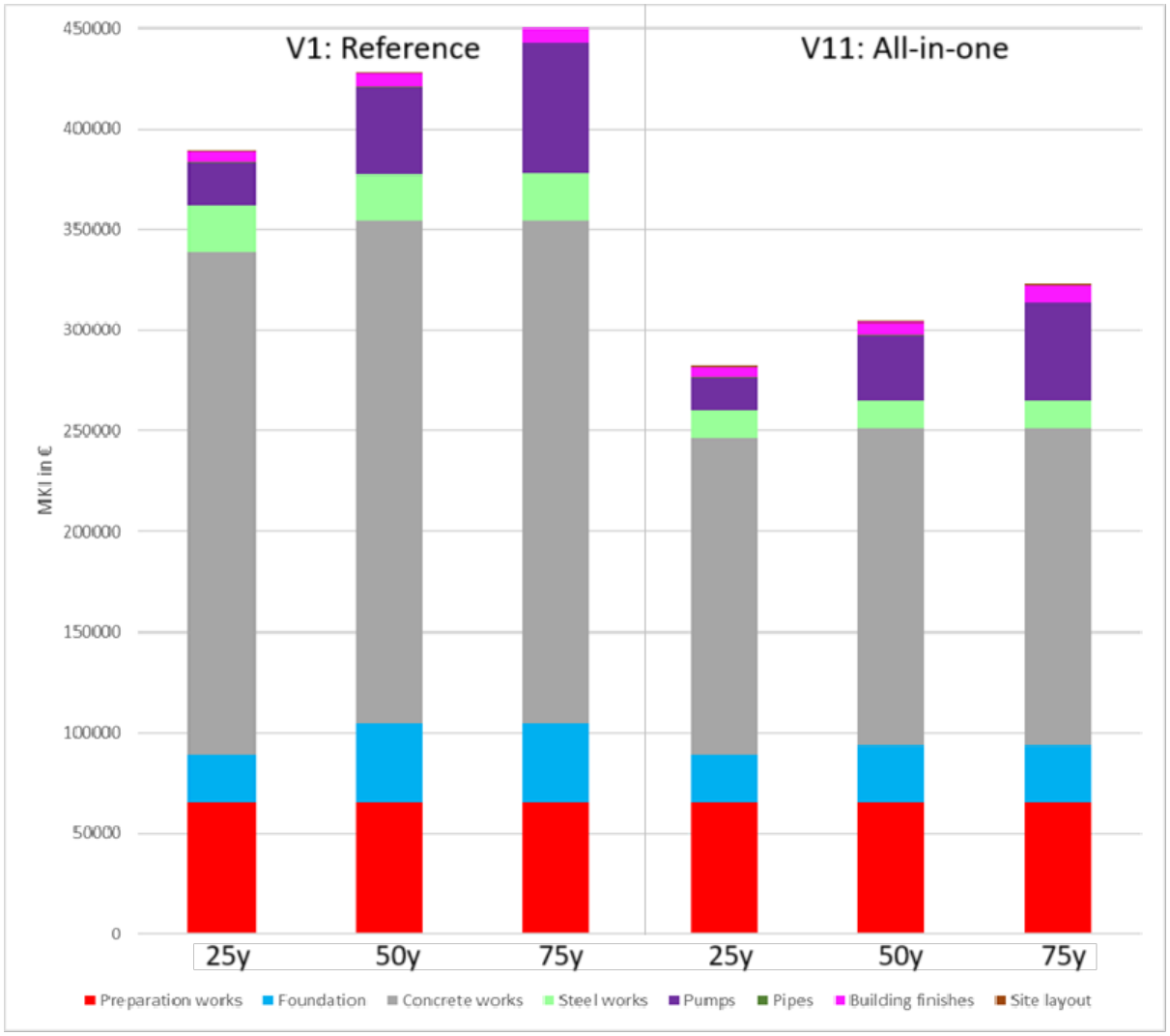


Figure 7.10: MKI/ECI Results De Drie Delfzijlen for 25, 50 and 75 years, Variant 1: Reference and Variant 11: All-in-one compared, without Energy use

circular design, the additional lifetime results in comparatively smaller environmental growth and better long-term performance.

So, extending the lifespan of water pumping stations is environmentally beneficial when paired with circular, low-impact interventions—making sustainable long-term design both viable and preferable.

7.4 Interpretation Phase

Following the Life Cycle Impact Assessment (LCIA), this final interpretation phase synthesises the key results and evaluates their robustness, limitations, and relevance to the overall research objectives. This step is critical in supporting sustainable design and decision-making for Dutch water pumping stations and ensuring the credibility of the study.

7.4.1 Identification of Significant Issues

The two case studies reveal clear patterns of environmental hotspots. For De Drie Delfzijlen, operational energy use dominates, accounting for approximately 77% of the total MKI in the reference scenario. In contrast, for Noordeinde- en Geerpolder, while energy use still leads, the relative contribution of materials—particularly concrete and steel in the foundation—plays

a larger role. In both cases, alternative design variants such as renewable energy integration, geopolymer concrete, and reused materials achieved MKI reductions of up to 50%.

A significant methodological issue emerged concerning the Global Warming Potential (GWP) outputs in DuboCalc. As observed in both cases, electricity use under the Dutch grey mix appeared to account for over 99.5% of the total CO_2-equivalent emissions. This magnitude of influence likely stems from outdated or static emission factors within the Nationale Milieudatabase, which leads to skewed outputs and undermines a nuanced interpretation of non-energy impacts.

Because of such distortions, energy-related CO_2 values were excluded from certain GWP graphs to enable meaningful comparisons across variants. These limitations highlight the necessity for a revised database (scheduled for 2026) and caution against over-reliance on absolute GWP values derived from current DuboCalc outputs.

7.4.2 Completeness Check

The Life Cycle Inventory (LCI) comprehensively includes all major system components: concrete and steel structures, pipelines, pumps, and electricity usage over the full 50-year lifespan. Variants also modelled extended pump lifespans, disassembly potential, prefabrication, and alternative foundation types such as EcoSheetPiles and PVC sheet piles. Maintenance and replacement cycles, including pump renewal every 15 years in the reference scenario, were included, fulfilling the completeness criterion.

While most subsystems were captured, limitations arise in the absence of MKI values for certain circular materials like Combar reinforcement or second-hand PVC sheet piles. DuboCalc lacked verified environmental profiles for several of these innovative options, leading to manual approximations or exclusions in some cases.

7.4.3 Consistency Check

The study follows ISO 14040 and ISO 14044 standards, applying a consistent functional unit—impact per pumping station over 50 years—and clearly defined system boundaries. Data modelling and assumptions are transparently documented. For example, the same grey or renewable electricity mix was applied across comparable variants, and shadow pricing remained consistent across all MKI computations.

Further, methodology and terminology align with national and EU-level LCA practices. Allocation procedures and lifespan assumptions were disclosed (e.g., for pump components), and scenario-based design variants were coherently developed for both case studies. However, the study rightly critiques DuboCalc's use of static shadow prices and uncorrected inflation, acknowledging the implications for future policy decision-making.

7.4.4 Sensitivity Analysis

Key sensitivities were tested throughout the thesis, particularly regarding:

Electricity Mix: Replacing the grey mix with the Dutch renewable mix led to CO_2 reductions of 99.6% and MKI reductions of 30%, confirming the centrality of energy supply assumptions. These results were consistent across both case studies.

Concrete Type: Substituting traditional cement with geopolymer concrete produced 7–12% reductions in MKI (up to 37% in the concrete component specifically). This proves sensitive to changes in binder composition.

Pump Lifespan: Extending the service life of pumps from 15 to 20 years led to small but measurable reductions in the MKI, primarily within the replacement component of the use phase.

Foundation Materials: Switching from traditional steel sheet piles to EcoSheetPiles or PVC alternatives yielded reductions of 12–14% in total MKI. The structural performance and normative acceptance of PVC piles remain a constraint, though potential exists under lighter load conditions.

The model's robustness is therefore strongest in energy and material choices but more limited for novel circular materials not represented in the database. These insights support the thesis conclusion that data quality and database transparency are crucial determinants of LCA reliability.

7.4.5 Comparison between the two pumping stations in capacity terms

To gain insight into the relative environmental impact of both pumping stations in relation to their functional output, a comparison is made by normalising the total MKI score over the designed operational lifespan (50 years) and discharge capacity (in m^3/min). This results in an indicative MKI per unit of capacity per year:

- **De Drie Delfzijlen:** 4,804,623 MKI / 1,800 m^3/min / 50 years = **53.4 MKI / year**
- **Noordeinde- en Geerpolder:** 58,900 MKI / 12 m^3/min / 50 years = **98.2 MKI / year**

From this, it appears that the environmental impact per unit of discharge capacity per year is lower for the larger-scale De Drie Delfzijlen. One possible explanation is that with higher-capacity installations, components such as foundation, casing, control systems, and structural works are shared across larger functional output, resulting in a more efficient use of materials in relative terms.

However, caution is warranted when interpreting these results. Many structural and infrastructural components—such as the casing, access structures, or housing—are required regardless of whether the station has one or two pumps, and are therefore not strictly proportional to pumping capacity. Furthermore, the two stations differ considerably in scale, design approach, material use, and complexity, making direct comparison challenging. The observed differences may therefore not only be the result of scale efficiency but also of differing design choices and component ratios.

8 Evaluation of LCA Challenges and Cost-Analysis of Sustainable Design Choices

This chapter critically evaluates the limitations of the MKI/ECI method and its application in infrastructure projects. Section 8.1 identifies key methodological challenges, such as data quality, system boundaries, and lack of socio-economic integration. Section 8.2 compares material costs with associated MKI/ECI scores to assess the financial implications of sustainable design decisions. The chapter then considers trade-offs between cost and environmental performance, supported by a detailed comparison of variants. This cost-benefit perspective highlights the importance of early design-stage sustainability integration and helps clarify where existing LCA tools fall short in informing balanced decision-making.

8.1 Challenges in the Application and Interpretation of DuboCalc for Life Cycle Assessment in Dutch Civil Engineering

The use of Life Cycle Assessment (LCA) in the Dutch civil engineering sector (Grond-, Weg- en Waterbouw, GWW) is becoming increasingly standardised, particularly through the adoption of DuboCalc, a software tool developed by Rijkswaterstaat. DuboCalc calculates environmental impacts using the Milieu Kosten Indicator (MKI) and aligns with national sustainability frameworks. Despite its widespread use, DuboCalc faces several methodological and practical challenges.

DuboCalc operates through a fixed database of processes, each assigned environmental impact values per functional unit over different life cycle stages. These data are classified by Stichting Bouwkwaliteit (SBK) into three quality categories: Category 1 (verified, brand-specific), Category 2 (verified, generic), and Category 3 (unverified, generic). To account for the greater uncertainty of Category 3 data, DuboCalc adds a 30% penalty to the MKI, aiming to encourage data verification by suppliers and manufacturers (Berenschot, 2019).

However, this penalty may distort design comparisons, especially for projects reliant on unverified data, where inflated MKI values do not necessarily reflect real environmental performance. Moreover, the MKI's single score format limits transparency, as it does not disaggregate into specific environmental impact categories such as climate change or eutrophication. This lack of granularity hampers the identification of optimisation opportunities.

In practice, data availability within DuboCalc varies widely between material types. For example, while sheet pile alternatives are well-represented, other materials may lack any verified LCA data. This imbalance complicates sustainability assessments and hinders the formulation of reliable recommendations, as noted by consultants such as Aveco de Bondt.

The Nationale Milieudatabase (NMD), upon which DuboCalc relies, also suffers from data quality concerns. There is insufficient distinction between LCAs intended for early-phase design and those for final delivery. Many data cards are outdated, and some compare non-equivalent products (e.g., doors with or without fittings), making MKI comparisons misleading. Users currently cannot evaluate the quality of datasets, as detailed product data are not public.

Stichting Bouwkwaliteit (SBK, or Foundation for Building Quality) is managing the 'Bepalingsmethode' and is attempting to address these issues. New protocols are being developed to improve consistency, and the NMD is being restructured to allow for more uniform product descriptions and clearer data feedback mechanisms. However, experts argue

that existing second-opinion reviews focus too much on procedural compliance rather than on substantive data quality (Berenschot, 2019).

Another point of concern is DuboCalc's opacity regarding materials and assumptions. Users often cannot trace how MKI values are derived, or which subcomponents are included in an analysis. This obscures the environmental logic behind project scores and limits efforts to meaningfully reduce impacts.

Despite these limitations, DuboCalc remains a valuable tool for embedding sustainability into infrastructure design. However, a more transparent and comprehensive approach is needed. Improvements in data granularity, verification processes, and methodological clarity will better support designers, contractors, and policymakers in making well-informed decisions.

8.2 Critical Review of DuboCalc and LCA Practice in Dutch Civil Engineering

System Transparency and Usability

DuboCalc is often described as a "black box" due to limited user access to underlying assumptions and datasets. Smaller contractors and niche project teams report difficulties in using the tool effectively, especially when modelling non-standard elements such as noise barriers or temporary infrastructure. Even experienced users note the lack of flexibility and transparency as barriers to providing well-supported environmental advice.

Data Quality and Classification Challenges

The NMD distinguishes between verified and unverified datasets, applying penalties to incentivise better data. Yet, these mechanisms can backfire when users rely on outdated or incomplete data. Furthermore, there is confusion between datasets meant for tenders and those for final project delivery, reducing their reliability. Some product comparisons are flawed due to mismatched specifications, and the absence of metadata hinders quality assessment.

Lack of Detail in Impact Categories

By focusing on a single MKI score, DuboCalc conceals detailed impact categories such as global warming, eutrophication, and resource depletion. This aggregation limits the tool's value for targeted environmental improvements and complicates alignment with specific sustainability goals.

More generally, LCA outcomes are highly sensitive to boundary conditions and assumptions. Whether recycled content is credited upstream or downstream, and how end-of-life is modelled, can change outcomes significantly (Marcel, 2024). Sector averages dominate the database, reducing the relevance of results for context-specific assessments (Haas, 2014).

Missing Dimensions and Overlooked Impacts

DuboCalc, like many LCA tools, prioritises environmental factors but overlooks social and economic sustainability indicators. Labour practices, human health, or noise pollution are not part of its scope, despite their importance to community well-being (Allacker et al., 2023). Critics warn that LCA can become an abstract academic exercise, detracting from practical interventions such as energy optimisation (Kubus, 2024).

Comparability and Harmonisation Issues

Differences in scope, assumptions, and impact modelling between LCA tools lead to incompatible results. Projects using different life spans, functional units, or system boundaries produce MKI values that cannot be directly compared.

The European Product Environmental Footprint (PEF) initiative aims to address this, but uptake has been limited (Haas, 2014).

Reform Efforts and Future Directions

SBK and Rijkswaterstaat acknowledge these shortcomings and are working on solutions. Planned updates include modernising outdated MKI metrics, improving audit protocols, and making Category 1 and 2 data more robust and accessible (Rijkswaterstaat, 2019). New guidelines for LCA practitioners should raise the standard of submitted datasets.

Practical Implications for Research and Design

To effectively apply DuboCalc in circular and sustainable infrastructure design, practitioners should:

- Clearly define scope, boundaries, and assumptions in all assessments.
- Validate results with additional indicators when possible.
- Consider using complementary tools (e.g., social LCA, life cycle costing).
- Acknowledge the interpretative limits of MKI-based comparisons.

In summary, while DuboCalc is a crucial instrument for integrating environmental metrics into Dutch infrastructure projects, its current form requires further refinement. Enhancing data quality, improving methodological clarity, and expanding its scope will strengthen its role in promoting circularity and sustainability across the sector.

8.3 Cost Analysis of Sustainable Design Choices

A cost comparison between the marginal price increase associated with more sustainable material alternatives and the calculated reduction in the environmental impact, as expressed by the Milieukostenindicator (MKI), presents a seemingly logical step for decision-makers. This stems from the fact that the MKI expresses environmental burden in euros, which intuitively invites direct comparison with financial costs. However, this assumption warrants caution. Although the euro-denominated MKI scores may suggest an equivalence to actual market prices, the underlying metrics are based on normalised and weighted environmental impact categories rather than real economic expenditure. As such, equating MKI reductions to monetary savings or expenditures can lead to misleading conclusions if not properly contextualised. While such comparisons may offer initial insights, particularly in procurement or early design stages, a more nuanced understanding is necessary to avoid oversimplified interpretations that could undermine sustainability objectives.

Despite some limitations in the method, such comparisons are still likely to be made in practice—especially by professionals looking to support material choices that balance both sustainability and cost-efficiency. For that reason, this section continues with a simplified comparative analysis. It compares the MKI per functional unit of material with the cost price of both standard (baseline) and more sustainable (alternative) options. This aims to give an initial impression of the trade-offs between environmental impact and financial cost at the material level.

Table 8.1 presents these values for a selection of materials, showing MKI scores (in €/unit) alongside indicative market prices (€/unit) for both traditional and alternative materials. While the overview is not complete or final, it can help guide early design decisions and support more informed choices—as long as users remain aware that environmental indicators like MKI do not translate directly into economic costs.

An in-depth comparison of material cost versus environmental performance using both A1 and projected A2 MKI datasets reveals important insights for sustainable material selection. Certain materials, such as Azobé wood sheet piles, demonstrate strong performance across both metrics, offering the lowest cost (€70.00/m²) and lowest environmental impact in both A1 (€2.29/m²) and A2 (€4.66/m²) datasets. Similarly, geopolymer concrete variants outperform traditional concrete in both price and MKI scores, with the "Slope Geop" mix costing less (€217.95/m³ vs. €225.90/m³) and emitting significantly less impact under both A1 (€20.74) and A2 (€35.28) compared to conventional C35/45 concrete. These materials offer a clear win-win scenario for cost-effective, future-proof construction. In contrast, some products marketed as sustainable, such as EcoSheetPile and EcoSheetPile Plus, while showing moderate A1 MKI scores (€8.40 and €8.07 respectively), experience a dramatic increase in A2 MKI values (€159.88 and €158.43), surpassing even traditional steel (€57.85). This discrepancy highlights the critical role of updated lifecycle data, as reliance on outdated A1 MKI scores may lead to unintended environmental burdens post-implementation. Furthermore, Combar fiberglass reinforcement—though more expensive than steel—shows a better A2 MKI profile, making it a compelling alternative for environmentally focused designs. Overall, the shift from A1 to A2 datasets emphasizes the importance of integrating forward-looking environmental indicators into material selection, ensuring that today's sustainable choices remain valid under tomorrow's assessment standards.

Category	Product Type	Material	Variant	Price/unit	Unit	A1 MKI/unit	A2 MKI/unit	Unit
Foundation	Sheet pile	Steel AZ		€110.00	m²	€24.82	€57.85	m²
	Sheet pile	PVC	GW650	€85.00	m²	€5.25	€12.16	m²
	Sheet pile	EcoSheetPile	AZ24-700	€152.46	m²	€8.40	€159.88	m²
	Sheet pile	EcoSheetPile Plus	AZ24-700	€159.30	m²	€8.07	€158.43	m²
	Sheet pile	Wood	Azobé	€70.00	m²	€2.29	€4.66	m²
	Capping beam	Concrete	50x50cm C30/37	€54.90	m	€7.49	€15.60	m
	Capping beam	PVC	GW503	€30.00	m			m
	Capping beam	Geopolymer concrete		€58.96	m			m
	Capping beam	Wood		€42.00	m			m
	Foundation beams	Steel	Sigma profile	€24.00	m			m
	Foundation beams	Wood	Azobe beam 10x10cm	€152.00	m			m
	Foundation beams	PVC	Double UNP100	€75.00	m			m
Concrete work	Concrete	C35/45 XC4 F4 N32		€225.90	m³	€36.36	€62.88	m³
	Geopolymer concrete	Geop C35/45 N16		€242.70	m³	€25.45	€44.02	m³
	Concrete	C20/25 XF3 S2 N32		€213.30	m³	€29.63	€50.40	m³
	Geopolymer concrete	Slope Geop		€217.95	m³	€20.74	€35.28	m³
	Reinforcement steel	Straight bars	8mm B500B	€0.51	m	€0.06	€0.14	m
	Reinforcement steel	Straight bars	12mm	€1.13	m	€0.13	€0.30	m
	Reinforcement steel	Straight bars	16mm	€2.00	m	€0.24	€0.56	m
	Reinforcement steel	Straight bars	20mm	€3.15	m	€0.37	€0.86	m
	Combar fiberglass reinforcement	Straight bars	8mm	€1.40	m	€0.07	€0.08	m
	Combar fiberglass reinforcement	Straight bars	12mm	€2.00	m	€0.14	€0.16	m
	Combar fiberglass reinforcement	Straight bars	16mm	€3.60	m	€0.25	€0.29	m
	Combar fiberglass reinforcement	Straight bars	20mm	€5.00	m	€0.52	€0.59	m
Pipes	Water pipe	HDPE		€100.00	m	€1.74	€3.20	m
	Water pipe	Cast iron		€200.00	m	€5.11	€8.76	m
	Water pipe	PVC		€120.00	m	€1.79	€2.96	m

Table 8.1: Material Costs and Environmental Cost Indicators (ECI/MKI)

9 Development of Practical Design and Implementation Strategies

This chapter synthesises findings into actionable strategies for improving the sustainability of water pumping stations. Section 9.1 outlines design recommendations based on CE principles such as modularity, resource recovery, and bio-based material use. Section 9.2 explores how these strategies can be integrated into early design stages. Section 9.3 discusses implementation pathways, including digitalisation tools (e.g., Material Passports and Digital Twins), procurement innovation, and cross-sectoral collaboration. By bridging research insights with practical guidance, this chapter aims to support engineers, water boards, and policymakers in advancing circular water infrastructure.

1. Energy Use and Operational Strategies

A primary focus for sustainable intervention lies in the operational energy consumption of water pumping stations. Over the lifespan of such infrastructure—especially those with extended service durations—the energy demand becomes the most significant contributor to environmental impact. Consequently, strategies targeting energy efficiency and renewable energy integration are of paramount importance.

An essential first step is to critically assess the sources of energy used to power these stations. While many utility companies claim their electricity is derived from 100% renewable sources, the reality is more nuanced. Due to the shared nature of electricity grids, renewable and non-renewable energy sources are mixed within the system. Although the proportion of renewable energy is steadily increasing, achieving a fully decarbonised grid remains a long-term goal. Thus, relying on grid electricity—even when sourced from certified "green" suppliers—still implicates indirect emissions.

A more proactive and reliable approach involves the local generation of renewable energy, such as through photovoltaic (solar) panels or small-scale wind turbines located at or near the pumping station. This would reduce reliance on grid electricity and contribute to on-site sustainability. However, several operational constraints must be considered. Water pumping often occurs during evening or nighttime hours or when it is cloudy, so when solar energy is not or in lesser extent available. To address this, battery storage systems would be required to store excess energy generated during daylight hours for later use. Nevertheless, the variability in both energy demand and generation poses a challenge, especially during periods of peak precipitation and flow. Due to the high and fluctuating energy requirements associated with pumping excess water during such events, complete energy self-sufficiency remains unfeasible with current technology. Therefore, a hybrid system—where on-site renewables provide partial energy coverage and the grid supplies the balance during peak events—is considered a more practical solution.

2. Construction Phase Interventions

In addition to operational strategies, substantial sustainability gains can be realised in the construction phase, particularly through material selection and design optimisation. The extent and type of intervention vary based on the scale of the pumping station.

a. Small-Scale Pumping Stations ($<$ 50 m³/min Capacity):

In smaller stations, the foundation components represent the most significant environmental burden, particularly sheet piles and foundation piles. To mitigate this, a collaborative approach involving engineers and ecologists should be undertaken to evaluate the feasibility of alternative materials. For example, PVC or other plastic-based sheet piles may offer acceptable structural performance while reducing environmental impact. However, their applicability must be assessed in terms of mechanical strength, durability, and compatibility with local ecological conditions.

Where plastic alternatives are unsuitable, more sustainable steel options should be considered. Products such as *EcoSheetPile*™ from ArcelorMittal provide a promising alternative. These sheet piles are manufactured using steel produced via electric arc furnaces powered by renewable energy sources, leading to a significantly lower carbon footprint compared to conventional blast furnace methods. Their use can meaningfully reduce embodied emissions while maintaining structural performance.

b. Large-Scale Pumping Stations ($>$ 500 m³/min Capacity):

For larger installations, the most environmentally impactful construction element is the use of concrete, including both the cement matrix and embedded steel reinforcement. A two-pronged strategy is advised for reducing this impact.

First, during the design phase, structural optimisation should be pursued to minimise the total volume of concrete required. This includes taking into account modular construction principles. Second, more sustainable forms of concrete should be utilised. For instance, geo-polymer concrete—a class of materials that use industrial by-products such as fly ash or slag instead of traditional Portland cement—offers significant environmental advantages, including lower embodied carbon and reduced energy consumption during production. These alternatives can achieve comparable strength and durability, thereby preserving the structural integrity and service life of the facility.

By integrating these construction-phase strategies, the environmental footprint of pumping stations can be reduced by about 30% in comparison to the reference scenarios without compromising on performance or longevity.

Notes and General Conclusions Following the Company Visit to 'De Drie Delfzijlen'

There is a clear willingness to adopt sustainable approaches, particularly through integrated collaboration with other stakeholders such as water boards. However, many of these parties remain constrained by administrative standards, regulations, and slow bureaucratic processes. As a result, innovations and technological developments are implemented at a very slow pace. For example, the use of 3D models and their associated benefits is still unfamiliar to certain water authorities such as Noorderzijlvest, which currently lacks the tools or knowledge to view or apply these models effectively.

Many innovations are not new, and in some cases, are already widely used in other sectors. In the housing sector, for instance, Building Information Modelling (BIM) is more advanced than in civil engineering. Similarly, the use and development of Life Cycle Assessment (LCA) has seen significant progress in the asphalt industry. This results in a stark contrast between private sector companies and public agencies in terms of their awareness and adoption of cutting-edge technologies—such as 3D modelling, the implementation of BIM, project planning with integrated data from the earliest design stages, and sustainability considerations embedded from the preliminary design phase. This includes knowledge of materials, their usage, average life spans, and end-of-life options and functions. These capabilities already exist and are

technically feasible today. However, effective communication, education, and training are essential to enable companies and water boards to adopt and implement them, and to foster a willingness to learn.

From an investment or project cost perspective, initial expenditures may be higher. Yet, if sustainability measures are implemented early—such as creating and maintaining a materials passport—long-term benefits become evident. A centralised repository of information would greatly assist the pumping station manager, for example, by offering insights into maintenance schedules, replacement cycles, and general operational data. This is crucial for both the usage and maintenance phases of infrastructure. Furthermore, the potential exists for further digitalisation through technologies such as Digital Twins. While more commonly associated with other civil assets like bridges or locks—where constant structural monitoring is required—digital monitoring of pumping stations also offers promising opportunities. These include tracking energy consumption, operating hours, and pump activity. This data can be used in model predictive control systems to efficiently manage operations in anticipation of rainfall or fluctuations in water levels—commonly referred to as 'smart pumping'.

Significant challenges remain. Some companies and engineering consultancies are more advanced than others in specific areas, and the same is true for water boards. To progress as a sector, it is vital that organisations learn from one another. This could be facilitated through joint knowledge-sharing sessions focused on sustainability in water infrastructure. Integrated solutions involving BIM, data management and control, digital twins, and shared experiences—both positive and negative—must be part of this collaborative approach. Only then can the sector make real progress and position the Netherlands, and Europe more broadly, to achieve their sustainability goals.

10 Discussion

This chapter critically reflects on the findings of the thesis in a broader context. Section 10.1 revisits the strengths and limitations of the applied LCA and MKI/ECI approaches. Section 10.2 analyses the influence of scale by comparing results from the large and small case studies. Section 10.3 discusses barriers to implementing CE principles, including procurement structures, institutional inertia, and data availability. Section 10.4 explores how policy, culture, and collaboration can support sector-wide transformation. The chapter closes with future research directions and outlines how the study contributes to the advancement of sustainable water infrastructure practices.

10.1 Methodological Reflections on LCA and MKI/ECI

The application of Life Cycle Assessment (LCA) via DuboCalc and the Environmental Cost Indicator (MKI/ECI) enabled a quantifiable evaluation of environmental impacts. However, the study revealed several critical methodological shortcomings that must be addressed to improve their reliability and relevance in infrastructure decision-making.

The MKI method, while beneficial in producing an aggregated, monetized environmental score that facilitates comparison across materials and designs, tends to obscure the contribution of specific environmental impact categories such as global warming potential, eutrophication, or toxicity. This aggregation hinders precise diagnosis of environmental hotspots and limits targeted design interventions. For example, although energy use emerged as the dominant driver of environmental burden, the MKI framework did not allow disaggregation into distinct emissions such as CO_2 versus NO_x, making the prioritization of mitigation measures less effective.

A second concern involves data quality and currency. Many innovative materials—such as geo-polymer concrete, recycled HDPE pipes, and prefabricated composite elements—lack robust environmental profiles in the Nationale Milieudatabase (NMD). Consequently, sustainable innovations may be undervalued or penalized through the application of conservative assumptions or default 30% uncertainty penalties for Category 3 data. This limitation was particularly evident in the modelling of Combar reinforcement and newer material applications where environmental data lag behind technological advancements.

Thirdly, when examining the definition of the functional unit, the current capacity-based normalisation raises a critical methodological issue regarding its completeness. While pumping capacity (i.e., volumetric flow) is a major determinant of infrastructure scale—and thus of material and energy requirements—other operational parameters, particularly pumping height (the vertical distance water must be lifted), also significantly influence system performance and environmental impact.

Pumping height determines not only the pressure demands but also the specific energy consumption of the system. Relying solely on volumetric capacity risks oversimplifying the functional representation and may obscure important differences between pumping stations operating under varying hydraulic conditions. This could result in misleading conclusions when comparing stations, as those facing greater vertical lift challenges inherently require more energy to achieve the same flow rate.

To better reflect the actual hydraulic work performed, a more comprehensive or alternative functional unit should be considered—one that incorporates both volumetric flow and vertical lift. For example, a revised unit such as 1 m^3/min per metre of pumping height per operational

year would more accurately account for total system effort. Such a definition would provide a more equitable and physically grounded basis for environmental comparisons across different geophysical contexts.

While this dimension was not incorporated into the current modelling approach, future assessments could benefit from its inclusion. A functional unit grounded in hydraulic work—such as kWh per $m^3 \cdot m$—would align more closely with system physics and offer deeper insights into the true efficiency and environmental footprint of water conveyance systems.

Additionally, the assumption of a static 50-year lifespan for all structural components, although conventional in civil engineering LCAs, introduces inaccuracies. Mechanical and electrical systems often require earlier replacement, while materials such as stainless steel and reinforced concrete may last significantly longer. A dynamic LCA that accounts for component-specific lifespans, maintenance cycles, and material degradation would improve the temporal accuracy of impact assessments.

Finally, the MKI framework relies on static shadow prices that do not reflect inflation, shifting societal priorities, or regional policy nuances. The current shadow pricing structure inadequately captures the rising urgency of climate mitigation. Without inflation-adjusted or policy-sensitive pricing mechanisms, the MKI risks misaligning infrastructure choices with long-term sustainability objectives.

10.2 Interpretation of Comparative Results and Scale Effects

The comparative case study analysis illuminated the intricate trade-offs between infrastructure scale, material usage, energy performance, and circularity potential. A particularly striking finding was that operational energy use accounted for 60–90% of the total MKI in both stations, confirming that energy efficiency and the integration of renewable electricity offer the most significant leverage in environmental performance. In modelled scenarios, transitioning to green energy sources alone reduced total MKI by up to 50%, underscoring the value of sustainable energy procurement.

The inclusion of A2 MKI data introduced a forward-looking lens that exposed the risk of underestimating environmental impacts when relying solely on A1 values. For example, materials like EcoSheetPile showed a sharp rise in environmental cost when evaluated using A2 MKI. This was reinforced with the costs comparison, where it became clear that sustainable materials are not only more environmentally favourable over longer lifespans but, in some cases, also economically viable. The interplay between updated MKI scores and cost analysis supports the need for dynamic, future-proof material selection frameworks.

In terms of material impact, Noordeinde- en Geerpolder, the smaller of the two stations, exhibited elevated MKI values relative to its flow capacity, largely due to its fixed construction footprint and limited opportunities for material optimization. Foundation elements—especially sheet piles and concrete—were major contributors, though the use of EcoSheetPiles or PVC alternatives proved effective in reducing impacts. By contrast, De Drie Delfzijlen, though materially more intensive, benefited from prefabrication, modular construction, and renewable energy upgrades, yielding more favourable MKI outcomes when normalized per m^3/min of discharge.

This challenges the conventional assumption that smaller infrastructure is inherently more sustainable. Instead, the findings point to the importance of strategic design, regardless of size, in achieving meaningful environmental gains. Sustainability, it appears, scales more with design quality and systems thinking than with absolute capacity.

Another notable insight relates to ecological features. Additions such as fish passages had only marginal influence on MKI, yet their ecological value—in terms of biodiversity protection and ecosystem function—is profound. This discrepancy signals a limitation in current LCA frameworks, which inadequately capture non-monetized ecosystem services. It suggests a need to embed multi-criteria assessment tools that combine environmental metrics with ecological and social dimensions.

10.3 Circularity in Practice: Barriers and Opportunities

Despite positive efforts, the integration of circular economy principles into water pumping station design remains partial and inconsistent. While both case studies explored Material Passports, component reuse, and detachable designs, these interventions were often ad hoc and hampered by fragmented data, non-standardised evaluation criteria, and limited institutional support.

Material Passports, though conceptually promising, were found to be static, underutilised, and rarely updated to reflect actual asset performance or reuse potential. Moreover, they remained disconnected from LCA tools, reducing their operational utility. Reuse decisions—such as reconfiguring tanks or reusing sheet piles—were made on a project-specific basis rather than guided by replicable frameworks or benchmarks.

Standardisation across circularity metrics was also lacking. Key terms like "recyclability" or "detachability" were interpreted differently across projects, making cross-comparison difficult. Tools like Het Nieuwe Normaal and the Material Circularity Indicator offer a foundation, but further harmonisation is needed to enable systematic implementation.

Another central barrier is rooted in the procurement and contracting structures of public infrastructure. Circularity is frequently introduced too late in the process—often during tendering—by which point design flexibility has already narrowed. Contractors tend to prioritise performance and budget compliance over long-term circular benefits, especially in the absence of strong contractual incentives or clear performance clauses. This "procurement paradox" effectively sidelines sustainability from the core design process.

Finally, a significant cultural and organizational challenge persists. Risk aversion, legacy practices, and closed responsibilities deter the adoption of novel materials or techniques. Even when environmental benefits are evident, the lack of standardized approval pathways or performance guarantees inhibits experimentation. Overcoming these barriers will require sustained capacity building, policy reform, and stakeholder engagement to shift both practices and mindsets.

10.4 Expert Insights and Institutional Dynamics

Interviews and stakeholder workshops revealed systemic tensions between strategic sustainability ambitions and operational realities. While water boards and engineering firms widely support the move toward climate neutrality and circularity, they are constrained by budget limitations, governance fragmentation, and regulations. A recurring theme was the difficulty in accessing reliable environmental data, particularly for hybrid, bio-based, or region-specific materials. Additionally, engineers voiced the lack of centralised databases or standard templates for documenting and comparing circular strategies.

Experts called for early-stage integration of LCA and MKI tools—ideally during conceptual design—to ensure sustainability considerations are embedded into design logic, not appended after key decisions are made. The need for digital integration platforms that combine material tracking, environmental profiles, and lifecycle modelling to support informed, real-time decision-making was also emphasized.

This discussion confirms that while LCA and CE frameworks offer valuable tools for steering water infrastructure toward sustainability, their full potential is yet to be realized. Methodological refinements, data transparency, regulatory alignment, and cultural change are essential for embedding these principles at scale. Importantly, the study challenges the assumption that smaller automatically means more sustainable, showing that design intelligence and systems integration are more critical than project size.

As the Netherlands faces a wave of infrastructure renewal under climate pressure, this thesis demonstrates that sustainability in water pumping stations is not just desirable but feasible—if approached through a holistic, data-driven, and collaborative lens. With the right tools, policies, and institutional commitment, these stations can evolve into benchmarks of resilient and circular infrastructure for a changing world.

11 Conclusions and Recommendations

This concluding chapter synthesizes the main findings of the research and offers strategic and practical guidance for improving the environmental performance and circularity of water pumping stations in the Netherlands. The study focused on two case studies—*Noordeinde-en Geerpolder* and *De Drie Delfzijlen*—and explored the application of Life Cycle Assessment (LCA), the Environmental Cost Indicator (MKI/ECI), and circular economy (CE) principles in evaluating and enhancing infrastructure sustainability. While rooted in the Dutch context, the conclusions offer broader relevance to engineers, policymakers, and infrastructure managers globally, particularly those engaged in climate-resilient infrastructure transitions.

11.1 Revisiting the Research Questions

SQ1: How are circularity and sustainability currently assessed in water pumping stations?

Current assessment practices for sustainability and circularity in water pumping stations remain limited and inconsistent. While national tools such as DuboCalc and the MKI/ECI framework are available, their application is often fragmented and focused primarily on the tendering phase, rather than integrated throughout the entire design and lifecycle. Circularity assessment is not yet systematically embedded, with key aspects such as material reuse, modularity, and end-of-life planning often overlooked. This thesis applied the Material Passport method to two case studies, revealing that while the concept is recognised, its operationalisation is still in early stages. Standardised procedures, reliable environmental datasets, and early-stage integration of sustainability tools are lacking, hindering robust circular evaluations.

SQ2: What are the environmental impacts of water pumping stations, considering different materials and design alternatives, using the MKI/ECI (LCA) method?

Using Life Cycle Assessment (LCA) and the MKI/ECI methodology in DuboCalc, the study quantified environmental impacts for two types of pumping stations. Results showed that the operational phase—particularly energy use—dominates the overall environmental footprint, contributing 60–90% of total MKI depending on the station size. Construction materials, particularly concrete and steel, also contributed significantly. Design interventions such as the use of renewable energy, prefabricated geopolymer concrete, and recycled steel reduced the MKI by up to 50% when implemented in combination. These findings confirm the potential of targeted material and system-level changes to improve sustainability outcomes in both small and large water pumping stations.

SQ3: What challenges exist within the MKI/ECI (LCA) method, how can they be improved, and how can environmental gains (MKI/ECI) be weighed against the additional costs of more sustainable materials and designs?

The study identified several limitations in the MKI/ECI methodology. These include outdated or incomplete environmental data for innovative or circular materials, lack of transparency in databases like the Nationale Milieudatabase, and the oversimplification of key modelling assumptions (e.g., fixed functional units and static lifespans). Furthermore, the aggregated MKI score can obscure environmental hotspots, such as CO_2 versus NO_x emissions. These limitations complicate cost-benefit comparisons. Nonetheless, combining environmental impact reductions with economic data showed that many sustainable alternatives offer favourable trade-offs with minimal added cost. Enhancements to the methodology, such as dynamic pricing, broader impact categories (as in MKI Set A2), and disaggregated reporting, are essential for more accurate and decision-relevant assessments.

SQ4: What concrete measures can be implemented in the (preliminary) design phase to enhance the circularity and environmental performance of water pumping stations?

A range of practical measures was identified for implementation in the early design phase. These include:

- Integrating renewable energy sources such as solar panels and wind turbines to reduce operational impacts;
- Selecting sustainable materials like geopolymer concrete, recycled steel, and PVC or composite sheet piles;
- Prefabricating components to lower on-site emissions and material waste;
- Extending the service life of mechanical systems through maintenance planning;
- Designing for disassembly and reuse using modular construction and using Material Passports.

These strategies not only reduce environmental burdens but also enhance long-term adaptability and resource efficiency. Importantly, early integration of CE principles—rather than post-design adjustments—is key to achieving significant impact reductions.

Main RQ: How can sustainability assessment methods and circular principles be applied to evaluate and improve the circularity and environmental performance of water pumping stations?

This study addressed the central research question through an integrated methodological approach, combining Life Cycle Assessment (LCA) modelling, Material Passport development, expert interviews, and comparative case study analysis. The findings demonstrate that sustainability assessment methods—particularly the MKI/ECI metric and LCA-based tools such as DuboCalc—provide a solid foundation for evaluating environmental performance. However, their effectiveness is greatly enhanced when complemented by circular economy (CE) principles and applied early in the design process.

To move beyond mere compliance or end-of-pipeline assessment, CE frameworks such as Het Nieuwe Normaal, the Material Circularity Indicator, and Material Passports must be embedded at the conceptual and preliminary design stages. These tools allow for better consideration of reuse potential, material origin, and design for disassembly—key aspects often overlooked in standard MKI-based approaches.

Case study analysis revealed that the Use & Maintenance phase, particularly operational energy consumption, is by far the most significant contributor to environmental impact, accounting for 60–90% of the total MKI score. Nevertheless, construction materials, especially concrete and steel, also play a considerable role. Strategic design interventions—such as the integration of renewable energy, the use of geopolymer concrete, and the application of recycled steel and low-impact sheet pile alternatives—were shown to reduce total environmental impacts by up to 50% when applied in combination.

Despite its utility, the MKI/ECI methodology exhibits several limitations. These include limited database transparency, outdated or missing environmental profiles for novel circular materials, and the use of static shadow prices. Additionally, simplified assumptions—such as uniform 50-year life spans and fixed functional units—can constrain the model's ability to reflect real-world variability. As such, there is a growing need for more dynamic and context-sensitive LCA tools capable of incorporating time-dependent performance, user behaviour, and maintenance strategies.

The combined evaluation of environmental indicators across different lifespans and the corresponding cost analysis confirms that certain material choices—such as geopolymer concrete and wood or fiberglass reinforcement—achieve a favorable balance between sustainability and cost. Crucially, the dramatic shift in MKI scores between the A1 and A2 datasets underscores the importance of integrating evolving environmental datasets into current planning. Long-term sustainability decisions cannot rely solely on present-day indicators and must anticipate stricter future environmental assessments. These findings reinforce the necessity for future-proof material selection processes and support the ongoing development of updated, dynamic LCA frameworks that reflect both financial and ecological realities over extended design lifespans.

So, the integration of up-to-date environmental datasets, expanded impact categories, and circular design strategies within LCA-based assessment frameworks presents a viable pathway for enhancing the sustainability and circularity of Dutch water pumping stations. A proactive, data-driven, and lifecycle-oriented approach enables these assets to evolve from standard utility infrastructure into forward-looking exemplars of climate-resilient and circular design.

11.2 Key Lessons from the Case Studies

The comparative analysis of *Noordeinde- en Geerpolder* (a small-scale, ecologically focused station) and *De Drie Delfzijlen* (a large-scale, electrified boezem station) challenged common assumptions. Sustainability outcomes were not strictly correlated with size. In fact, *De Drie Delfzijlen*, through prefabrication, modularity, and renewable energy sourcing, outperformed the smaller station in MKI per discharge capacity.

The bundling of sustainable interventions—such as renewable energy use, material substitution, and modular construction—proved more effective than isolated measures. Notably, fish passages and component reuse offered strong environmental returns at relatively low cost, underlining the importance of including ecological features within environmental impact assessments.

11.3 Strategic and Practical Recommendations

To realise the full potential of circular and sustainable water infrastructure, the research recommends institutional, technical, and design-based changes. At the institutional level, public procurement processes should embed circularity and environmental performance into their core criteria, not as secondary evaluation points. Material Passports should be standardised and made mandatory for all new infrastructure projects, ideally linked with Building Information Modelling (BIM) platforms to ensure continuous tracking and future reuse.

From a design perspective, engineers and planners should embrace modularity, reversible construction methods, and low-impact materials. Design for disassembly, reuse, and long-term adaptability should be the norm, not the exception. Operational systems, including pumps and control units, should be optimized for energy efficiency and integrated with renewable sources like solar panels or heat buffers. Material selection must prioritize products with verified environmental profiles to ensure accurate LCA results and meaningful performance benchmarking.

Policy frameworks should support these efforts by requiring circularity assessments for public infrastructure projects above a certain investment threshold, updating MKI and DuboCalc methodologies in line with current European standards, and offering financial incentives—such as subsidies or tax reductions—for projects that achieve high environmental and circular performance. At the same time, investments in knowledge sharing, professional training, and cross-sector collaboration are essential to scale best practices and overcome cultural resistance to innovation.

Recommendations for Future Research

Building on the limitations and opportunities identified in this thesis, several avenues for future research are recommended:

1. **Dynamic LCA and MKI modeling** that includes component-specific lifespans, regionally adapted assumptions, and inflation-adjusted shadow pricing to improve long-term decision support.
2. **Expansion and standardisation of environmental databases**, especially for emerging materials, reused components, and bio-based alternatives relevant to hydraulic infrastructure.
3. Development of **quantitative circularity metrics** that move beyond qualitative scoring to capture material reuse rates, reversibility, and lifecycle performance in a consistent manner.
4. Execution of **longitudinal studies** on operational stations to monitor real-world environmental and economic performance of circular design elements.
5. Creation of **integrated design tools and digital twins** that couple LCA data with energy simulations and scenario testing for robust early-phase planning.
6. Investigation of **governance models and procurement frameworks** that incentivize circularity, including lifecycle-based contract mechanisms and performance-based environmental clauses.
7. Exploration of **mid-sized water pumping station case studies** to fill the analytical gap between small and large-scale installations and assess scale-related sustainability trade-offs.

11.4 Broader Implications and Outlook

The transition to circular water infrastructure is not just a technical endeavour—it requires systemic transformation across policy, procurement, engineering culture, and governance. While pilot projects demonstrate feasibility, broader impact will only come through standardization, regulatory alignment, and shared tools and metrics.

As infrastructure managers face the dual challenges of climate adaptation and asset renewal, the water sector has a unique opportunity to lead in sustainable design. Digital twins, smart sensors, and AI-based maintenance forecasting will increasingly complement LCA and CE tools, enabling a shift from reactive maintenance to proactive infrastructure stewardship.

This thesis underscores that water pumping stations, while often overlooked in sustainability discourse, offer rich opportunities for environmental and circular innovation. When designed with foresight and assessed using holistic tools, they can evolve into regenerative, resilient infrastructure systems—serving not just technical functions but also ecological and societal goals.

11.5 Final Reflection

In conclusion, this thesis has demonstrated that applying MKI-based LCA together with circular design principles provides a robust framework for guiding the sustainable transformation of water pumping stations. It has shown that environmental innovation in water infrastructure is not only possible, but increasingly necessary. Through early-stage integration of CE strategies, dynamic assessment methods, and cross-sector collaboration, water boards, engineers, and policymakers can reimagine these essential infrastructures as exemplars of sustainable and climate-adaptive engineering.

By adopting a systems-based, data-driven, and future-oriented approach, water infrastructure projects—particularly water pumping station projects—can set a benchmark for aligning functionality, resilience, and sustainability in the built environment.

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A Modelling Assumptions

Some assumptions or shortcomings which had to be done with educated and calculated best-guesses in DuboCalc:

- Assume that the supply of materials and pre-made elements will be transported by truck, for a distance of 150 km.
- Assume that the disposal of materials after their respective end-of-life will be transported by truck as well, over a distance of 50 km.
- For the small water pumping station, the assumed amount of wooden formwork for pouring the concrete will be per 1 m3 on every side except up, so 5 m2, since this form is a small cubic form.
- For **De Drie Delfzijlen** since it is more of building with big walls etc and not cubic, the assumed amount of wooden formwork per 1m3 of concrete is 3 m2, which is a bit less, but logical when having thick long walls and slabs instead of cubes.
- Out of old technical drawings the foundation piles could be seen for the water pumping station De Drie Delfzijlen, but it could not be seen how much there were exactly and how deep they are situated in the ground. Together with a construction foundation expert at Aveco the estimated amount of piles and location has been determined. With the soil composition CPT graphs from DINO-Loket, an open source underground data and information centre, the average depth of the sand layer could be determined, so also the depth of the foundation piles. This is at a depth of 12 to 15 meters. The depth of the under side of the foundation concrete slab in the -5.9 meters below NAP, so the estimated length of the piles are then 10 meters, such that they will definitely reach the sand layer below the structure.
- Pipelines have a standard diameter represented in DuboCalc, and scaling is allowed to get to the right amounts and thus impacts. The way of scaling has been assumed that they scale quadratically. Like the following parts elaborate on.

  Scaling Cast Iron Pipe Lengths for Equivalent Mass To scale a 450 mm diameter cast iron pipe to be correctly represented in a model that assumes a default pipe diameter of 100 mm, we need to convert the length of the 450 mm pipe to an equivalent length of 100 mm pipe based on weight per metre.

-
  - Standard diameter: 100 mm
  - Weight at 100 mm: 15.9 kg/m
  - Target diameter: 450 mm
  - Length at 450 mm: 18.2 m

  The weight of the pipe scales **quadratically** with diameter, since both circumference and wall thickness typically increase with pipe size, this gives the following equation:

$$w_{450} = w_{100} \times \left(\frac{450}{100}\right)^2 = 15.9 \times (4.5)^2 = 15.9 \times 20.25 = 321.975 \text{ kg/m}$$

To find the equivalent length L_{100} (in metres of 100 mm pipe) that has the same total mass as 18.2 m of 450 mm pipe:

$$L_{100} = 18.2 \times \frac{w_{450}}{w_{100}} = 18.2 \times \frac{321.975}{15.9} = 18.2 \times 20.25 = 368.55 \text{ m}$$

Scaling HDPE Pipe Lengths for Equivalent Mass

- Standard diameter: 100 mm
- Weight at 100 mm: 2.19 kg/m
- Pipe 1: 315 mm diameter, 20.5 m length
- Pipe 2: 100 mm diameter, 9.1 m length

We assume the weight scales **quadratically** with the diameter:

$$w_{315} = w_{100} \times \left(\frac{315}{100}\right)^2 = 2.19 \times (3.15)^2 = 2.19 \times 9.9225 = 21.7363 \text{ kg/m}$$

Equivalent Lengths Pipe 1: 315 mm diameter

$$L_{100}^{(1)} = 20.5 \times \frac{w_{315}}{w_{100}} = 20.5 \times \frac{21.7363}{2.19} = 20.5 \times 9.9225 = 203.43125 \text{ m}$$

Pipe 2: 100 mm diameter This diameter matches the model, so:

$$L_{100}^{(2)} = 9.1 \text{ m}$$

Total Equivalent Length

$$L_{100}^{\text{total}} = L_{100}^{(1)} + L_{100}^{(2)} = 203.43125 + 9.1 = \boxed{212.5 \text{ m}}$$

This accounts for 20.5 metres of 315 mm pipe and 9.1 metres of 100 mm pipe, scaled to the model's reference diameter.

- Placement of a temporary pump at the Noordeinde- en Geerpolder is not taken into account, because this was necessary for replacement, but for newly built, it is assumed this is not the case. Also a temporary pump for about 8 weeks will not do much in terms of impact in total life cycle of the water pumping station.
- Assume that the pumps will be made of the same sort and amount ratio of materials used as in the process of a 'Aandrijfmechanisme sluis, Elektrohydraulisch conventioneel deuren' Sluice gates, because there in, a big pump and electric motor is modelled in the following way; the pump exists of 20 kg cast iron and the motor for the pump exists of 100 kg copper.

The small pump composition parts have not been taken into account in the LCA modelling in DuboCalc, such as small valves, shuts, hoses and small parts and its replacements, since it has negligible volumes and masses and has a very small, deniable impact.

B Material Passports

1. Materials

Used Materials	Type/Quality	Amount	Unit	Density	Volume	Mass	% New	% Renewable	% Recycled	% Reused	Lifespan	Detachability	Joint type	Location	Accessability	% available	% available	% available	% available	Re-use	CO2-eq.	CO2-eq.
				kg/m3	m3	kg	(primary)	(Biobased)	(Secondary)	(Secondary)	years			exact		reuse	recycling	incineratio	landfill	7R	kg CO2 /kg	kg CO2
Groundworks / infra																						
Excavation of construction pit sand	Sand	360	m3	1600	360	576000	100	0	0	0	100	Difficult	N/A	Constructio	Difficult	0	90	0	10	3	0,00096	554,112
Civil																						
Installation of temporary sheet pile, az18	Steel	177	m2	7850	1,77	20886	0	0	0	100	50	Easy	Interlock	Perimeter	Easy	20	80	0	0	3	1,87562	39174,2
Hardwood sheet piles, azobe 8m	Hardwood	69	m2	1200	4,14	4968	100	100	0	0	50	Moderate	Interlock	Perimeter	Moderate	30	50	20	0	3	0,20115	999,296
Steel pipe piles, filled with concrete (~1(	Steel	116	m1	7850		7327,72	80	0	20	0	50	Difficult	Driven	Foundation	Difficult	0	90	0	10	5	1,87562	13744
Concrete in steel pipe piles	C30/37 CEMIII	116	m1	2400		15953,5	90	0	10	0	50	Difficult	Monolithic	Foundation	Difficult	0	90	0	10	5	0,06754	1077,53
Steel sheet piles front and rear side	Steel	300	m2	7850		41010	80	0	20	0	50	Moderate	Interlock	Waterfront	Moderate	20	80	0	0	3	1,87562	76919,1
Steel sheet pile corner needles	Steel	8	pcs.	7850	0,04	310	80	0	20	0	50	Moderate	Interlock	Corners	Moderate	20	80	0	0	3	1,87562	581,442
Hardwood Azobé sheet pile silt barrier	Hardwood	21	m2	1200	1,26	1512	100	100	0	0	50	Moderate	Interlock	Waterfront	Moderate	30	50	20	0	3	0,20115	304,134
Concrete capping beam 50x50cm on ste	C30/37 CEMIII	21,5	m1	2400	5,38	12910	90	0	10	0	50	Difficult	Monolithic	Sheet Pile Tc	Easy	0	90	0	10	5	0,06754	871,964
Prefab concrete pumping pit	C30/37 CEMIII	17,5	m3	2400	17,5	42000	90	0	10	0	50	Moderate	Bolted	Pumping Pit	Moderate	10	90	0	0	3	0,06754	2836,75
Concrete for fish passage front and rear	C30/37 CEMIII	2,5	m3	2400	2,5	6000	90	0	10	0	50	Difficult	Monolithic	Fish Passage	Moderate	0	90	0	10	5	0,06754	405,25
Concrete slab bottom protection	C30/37 CEMIII	1,12	m3	2400	1,12	2690	90	0	10	0	50	Difficult	Monolithic	Pit Bottom	Difficult	0	90	0	10	5	0,06754	181,687
Reinforcement in concrete	Steel	1740	kg	7850		1740	80	0	20	0	50	Difficult	Embedded	Concrete El	Difficult	0	95	0	5	5	1,87562	3263,58
Steel trash rack and support beam (0.04(	Steel	1	pcs.	7850	0,04	321	80	0	20	0	50	Easy	Bolted	Inlet	Easy	20	80	0	0	3	1,87562	602,074
Metal cover plate for pumping pipeline o	Steel	2,25	m2	7850	0,02	15,9075	80	0	20	0	50	Easy	Bolted	Outlet	Easy	20	80	0	0	3	1,87562	29,8364
Steel beam HEA frame for pumping pipeli	Steel	9	m1	7850	0,05	155	80	0	20	0	50	Easy	Bolted	Pipeline Sup	Moderate	20	80	0	0	3	1,87562	290,721
Steel UNP 380mm profile for fish pipeline	Steel	20	m1	7850	0,14	1288	80	0	20	0	50	Easy	Bolted	Fish Pipeline	Moderate	20	80	0	0	3	1,87562	2415,8
Housing cabinet Steel sandwich panels	Steel	25	m2	7850		176,75	80	0	20	0	50	Easy	Bolted	Walls/Roof	Easy	20	80	0	0	3	1,87562	331,516
Housing EPS in sandwich panels	EPS	25	m2	20		49,5	100	0	0	0	50	Moderate	Adhesive	Walls/Roof	Moderate	0	30	60	10	6	3,47343	171,935
Steel balustrade (25kg/m1)	Steel	160	kg	7850		160	80	0	20	0	50	Easy	Bolted	Walkway	Easy	20	80	0	0	3	1,87562	300,099
Coated fencing, 2m high incl. swing gate	Steel	24	m1	7850		720	80	0	20	0	50	Easy	Bolted	Perimeter	Easy	20	80	0	0	3	1,87562	1350,45
Concrete grass tiles paving (120kg/m2)	C20/25	100	m2	2400		12000	90	0	10	0	50	Easy	Placed	Paved Area	Easy	30	70	0	0	3	0,06754	810,501
Mechanical																						
Check valves (pumping and fish pipeline:	Cast Iron	2	pcs.	7200	0,005	50	80	0	20	0	50	Easy	Bolted	Pipeline	Moderate	20	80	0	0	4	1,67431	83,7155
Large Pump and motor	Cast iron	650,4	kg	7200		650,4	80	0	20	0	15	Easy	Bolted	Pump Room	Easy	10	90	0	0	4	1,67431	1088,97
Large Pump and motor	Stainless steel	120	kg	7900		120	80	0	20	0	15	Easy	Bolted	Pump Room	Easy	20	80	0	0	4	4,72264	566,717
Large Pump and motor	Copper	132,165	kg	8960		132,165	80	0	20	0	15	Easy	Bolted	Pump Room	Easy	10	90	0	0	5	1,92279	254,126
Small fish passage pump and motor	Cast iron	60	kg	7200		60	80	0	20	0	15	Easy	Bolted	Fish Passage	Easy	10	90	0	0	4	1,67431	100,459
Small fish passage pump and motor	Stainless steel	10	kg	7900		10	80	0	20	0	15	Easy	Bolted	Fish Passage	Easy	20	80	0	0	4	4,72264	47,2264
Small fish passage pump and motor	Copper	13,2165	kg	8960		13,2165	80	0	20	0	15	Easy	Bolted	Fish Passage	Easy	10	90	0	0	5	1,92279	25,4126
Cast iron pipelines, all ~450mm	Cast Iron	18,2	m1	7200	0,25	1810	80	0	20	0	50	Easy	Bolted	Pipeline	Moderate	10	90	0	0	5	1,67431	3030,5
Automatic butterfly valve Ø300mm	Cast Iron	2	pcs.	7200	0,03	200	80	0	20	0	50	Easy	Bolted	Pipeline	Moderate	20	80	0	0	4	1,67431	334,862
Air vent with ball valve	Brass	2	pcs.	8400	0,01	40	30	0	70	0	50	Easy	Bolted	Pipeline	Moderate	20	80	0	0	4	5,08732	203,493
HDPE pipelines fish passage, ~315mm	HDPE	20,5	m1	950	0,29	270	70	0	30	0	50	Moderate	Mechanica	Fish Passage	Moderate	5	50	45	0	5	1,97276	532,645
Pressure pipeline Ø100mm	Steel	9,1	m1	7850	0,01	110	80	0	20	0	50	Moderate	Mechanica	Pipeline	Moderate	5	50	45	0	5	1,87562	206,318
Slide valve for pressure pipeline	Cast Iron	2	pcs.	7200	0,01	100	80	0	20	0	50	Easy	Bolted	Pipeline	Moderate	20	80	0	0	4	1,67431	167,431
Electrical																						
Power supply cables	Copper	70	m1	1400	0,25	350	50	0	50	0	50	Moderate	Connectors	Conduit/Tre	Moderate	10	80	10	0	5	1,92279	672,977

Figure B.1: Material Passport Noordeinde- en Geerpolder including CO2 equivalent

Used Materials	Type/Quality	Amount	Unit	Density	Volume	Mass	% New (pri	% Renewa	% Recycle	% Reused	Lifespan	Detachabil	Joint type	Location	Accessabi	% availabl	% available	% available	% available	Re-use	CO2-eq.	CO2-eq.
				kg/m3	m3	kg					years			exact						7R-values	kgCO2/kg	kgCO2
Groundworks / infra																						
Excavation of construction pit sand	Sand	13650	m3	1600	13650	21840000	100	0	0	0	100	Difficult	N/A	Constructi	Difficult	0	90	0	10	3	0,000962	21010,08
Civil																						
Temporary sheet pile, az18, 20-week rental	Steel	2025	m2	7850		238950	100	0	0	0	<5	Easy	Interlock	Perimeter	Easy	20	80	0	0	3	1,875619	448179,1
Concrete foundation piles (0.4x0.4x10m deep	Concrete	309	pcs.	2400	494,4	1186560	100	0	0	0	50	Difficult	Driven	Foundatio	Difficult	0	90	0	10	5	0,067542	80142,33
Steel sheet piles (15m long)	Steel	660	m2	7850		90222	100	0	0	0	50	Moderate	Interlock	Waterfront	Moderate	20	80	0	0	3	1,875619	169222,1
Azobé sheet piles	Hardwood	8	m2	1200	0,48	576	100	0	0	0	50	Moderate	Interlock	Waterfront	Moderate	30	50	20	0	3	0,201147	115,8604
Floor foundation slabs incl. reinforcement	Concrete	1061,21	m3	2500	1061,21	2653025	100	0	0	0	50	Difficult	Monolithic	Foundatio	Difficult	0	90	0	10	5	0,067542	179189,9
Cantilevered floors incl. reinforcement	Concrete	976,5	m3	2500	976,5	2441250	100	0	0	0	50	Difficult	Monolithic	Floors	Moderate	0	90	0	10	5	0,067542	164886,3
Cellar walls incl. reinforcement	Concrete	169,52	m3	2500	169,52	423800	100	0	0	0	50	Difficult	Monolithic	Walls	Moderate	0	90	0	10	5	0,067542	28624,19
Retaining wall on dike	Concrete	15	m1	2500	19,125	47812,5	100	0	0	0	50	Difficult	Monolithic	Dike	Moderate	0	90	0	10	5	0,067542	3229,339
Solid load-bearing walls incl. reinforcement	Concrete	2632,39	m3	2500	2632,39	6580975	100	0	0	0	50	Difficult	Monolithic	Walls	Moderate	0	90	0	10	5	0,067542	444490,5
Steel trash racks	Steel	6727,5	kg	7850	0,857006	6727,5	100	0	0	0	50	Easy	Bolted	Inlet	Easy	20	80	0	0	3	1,875619	12618,23
Steel grates front and inside combined	Steel	9246,4	kg	7850	1,177885	9246,4	100	0	0	0	50	Easy	Bolted	Interior	Easy	20	80	0	0	3	1,875619	17342,72
Steel balustrade	Steel	210	m1	7850		5250	100	0	0	0	50	Easy	Bolted	Walkway	Easy	20	80	0	0	3	1,875619	9846,999
Concrete grass tiles paving	Concrete	40	m2	2400		6333,333	100	0	0	0	50	Easy	Placed	Paved Are	Easy	30	70	0	0	3	0,067542	427,7644
Steel sandwich panels	Steel	235	m2	7850		1661,45	100	0	0	0	50	Easy	Bolted	Walls/Roo	Easy	20	80	0	0	3	1,875619	3116,247
EPS in sandwich panels	EPS	235	m2	20		465,3	100	0	0	0	50	Moderate	Adhesive	Walls/Roo	Moderate	0	30	60	10	6	3,473428	1616,186
Isolation layers EPS 100 floor and roof	EPS	1113	m2	20		2203,74	100	0	0	0	50	Easy	Placed	Floor/Roof	Moderate	0	30	60	10	6	3,473428	7654,531
Lighting fixtures	Aluminium	15	pcs.			90	100	0	0	0	50	Easy	Bolted	Ceiling	Easy	10	90	0	0	5	9,390808	845,1727
Frames and doors steel	Steel	36	m2	7850		1620	100	0	0	0	50	Easy	Bolted	Door Open	Easy	20	80	0	0	3	1,875619	3038,502
Glazing, double glass	Glass	371	m2	2500		9275	100	0	0	0	50	Moderate	Gaskets	Windows	Easy	5	95	0	0	5	1,017024	9432,894
Steel frames for glass	Steel	265	m2	7850		3975	100	0	0	0	50	Easy	Bolted	Windows	Easy	20	80	0	0	3	1,875619	7455,585
Steel stairs	Steel	6	pcs.	7850		978	100	0	0	0	50	Easy	Bolted	Stairwell	Easy	20	80	0	0	3	1,875619	1834,355
Steel balustrade	Steel	5250	kg	7850		5250	100	0	0	0	50	Easy	Bolted	Walkway	Easy	20	80	0	0	3	1,875619	9846,999
Concrete grass tiles paving	Concrete	4800	m2	2400		4800	100	0	0	0	50	Easy	Placed	Paved Are	Easy	30	70	0	0	3	0,067542	324,2004
Mechanical																						
Trash rack cleaner motor cast iron part	Cast iron	12	kg	7200		12	100	0	0	0	50	Easy	Bolted	Inlet	Easy	10	90	0	0	4	1,67431	20,09171
Trash rack cleaner motor copper part	Copper	13,2165	kg	8960		13,2165	100	0	0	0	50	Easy	Bolted	Inlet	Easy	10	90	0	0	5	1,92279	25,41256
Trash rack cleaner steel incl. suspension syst	Steel	18059,5	kg	7850	2,300573	18059,5	100	0	0	0	15	Easy	Bolted	Inlet	Easy	20	80	0	0	4	1,875619	33872,74
Steel sluice gate door incl. suspension system	Steel	48568	kg	7850	6,187006	48568	100	0	0	0	15	Easy	Bolted	Sluice	Easy	20	80	0	0	4	1,875619	91095,05
Sluice gate motor cast iron part	Cast iron	50,4	kg	7200		50,4	100	0	0	0	15	Easy	Bolted	Sluice	Easy	10	90	0	0	4	1,67431	84,3852
Sluice gate motor copper part	Copper	132,165	kg	8960		132,165	100	0	0	0	15	Easy	Bolted	Sluice	Easy	10	90	0	0	5	1,92279	254,1256
Fish passage sluice gates (2 pcs.)	Steel	23000	kg	7850		23000	100	0	0	0	15	Easy	Bolted	Fish Passa	Easy	20	80	0	0	4	1,875619	43139,23
Housing for electrical cabinets	Steel	113	m2	1600		798,91	100	0	0	0	50	Easy	Bolted	Electrical F	Easy	20	80	0	0	3	1,875619	1498,451
Large pumping station pumps (2 pcs.)	Cast iron	4428	kg	7200		4428	100	0	0	0	15	Easy	Bolted	Pump Roo	Easy	10	90	0	0	4	1,67431	7413,842
Large pumping station pumps (2 pcs.)	Stainless steel	552	kg	7900		552	100	0	0	0	15	Easy	Bolted	Pump Roo	Easy	20	80	0	0	4	4,722644	2606,899
Large pumping station pumps (2 pcs.)	Copper	1104,312	kg	8960		1104,312	100	0	0	0	15	Easy	Bolted	Pump Roo	Easy	10	90	0	0	5	1,92279	2123,36
Fish passage pump	Cast iron	4320	kg	7200		4320	100	0	0	0	15	Easy	Bolted	Fish Passa	Easy	10	90	0	0	4	1,67431	7233,017
Fish passage pump	Stainless steel	500	kg	7900		500	100	0	0	0	15	Easy	Bolted	Fish Passa	Easy	20	80	0	0	4	4,722644	2361,322
Fish passage pump	Copper	1057,32	kg	8960		1057,32	100	0	0	0	15	Easy	Bolted	Fish Passa	Easy	10	90	0	0	5	1,92279	2033,004
Water pipelines	Cast iron	872	kg	7200		872	100	0	0	0	50	Easy	Bolted	Pipeline	Moderate	10	90	0	0	5	1,67431	1459,998
Electrical																						
Power supply cables	Copper	100	m1	1400	0,357	499,8	100	0	0	0	50	Moderate	Connector	Conduit/Tr	Moderate	10	80	10	0	5	1,92279	961,0105

Figure B.2: Material Passport De Drie Delfzijlen including CO2 equivalents per material