

ENVIRONMENTAL IMPACT OF FOUNDATION PILES: ANALYSIS AND REDUCTION STRATEGIES

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ABSTRACT

In foundation engineering, increasing attention is being given to the electrification of equipment and construction site processes as a means to reduce environmental impact. Although this is a positive development, simplified environmental assessments indicate that such measures have only a limited effect on the overall environmental impact of foundation piles. To provide clearer insight into where meaningful reductions can be achieved, this paper traces the environmental impact of several commonly used pile systems in the Netherlands back to their components through a simplified life cycle assessment (LCA). The analysis focuses on materials such as concrete, grout, reinforcement and steel tubes, as well as installation processes, and compares four scenarios reflecting current practice and foreseeable future developments. Previous studies on foundation decarbonization have primarily focused on material optimization in individual pile types, demonstrating that substituting conventional concrete and steel with lower-carbon alternatives yields the largest reductions in embodied emissions. (Abushama, Hawkins, Pelecanos, & Tim, 2023), (Pujadas-Gispert, Vogtländer, & Moonen, 2021), (Wenkai, Sandanayake, & Zhang, 2018). This study provides a comparative, broader component-level study with a specific focus on the Dutch practice. Based on the results, the paper identifies the most effective levers for reducing environmental impact and highlights practical strategies that can support the decarbonization of foundation design worldwide.

Keywords: Life Cycle Assessment (LCA), environmental impact, foundation piles, deep foundations, decarbonization, reduction strategies

INTRODUCTION

Background and problem statement

The construction sector plays a significant role in national CO₂ emissions, and underground structures contribute disproportionately to the total impact of buildings due to the large material volumes and the high carbon footprint of the required material. Internal studies within ABT on different types of buildings indicate that foundation and basement structures can account for 30–60% of the environmental impact of a building's structural shell (Fig. 1). This highlights the need for a deeper understanding of which components of foundation piles dominate the environmental performance and where the most effective decarbonization strategies can be found.



Fig.1. Contribution of foundation and basement to environmental impact of different building.

Research objective and scope

The primary goal of this study is to quantify and assess the environmental impact of several commonly used foundation piles in the Netherlands, in order to trace back the environmental impact to the different components and support more sustainable design decisions. The study includes all relevant materials and components of the foundation piles, such as concrete, grout, reinforcement, and other associated elements, to ensure a comprehensive and realistic evaluation. To make the results comparable, the environmental impact is expressed using the functional unit GWP (climate change/global warming potential) in kg CO₂-eq, providing an intuitive measure of climate-related environmental impact.

METHODOLOGY

Life cycle assessment (LCA)

To determine the environmental impact of buildings, civil engineering works, and, more specifically, foundations in a realistic fashion, it is necessary to consider their entire life cycle. Understanding this life cycle requires addressing questions such as: *What construction materials are needed? What processes occur during the construction and use phases? How long is service life? And what happens when the structure reaches the end of its service life?* The LCA applied in this study follows the principles and guidelines of (ISO14010, 2006). It provides a systematic framework for estimating environmental impacts, albeit in a simplified form. The method used is also described in the new version of the Dutch *Handboek Funderingen*, which will be published in 2026 by CROW.

An LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributed to the functioning of a product or service system throughout its life cycle. An LCA comprises four phases, which are explained sequentially in the following paragraphs.

Goal and scope definition

The first step is defining the goal and scope of the study. The goal definition has already been done at the beginning of this paper, so it will not be repeated here. The scope of this LCA study is determined using system boundaries, in line with (NEN-EN15804, 2019).

Inventory analysis

The inventory analysis focuses on identifying all relevant components and processes that must be included in the environmental assessment of a foundation pile. Fig.2 presents a design life-cycle model that serves as a framework for identifying the components required for an environmental impact assessment. Typically, the components are quantified using physical measures such as mass (m), length (L) or volume (L³). Fig.2 provides an overview of the processes associated with each life-cycle phase, with the module colors corresponding to those used in Fig.3. The inventory of the relevant components for this study is further included in the section on *Pile systems and variables*.

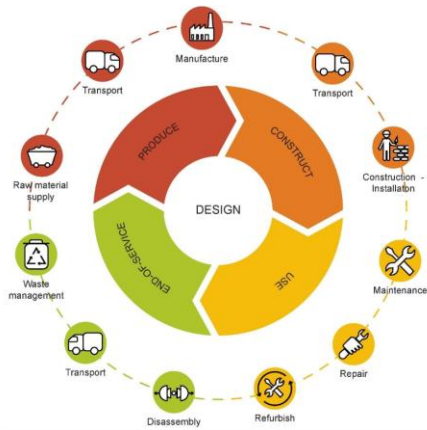


Fig.2. Life Cycle of a design (from TU Delft course - Circular Economy for a Sustainable Built Environment)

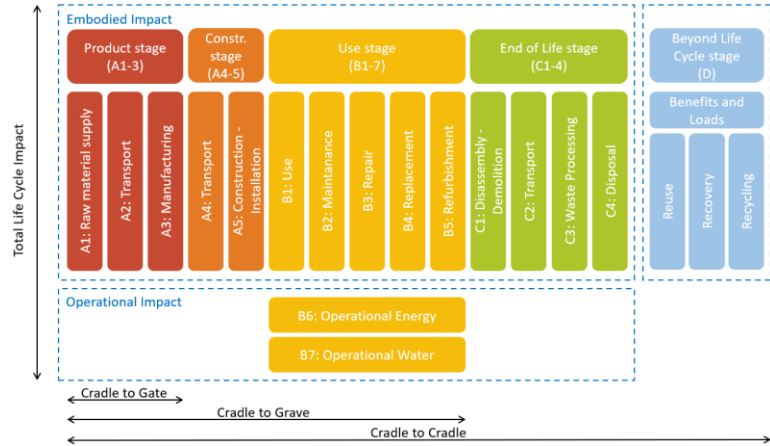


Fig.3. System boundaries of the phases in the Life Cycle Assessment (LCA).

The life cycle is divided into four modules (A–D), each representing a distinct phase in the lifespan:

- 1) Production and construction phase (A): This module covers the production of materials and products (A1-3), transport to the construction site (A4), and construction/installation (A5).
- 2) Use phase (B): This module is generally not relevant for geotechnical structures because it mainly concerns the operational aspects and maintenance of a building.
- 3) End-of-life phase (C): In this module the structure is demolished (C1), transported to a waste processing facility (C2), and treated (C3). Material or value loss during processing is accounted for in (C4).
- 4) Beyond life phase (D): This module reflects the benefits and costs outside the system boundaries. For example, the residual value of processed waste streams or dismantled parts. Values in this module are usually negative (decrease in environmental impact) because they provide a benefit for a new project. It should be noted that there are different approaches for materials with a ‘closed’ cycle, such as steel. This study follows the international practice with the *Net Scrap Approach*, which assigns environmental benefits based on the difference between the amount of scrap a product uses during production and the amount it returns to the system at end-of-life.

Impact assessment

Once the components required for the study have been determined, the environmental impact can be calculated using data from Environmental Product Declarations (EPDs) or LCA studies. This is done in the Impact Assessment, where this data is used to convert physical properties into environmental impact.

Given the type of elements considered (foundation piles) the environmental impact is expressed in the form of $y = ax + b$. Here, ‘a’ represents a variable component that applies per meter pile length ‘x’ ($EnvI_{var.}$), and b represents a fixed value per pile ($EnvI_{fixed}$). In principle, this formula can be applied to all sorts of products, elements, and materials. If ‘a’ or ‘b’ is not applicable, it can be set to 0.

The environmental impact of a geotechnical element ($EnvI_{pile}$) is then calculated by taking the summation of the environmental impact across all or part of the LCA modules:

$$EnvI_{pile} = \sum_f(EnvI_{f,var.}) \cdot x + \sum_f(EnvI_{f,fixed}) \quad [1]$$

Where f = A specific step/phase from the LCA: A1-3, A4, A5, C1, C2, C3, C4 or D; $EnvI_{f,var}$ = Variable part of the environmental impact in a specific phase f , which applies for example per m' , m^2 or m^3 ; $EnvI_{f,fixed}$ = The fixed value of the environmental impact in a specific phase f , which applies per pile.

More details on the pile systems and components considered can be found in the section on *Pile systems and variables*.

Interpretation

The final step of the LCA is the interpretation and presentation of the results of the calculation. This is done in the section of results and interpretations.

Pile systems and variables

In this study, six pile systems commonly used in the Netherlands are considered. It should be noted that a detailed comparison of bearing capacity lies beyond the scope of this study and has only been considered in a limited manner when selecting the pile dimensions. The analyzed pile systems are therefore not functionally equivalent and should be interpreted as indicative environmental trends rather than direct comparisons. The systems included are given below, together with assumptions on materialization based on the Dutch practice. A schematic drawing of the systems is added in Fig.4:

- 1) Prefab #420 mm: A prefab pile is a factory-produced reinforced or prestressed concrete pile with a solid square cross-section (420×420 mm). The pile is driven into the ground using a hydraulic or diesel hammer, displacing the surrounding soil laterally without excavation. The assumed material properties are concrete C45/55 XC2 with 1.25% reinforcement over the full length of the pile.
- 2) CFA Ø550 mm: A continuous flight auger (CFA) pile is a vibration-free, cast-in-place foundation pile installed by rotating a hollow-stem auger into the soil to the required depth. During withdrawal of the auger, concrete is pumped through the hollow stem, forming a cylindrical concrete shaft (Ø550 mm) while the excavated soil is removed, making this a non-displacement pile system. The assumed material properties are concrete C20/25 XC2 with 0.5% reinforcement over 30% of the pile length.
- 3) Fundex-GI Ø460/560 mm: The Fundex-GI pile is a vibration-free, cast-in-place displacement pile installed by screwing a temporary steel casing with a sacrificial drill tip into the ground under axial pressure and torque, combined with grout injection (WCF 2.0). After reaching the required depth, the reinforcement cage is placed in the casing. The casing is subsequently filled with concrete and withdrawn, leaving the drill tip in the soil. The resulting cross-section consists of a cylindrical concrete shaft surrounded by grout, and the assumed material properties are concrete C30/37 XC2 with 0.8% reinforcement over 70% of the pile length.
- 4) FundexC-GI Ø460/560 mm - #290 mm: Similar to the previous pile system, but instead of casting the shaft in-situ, a prefabricated concrete element (290x290 mm) is inserted into the casing, which is subsequently filled with grout (WCF 0.45), instead of the in-situ concrete. The resulting cross-section consists of a square concrete core surrounded by grout. The assumed material properties are concrete C45/55 XC2 with 1.2% reinforcement over the full length of the pile.
- 5) Vibro Ø456/506 mm: The vibro pile is a driven, cast-in-place displacement pile installed by driving a closed-ended temporary steel casing (Ø456 mm) with a sacrificial base plate (Ø506 mm) into the ground. After reaching the required depth, a reinforcement cage is placed and the casing is filled with concrete, which is compacted as the casing is gradually withdrawn by vibration or hammering. The assumed material properties are concrete C30/37 XC2 with 0.8% reinforcement over 70% of the pile length.

- 6) Tubex-GI Ø406/560 mm: The Tubex-GI pile is a vibration-free displacement pile installed by screwing a permanent steel casing (Ø406 mm) with a sacrificial drill tip (Ø560 mm) into the ground under axial pressure and torque, combined with grout injection (WCF 2.0). After reaching the required depth, the reinforcement cage is placed in the casing and the casing is filled with concrete, forming a composite cross-section consisting of a permanent steel tube and an inner concrete core. The assumed material properties are concrete C30/37 XC2 with 0.5% reinforcement over 30% of the pile length.

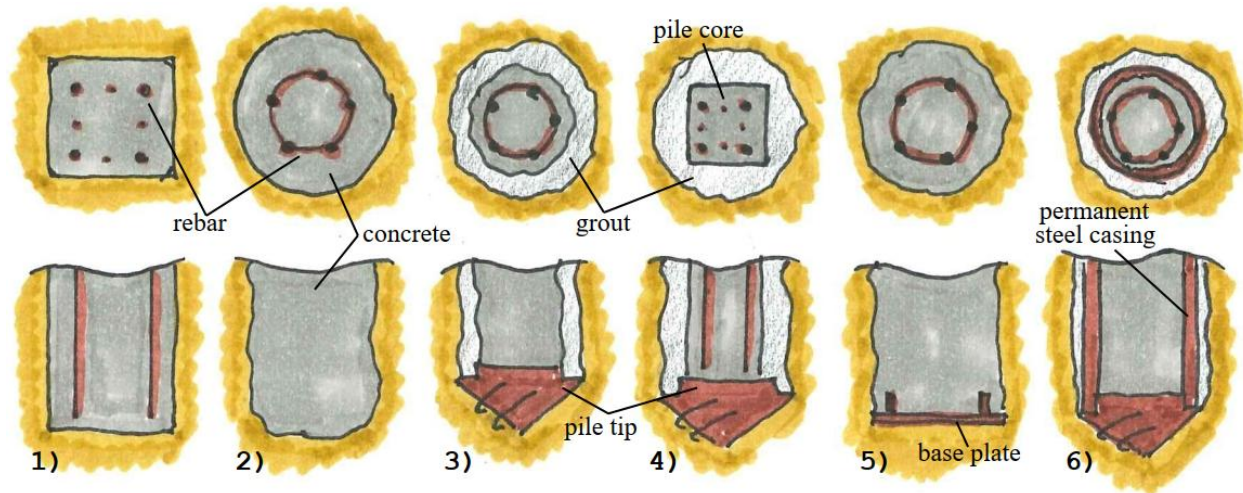


Fig.4. Schematic cross-section of pile shaft and pile tip for the considered pile types: 1) Prefab, 2) CFA, 3) Fundex-GI, 4) FundexCombi-GI, 5) Vibro, 6) Tubex-GI.

Based on the Dutch practice, for all pile systems a length of 15 m is assumed and an end-of-life scenario, in which the pile heads are cut off at approximately 1.5 m below ground level. The removed upper section is recycled (10%), while the remaining pile shaft is left in the ground.

Scenario modelling and data declaration

To determine the state of the art in terms of the environmental impact of foundation piles and the options available for reducing this impact, this paper distinguishes between four scenarios:

- 1) Worst case. This scenario primarily represents the situation with the highest environmental impact. Concrete and grout are produced using 100% Portland cement clinker (CEM I). All steel components such as rebar, pile tips, and tubes are newly manufactured in blast furnaces. In addition, building place processes, including pile driving and pile-head cutting, are carried out using diesel-powered machinery.
- 2) Average NL. This scenario represents the average situation in the Netherlands. For concrete production, 50–60% of the clinker is replaced by slag. Steel components from different production routes (BF/EAF) are used. Reinforcement steel is largely produced from scrap metal, in line with industry practice in Western Europe. Steel tubes are typically manufactured from primary blast-furnace steel, and the grout mixtures applied are, on average, comparable to CEM III/A. Most building place processes are still carried out using diesel-powered machinery.
- 3) Best Practice NL. This scenario represents best practice in the Netherlands. Concrete mixtures contain up to 70% slag substitution, steel is predominantly produced from scrap in Electric Arc Furnaces, and CEM III/B is used for grout production. In addition, the first electric pile-driving machines are already in operation, powered by the average Dutch electricity mix.

- 4) Possible Future. This scenario describes what appears feasible within the next 10 to 30 years. The construction industry is making significant progress in developing more sustainable materials. For concrete, advances are being made in geopolymer concrete; for reinforcement, experiments with basalt reinforcement are underway; and in steel production, direct-reduction technologies are gaining ground. Most steel is expected to be produced from scrap. In addition, the energy transition in building place processes is assumed to have been completed, resulting in a substantially lower environmental impact of the energy mix.

The assumptions for materials per scenario are summarized in the Table 1 below. The input for the scenarios is based on the experience in the field.

Table 1. Summary assumed materials per scenario

Variables	Worst-case	Average NL	Best Practice NL	Possible Future
Concrete binder	100% Clinker ¹⁾	50-60% Clinker 50-40% Slag ¹⁾	35-30% Clinker 65-70% Slag ¹⁾	Geopolymer ²⁾
Reinforcement	100% New steel ³⁾	Dutch Practice, background unclear ⁴⁾	100% Scrap metal ⁵⁾	Basalt Rebar ⁶⁾
Grout	100% Clinker ⁷⁾	50% Clinker 50% Slag ⁸⁾	30% Clinker 70% Slag ⁹⁾	30% Clinker 70% Slag ⁹⁾
Pile/drill tip	100% New steel/iron ¹⁰⁾	100% Scrap metal ¹¹⁾	100% Scrap metal ¹¹⁾	100% Scrap metal ¹¹⁾
Steel tube	100% New steel ¹²⁾	75% New steel 25% Scrap metal ¹³⁾	75+% Scrap metal ¹⁴⁾	100% Scrap metal ¹⁵⁾
Building place processes	Diesel driven engines ¹⁶⁾	Diesel driven engines ¹⁶⁾	Electric, average Dutch energy mix ¹⁷⁾	Electric, green. ¹⁸⁾
Transportation	Transport in A4 and C2 is very limited compared to and therefore excluded from the variables. For all scenarios average Dutch emissions are used.			

- 1) & 2) From ABT calculations on concrete mixtures, in line with the method of (Ontwerptool Groen Beton v7).
- 3) Based on steel rebar produced from primary steel. (Raajratna Metal Industries Limited, 2023)
- 4) Based on the steel rebar in the Netherlands according to the Stichting NMD (National-Milieudatabase).
- 5) Based on steel rebar produced from 100% scrap metal. (CRSI, 2022)
- 6) Based on basalt fiber reinforced polymer rebar. (Orlimex Composite Systems, 2022)
- 7) Based on EPD CEM I 42,5 N (ENCI B.V., 2020)
- 8) Based on CEM III/A 42,5 N (ENCI B.V., 2020)
- 9) Based on EPD CEM III/B 42,5 (ENCI B.V., 2020)
- 10) Derived from the EPD for steel rebar produced from primary steel. (Raajratna Metal Industries Limited, 2023)
- 11) Based on drill tips applied in the Netherlands. (Proferro NV, 2024)
- 12) Based on spirally welded steel pipes. (Supplier Marine & Foundation Products BV, 2025)
- 13) Based on averaging of scenarios: 75% WC and 25% bpNL.
- 14) Based on steel tubes produced from 75+% scrap metal. (ArcelorMittal Europe, 2023)
- 15) Based on steel from 100% scrap metal. (ArcelorMittal Europe, 2023)
- 16) Based on LCA on building place processes Hoofdstuk 1000 t/m 8000 Processen for Heistelling, hydraulisch, heien/trillen. diesel, Heistelling, hydraulisch, schroeven, diesel and Graafmachine met sloophamer/knijper/grijper, diesel. (Sant Verde, SGS Search, Witteveen+Bos, 2020)
- 17) Converted from building place processes (diesel to electricity) and based on Dutch residual energy mix of 0.382 kgCO₂e/kWh. (AIB, 2025)
- 18) Converted from building place processes (diesel to electricity and based on French residual energy mix (mainly nuclear energy) of 0.0235 kgCO₂e/kWh. (AIB, 2025)

RESULTS AND INTERPRETATION

Environmental impact traced to the components

To determine the effectiveness of reduction strategies, first the contribution of the different components is investigated for the six commonly applied pile systems in the Netherlands. The results of the calculations are shown in Table 2 and Fig. 5 for the average Dutch practice.

Table 2: Environmental impact of the considered pile systems traced back to the different components in kg CO₂-eq. Relative contribution shown in %.

	Prefab #420 mm		CFA Ø550 mm		Fundex-GI Ø460/560 mm		FundexC-GI Ø460/560 mm - #290		Vibro Ø456/506 mm		Tubex-GI Ø406/560 mm	
Concrete	663	62%	742	89%	562	48%	316	21%	567	74%	366	9%
Rebar	329	31%	44	5%	141	12%	152	10%	138	18%	27	1%
Pile tip	-	-	-	-	65	6%	65	4%	15	2%	65	2%
Steel tube	-	-	-	-	-	-	-	-	-	-	3412	80%
Grout	-	-	-	-	347	30%	937	62%	-	-	347	8%
Installation	75	7%	43	5%	62	5%	49	3%	47	6%	44	1%

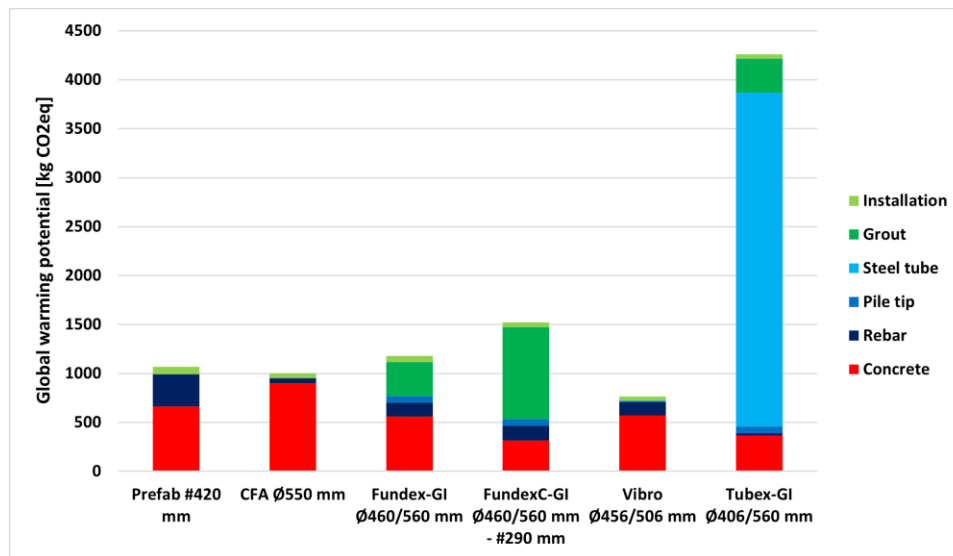


Fig. 5. Environmental impact of the considered pile systems traced back to the different components

For the Prefab, CFA, and Vibro systems, concrete is the dominant source of carbon emissions, accounting for 62%, 89%, and 74% of the total GWP, respectively. The high GWP value reflects the relatively large concrete volumes and, for the prefab elements, the use of clinker-rich binders. Steel reinforcement forms the second largest contribution in pile systems, ranging from 5–31%, with the highest fraction observed in the Prefab pile due to its high amount of reinforcement.

Grout-injection systems like Fundex show a different distribution, with grout representing a major contribution of 30% in the ‘traditional’ and 58% in the ‘combi’ variant, due to the cement intensive nature of displacement drilling and the need to create a fill around the pile core. Concrete contributes significantly in Fundex-GI (48%) but becomes less dominant in the combi-variant (19%).

Steel pipe piles like Tubex-GI display the most distinct environmental impact values, with the steel tube alone contributing 80% of the total GWP, far exceeding all other materials. Here, concrete and grout represent only 9% and 8%, respectively, highlighting the disproportionate impact of the steel casing.

Finally, pile tips only account for 2–6%, and installation impacts remain relatively low across all systems (1–7%), indicating that material production is the primary source of total GWP.

DECARBONIZATION STRATEGIES

Choice of pile system

The first reduction strategy concerns the choice of pile systems. The results of Fig. 5 show that steel pipe piles have a significantly higher environmental impact than all other systems. From an environmental perspective, it is therefore advisable to avoid steel pipe piles whenever possible and to use them only when no suitable alternative exists. Among the concrete-based systems, piles with grout injection exhibit a slightly higher impact and are therefore a less preferable option. The use of a prefabricated pile core, which is becoming increasingly common in the Netherlands, should also be avoided where possible. It should be emphasized that these strategies are based solely on environmental impact. In practice, there may be valid reasons for selecting specific pile systems. For example, the use of prefabricated pile cores can reduce the risk of integrity issues in the pile shaft after installation, thereby lowering the likelihood that a pile will be rejected and must be replaced; a process that also results in additional environmental impact. Moreover, the choice of pile system may be driven by project-specific requirements, such as inner-city construction with strict noise and vibration limits or situations involving exceptionally high loads, or soil conditions for which certain pile systems are not suitable.

Decarbonization of materials

Overall, the results in Fig. 5 indicate that material choices have a greater influence on GWP than installation energy. Reductions in cement content, grout volumes, and the use of steel piles offer the greatest potential for lowering the environmental impact of pile foundations. To explore these possibilities, the results for the four different scenarios – Worst Case, Average NL, Best Practice NL, and Possible Future are compared. The outcomes are presented in the following Fig. 6 for each pile system.

For concrete, it can be concluded that current Dutch practice offers promising opportunities. Compared to the national average, “quick wins” of approximately 30–35% are achievable simply by selecting an optimized concrete mixture. This can have a substantial influence on the total environmental impact, reducing it by up to 30%. In the future, this may increase to approximately 45%. It should be noted that optimized concrete mixtures often rely on cementitious materials such as blast furnace slag. While long-term availability of certain industrial by-products may evolve as heavy industry decarbonizes, alternative binders and emerging technologies (e.g. calcined clays) provide additional pathways for clinker reduction.

Most reinforcement steel is already produced from scrap metal. Relative to the Dutch average, reductions of up to 9% are currently achievable. Looking ahead, this may increase to roughly 14% if alternative reinforcement materials such as basalt reinforcement become widely available. Similar considerations apply to grout and pile tips. Dutch practice regarding grout is relatively favorable; however, caution is required to avoid reverting to CEM I grout mixtures, as this would increase the environmental impact by more than 100%. Nearly all pile tips used in the Netherlands are supplied by a single manufacturer, who produces them almost entirely from scrap metal, resulting in comparatively low impacts in this category.

When considering steel, it has already been noted that its use should be limited to situations in which no viable alternatives exist. In current Dutch practice, however, a substantial share of steel pipe piles is still produced from primary steel, often for cost-related reasons. Within Western Europe, several options already exist for sourcing steel tubes with a recycled content exceeding 75%, which can reduce the environmental impact of steel pipe piles by approximately 70%.

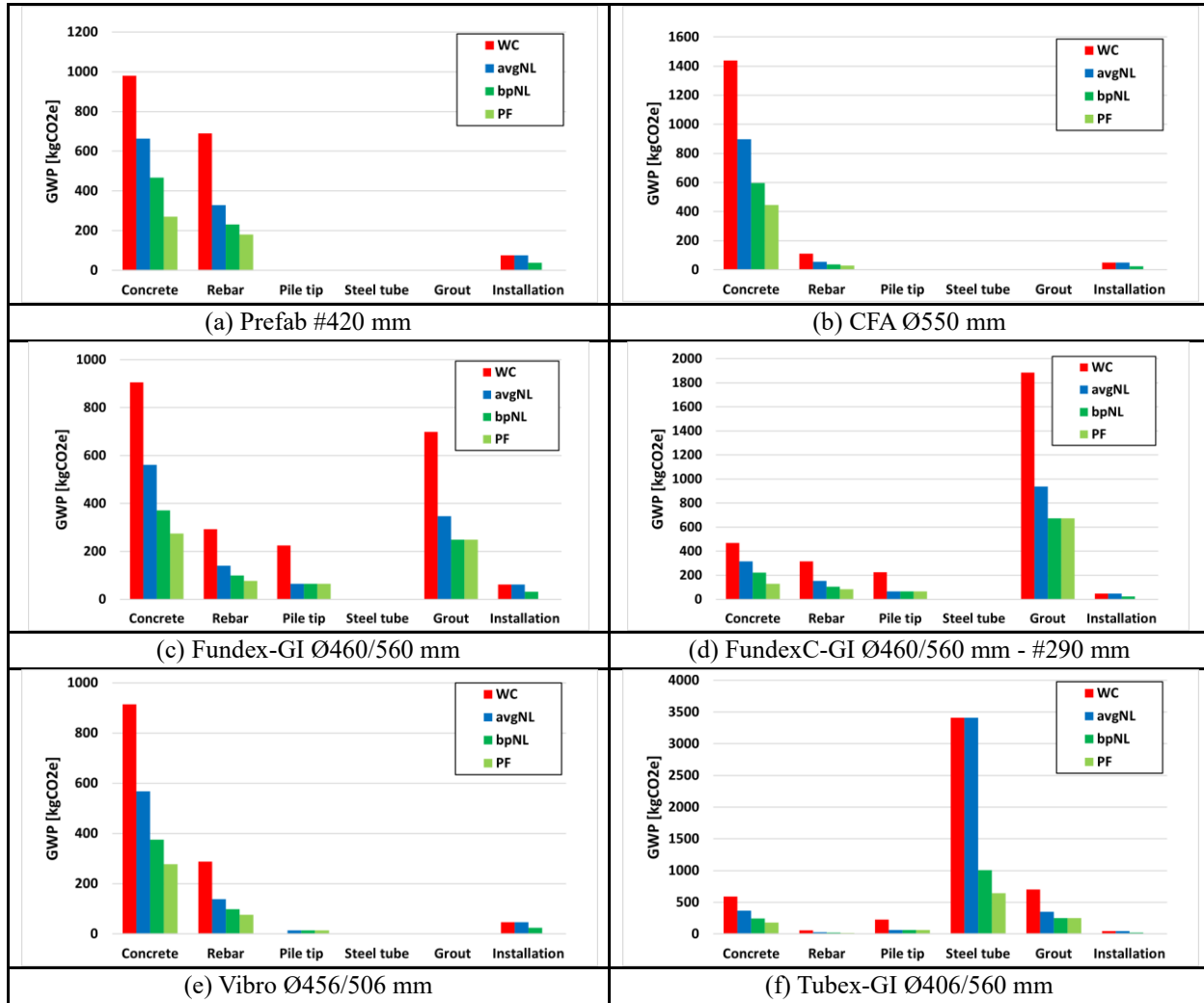


Fig. 6. Environmental impacts of four scenarios, worst case (WC), Dutch average (avgNL), Dutch best possible (bpNL), and potential future (PF) for the individual components of multiple pile types.

Decarbonization in construction and installation phase

There are several ongoing developments in building place processes such as pile driving, particularly in the electrification of machinery and, to a lesser extent, the use of hydrogen as a fuel. With electrification of the building place processes and assuming the current Dutch residual energy mix with an emission factor of 0.382 kg-CO₂-eq/kWh, it is possible to reduce the environmental impact of these processes by almost 50%. This reduction, however, results in only a 3% decrease in total GWP. In the future, reductions of up to 95% appear feasible, which would increase the total GWP reduction to around 7%. Although these reductions in total impact remain modest, advances in this area are nonetheless valuable, particularly in addressing the nitrogen emission problem in the construction sector.

DISCUSSION AND LIMITATIONS OF THE STUDY

This study shows that concrete and steel are the main contributors to the environmental impact of foundation piles. The results are based on available data and assumptions, and therefore some uncertainty remains. The analyzed pile systems are not functionally equivalent and were not designed for identical bearing capacities; instead, representative dimensions were selected to reflect common Dutch practice. Consequently, the results should be interpreted as indicative environmental trends rather than direct performance-based comparisons.

For comparability, a fixed pile length of 15 m was assumed for all systems, which may not reflect project-specific optimization. In addition, assumptions were made regarding reinforcement ratios, grout compositions, concrete binder contents, and steel production routes, based on typical Dutch practice and available Environmental Product Declarations. The end-of-life scenario was simplified, assuming removal of the pile heads and partial recycling (10%), while the remaining pile shaft is left in the ground.

The four scenarios, from worst case to possible future, illustrate previous conditions and potential carbon reduction strategies, but rely on assumptions about future material availability, production technologies, and energy systems that may not yet be widely achievable. Concrete mixes can vary between suppliers and projects, and the type and origin of steel can significantly influence global warming potential values.

Despite these limitations, key trends for pile foundations are clear: material production dominates the total emissions. The findings highlight the areas where decarbonization efforts are most effective and underline the importance of project-specific optimization in low-carbon foundation design.

SUMMARY AND CONCLUSION

This study assessed the environmental impact of six commonly used pile foundation systems in the Netherlands through simplified life-cycle analyses, with the goal of identifying the most effective strategies for reducing global warming potential. Across all systems, material production proved to be the dominant contributor to total emissions, far outweighing the impact of, for example, building place processes like pile installation. This demonstrates that meaningful decarbonization must focus primarily on reducing the use of high-carbon materials rather than relying on electrification or process efficiency alone.

The results highlight several key reduction strategies. First, selecting pile systems with limited reliance on steel tubes and grout-intensive processes can substantially lower environmental impact. Second, optimizing concrete mixtures, particularly by increasing clinker substitution or moving toward different types of binders, offers major reductions with relatively low implementation barriers. Similarly, maximizing recycled content in steel components and avoiding grout mixes with high clinker content provide additional, immediate gains. Where steel tubes are unavoidable, sourcing tubes with a high scrap content can reduce emissions by up to 70%. Finally, electrifying installation equipment contributes meaningfully to local air-quality and nitrogen goals, though its effect on total GWP remains modest.

Overall, the study shows that the most effective decarbonization pathways lie in material choices and system selection, underlining the need for project-specific low-carbon design decisions. Regardless of the location of a project, the findings of this study can be used to find possibilities for decarbonization.

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