Grounds for Climate Neutrality

Exploring Post-carbon Futures of Gas Stations in the Urban and Peri-urban Environment of Arnhem






Master Thesis | Landscape Architecture Chair Group WUR | Vanessa Baumgardt

Colophon

©Wageningen University & Research
Date 04/12/2025
Landscape Architecture and Spatial planning cluster

Contact information
Postbus 47
6700AA Wageningen
The Netherlands
Phone: +31 317482166
Fax: +31 3117482166
E-mail: office.lsp@wur.nl

©**Author**
Vanessa J. Baumgardt
Studentnumber: 1035480
Phone: +31 622784598
E-mail: vanessa.j.baumgardt@gmail.com
MSc Thesis Landscape Architecture
& Design Practice

All figures and tables are created by the author, unless otherwise indicated.

SUPERVISOR

Prof.Dr.ir. Sven Stremke

Wageningen University & Research

EXAMINER

Sjoerd Brandsma Msc

Wageningen University & Research

COURSE COORDINATOR

Dr.ir. Agnès Patuano

Wageningen University & Research

WAGENINGEN
UNIVERSITY & RESEARCH

Table Of Contents

Abstract

Cities are the places where activity agglomerates and with it, the need for energy. This makes cities key contributors to global climate change and a place where many transformations have to unfold to achieve climate neutrality by 2050. In the course of the transition towards climate neutrality, land uses that are related to the extraction or retail of fossil fuels lose their economic relevance. As combustion engine vehicles are being replaced by electric vehicles and charging options are available throughout the city, gas stations in urban and peri-urban areas are becoming one of them. By mapping, studying, and exploring these fossil fuel spaces, places for intervention can be found within the existing urban fabric.

This study explores how gas stations in the urban and peri-urban environment of Arnhem can be transformed by integrating strategies for climate neutrality with spatial quality improvements of the site. This exploration has led to the proposal of a new layer of public spaces for the municipality of Arnhem. These spaces contribute to the climate neutrality of the city by applying strategies to produce and store renewable energy, improving cyclist and pedestrian experiences, and sequestering carbon through nature-based solutions. At the same time, they have the potential to become meaningful places for the neighbourhoods they are located in.

Through a research-through-design set up, six design alternatives for three gas stations in Arnhem have been tested and evaluated. The outcome of the study includes a final site design for the three gas stations as well as a list of design principles that can guide the transformation of gas stations to contribute to the climate neutrality of the city and the spatial quality of the site.

Exploring Post-carbon Futures of Gas Stations in the Urban and Peri-urban Environment of Arnhem

Chapter 1: Introduction

1.1 Problem Statement

Cities are responsible for about 70% of all greenhouse gas (GHG) emissions, which makes them a key contributor to global climate change (Gurney et al., 2022). The biggest share of these emissions is related to mobility and housing (UN Environment Programme, n.d.). To reach climate neutrality by 2050, cities will have to undergo transformative change. Addressing the challenges to reach climate neutrality requires space, which is already scarce within urban areas.

Adjoining the need for new land uses within the urban fabric, the transition towards climate neutrality also redefines the importance of already existing ones, specifically those related to fossil fuels. Through land uses dedicated towards the refining, distribution, and retail of gasoline, the fuel era is ingrained in the urban fabric of cities (Hein, 2018).

As electric vehicles (EVs) replace combustion engine vehicles, one of those land uses that might become derelict within the urban fabric is gas stations. Currently, there are about 4131 gas stations in the Netherlands. Media reports and studies suggest that within the coming 5 to 10 years, already 50% of all gas stations will have given up their businesses due to economic unprofitability (Banken.nl, 2024). Electrification seems the most promising trajectory for private cars, and its adoption is becoming more widespread (European environemntal agency, 2025). In urban areas, the most common way to recharge EVs is while parked and attending to other activities. As charging facilities are located throughout the city, the spatial flexibility of recharging cars increases, and the need for a separate land use diminishes. That means that gas stations in the urban area might belong to an extinct species of fossil fuel land use and have the potential to contribute to the climate neutrality of the city.

1.1.2 Study Area

ARNHEM

The municipality of Arnhem has been chosen as the study area of this thesis. Arnhem is located in Gelderland, the Netherlands. It is located next to the Rhine and, together with Nijmegen, forms the Green Metropolitan region of the Netherlands. Arnhem is also part of the Gelders Energy Agreement on the provincial scale and the Regional Energy Strategy (RES) on the regional scale, which are embedded in the National Climate Agreement.

In the municipality of Arnhem, 28 gas stations fit the research objective. The reclaimable amount of surface area of these 28 ga stations is about three times the size of the Musipark (7ha). This presents a potential opportunity for implementing measures that can contribute to the climate neutrality of the city. An overview of all gas station in Arnhem can be found in the next page, including a map indicating their locations. The gas stations have been given a number and a name which are used throughout the report to refere to a specific gas station.

Figure 1 showing the boundaries of the RES Arnhem-Nijmegen in blue, the boundaries of Arnhem in organge and a neighborhood in Arnhem in white (Gemeente Arnhem, 2019)

Number	Name (from google maps or roadname	Number	Name (from google maps or roadname
1	Kuster Energy Total Express Arnhem	17	Shell Marga Klompélaan
2	AVIA Xpress Arnhem	18	TotalEnergies Marasingel
3	Tango Arnhem Hommelseweg	19	BP Express Elderveld
4	TinQ Kemperbergerweg	20	BP Meinerswijk
5	TotalEnergies Boszicht	21	TinQ Kemperbergerweg
6	Shell Kramersgildeplein	22	TotalEnergies De leeren doedel
7	Haan Dr. C. Lelyweg	23	Shell Amsterdamseweg
8	TotalEnergies Presikhaaf	24	ESSO Overmaat
9	Tango Vlamoven	25	TotalEnergies Express Van Dijkhuizen Elden
10	Esso Ijsseloord	26	Tango Papenkamp
11	Shell Westervoortsedijk	27	ESSO Express Lange Water
12	ESSO Express Dr. C. Lelyweg	28	Shell Barkenbergseweg
13	BP Snelliusweg	29	ESSO Slenkweg
14	Shell Salvatorplein	30	Shell Europaweg
15	Berkman		
16	ANAC Overmaat		

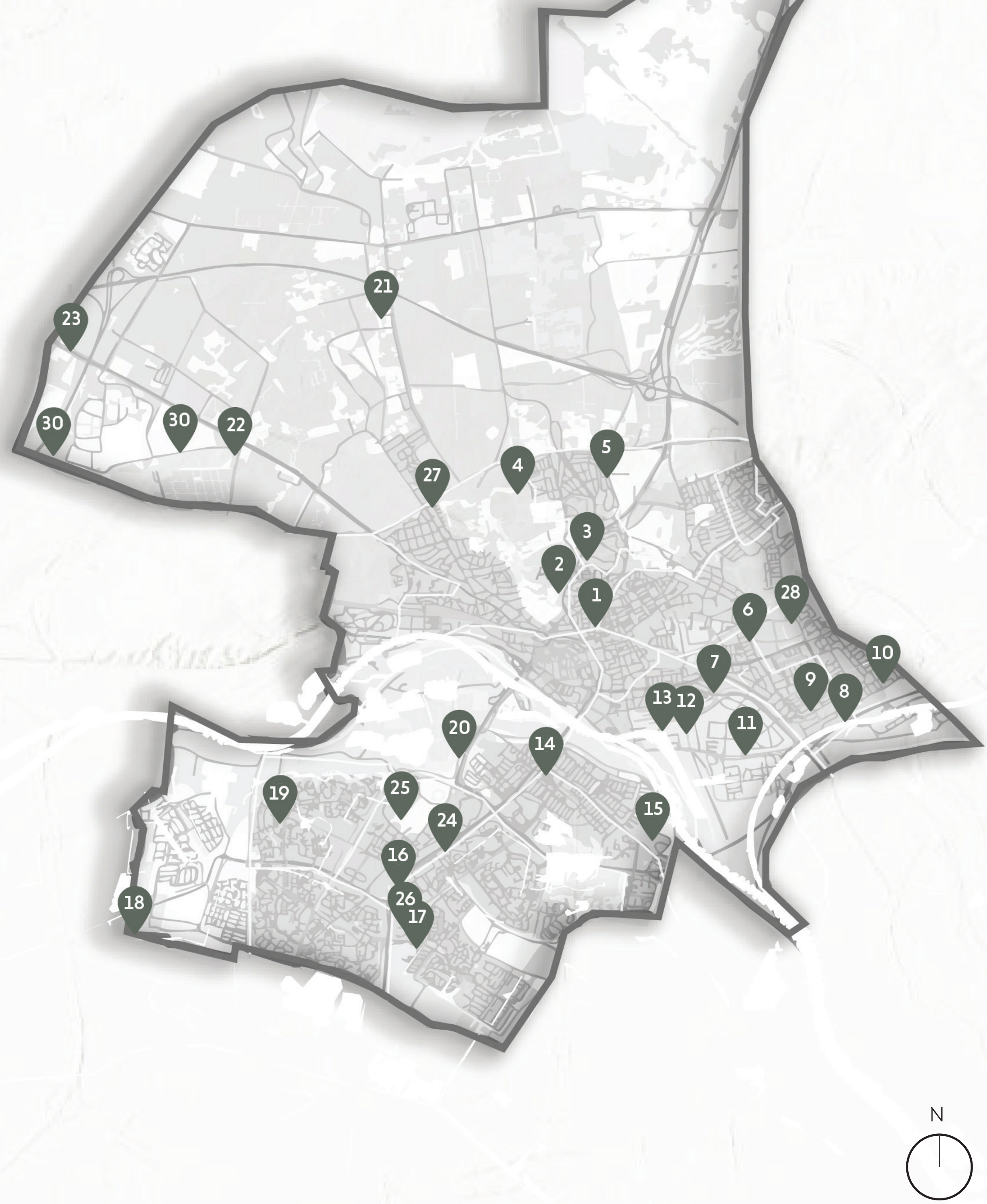


Figure 2: Map of the municipality of Arnhem indicated by the grey line and locations icons indicating the location of gas stations.

1.1.2 Knowledge gap

A growing body of publications has been published on how to design renewable energy landscapes, especially solar power plants. There is a growing awareness of the role that spatial quality plays in designing sustainable landscape transformations. Besides the energy transition, climate neutrality also asks for a mobility and land use transition. These will have to unfold within the public realm. New additions to people's living environments can often cause local opposition, which is why it is essential to investigate how to implement these strategies without compromising spatial quality and, in doing so, further the transition towards climate neutrality.

Furthermore, little is known about how current fossil fuel land uses can be transformed to contribute to climate neutrality. The amount of land that can be converted to host these new functions needs to be investigated and mapped. By identifying these spaces, places of intervention can be found. As it is projected that the population of active gas stations will be halved within the next decade, it is necessary to reimagine these places in a way that contributes to the city's climate neutrality and enhances the spatial quality.

PRECEDENTS

There are several examples of gas station transformations. The two most common approaches are reuse and redevelopment.

Examples for the first strategy are the repurposed gas stations in the Noorderpark in Amsterdam (figure 4). Additionally, there are several other examples where the building of the station has been repurposed to fulfill new functions such as restaurants, bakeries, theatres, and workshops (Jordan, 2019). This demonstrates that gas stations have the potential to make meaningful contributions to the community. Their accessibility and prominence within the street-scape make them attractive for reuse.

An example of a different strategy is from Montreal, Canada. Here, they transformed a derelict gas station into a small urban park with a water feature shown in figure 3 (EXP., 2024).

There are also more futuristic imaginations of the new gas station. For example, the project by Yan, Wen, Zhang & Yu shows how gas stations can be repurposed as food hubs (Gas to Green, n.d.). Others envision the future of gas stations as drive-through community hubs where you can charge your car and utilize the amenities offered (Goldstein & Brooker, 2022).

Although these examples are interesting in their own right, they do not connect to the legacy of gas stations being a relic of the fossil fuel era. This leaves room to investigate what functions are needed when transitioning away from fossil fuels beyond multifunctional charging stations for EVs. In this thesis, both approaches, repurposing and redevelopment, have been considered, depending on site-specific considerations, to determine whether repurposing the existing construction or redevelopment fits within the design proposal.

Figure 3: Image retrieved from https://www.exp.com/experience/place-des-fleurs-de-macadam/

Figure 4: Image retrieved from Roze Tanker - Noorderpark. (2024, March 21). Noorderpark. https://noorderpark.nl/locaties/roze-tanker/

1.2 Thesis Statement

1.2.1 Research objective

The objective of this research is to explore how gas stations in urban and peri-urban environments can be transformed to contribute to the climate neutrality of the urban area. The study will investigate what strategies for climate neutrality can be used to transform these sites and assess their potential contribution on the city scale. Furthermore, the proposed transformation will be evaluated on chosen criteria for spatial quality to assess its qualitative contribution to the site.

1.2.2 Research questions

The figure below lists the different research questions that must be answered to achieve the objective of the research. Additionally, it also provides a list of the necessary materials and methods used.

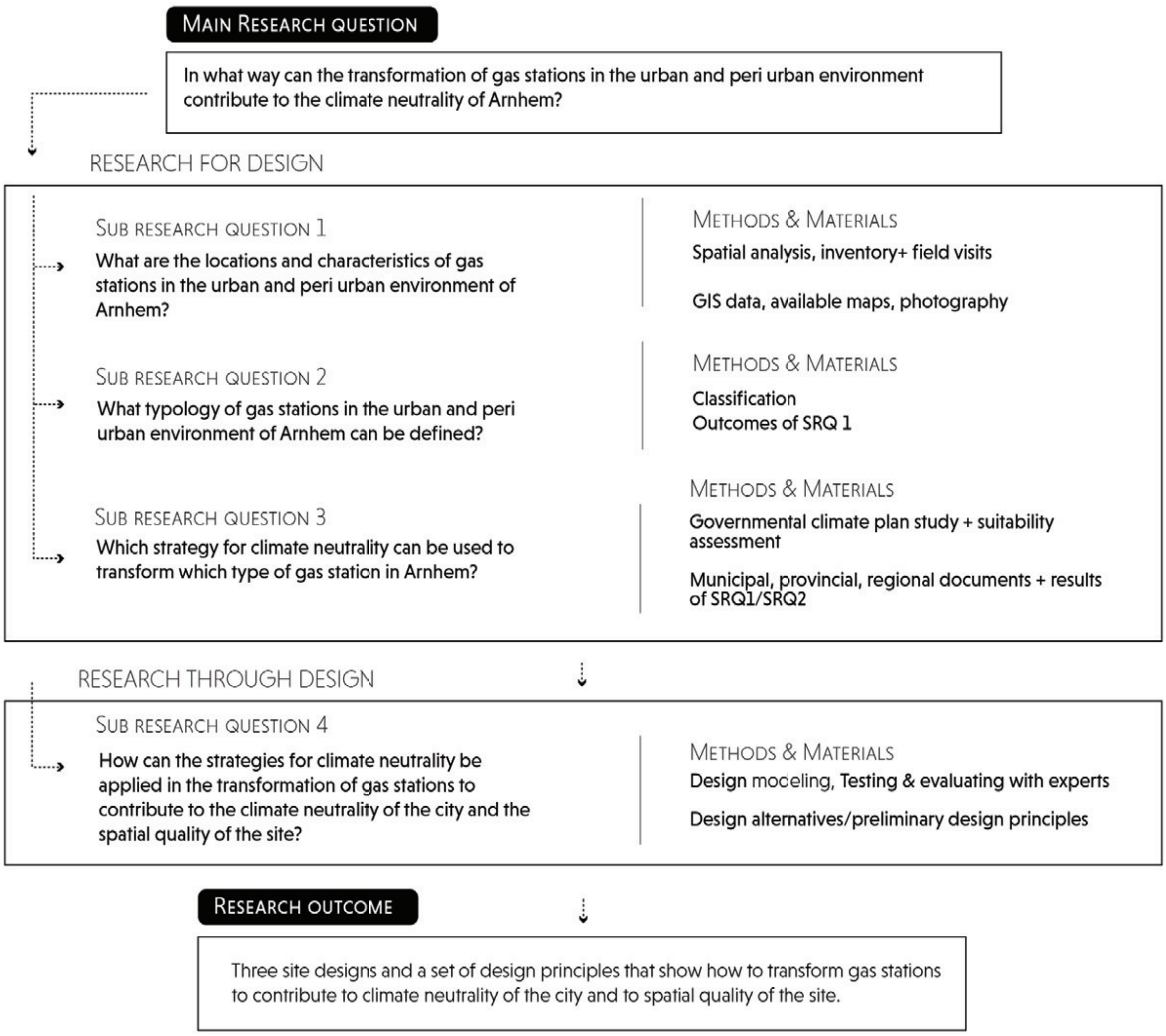


Figure 5: overview of research questions and corresponding methods and materials that will be used

1.3 Methods and Methodology

1.3.1. Key concepts

CLIMATE NEUTRALITY

According to the United Nation, climate neutrality can be defined as the following: "Climate neutrality refers to the idea of achieving net zero greenhouse gas emissions by balancing those emissions so they are equal to, or less than, the emissions removed..." (United Nations Climate Change, 2021) To achieve climate neutrality Dutch governments have developed 'climate plans'. These climate plans discuss the envisioned trajectory for decarbonising five sectors of society. In these reports, strategies for each sector are illustrated. These strategies are used to determine the future use of the gas station sites.

SPATIAL TRANSFORMATION

Within this research 'space' is seen as a social construct. This implies that spatial transformations are part of ongoing socio-spatial processes (SMUS, n.d.). In the context of climate neutrality, this means that, as we redefine the social importance of fossil fuels, the spaces related to their extraction, retail, and consumption will also need to be redefined.

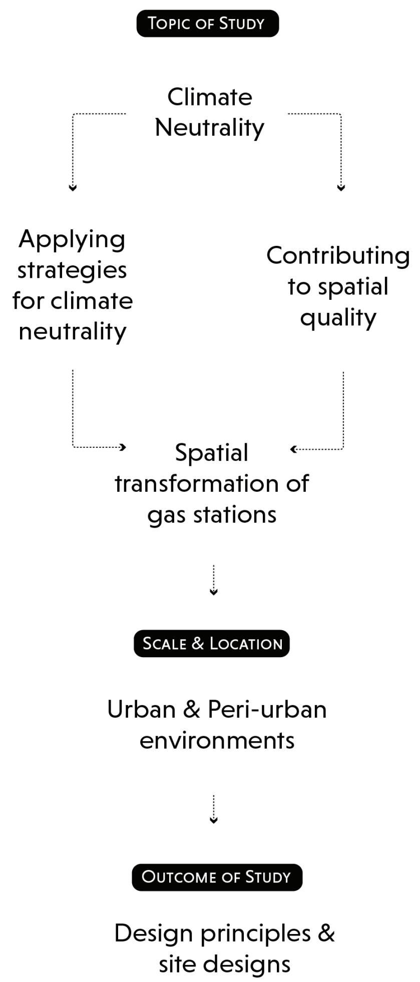
SPATIAL QUALITY

Spatial quality can be defined as a boundary term (Bakx et al., 2023). This means that it is open to interpretation and can have different meanings in different contexts. This is why a framework is needed to communicate the understanding of this concept. In this study, the framework proposed by Bakx et al. (2023) will be employed. They define four dimensions, with each having several aspects. As this framework has been developed for flood risk management, it has been slightly adapted (see Table 1). It will be used to ensure that the proposed solutions not only contribute to climate neutrality but also improve the spatial quality of the site. Selected aspects will be used to investigate the current spatial qualities of the sites and to assess the effect of the proposed design solutions.

URBAN AND PERI-URBAN ENVIRONMENTS

This study focuses on the transformation of gas stations within the urban and peri-urban environment. It is assumed that within these environments, gas stations will disappear first. In urban areas, the most common way to recharge electric vehicles will be while parked. Outside of urban areas, for example, along highways, gas stations might remain as they also fulfill other functions, such as serving as rest and charging stops for long-stance travelers.

Conceptual framework



Spatial quality framework

USE QUALITY

ASPECT	DESCRIBTION
MULTIFUNCTIONALITY	The degree to which a certain landscape combines different types of land use
ACCEABLITIY	The degree to which people have access to different parts of a landscape
SAFETY	The degree to which landscape users are protected from harmful events

ECOLOGICAL QUALITY

ASPECT	DESCRIBTION
BIODIVERSITY	The variety of species in a landscape
NATURAL PROCESSES	The degree to which natural processes, such as erosion, sedimentation and ground water flows support human and ecosystem needs
ECOLOGICAL CONNECTIVITY	The degree to which different habitats are connected to each other
ABIOTIC QUALITY	The quality of soil, water, and air

EXPERIENTIAL QUALITY

ASPECT	DESCRIBTION
CUES OF CARE	The degree to which a landscape looks taken care of
UNIQUENESS	The degree to which a landscape has distinctive features
SOUNDS AND SMELLS	The presence of pleasant and unpleasant olfactory and auditory stimuli
NATURALNESS	The degree to which the appearance of a landscape seems tobe the result of natural processes
UNITY	The degree to which landscape features seem to fit together
VISUAL DIVERSITY	The visual variety of landscape features
LANDSCAPE HISTORY	The degree to which historic landscape characteristics can be recognized

LONGTERM QUALITY

ASPECT	DESCRIBTION
MAINTAINABILITY	The ease with which measures can be maintained in future
FLEXIBILITY	The ability of measures to be adjusted to changing future conditions
ROBUSTNESS	The ability of measures to withstand future external disturbances

Table 1 showing the spatial quality framework with its 4 dimensions and aspects. Adapted from Bakx et al. (2023)

1.3.2. Methodology

The research is divided into four sub-research questions. In the following paragraphs, each research question and its corresponding methods will be briefly explained. A detailed description of the approach can be found in each corresponding chapter. An overview of the methodological framework is shown in Figure 6.

RESEARCH FOR DESIGN (RFD)

The first phase of the research is research for design (RFD). The RFD method is used to gather background information and data (Lenzholzer, Duchhart & Koh, 2013). The first and second research questions will be answered in this phase. The outcomes of the first research question have been used to derive a typology of gas stations in urban and peri-urban environments. This allowed for the systematic differentiation between various types of gas stations in Arnhem.

SRQ1 SPATIAL ANALYSIS, FIELD VISIT AND INVENTORY

The first research question includes the steps of spatial analysis, field visits, and the inventory of site characteristics. These steps aim to produce contextual knowledge about the study area, as well as an inventory of specific characteristics of gas stations that can be used in SRQ2 to derive the typology, and in SRQ3 to determine the suitability of certain interventions. The methods used for spatial analysis include ArcGIS buffer analysis and field visits.

SRQ2 CLASSIFICATION

The second research question is about the classification of gas stations. To systematically study the phenomenon of gas stations, the methodology described by Deming and Swaffield (2011) will be employed. In chapter eight, the classification strategy "typology" is described. The typology creation is chosen as a classification strategy for this research. The outcome from SRQ1 guided this step, as SRQ1 served as a data collection step for the classification.

SRQ3 SUITABILITY ASSESSMENT

The third sub-research question will synthesise contextual knowledge to establish relationships between the different types and the strategies for climate neutrality. Regional, provincial, and municipal climate plans will inform this process. From these reports, policy strategies for climate neutrality have been collected. The strategies have been selected based on their applicability to the scale of a gas station site. Then, requirements for each of the strategies have been formulated. This made it possible to assess their suitability for each of the sites.

RESEARCH THROUGH DESIGN (RTD)

According to Lenzholzer, Duchhart & Koh (2013), research through design is the academic practice of producing knowledge through designing. It is particularly helpful in bridging the gap between science and practice (Lenzholzer et al., 2013). The last two sub-questions of this thesis are RTD questions.

SRQ4 TESTING AND EVALUATION

The fourth and final sub-research question concerns the application and testing of the knowledge derived in the previous steps. An iterative design modelling exercise has been carried out. For the design modelling, one site of each host landscape type has been chosen. For each site, two alternative models have been developed, resulting in a total of six design models. These have been evaluated by 9 experts based on criteria for spatial quality. Based on the outcome of the design modelling exercise, the models have been refined to arrive at a final design proposal. These design proposals illustrate how gas stations in urban and peri-urban areas can be transformed through strategies for climate neutrality. The gained knowledge on the transformation of gas stations has then been summarized in a set of design principles.

Methodological framework

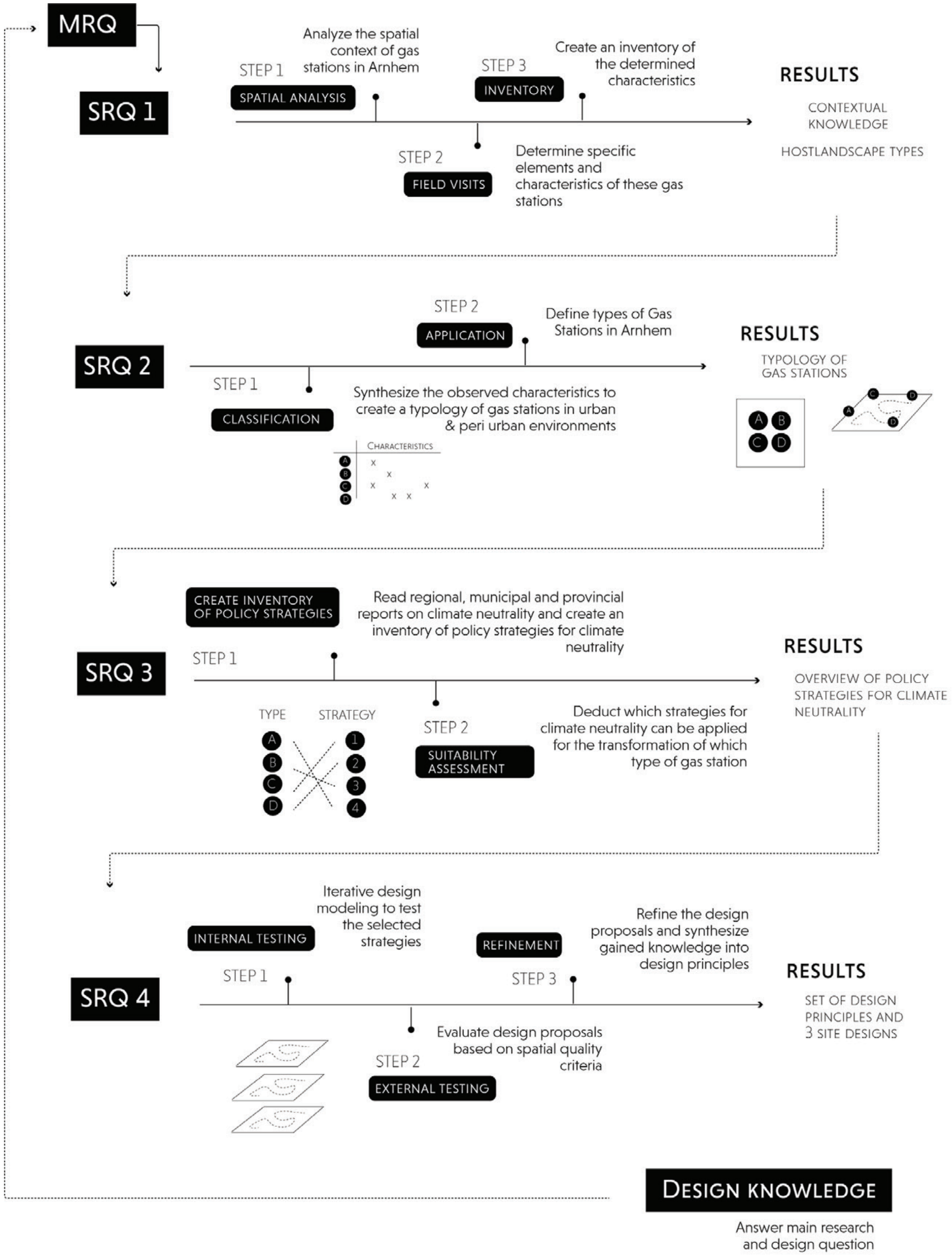


Figure 6: methodological framework

Figure 7: Showing the closed store, graffiti and damaged pavement at the gas station BP Express Eldenveld and the high-rise building in the background

Chapter 2: Spatial Analysis

Hostlandscape analysis and field observations

2.1.1. Approach

The first step of the research consisted of a host landscape analysis using ArcGIS. The TOPNL10 dataset was used as the input. Then, a buffer analysis was done. Three different diameters have been tested to determine the suitable diameter. The 300m buffer has been chosen for the creation of host landscape types. This diameter includes sufficient detail to distinguish between different types of host landscapes, but not so much that it would require extensive processing. For this analysis, five layers of the TOPNL10 dataset have been selected (see figure 8). They include the information that was needed to analyse the host landscape of the gas station sites, such as the amount and type of built-up area, the type and amount of green space, waterbodies, road networks etc.. The output of the buffer analysis has been processed to minimize overlapping data, ensuring a realistic representation that closely approximates the actual area size. This has been checked and excluded if necessary. The areas have been consistently renamed throughout the analysis and are presented in percentages of the total area. The output of this analysis has been summarized in pie charts per gas stations, which was used to deduce the host landscape types. Three different types have been found: Residential built-up, industrial built-up, and non-built. Their distribution throughout the city is represented in the map on the next page (Figure 9).

2.1.2. Results

The GIS analysis has resulted in three types of host landscapes. The term 'host landscape' has been chosen because the environment in which the gas station is situated will determine its future use and users. The type of host landscape is representative of specific spatial characteristics. These characteristics can provide insights into which strategies for climate neutrality will be suitable for the type of gas station, as well as which program can be applied to improve the spatial quality.

The distinction between different types of host landscapes makes it possible to distinguish between the different opportunities each site can fulfil. This will become relevant in the third sub-research question. Furthermore, the three host landscape types will also serve as a starting point for the typology in sub-research question two. In Section 2.2 of this chapter, the results of this analysis, combined with the insights from the site visits, will be discussed in more detail.

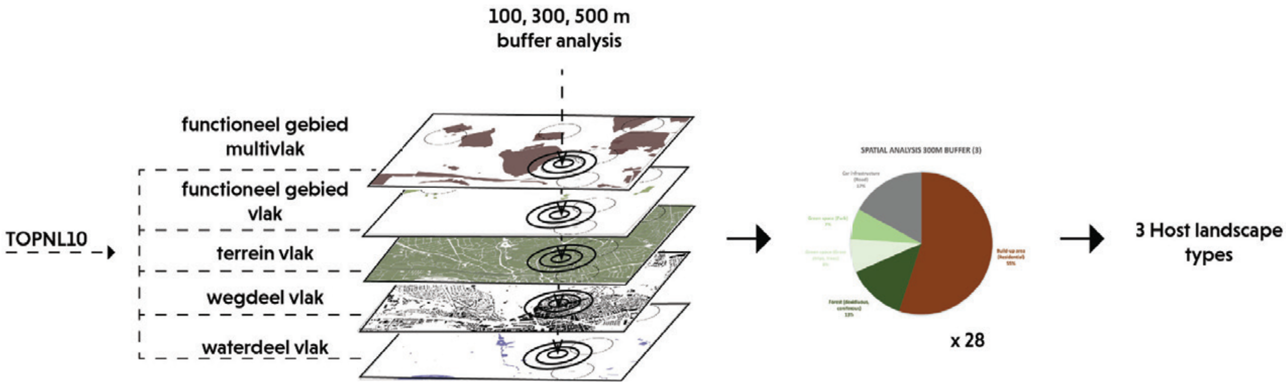


Figure 8: Flowchart showing the different layer that have been analyzed and resulted in the creation of the host landscape types

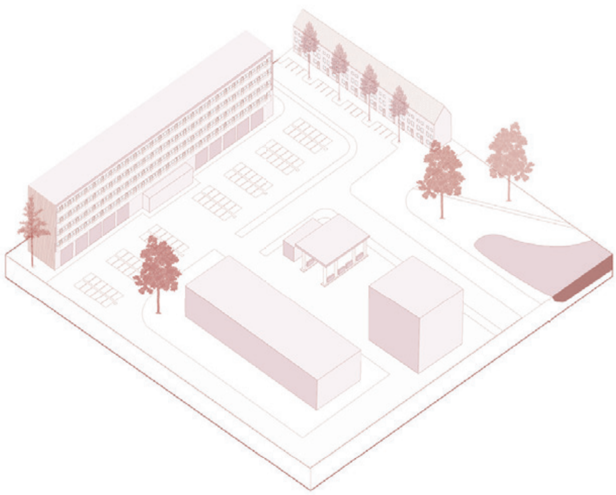
Figure 9: Map of Anrhem showing the distribution of the host landscape types thorughout the city. Green represents the non-built ype, red the residential and pink the industrial


6
28
7
10
9
8
13
12
11
15
Beeldmateriaal.nl, Land NRW, Maxar, Microsoft

RESIDENTIAL HOSTLANDSCAPE TYPE

The residential type has the residential built-up area as the main land use (54% on average). The graph below shows the average land use cover of this type of host landscape. Distinctive characteristics of this type of host landscape include, for example, the presence of functions such as schools and additional parking spaces, but fewer natural land uses and a lower amount of green space compared to the non-built type.

As the residential host-landscape type is located within neighbourhoods, the transformed spaces should become public spaces in the form of pocket parks, squares, or tiny forests. The addition of green spaces within neighbourhoods lacking greenery would contribute to the spatial quality. The sites that fall under this host-landscape type are represented in table 2.



During the field visits, other features of this host landscape could be identified. The ArcGIS analysis was unable to distinguish between shops and residential buildings. It was found that these gas stations are often located in the vicinity of commercial areas, such as shopping streets or shopping centres (1, 6, 14, 28).
During the field visits, it was also found that gas stations that fall into this host landscape type often include other functions, such as a bakery/café or ice cream shop. They also offer seating options and can function as meeting points. Their customer base appears to be wider than just people who need to refuel their vehicles, and also includes pedestrians.
These sites might score higher on the spatial quality assessment due to their additional amenities. However, they only provide a one-dimensional spatial quality (use quality) as other dimensions, such as ecological quality, are absent in these places. In the transformation, it should be aimed at a multidimensional improvement of the spatial quality score.

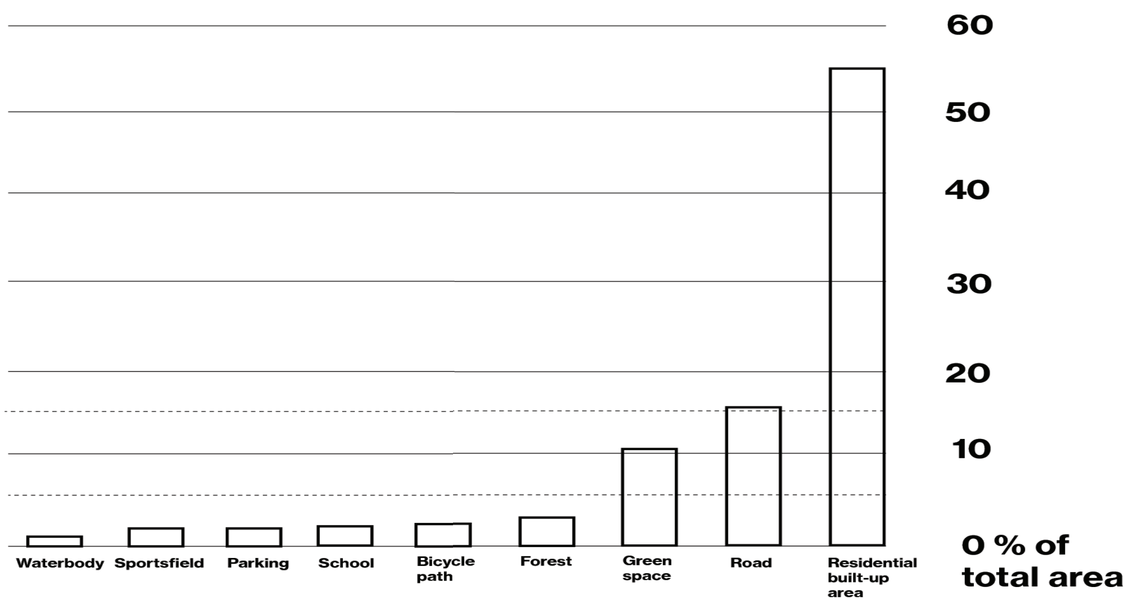


Figure 10: Graph representing the average amount of surface area covered by a certain land use represented in percentages of the total area

Figure 11: Showing the seating space in front of the gas station at Kramersgildeplein

Figure 12: Photograph of GS at Salvatorplein showing an elderly person resting on the bench

Figure 13: Photograph of seating space at Kramersgildeplein

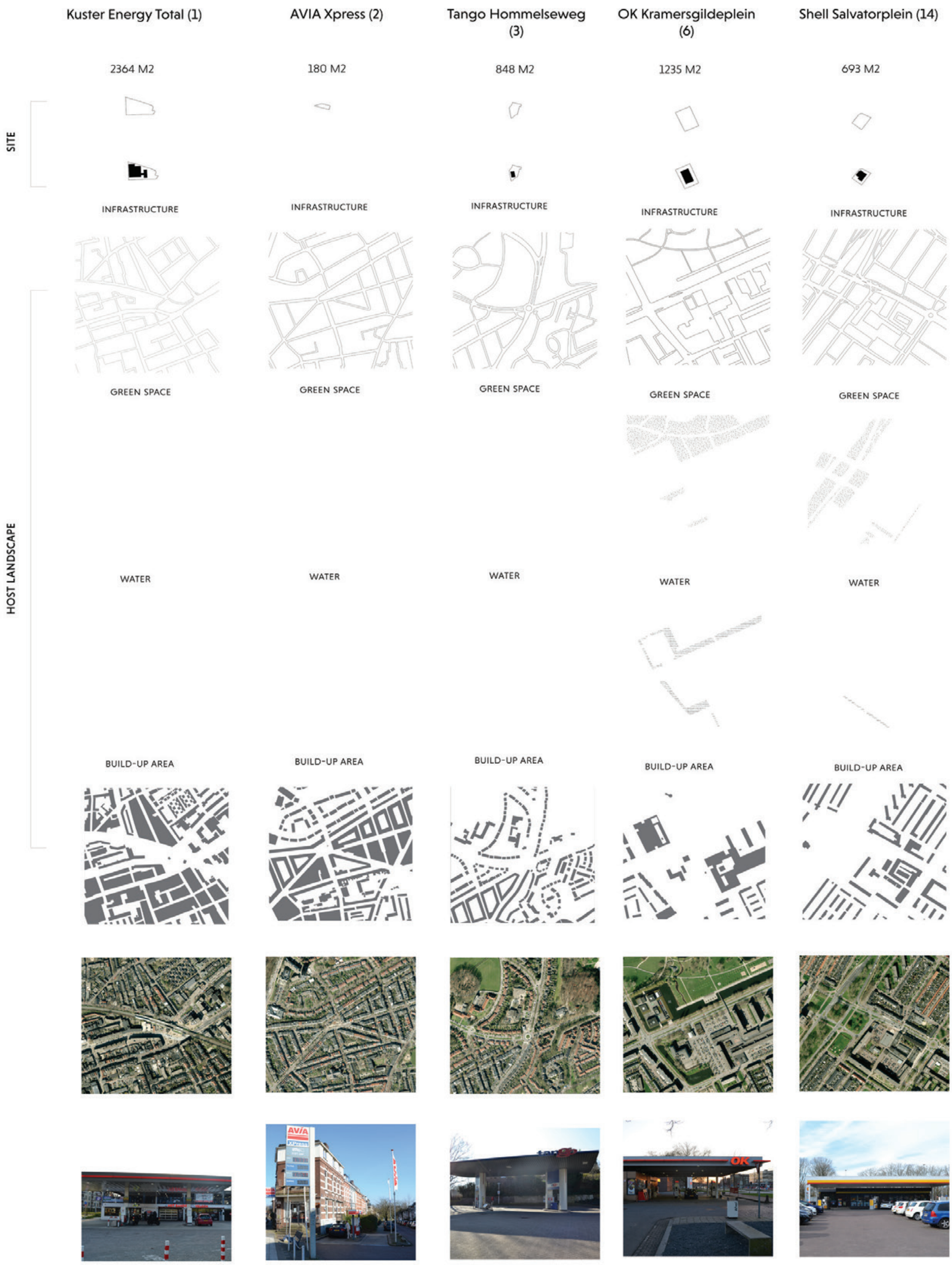


Table 2: Listing all sites that fall under the residential host landscape type

Total Energies Express (25)
BP Express Elderveld
Shell Barkenbergseweg (27)
ESSO Express Lange Water (28)
1521 M2
421 M2
1207 M2
1870 M2
INFRASTRUCTURE
GREEN SPACE
WATER
BUILD-UP AREA

INDUSTIRAL HOSTLANDSCAPE TYPE

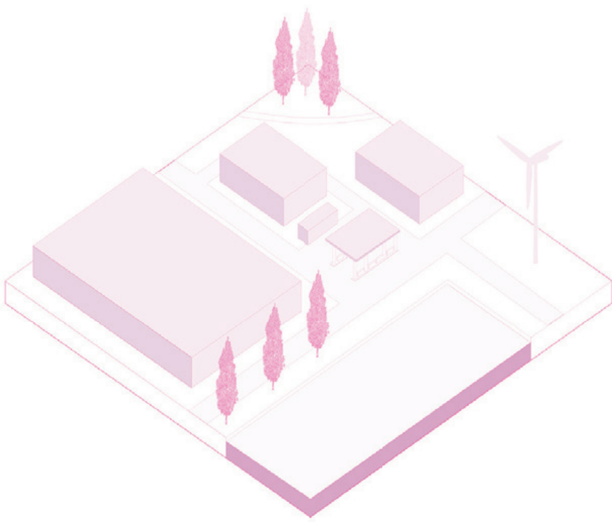
The industrial host landscape type is characterized by industrial built-up area being the predominant land use cover (on average 42%). They also include other industrial functions such as a harbour, wind turbine park, and railway track.

The field visits have revealed the kind of industrial land use. In Arnhem, there is no heavy industry. The industrial built-up area in Arnhem also includes more commercial uses, such as hardware and furniture stores, as well as shopping centres and repair workshops. Additionally, many offices are located in the industrial built-up area of Arnhem. However, more energy-intensive functions, such as production processes of, for example, bread, can also be found (GS7). The Cleantech park is also an industrial land use in Arnhem. Here, start-ups and educational institutions that work on the energy transition and related topics are located (Cleantech Park).

As businesses are concentrated in the industrial build-up area, the former gas station can host functions that can contribute to the needs of these companies, for example, making it possible for certain businesses to adopt renewable energy sources. Collective solutions could be applied by exchanging different forms of energy between companies or between built-up areas.

The residential and industrial land uses have different energy demands that vary in time and throughout the year. However, industrial uses can also be a source of energy. Through the collection of residual heat, industrial processes can supply heat for residential uses or offices.

However, the freed space could also be used to produce energy. Some industrial gas stations are as large as 8360 m2. Solar energy production on these sites could also contribute to the energy self-sufficiency of the industrial area, thereby accelerating the energy transition.



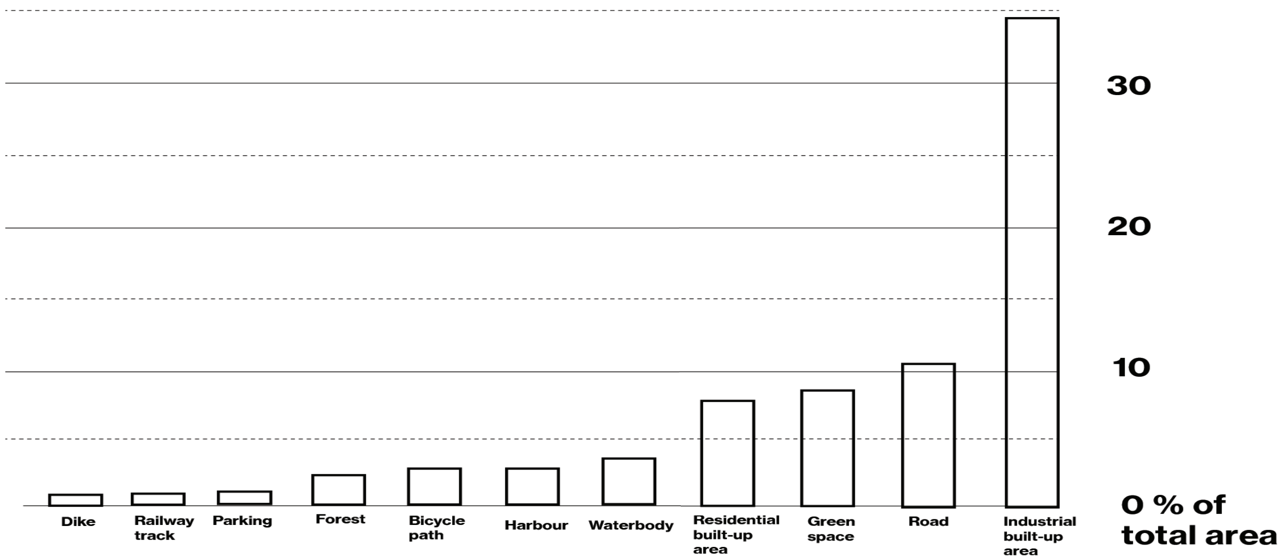


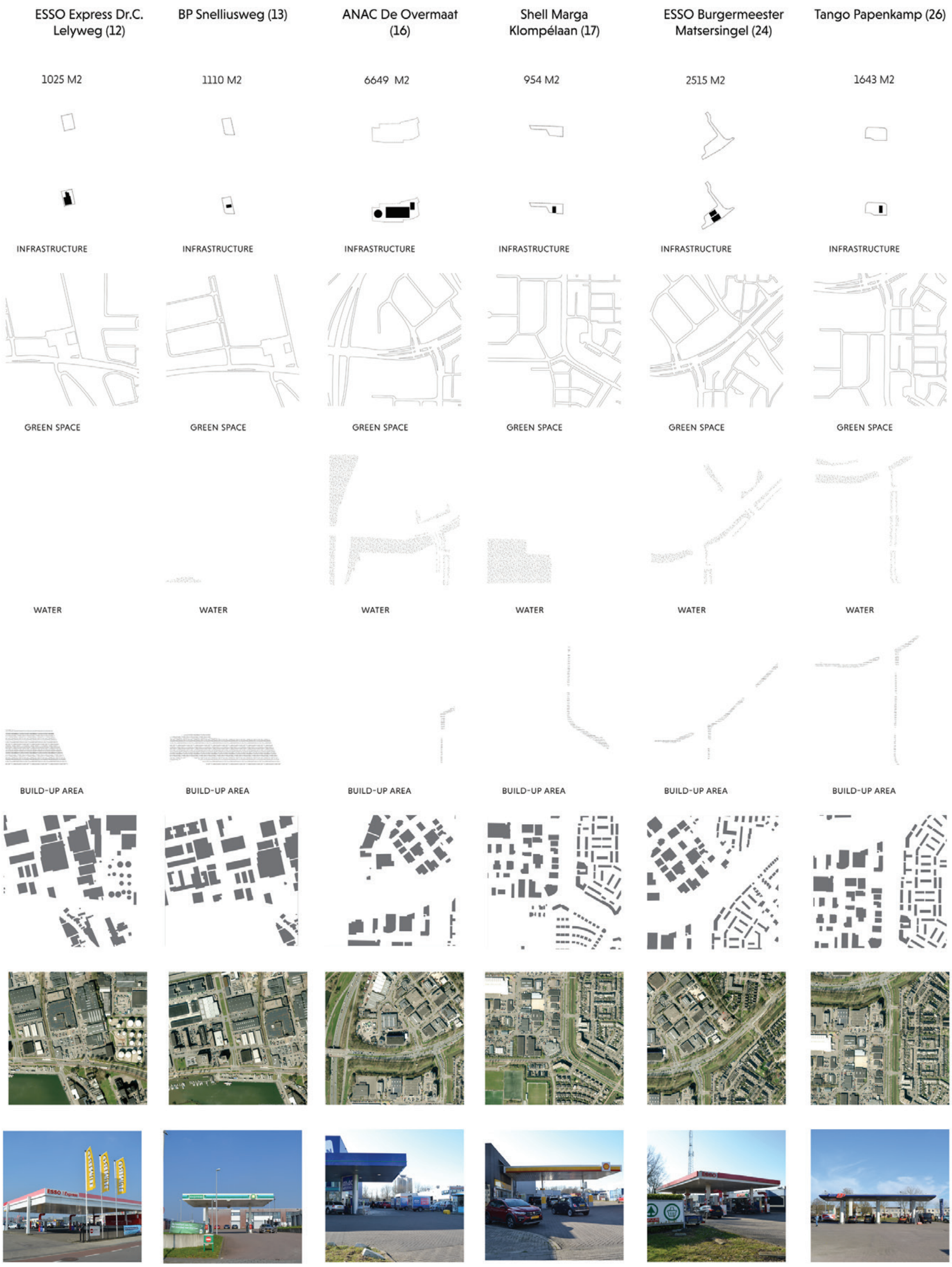
Figure 14: Graph representing the average amount of surface area covered by a certain land use represented in percentages of the total area

Figure 15: Photograph taken from the bicycle path towards GS at Westervoortsedijk

Figure 16: Photograph taken at GS showing the office building next to it

Figure 17: Photograph of GS showing the business in the background

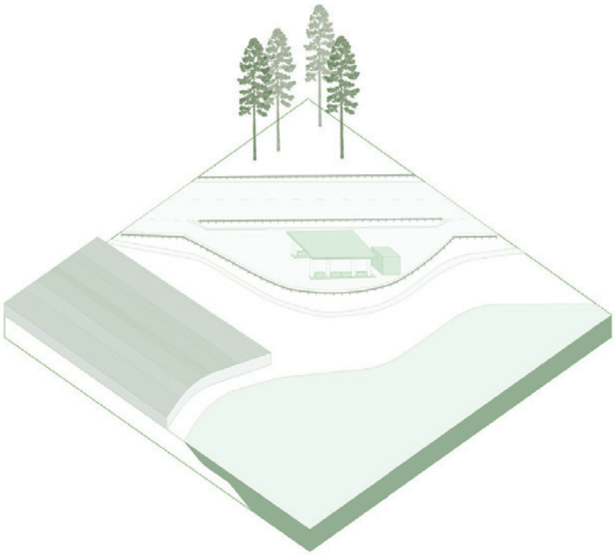
Table 3: Listing all sites that fall under the industrial host landscape type


ESSO Express Dr.C. Lelyweg (12)
BP Snelliusweg (13)
ANAC De Overmaat (16)
Shell Marga Klompélaan (17)
ESSO Burgermeester Matsersingel (24)
Tango Papenkamp (26)
1025 M2
1110 M2
6649 M2
954 M2
2515 M2
1643 M2
INFRASTRUCTURE
GREEN SPACE
WATER
BUILD-UP AREA

NON-BUILT HOSTLANDSCAPE TYPE

The non-built host landscape type has predominantly natural land uses. The most common land use is the nature reserve, accounting for almost 30% of the land cover on average. They can include some residential built-up area, however, only to a limited extent. This provides opportunities for the sites to serve these residential areas through energy production. The non-built type also includes other natural land uses such as floodplains and cropland. They are more often located near waterbodies and have the highest percentage of forests, grass fields, and sports fields. When transforming gas station sites, the natural system should be considered, and any eventual gaps left in the local ecosystem by the gas station can be restored. Additionally, waterbodies can also be a source of heat that could provide for the residential area by implementing an aqua thermal power plant on the gas station site.

The field visits have revealed that these gas stations are located near recreational routes, and cyclists and recreationists frequently pass by or use them as a stop on their cycling routes.



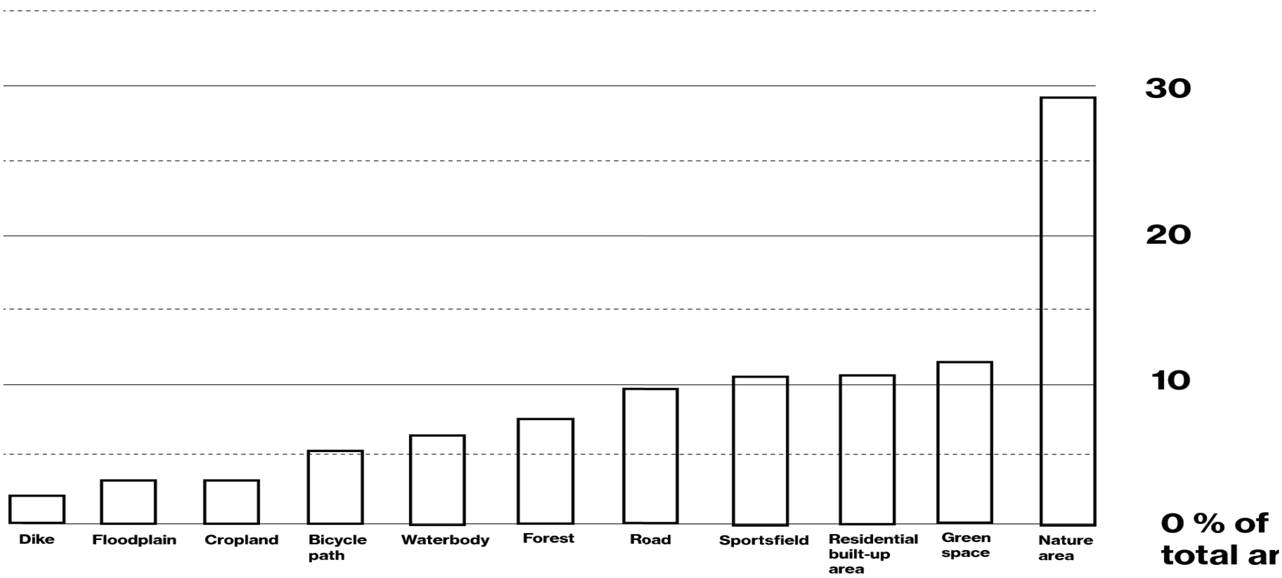


Figure 18: Graph representing the avergae amount of surface area covered by a certain land use represented in percentages of the total area

Figure 19: Photograph of a men taking a walk along the gas station

Figure 20: Photograph of cyclists passing the gas station

Figure 21: Photograph of water body which is a popular canoe route infront of the gas station

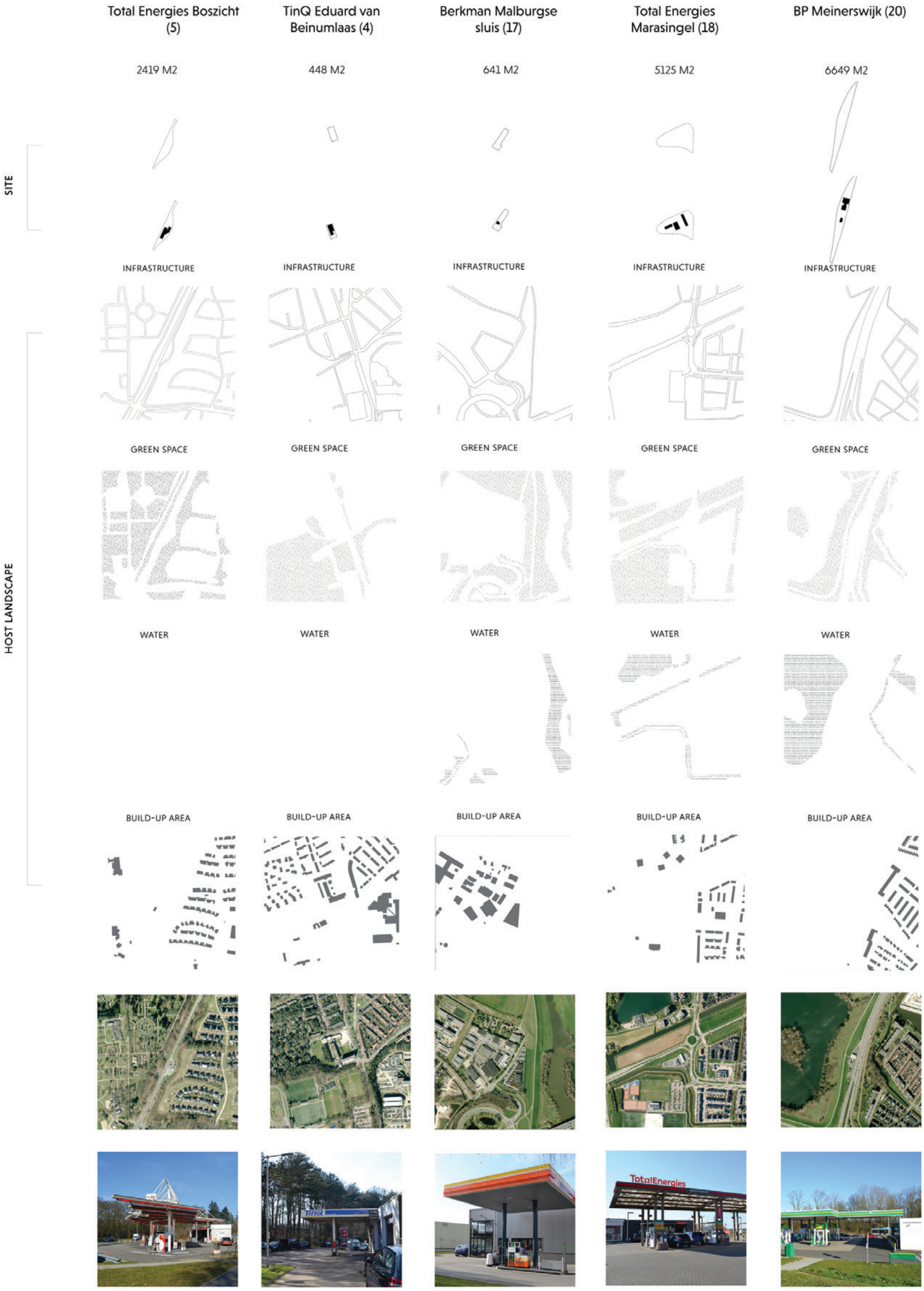


Table 4: Listing all sites that fall under the non-built host landscape type

TinQ Kemperbergerweg (21)	Total Energies De Leren Doedel (22)	Shell Amsterdamseweg (23)
342 M2	2663 M2	3045 M2
		
		
INFRASTRUCTURE	INFRASTRUCTURE	INFRASTRUCTURE
		
GREEN SPACE	GREEN SPACE	GREEN SPACE
		
WATER	WATER	WATER
BUILD-UP AREA	BUILD-UP AREA	BUILD-UP AREA
		
		
		

Chapter 3: Classification

This chapter discusses the approach and result of the classification. It also provides and overview of the most common type of gas stations in the Arnhem based on the typology created. The most common type will serve as a first selection for the design exercise.

3.1 Approach

The classification approach of 'typology creation' has been chosen as a method. To develop a typology of gas stations, deductive reasoning has been employed. This has been achieved by identifying the characteristics that can be used to distinguish between different types of gas stations. After exploring multiple variations, four layers of distinction have been chosen for the typology: The host landscape, multifunctionality of the site, the size of the surface area that can be repurposed, and the type of building.

The outcome of the GIS analysis served as the starting point for the classification. Three host landscape types have been identified: Residential built-up, industrial built-up, and non-built. The distinction between the three host landscapes is based on the percentages of land use. The host landscape has been chosen as the first layer of distinction because it carries significant weight in determining the site's future use. It reveals the potential landscape user and, with that, their needs regarding climate neutrality and additional programming.

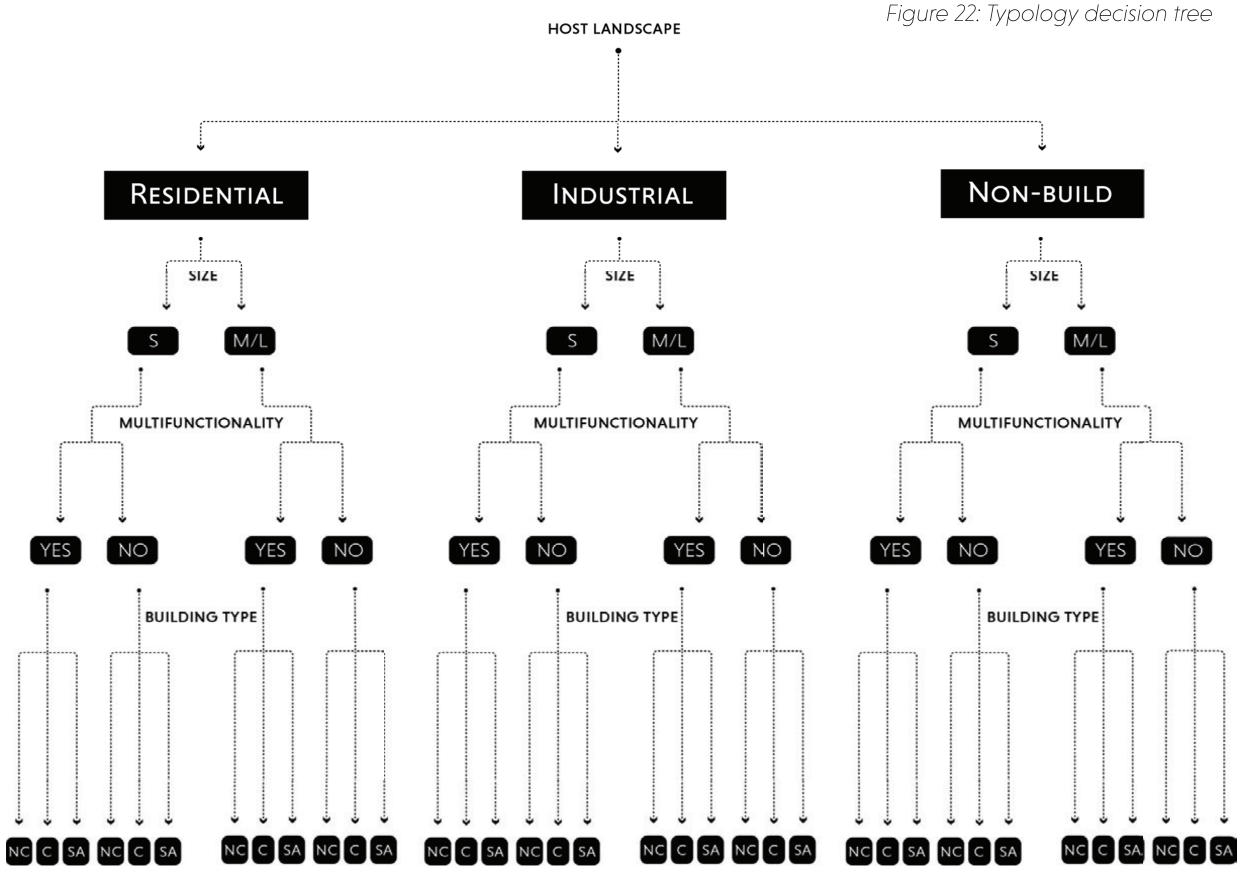
The surface area, or size, of the gas station has been chosen as the second level of distinction. The size is crucial in determining the site's future use. By creating classes of size, the future uses can be determined based on the type, as certain uses require a specific amount of area to be implemented. ArcGIS has been used to determine the size of the gas stations. A distinction has been made between small gas stations (up to 1,583 m^2) and those that are larger than 1,583 m^2. Previously, the sites have also been analysed through field visits.

The field visits were used to gain insights about the multifunctionality and use of the gas stations. This allowed the collection of characteristics of the different sites. A site has been classified as multifunctional if it offers multiple services in addition to its primary function of selling fuel (e.g., an ice cream shop, convenience store, cafe, car repair services, car wash, etc.). An overview of all characteristics collected can be found in Appendix 2. The typology tree is shown in figure 22.

3.2 Results

This differentiation resulted in 12 different types of gas stations in the urban and peri-urban area of Arnhem. The types are shown in the figure 23 on the next page.

Figure 22: Typology decision tree



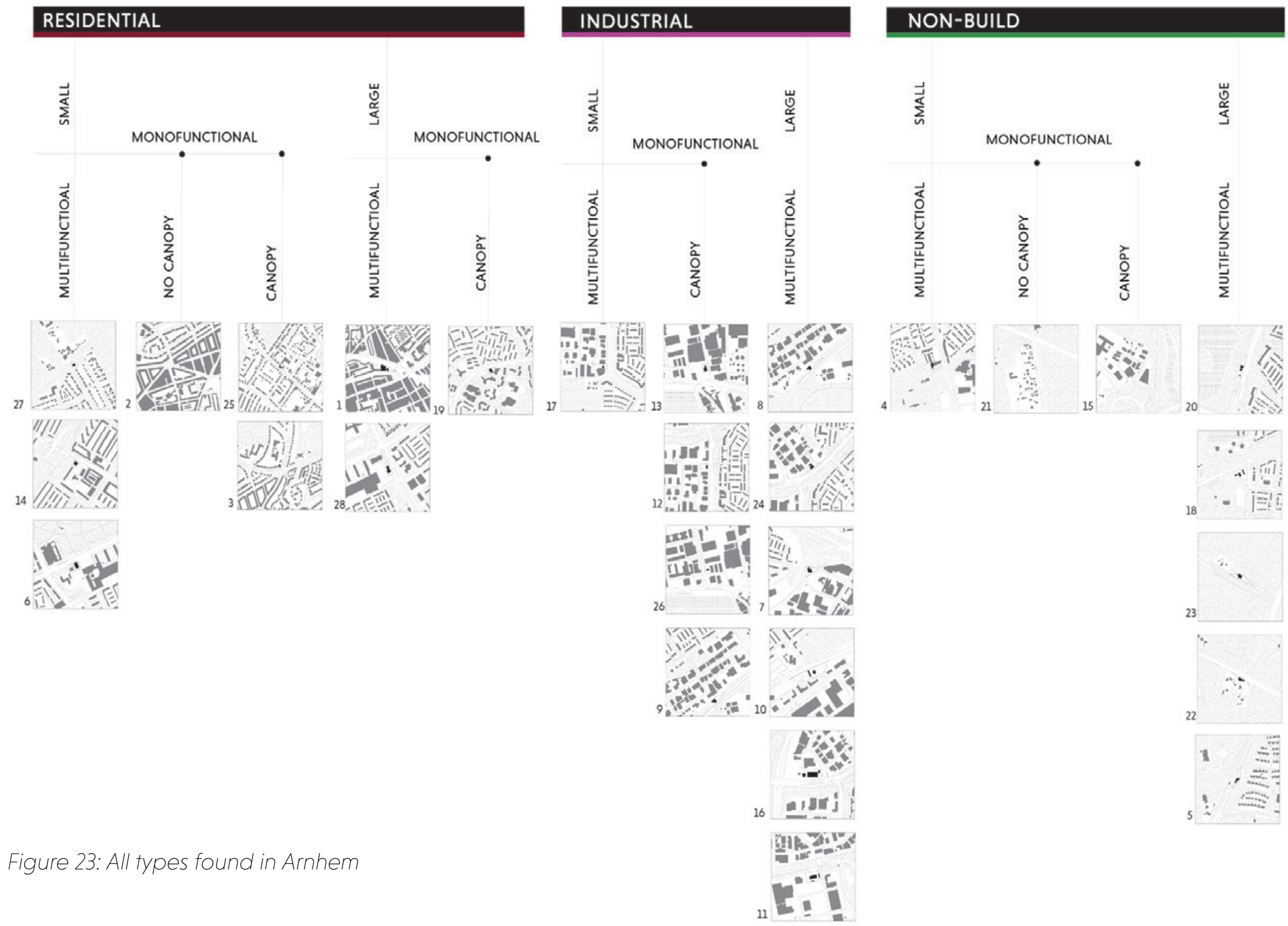


Figure 23: All types found in Arnhem

RESIDENTIAL HOSTLANDSCAPE TYPES

The most frequent residential host landscape type is the small multifunctional type with a canopy construction. Three of the nine residential sites fall into this type. Due to their smaller size, the available surface area is a constraint when implementing new functions. The size of this type ranges from 700 to 1250 m^2. They are located within neighbourhoods, and two out of the three are situated in a parking lot of a commercial area.

INDUSTIRAL HOSTLANDSCAPE TYPES

The most frequent industrial host landscape type is the large multifunctional type with canopy construction. The availability of industrial land uses characterises the industrial type. The most common is the business and commercial activity. They include the sites with the largest surface area. Two of them are located along major roads and are currently only accessible by car. Industrial activity requires a large amount of energy. Electrifying industrial processes is still a challenge due to network congestion. Implementing storage options or producing and using electricity locally within these areas could accelerate this trajectory.

The area around the gas stations is a monotonous environment. However, many people spend their workday here. This creates opportunities to provide the area with features that can contribute to the spatial quality of the area. For example, creating a designated area or route that workers can use during their lunch breaks.

NON-BUILT HOSTLANDSCAPE TYPES

The most frequent non-built host landscape type is the large multifunctional type with canopy construction. They are situated on the city's edge. Their size ranges from 2500 to 5000 m^2.

The non-built types are located next to non-built land uses such as agricultural fields, nature reserves, forests, and water landscapes. The non-built types are typically located in the vicinity of or adjacent to nature reserves and forests. This creates opportunities to fill the gap in the local ecosystem that the gas station has left.

Figure 24: Photograph taken at the gas station at Westervoortsedijk with a wind turbine in the background

Chapter 4: Policy Strategies

Defining strategies for climate neutrality based on Dutch governmental climate plans

This chapter first introduces the climate plans and the policy structure they entail. Secondly, it provides an overview of which of these strategies can be applied to the transformation of gas stations and their specific requirements for implementation.

4.1 Introduction to the climate plans

On their mission towards climate neutrality, municipalities and provinces have produced documents that explain which strategies they need to deploy to achieve this goal (climate plan). These documents are based on the national climate agreement.

The national climate agreement has worked out a framework for the Netherlands. This framework introduces five sectors. Each sector requires its own set of strategies to achieve climate neutrality. Provincial documents, such as 'Gaaf Gelderland,' translate the national climate agreement to the provincial governance level, and each municipality has its own. For this study, the climate plans of the municipalities of Groningen, Arnhem, and Amsterdam have been chosen as sources. In these municipal and provincial climate plans, the strategies are distributed across five sectors: renewable energy, the built environment, industry, mobility, and land use change.

The following section provides a summary of the strategies proposed by the plans. In section 4.2, a selection of strategies has been grouped into new categories to align with the research aim. These also form the basis for the design exploration, which will be discussed in Chapter 5.

RENEWABLE ENERGY

Biomass, solar and wind energy are currently the most significant sources of renewable energy in the Netherlands (Centraal Bureau voor de Statistiek, 2025). Strategies for the production of electricity from solar mentioned in the climate plans include solar panels on roofs, along infrastructure, and at park-and-ride locations (Gemeente Amsterdam, 2020, p. 131). Furthermore, it is mentioned that renewable energy production can be combined with many competing functions to increase the multifunctionality of energy production landscapes (Gemeente Amsterdam, 2020, p. 138). Gemeete Groningen (2018) states that solar energy production on roofs and parking lots will not suffice; thus, the construction of solar parks in other locations will be necessary.

For the heat transition, constructing a heat network is mentioned as a strategy. Renewable heat sources that are proposed by the climate plans are aqua-thermal and geo-thermal heat (Provinciale staten, 2018, p. 6) as well as residual heat from datacenters (Gemeente Amsterdam, 2020, p. 71).

The increased demand for electricity and the implementation of a heat network require additional transmission and transformation infrastructure to be placed in public space (Gemeente Amsterdam, 2020, p. 63).

BUILT ENVIRONMENT

The built environment strategies overlap to some extent with the strategies for renewable energy. The main concept that is mentioned by all plans is the "natural gas-free neighbourhood". This means that the existing built environment needs to become natural gas-free. This can be achieved in different ways. The two main ones are: the all-electric neighbourhood

and neighbourhoods that are connected to a central heat network (Aquathermie thermische energie uit water, n.d.). Each of them requires different network components that will become visible within the public space.
All electric neighbourhoods will have a higher electricity demand. This means that additional transformation stations need to be installed within the neighbourhood to support collective or individual heat pumps. The collective heat pump itself requires space and needs to be placed. The collective heat pump itself is also mentioned as a strategy by the reports (Gemeente Arnhem, 2019, p. 48).

Due to the fluctuating availability and increased demand for renewable energy, buffering and storing capacities need to be improved. One solution for storing energy mentioned in one of the reports is the neighbourhood battery (Gemeente Amsterdam, 2020, p. 176).

INDUSTRY

The key strategies to decarbonise the industrial sector are implementing alternative energy sources and capturing and storing CO2 from industrial processes that can not be electrified.

Since the industrial sector utilises natural gas as a heat source, alternatives need to be found. Possible alternatives mentioned are: biomass, green hydrogen, and electric heat pumps (Gemeente Groningen, 2018, p. 42; Gemeente Amsterdam, 2020, p. 151).

A complementary solution to the alternative source is the residual heat network. The municipality of Groningen's climate plan states that businesses can exchange residual heat to use the produced heat as efficiently as possible (Gemeente Groningen, 2018, neutraal, p. 42).

MOBILITY

A common goal that can be found in all the climate plans is the reduction of car infrastructure within cities. The mobility hub is a common strategy to achieve this (Provinciale staten, 2018, p.5, Gemeente Arnhem, 2019, p. 16, Gemeente Amsterdam, 2020, p. 111).

Other strategies mentioned in the climate plans include reducing the need for mobility (Gemeente Groningen , p. 43) and encouraging the use of non-motorised mobility by improving the safety and experience of pedestrians and cyclists (Gemeente Amsterdam, 2020, p. 115). This includes the availability of bicycle parking facilities and traffic infrastructure that prioritises cyclists (Gemeente Amsterdam, 2020, p. 110). Furthermore, the municipality of Amsterdam proposes reducing car infrastructure and facilities (Gemeente Amsterdam, 2020, p. 110-111).

Increasing the quality and availability of public transportation is also mentioned in the municipality of Amsterdam's climate plan (Gemeente Amsterdam, 2020, p. 111). The importance of emission-free, fossil-free mobility is highlighted in the report (p. 52). This includes infrastructural adaptations as well as a mentality shift to create a cleaner and safer mobility system (Gemeente Arnhem, 2019, p. 52).

To achieve emission-free mobility, the EV charging network has to be scaled up. For that, charging facilities in the public and semi-public spaces need to be constructed (Gemeente Amsterdam, 2020, p. 115).

LAND USE CHANGE

To reduce the emissions of non-built land uses, several land use changes have been proposed in the report Gaaf Gelderland. A strategy to reduce emissions from agricultural lands is nature-inclusive agriculture and the protein transition (Provinciale staten, 2018, p. 5-6). Furthermore, the amount of forested area needs to increase and ecosystems need to be restored (Provinciale staten, 2018, p 5-6). The importance of ecosystem services like carbon sequestration of functioning ecosystems is highlighted by the climate plan of the province of Gelderland (Provinciale staten, 2018, p. 6).

4.1.1 Overview of strategies

To further specify the strategies and reduce the overlap between the sectors, they have been grouped into three categories: energy network components, mobility nodes and nature-based solutions for carbon capture (see figure 25). Furthermore, it is worth noting that only strategies applicable to the scale of the gas station sites are selected in this step.

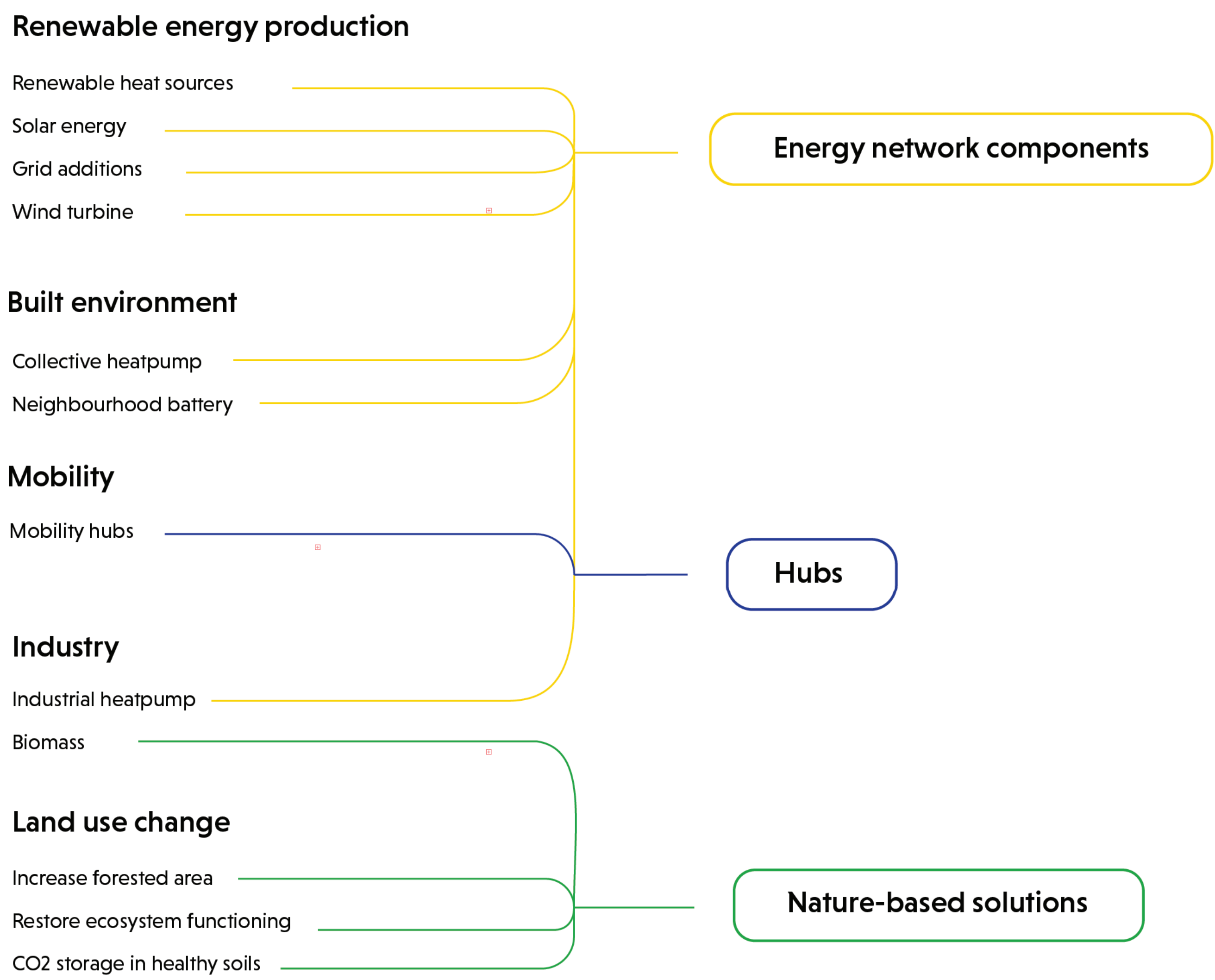


Figure 25: Overview of strategies that can be applied to the gas station sites and the how they are grouped into the three new categories (energy network components, hubs and nature-based solutions)

ENERGY NETWORK COMPONENTS

The electrification and decentralisation of our energy system have spatial consequences. Energy infrastructure components will become more visible in our living environment. The components that need to be integrated in our landscapes and cities can be divided into three categories: production, transformation/transmission and storage.

PRODUCTION

One potential function that can be used to transform gas station sites is energy production. Three main strategies have been taken from the reports. Their spatial requirements and impacts will be discussed in the following paragraphs.

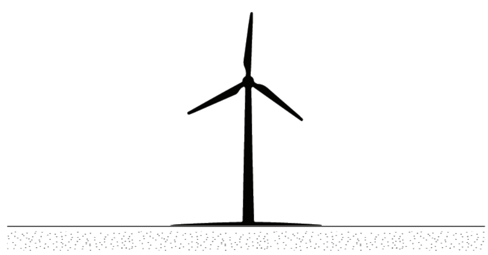
SOLAR ENERGY

They emphasise that solar energy should be implemented multifunctionally. The priority goes out to solar panels on roofs and facades. Secondly, unused spaces within the urban fabric should be explored. After that comes unused land outside of the built environment, and lastly, agrarian and natural landscapes.

To find a suitable location for implementing solar energy production, several other criteria also play a role. The site should receive sunlight throughout the day. Furthermore, the vicinity of built-up areas should also be considered to ensure exergy-efficient implementation of renewable energy sources (Stemke et al., 2011). However, solar panels are modular structures that come in different shapes, colours and transparencies, which make them suitable in many contexts.

WIND

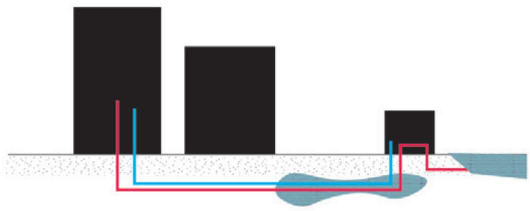
Due to noise pollution and shadow cast, wind turbines are often not considered within cities or close to built-up areas. Another concern that has been mentioned is that they could result in visual noise, as they are visible from far away and require large distances between them. Smaller wind turbines can reduce the visual and sound impact that larger wind turbines cause; however, their energy production is also much lower.



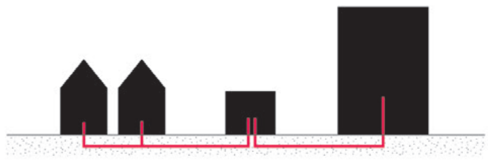
Though they might still be an interesting solution to consider on a gas station site. Wind energy exhibits distinct patterns compared to solar energy. It can contribute to the energy supply of residential and industrial areas at times of the day/year that differ from those of solar energy. The requirements for implementation include distance to built-up areas and wind availability from the dominant wind direction.

HEAT

For aqua thermal heat, the source of heat can be found in surface water bodies. This can be rivers, lakes and ditches. Alternative sources are drinking water or sewage water. To increase the water temperature to the required level, a heat pump needs to be installed. There are two types of aqua thermal heat networks: high-temperature and low-temperature networks. In the high-temperature network, a collective heat pump is being installed that heats the water to the required temperature and then transports it to the housing units. A different option is a low-temperature network. Here, individual heat pumps in the housing units heat the water before it can be used for heating and hot tap water (Aquathermie (thermische energie uit water), n.d.).

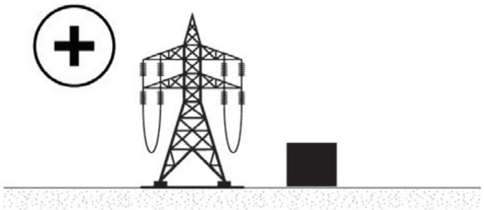


Residual heat can be another way to use the produced heat sustainably. Sources for that usually come from industrial processes. Thus, a requirement for residual heat is the availability of excess heat from such a process. A potential source includes, for example, data centres or industrial bakeries, as well as the production of other goods.



TRANSMISSION/TRANSFORMATION

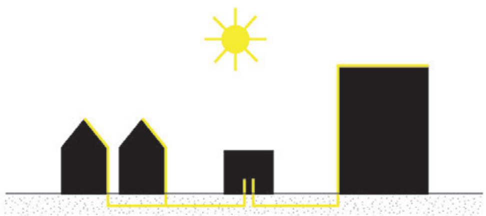
Other network components required for the transmission and transformation of energy include substations and transformation stations. According to Netbeheer Nederland (2019), approximately 500 MS-LS stations are needed per 100,000 inhabitants in the coming years. These require between 10 and 35 m2. However, additional larger stations will also be needed, such as MS and TS/MS stations. Like the MS-LS stations, the MS stations also need to be located within the neighbourhood. MS stations require between 200 and 4000 m2. Netbeheer Nederland (2019) predicts that about 20 will be needed per 100.000 inhabitants. The TS/MS, on the other hand, are usually located on the edge of the city. They require between 2,000 and 10,000 m^2, and about 5 of them are needed per 100,000 inhabitants (Netbeheer Nederland, 2019).



The aesthetic concern is often a reason for local opposition, which delays the placement of these stations. There are several examples of stations that addressed this issue. One example is the Bent Cross station. Here, local artists designed the exterior shell of the station, creating a new landmark (Figure 26).

Figure 26: Image showing the transformation station Bent Cross retrieved from Https://Www.Ifdo.Co/Projects/Brent-Cross-Town-Substation.

STORAGE



Additionally, renewable energy sources like wind and solar have their own patterns of availability. This brings challenges when matching supply and demand. Additional solutions that can store renewable energy need to be explored (Gemeente Amsterdam, 2020, p. 131). One technology that can be applied is the battery. A battery can be used in residential contexts, which is known as a neighbourhood battery, but it is also applied in other contexts.

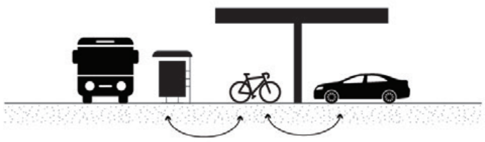
The neighbourhood battery can be applied to increase flexibility in the energy supply and demand. This can reduce net congestion and increase the amount of energy that can be produced and used locally.

HUBS

Gas stations are currently nodes in the fossil fuelled car system. Their current network situation also makes them a suitable location for alternative mobility nodes. Since they are placed throughout the city, they can act as strategic intervention points for alternative mobility solutions.

MOBILITY HUBS

One possible application is the mobility hub. The mobility hub has become a well-established and promising concept for transitioning from a private-car-based mobility system to a more sustainable one. Weustenenk & Mingardo (2023) have proposed a typology of mobility hubs. Their layout and service availability depend on the context they need to serve. However, they also argue that they need to be implemented in accordance with specific requirements. In the following paragraphs, the requirements of relevant mobility hub types will be described.



COMMUNITY HUB

The community hub is a mobility hub that serves a selective group of people within an area that is not well-connected to the public transportation network. These groups typically consist of employees from a company or a group of residents. They are located on privately owned land, like parking lots or garages. Community hubs offer shared EVs, (e-) bicycles, and mopeds, and typically do not offer other services besides shared mobility (Weustenenk & Mingardo, 2023).

NEIGHBOURHOOD HUB

The neighbourhood hub offers the same modes of shared mobility as the community hub; however, it is typically also well-connected to the public transportation network. Through that, they offer a transition point from one mode to the other. They can also offer additional services such as package pick-up points. Neighbourhood hubs are typically located in the vicinity of commercial destinations such as grocery stores (Weustenenk & Mingardo, 2023).

CITY EDGE HUB HUB

The city edge hub can be described as a park-and-ride location. They are located on the edge of the city, along ring roads, and serve as a transfer point between cities and the surrounding area. City edge hubs should be connected to a different mode of transportation, such as buses, trains/trams. Services they offer include sufficient parking space, carpool facilities, and charging stations for EVs. They serve the transfer from private cars to collective transportation (Weustenenk & Mingardo, 2023).

LOGISTIC HUB

Logistic hubs can vary in scale and function, similar to the mobility hub. There are industrial logistics hubs as well as neighborhood logistics hubs. The neighbourhood logistics hub focuses on reducing traffic within neighbourhoods, for example, through the establishment of package drop-off points (Gemeente Amsterdam, 2020 , p. 111).

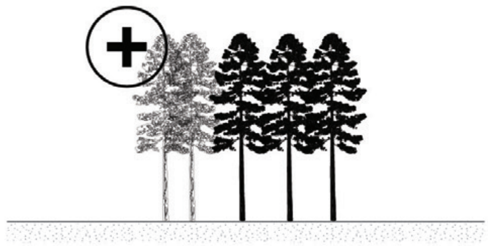
NATURE-BASED SOLUTIONS

Nature-based solutions for carbon sequestration in urban areas can be divided into terrestrial and water nature-based solutions (Pereira et al., 2024).
Solutions that belong to the first category are: urban forests and parks. Urban forests and parks also have the highest carbon potential. Solutions that require less space but are also slightly less effective for carbon storage are: green roofs/walls/facades, gardens and corridors. The smallest size of solutions includes single trees, hedgerows, rain garden and bioswales. These also have the lowest carbon potential of the terrestrial category (Pereira et al., 2024).

Implementing nature-based solutions in urban areas also has other beneficial effects besides carbon removal. For example, educating the urban population about the positive effect of ecosystems on the climate balance, reducing air pollution, contributing to the thermal comfort of public space, regenerating soils, etc..

Forests can be planted within cities to create patches of urban forests. But also on the edge of the city to contribute to a greener transition zone in the peri-urban area.

Potential forest types include dry forest and wet forest. For a dry forest, a well-drained soil is a requirement. Wet forest needs to be flooded for at least some parts of the year, and high groundwater levels are a requirement.



Wildflower meadows can be sown, which also have a high carbon removal rate. They require sun throughout the day as well as well-drained soil. Including clover in the meadow can also contribute to the remediation of the contaminated soil.

Another nature-based solution for carbon removal is biomass harvesting and cultivating biomass crops. Bamboo is a suitable species to include (Pan et al., 2023). So are reed and trees like willow and poplar. These also have the benefit of being suitable species for the remediation of contaminated soil (Kafle et al., 2022). Biomass harvesting has no specific requirements, as the suitability depends on the species used.

4.2 Suitability assessment

To identify the strategies suitable for transforming the sites, a suitability assessment has been developed. The method of Stahlschmidt (2017) has been adapted to fit this research. The chapter "Site selection and landscape potential" provides the basis for this approach. However, in the chapter, the method helps identify a suitable location for a new development. The starting point of this research is obsolete gas station sites. Thus, the location is non-negotiable. Still, the key strategies (new development) still need to be placed on a suitable site. For that, the requirements of the strategies have been defined and assessed for their suitability for three chosen sites. Thus, this approach aims to create a suitability assessment that determines which key strategy can be hosted on each site, informing the design exploration.

The properties and characteristics of the sites have been researched in the previous steps (spatial analysis and classification). Based on these characteristics, potentials and constraints can be concluded. The figure below illustrates how the site characteristics and key strategy requirements are utilised to create a selection that can be used for the design exploration in a later step.

4.2.1 Selection of strategies for the three sites

In the following paragraphs, the specific characteristics of the site Salvatorplein (R14), Westervoortsedijk (I11) and Meinerswijk (NB20) will be discussed, as they have been selected as the sites for design modelling. The paragraphs will summarise the outcome of the suitability assessment and present the strategies that seem promising for the transformation of the site.

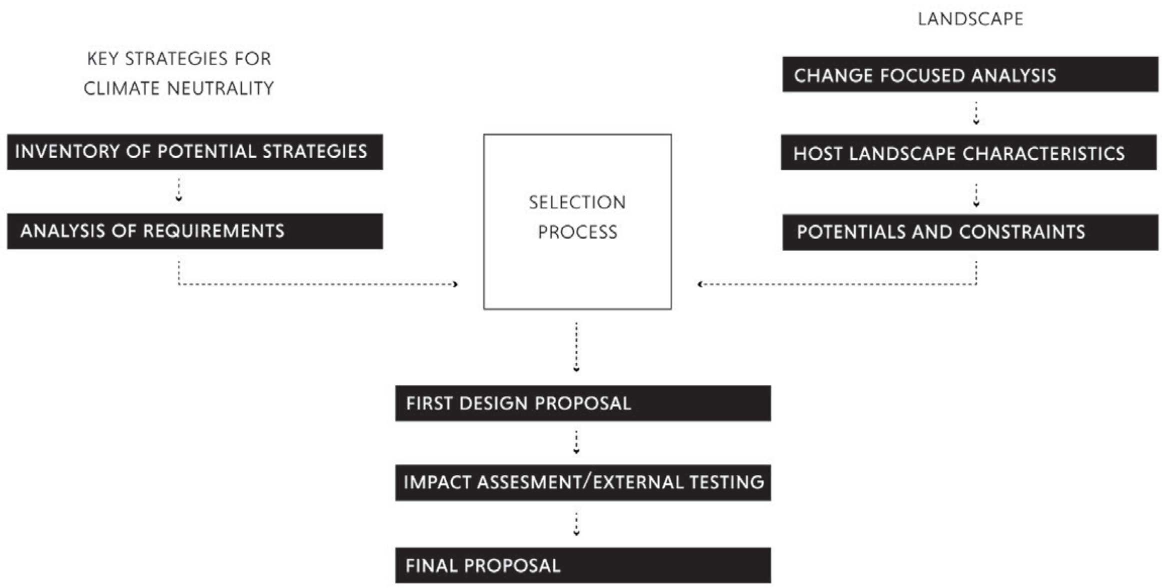


Figure 27: Illustrating the suitability assessment adapted from Stahlschmidt, 2017

Suitablity assessement

	Hubs	R(14)	I(11)	NB(20)
	Neighbourhood hub requirements			
	In vicinity of public transportation	x		
	Next to parking lot	x	x	
	Next to commercial area	x		
	suitability	++	-	-
	Community hub requirements			
	Absent public transportation			x
	Adjacent to privately owned land		x	
	Availability of select group of users		x	
	suitability	-	+	-
	City edge hub requirements			
	Located on the edge of the city			x
	In vicinity of public transportation		x	
	Close to ring road			x
	suitability	-	-	+
	Energy network components	R(14)	I(11)	NB(20)
Production	**Solar energy requirements**			
	Vicinity to built-up area	x	x	x
	Not covered by shadow	x	x	x
	suitability	++	++	++
	Wind energy requirements			
	Distance to built-up area			x
	Site not blocked in dominant wind direction		x	x
	suitability	-	-	++
	Aquathermal heat requirements			
	Next to water body			x
	Next to built-up area		x	x
	suitability	-	-	++
	Residual heat requirements			
	Availabilty of excess heat from industry			
	Next to built-up area	x	x	x
	suitability	-	-	-
Transmission/transformation	**TS/MS station requirements**			
	between 2000-10000 m2		x	x
	on the edge of the city			x
	suitability	-	-	++
	MS station requirements			
	between 200-4000 m2	x	x	x
	within neighbourhood	x		
	suitability	++	-	-
	MS/LS station requirements			
	between 10-35 m2	x	x	x
	within neigbourhood	x		
	suitability	++	-	-
	(Neighbourhood) battery requirements			
	Next to built up area	x	x	x
	Can be combined with energy production	(x)	x	x
	suitability	++	++	++
	Nature-based solutions	R(14)	I(11)	NB(20)
	Frorest (dry)			
	drained soil	x	x	x
	suitability	++	++	++
	Forest (wet)			
	saturated soil			
	suitability	-	-	-
	Wetland			
	high groundwater levels			
	Partially floddable		x	
	suitability	-	-	-
	Wild flower meadow			
	Sunny	x	x	x
	drained soil	x	x	x
	suitability	++	++	++
	Phytoremediation			
	Comtaminated soil	x	x	x
	suitability	++	++	++
	Biomass harvesting			
	No specific criteria			
	suitability	++	++	++

Legend	
++	very suitable
-	not suitable

Table 7: Suitability assessment for the three chosen sites Salvatorplein (R14), Wastervoortsedijk (I11) and Meinerswijk (NB20)

RESIDENTIAL BUILT UP AREA TYPE: SALVATORPLEIN

HUBS

In the context of the site Salvatorplein, the neighbourhood mobility hub is a suitable strategy to apply. It meets all the requirements, as it is situated next to a bus stop, a parking lot, and a commercial area.

ENERGY NETWORK COMPONENTS

For the selected residential host landscape site, only the solar panels can be applied to produce energy. For the transformation of electricity, the MS or MS/LS station could be placed on the site. Their requirements are met when the site is between 10-35 m2 or 200-4000 m2, respectively. Furthermore, they need to be located in a neighbourhood. The neighbourhood battery can also be applied to store electricity

NATURE-BASED SOLUTIONS

The ecosystems that can be applied to this site are dry forest, as the soil is well-drained. Furthermore, the site is sufficiently covered by sunlight, which would make it possible to implement a wildflower meadow. Traces of soil contamination can be found when viewing the data on the bodeminformatie map (bodeminformatie, n.d.). This means that the soil needs to be cleaned up, which can be done by phytoremediation. Additionally, biomass harvesting could be applied to the site, as this intervention has no specific requirements. The suitable species will need to be selected based on the site conditions (an overview can be found in table 8).

INDUSTRIAL BUILT UP AREA TYPE: WESTERVOORTSEDIJK

HUBS

For the selected site, no mobility hubs are suitable based on the requirements defined. However, a community hub is slightly suitable because the site is adjacent to privately owned land and a select group of users. The only criterion that makes it unsuitable is the lack of public transportation.

ENERGY NETWORK COMPONENTS

Energy network components that could be implemented on the site are solar energy, as solar energy does not have many requirements except the availability of sunlight. Besides solar energy, no other form of energy production is suitable for the site. Another energy function that can be applied to the site is battery storage.

NATURE-BASED SOLUTIONS

The strategies suitable for the Salvatorplein are equally applicable to the Westervoortsedijk site.

NON-BUILT TYPE: MEINERSWIJK

HUBS

For the selected site, no mobility hubs are suitable based on the requirements defined. Due to their location on the outskirts of the urban area, a relevant type of mobility hub would be the city edge hub. However, the gas station is not connected to public transportation systems, which makes changing modes of transportation impossible at this point. Thus, it is not considered a suitable strategy for the design, as it does not align with the current characteristics of the site.

ENERGY NETWORK COMPONENTS

Due to their characteristics, the non-built types offer opportunities for implementing various energy network components. One of them is a TS/MS station. They require between 4,000 and 10,000 m^2 and should be located on the edge of the city.

NATURE-BASED SOLUTIONS

The strategies suitable for the Salvatorplein site and the Westervoortsedijk site are equally applicable to the Meinerswijk site.

Figure 28: Photograph of a residential neighbourhood with a gas station in the front yard

Chapter 5: Design

5.1 Approach

The strategies most suitable for the three sites have been further explored during the design exercise. To test if they can not only contribute to the climate neutrality goals but also contribute to the spatial quality of the site.

RESEARCH THROUGH DESIGN

The application of key strategies was first explored during the internal testing phase. Through a modelling exercise, a design proposal has been developed. This design proposal has undergone expert evaluation. For this evaluation, a group of (aspiring) landscape architects has been asked. The criteria for the evaluation were based on the aspects of spatial quality developed by Bakx et al.. The outcome of the expert evaluation informed the reflection on the proposed transformation of the gas station sites and their effect on the spatial quality of the site. Through the reflection, design principles will be formulated to summarise the findings of the design exploration.

This approach has been chosen to explore the potential of different types of gas stations and how strategies can be applied in various contexts throughout the city. Not all strategies that are applicable to each site will be tested in the evaluation due to time constraints.

TESTING AND EVALUATION

The experts who seemed most relevant for this evaluation are landscape architects. The experts who have been asked to perform the evaluation are from Wageningen University and Research and have a background in landscape architecture. The participants consisted of two academic landscape architects, one PhD and 6 MSc students. During a collective meeting, they were asked to evaluate the design proposals based on the selected aspects of spatial quality. First, the solutions were presented, after which questions could be asked to improve the understanding of the models.

Then, the participants received an online questionnaire in which they were asked to evaluate the current site as well as the two design models for each site. The questions asked them to rate the site and proposed design alternatives on a scale of one to five, with one being "not at all" and five being "very much so". The questionnaire can be found in Appendix 3.

The questionnaire is based on the four dimensions of Spatial quality by Bakx et al. (2023). Relevant aspects from each dimension have been selected from the list and framed as a question. Spatial quality is a relevant measurement when dealing with spatial transformations. It should be ensured that when transforming one land use to another, the quality of the landscape improves instead of declines.

The proposed design solutions have been evaluated to determine which strategies can contribute the most to the spatial quality of the site. The outcome of the evaluation guided the development of the final design for the different sites.

To test the potential of the strategies to contribute to the site's spatial quality, two products per model have been created. The models show how the former gas station site can be transformed by applying key strategies for climate neutrality. The models consist of a plan view as well as a section, which will be discussed in depth in section 5.3.

Figure 29: Photograph of a gas station no longer in use which is represented on in figure 30 by circle A

5.2 Transformation of gas stations

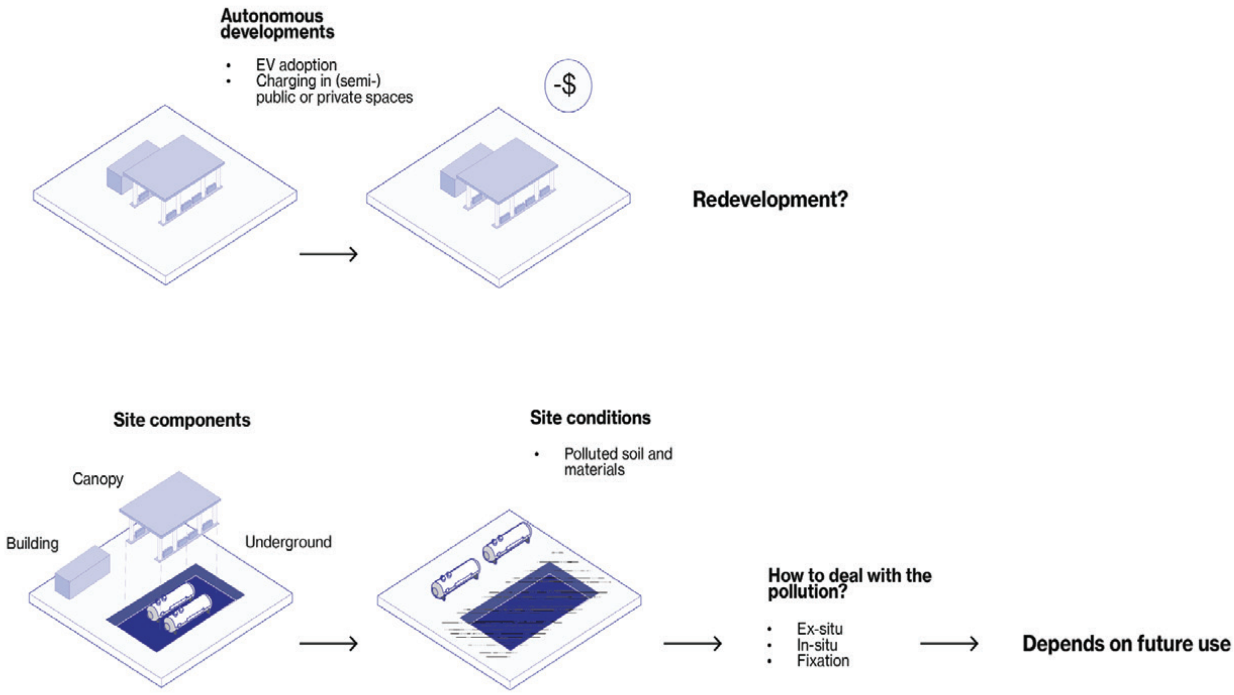
To transform a former gas station site, several key parameters are essential to consider. Firstly, the degree of contamination of the site. The degree of contamination depends on several factors. The most important ones are age and any accidents that may have occurred. Modern gas stations are constructed with impermeable pavement and feature safety tanks that are less prone to leaks than older tanks. However, even these tanks need to be replaced after a period of time.

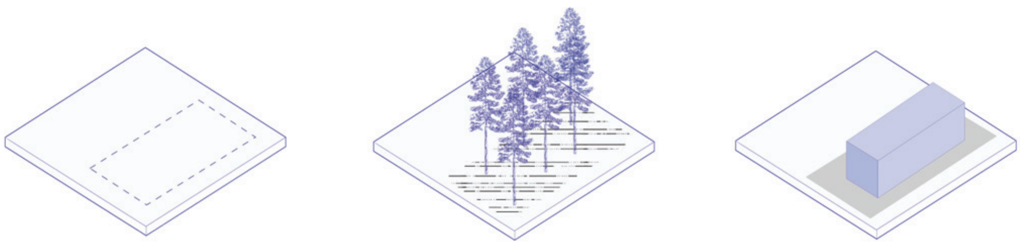
Another aspect of age is the period of time that a gas station has been located at the same place. Older gas stations were built with fewer protective measures to prevent leaks. This means that historical gas station sites often exhibit higher levels of contamination, even when the station was constructed to modern standards. Nowadays, gas station sites are being monitored for potential leaks to prevent contamination from spreading. The map Bodeminformatie of the municipality of Arnhem shows the sample points taken and reveals any past or existing contamination. With most modern gas stations, it is evident that past contamination has been remediated. However, some sites still show punctual contamination and not all former gas station sites have been remediated. Some can still be identified on the soil contamination map of Arnhem (see figure 30).

After the gas station has closed down, remediation of soil or groundwater is often performed during the excavation of the tanks. Then, most of the soil is removed, and the site is pumped dry to clean any polluted groundwater.

Figure 30: Map showing soil contamination. The circle marked with a C shows the contamination at the GS Salvatorplein which has been remediated. Circle A indicated a gas station that is no longer active but has been remediated and circle be indicates a fomer gas station site that is not visible above ground anymore but the contamination remains. Retrieved from https://arnhem.maps.arcgis.com/apps/instant/sidebar/index.html?appid=1650b84f5ded4ac4b92a7a5ab2f0f980

Transformation of gas stations





	Ex-situ	In-situ (Phytoremediation)	Fixation
Method	• Removing and replacing soil	• Breakdown over time	• Fixate pollution on site
When	• Useful when contact with soil and water is intended • For example when implementing a playground, water buffer/filter or fountain	• Can be combined with the implementation of solar arrays, forest planing or wildflower meadows	• Prevents contact with polluted soil through a concrete layer • Can be used when building a new construction on site
Advantages	• Immediate and thorough cleaning	• Can be done cost-effectively using plants (phytoremediation) • Natural carbon sink	• No transportation needed as soil remains on site
Disadvantages	• Transportation of polluted and clean soil necessary • Replacement of pollution to another location	• Takes time	• Pollution remains

Figure 31: illustrating the different steps and approaches of the remediation of gas stations

REMEDIATION

Based on a consultation with an expert on soil contamination and remediation, the following insights have been gained and summarized in figure 31.

To remediate the site, three approaches can be considered. First, the ex-situ approach. This approach can be used when the site needs to be thoroughly cleaned in a short amount of time, or when the surface needs to be paved, for example when transforming the site into a public space. A paved surface area does not leave room for phytoremediation. Additionally, when contact with soil or water is intended, for example in a playground this approach should be chosen. The approach involves the removal of contaminated soil and placing clean soil in its place.

The second approach that can be used the in-situ remediation. As oil is biodegradable it can be broken down by plants and micro-organisms. One low-tech and cost affective way to do so, is phytoremediation. Here, plants are used to break down the contamination over time. This approach involves leaving the contaminated soil on side and planting the right species to clean the soil. A list of suitable species can be found in the table below.

The third approach involves the fixation of the pollution to prevent that people can get into contact with it. This approach deals with the contamination from 'cover-up' perspective and does not treat the contamination but leaves it in place. This approach can be chosen for example when a building is built on top of it.

Although the contamination from gas stations is localised, it is essential to clean the soil to prevent it from leaching into the groundwater.

			used for	Phytoremediation	Carbon Sequestration
Groundcover	**Clover and legumes**				
	Alfalfa	*Medicago sativa*		x	
	White clover	*Trifolium repens*		x	x
Grasses	**Poaceae (Grasses)**				
	Mais	*Zea mays*		x	
	Rabbits footgrass	*Polypogon monspeliensis*		x	
	Bermuda grass	*Cynodon dactylon*		x	
	Bamboo	*Bambusa vulgaris*		x	x
woody, decidiuous	**Trees**				
	Willow	*Salix ssp*		x	x
	Poplar	*Populus alba*		x	x
	European aspen	*Populus tremula*		x	
	Robinia	*Robinia pseudoacacia*		x	
herbaceous	**Wetland species**				
	Cattail	*Typha*		x	x
	Common rush	*Juncus effusus*		x	
	Perennial reed grass	*Calamagrostis × acutiflora*		x	
	Aquatic plants				
	Water hyacinth	*Pontederia crassipes*		x	
	Carolina mosquito fern	*Azolla filicouloides*		x	
	Pond water starwort	*Callitriche stagnalis*		x	
	Threadleaf Crowfoot	*Ranunculus trichophyllus*		x	
	Parrots feather	*Myriophyllum aquaticum*		x	
	Blumea species				
	Holy rope	*Eupatorium cannabinum*		x	
	Sun flower	*Helianthus annuus*		x	
	Brassica				
	Broccoli	*Brassica oleracea var. italica*		x	
	Rapeseed	*Brassica napus*		x	

Table 8: Species overview (Species phytoremediation based on Kafle et al., 2022)

TRANSFORMATION

Precedents have revealed two primary approaches to transforming gas station sites. The first option is to repurpose existing buildings for new functions, such as restaurants, communal spaces, and event venues. The second option is to redevelop the site to host new public functions, such as pocket parks.

An example of the first approach is the two former gas stations in the Noorderpark in Amsterdam. Here, two former gas stations have been given a new function. The original architecture has been kept and repurposed. Nowadays, the two gas stations are prominent features in the park and are used for gatherings, events, and are run by an artist collective. An Example of the second approach is the Place des fleurs de macadam in Montreal, Canada. Here, a former gas station site has been transformed into a water-filtering pocket park featuring a water square where children can play. The site has been decontaminated, allowing for its transformation into an urban oasis.

THE ROLE OF THE POLICY STRATEGIES

To determine the new function the site can host, strategies have been defined and their suitability assessed for the three chosen sites. The strategies guide the development of the models.

As climate neutrality can be seen as a combination of reducing emissions through the application of renewable energy sources, as well as offsetting the remaining emissions, it has been chosen to develop two models that focus on each of these. For the three sites, two models have been developed: one focusing on the application of renewable energy production and the other on the implementation of nature-based solutions to sequester carbon. The application of the mobility hub has not been developed into a separate model. It is only suitable for one of the sites and has been applied in the renewable energy model. Another consideration is to exclude the transformation/transmission category of energy network components. This has been done as it would involve designing a building or construction that can host this function, rather than a public space.

The layout of the models has been kept the same to ensure they remain comparable in the evaluation. The modelling variable is the type of strategy, which varies between renewable energy production/storage and the creation of natural carbon sinks.

CULTIVATING POST-CARBON MINDSET

As the climate plans revealed, the climate-neutral city will be walkable and cyclable. This means that space for cars will have to be transformed to fit the needs of pedestrians and cyclists. Furthermore, we will need space for shared mobility and public transportation, as well as space to generate and store renewable energy, and to regenerate our ecosystems.

During the creation of the site design, the goal was to rethink the space from a post-carbon perspective. Considerations that have been done are: the reduced importance of motorised vehicles, the creation of pleasant cycling and pedestrian experiences, and the rediscovery of the local scale, leading to the exclusion of cars in the transformations.

DESCRIPTION OF THE SITES AND MODELS

In the following pages, the three sites will be discussed separately. At first, the site will be introduced, followed by a discussion of the alternative models, including the results of the expert assessment. After that, the site design will be presented.

The final design is based on the evaluation of the models. The insights gained from the evaluation have been used to improve the designs. The questionnaire used for the assessment can be found in Appendix 3. The evaluation is based on the four dimensions of spatial quality defined by Bakx et al., 2023. For each dimension, one aspect has been chosen and formulated as a question. The results of the evaluation are presented as a score to visualise the result (from 1 being the lowest and 5 the highest).

The capacities of the different models and designs in terms of renewable energy production and carbon sequestration have been estimated. Only the results of these calculations will be mentioned in the following pages. The explanation of the calculations can be found in Appendix 4.

Salvatorplein

The following pages discuss the site analysis and alternative models for the gas station at the Salvatorplein, Arnhem.


REVOLUTION
TEXTIELWASSERETTE
WAS 18 KG
WAS 8 KG
boedelbak

5.3 Description of the sites and design models

5.3.1 Salvatorplein (GS14)

SITE ANALYSIS

The first site is located at the Salvatorplein in Arnhem and falls within the residential host landscape type. The site is located in a residential neighbourhood, next to a bus stop that connects the south of Arnhem with the North. Next to the site is a large parking lot and commercial area, which, in the future, may be utilised for energy production through solar carports, and the commercial area also has significant roof space. There is no accessible green space in the surrounding area of the gas station, except for a football field.

The site itself already functions as an unofficial square with seating and gathering spaces used by residents, creating opportunities to transform it into an actual public space, combined with the strategies for climate neutrality. The area surrounding the site feels car-centric, and there were multiple occasions where I felt neglected as a pedestrian, not knowing where I should walk due to missing sidewalks on a road crossing, for example. The parking lot next to the side transforms into a market once or twice a week. This is when the neighbourhood comes alive. The commercial area as a whole feels like the center of activity, where you can see families gathering during summer, eating ice cream, and kids playing in the market. However, it remains a parking lot with few

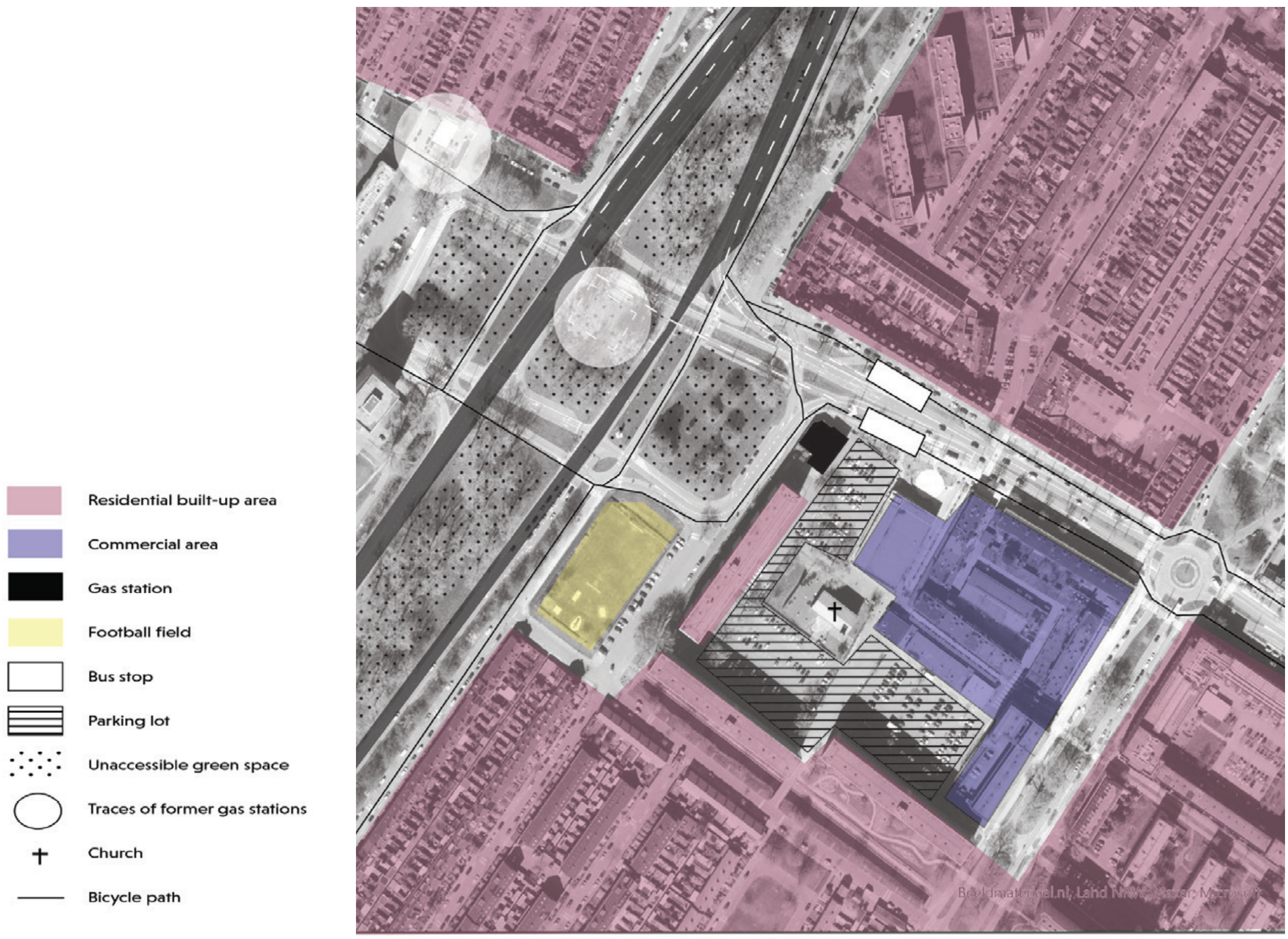


Figure 32: Host landscape analysis based on land use analysis

choices made with pedestrians in mind. Some parts of the area have already been adapted through new street furniture and greenery. But an intuitive excess point from the west side is still missing. The findings of the experience-based analysis can be found on the next page in figure 38.

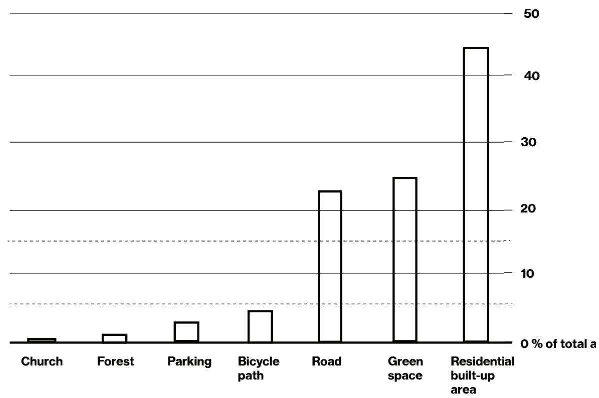


Figure 33: Graph summarizing the land use analysis of the host landscape of Salvatorplein

Figure 34: Photograph of canopy side view

Figure 35: Photograph of parking lot and high-rise building

Figure 36: Photograph of canopy front view

Figure 37: Photograph of green space isolated by the road network with the gas station in the background

UNACCESSIBLE GREEN SPACE - FRAGMENTED BY TRAFFIC

BENCHES AT THE GAS STATION ARE USED FOR RESTING AND GATHERING BY RESIDENTS

FEELING NEGLETED AS A PEDESTRIAN - NO DESIGNATED WALKING PATHS

Figure 38: Summarizing the insights from the field visit/qualitative host landscape analysis

What spatial qualities does the site hold?

EVALUATION RESULTS

To reveal existing spatial qualities of the site, the current sites have been evaluated by the 9 experts in the spatial quality assessment. The result of this evaluation is shown in the figure below. The figure on the next page shows a collage of the current site. Materials and individual elements have been collected in photographs to encapsulate the atmosphere of the site.

As is apparent from the scores presented in figure 39 , the evaluation revealed an absence of spatial qualities rather than their presence. The ecological quality scores the lowest, and with a score of 1, is deemed absent. The experiential and use quality score 0.4 points higher. This may be due to the presence of multiple amenities on the site, along with the fact that a gas station can be a busy environment with many activities happening simultaneously. This means that a complete absence of this quality can not be detected; however, it still reveals a deficiency. The long-term quality scores the highest, but, with a score of 1.6, this still reflects a lack of this quality.

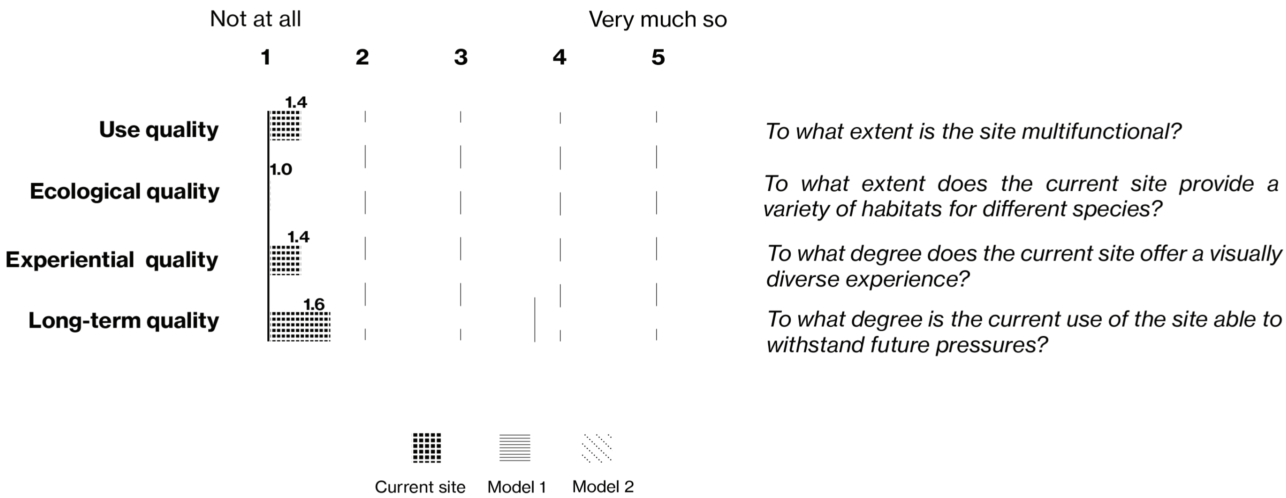


Figure 39: Outcome of the expert assessment of the current site (Salvatorplein) including the questions from the questionnaire

Figure 40: Site collage

Salvatorplein first Alternative: Neighbourhood battery as a public space

DESCRIPTION

The main design objective of the gas station transformation is to create a space for residents to gather, sit, and play. It should improve the pedestrian and cyclist experience to encourage the use of non-motorized mobility.

The first alternative, shown in figures 41 and 43, repurposes the iconic element of the gas station, the canopy, into a solar canopy. The sheltering function of the canopy remains; however, it now protects cyclists and pedestrians during harsh weather conditions, or it serves as a gathering space. The site now also hosts a mobility hub with bicycles and cargo bikes, providing the opportunity to switch between modes of transportation.

The underground space is being repurposed by implementing a water filtration installation that can feed a fountain on the square. Additionally, a construction can be built to host a neighbourhood battery underground. The capacity of the battery is approximately 30000 kWh. The solar canopy has a yearly electricity output of about 54074 kWh, which is about the same amount as 22 households use per year. The solar canopy also restricts the amount of vegetation that can be integrated into the model. This is also represented in the amount of CO_2 that can be sequestered by the planting choice, which is estimated to be 0.1 t/y.

The model combines three strategies for climate neutrality: The mobility hub, solar energy production, and the neighbourhood battery.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 42. The current site scores

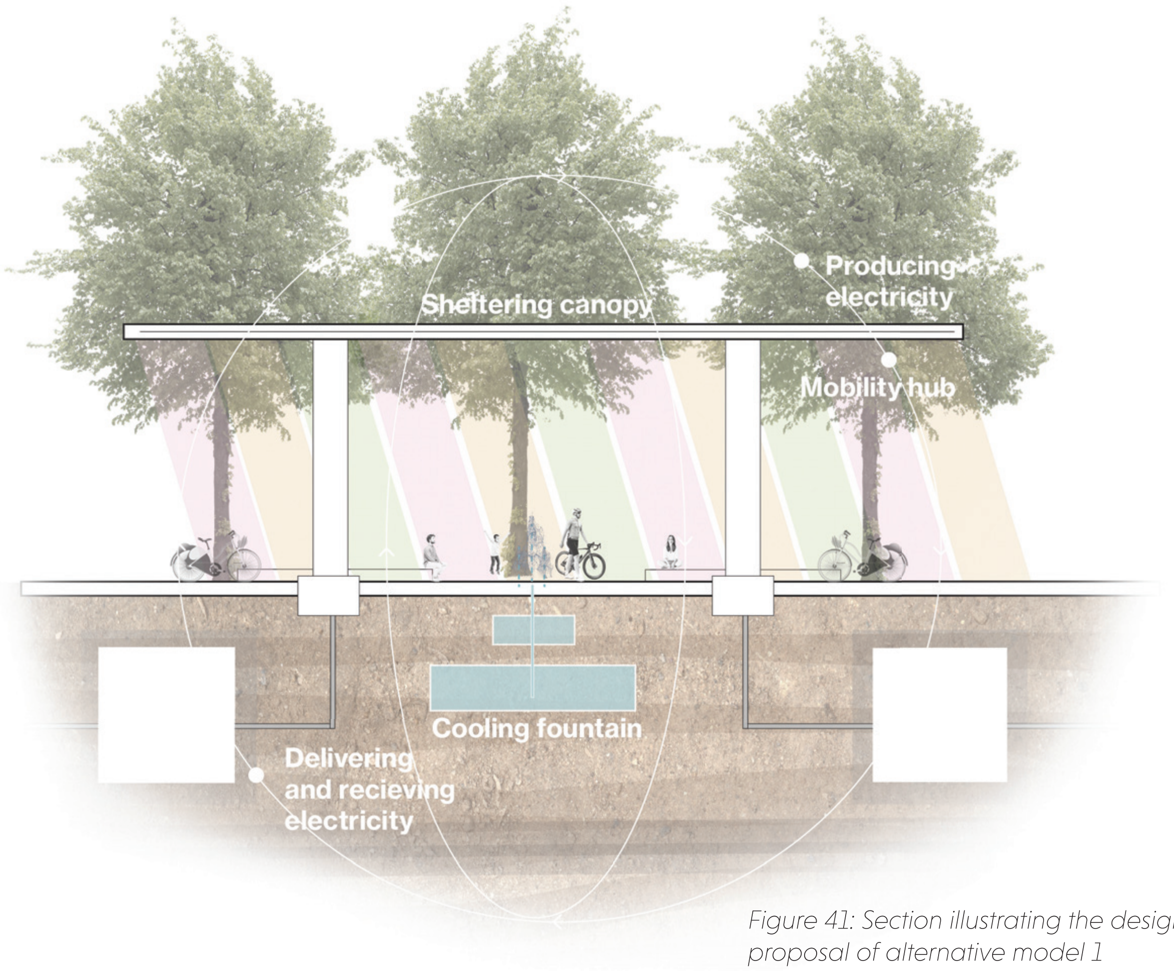


Figure 41: Section illustrating the design proposal of alternative model 1

insufficiently in all four dimensions of spatial quality. The ecological quality scores the lowest and is deemed absent. The experiential and use quality score 0.4 points higher.

With a total score of 14,5, the first model is slightly superior in providing spatial quality improvements. The first model also provides the most improvement in multiple dimensions. However, it does not sufficiently improve the biodiversity score of the site. This means additional greenery should be incorporated into the design to improve this score.

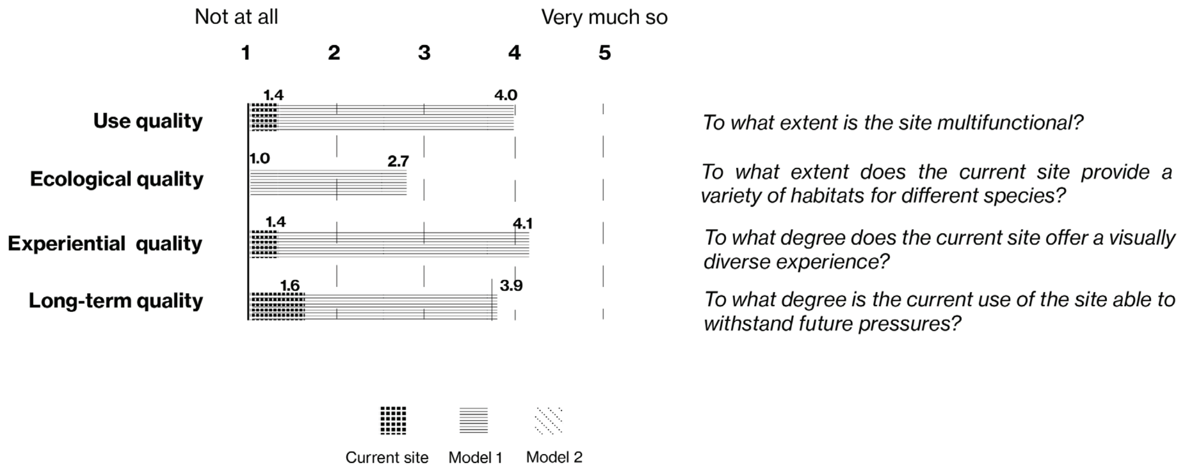


Figure 42: Outcome of the expert assessment of alternative model 1 including the questions from the questionnaire

Figure 43: Plan view of alternative model 1

Salvatorplein secoond alternative: Tiny forest canopy

DESCRIPTION

Another way to reinvent the canopy is to replace the man-made structure with a canopy formed by trees. The second model shown in figures 44 and 46 focuses on regenerating the soil through a tiny forest. The species used can clean the polluted soil through phytoremediation and are effective in sequestering carbon from the atmosphere. The dense forest canopy can provide shelter naturally, creating cool environments during the summer and protecting pedestrians from the sun and wind. As shown in the plan, the tiny forest becomes part of the street profile, separating pedestrians from the parking lot, and adds diversity to the walking experience. This model applies the strategy of afforestation and can sequester about 0.6 tons of CO2 per year.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 45. The second model shows the biggest improvement in ecological and long-term quality. However, with a total score of 14 points, it is still lower than the first model.

Based on the evaluation results, the first model has been further developed into the site design, which will be introduced in the following paragraphs and presented on the following pages.

Figure 44: Section illustrating the design proposal of alternative model 1

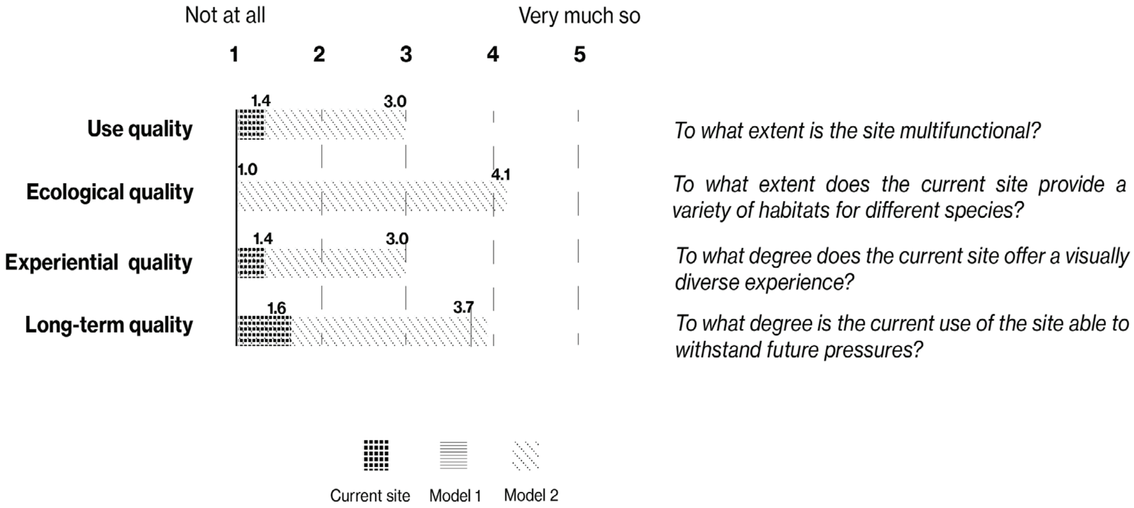


Figure 45: Outcome of the expert assessment of alternative model 2 including the questions from the questionnaire

Figure 46: Plan view of alternative model 1

Salvatorplein

The following pages discuss the site design for the gas station at the Salvatorplein, Arnhem.

Neighbourhood energy square

The conceptual diagram in figure 48 shows how the site is connected to the host landscape. Through the transformation the site can become a new entrance to the commercial area, which is the centre of activity of the neighbourhood. It focusses on improving the pedestrian and cyclist experience, functions as a mobility hub and a neighbourhood battery.

Pedestrians and cyclists are, by definition, exposed to the weather. With more extreme weather, shelters for shade and protection from rain can improve the comfort of this group of city dwellers. Furthermore, a shelter creates a public space for social interaction and gathering.

The canopy does not only serve as a public space but can also produce electricity through the tinted transparent solar panels integrated in the canopy. These panels also create colourful effects through sunlight penetration on the square adding to a friendly and playful atmosphere.

Underneath the solar canopy, a water fountain provides a cooling environment during summer months, along with seating and a swing as a play element. On the north side of the square, the rental bikes are parked. Here, residents can rent bicycles and cargo bikes. Underneath the rental bikes, an underground neighbourhood battery is located. The batteries are placed in a ventilated space accessible via a staircase.

The output of the solar canopy is estimated to be 54074 kWh/y and the battery can store approximately 30000 kWh.

An impression of the square can be seen in the figure below. The detailed site plan and section are presented in the following pages.

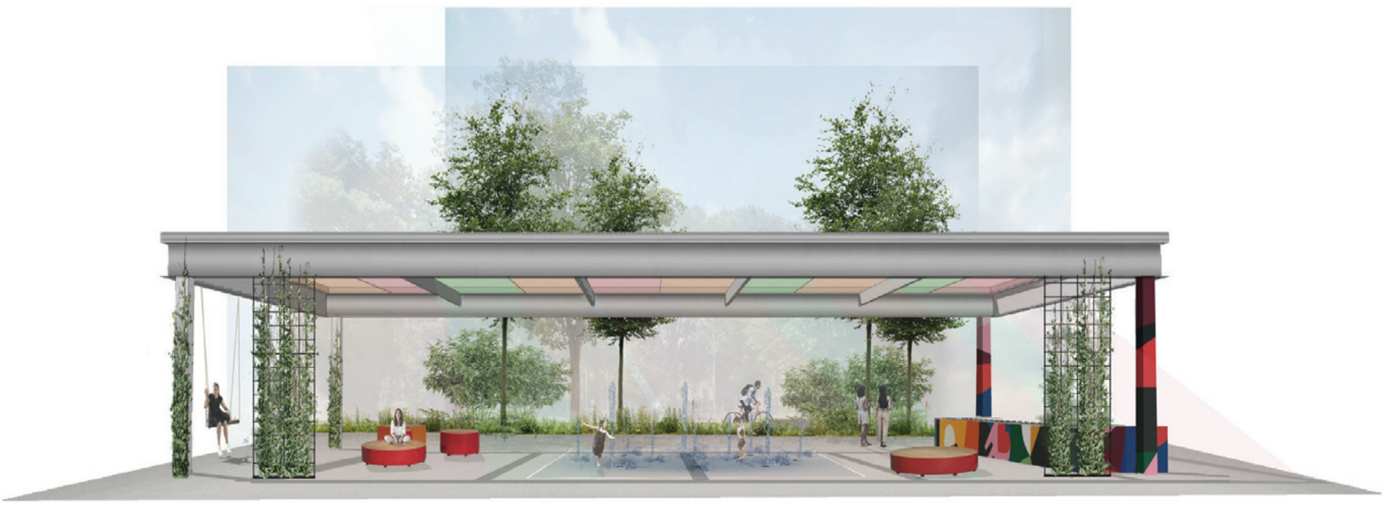


Figure 47: Visualisation of the neighbourhood energy square

Figure 48: Conceptual diagram

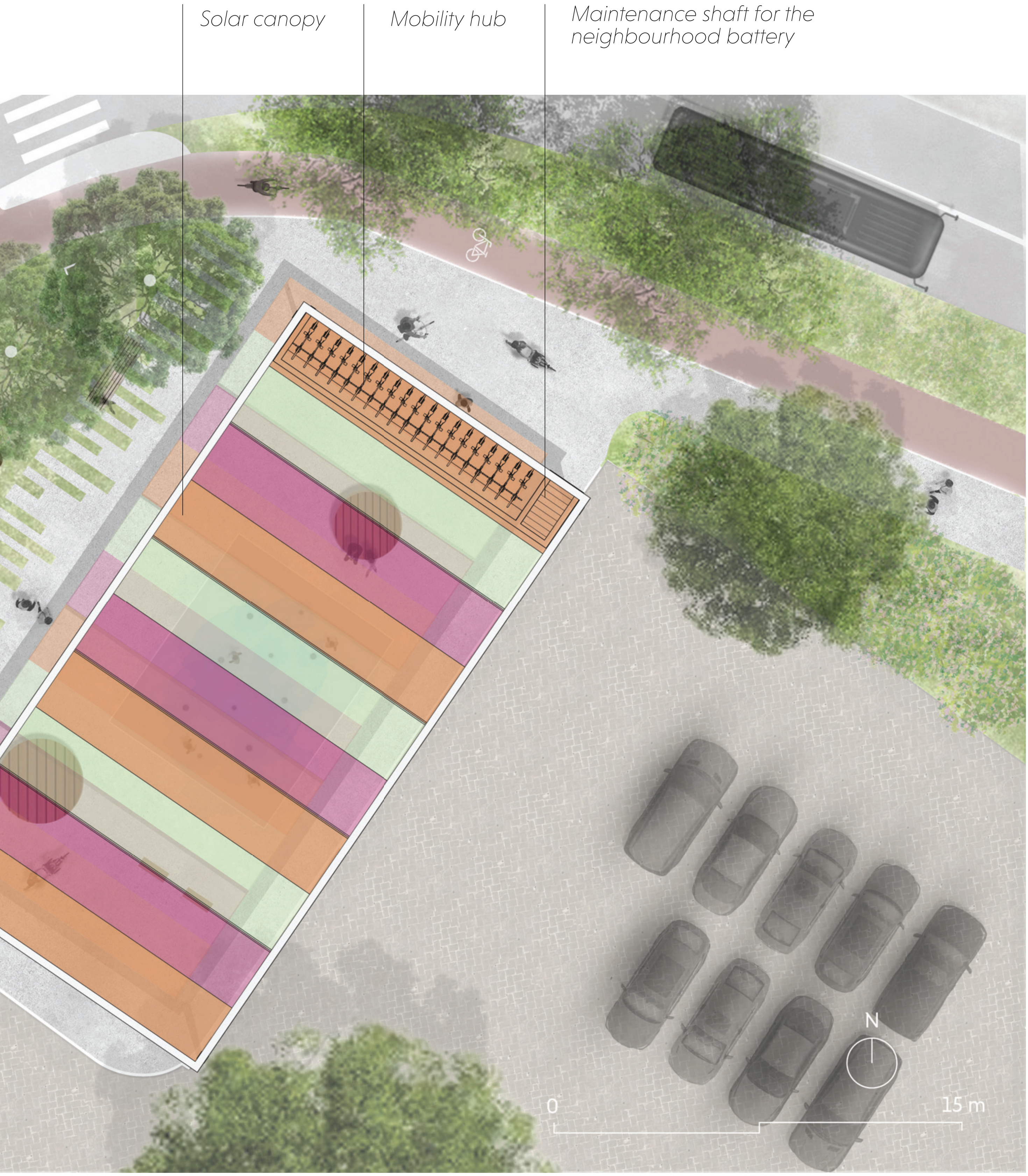


Figure 49: Site design master plan

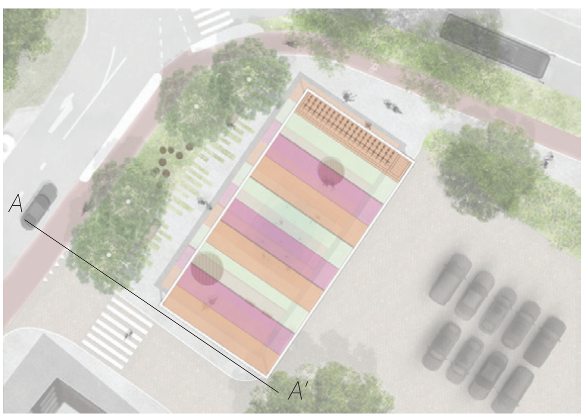

A
A'

Figure 50: Site design section

Westervoortsedijk

The following pages discuss the site analysis and alternative models for the gas station at the Westervoortsedijk, Arnhem.


Shell
Wasbox

5.3.2 Westervoortsedijk (GS11)

SITE ANALYSIS

The site is situated along the Westervoortsedijk in an industrial area, surrounded by numerous offices, which means that many people commute to work in this area. The area is characterised by a monotonous environment with large-scale buildings, and only one green strip along the gas station site. There are also many energy functions already in place, such as solar panels on roofs and ground-mounted installations, as well as a wind turbine park. On the south side of the gas stations, the clean-tech park is located, housing many companies and offices that work in the energy and material transition.

The experience of the site is influenced by the presence of the wind turbine park in the background, as well as the industrial buildings. The site is located very centrally in the business area, which means it could become a space where workers can take their lunch break walks, and a green network throughout the area could be established. During the field visits, people on their lunch break walk could be observed. However, the area does not offer much space for pedestrians to walk.

The site itself has a large canopy with a wave-like shape. It provides many opportunities for repurposing due to its size. In the background of the site, the view of the industrial area provides an interesting skyline featuring wind turbines and industrial buildings. The findings of the experience-based analysis can be found on the next page in figure 56.

Figure 50: Host landscape analysis based on land use analysis

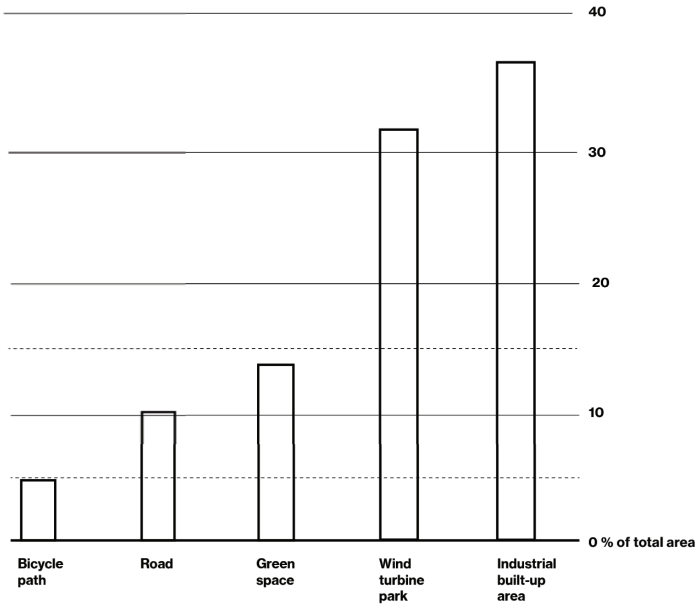


Figure 51: Graph summarizing the land use analysis of the host landscape of Westervoortsedijk

Figure 52: Photograph of canopy from cycle path

Figure 53: Photograph of cycle path and tree lane

Figure 54: Photograph of washbox with the office building in the background

Figure 55: View from cycle path towards the site with the wind turbine in the background


PEOPLE ON THEIR LUNCH BREAK WALK
IN A CAR DOMINANT ENVIRONMENT -
NO SHADING DURING SUMMER
TREE LANE - CONNETION BETWEEN
ARHEM, WESTERVOORT AND DUIVEN
MANY BOX-LIKE BUILINGS - PEOPLE
ARE INVISIBLE - NO OUTDOOR SPACES

Figure 56: Summarizing the insights from the field visit/ qualitative host landscape analysis

What spatial qualities does the site hold?

EVALUATION RESULTS

To reveal existing spatial qualities of the site, the current sites have been evaluated by the 9 experts in the spatial quality assessment. The result of this evaluation is shown in the figure below. The figure on the next page shows a collage of the current site. Materials and individual elements have been collected in photographs to encapsulate the atmosphere of the site.

The current site scores deficiently in all four dimensions of spatial quality, with ecological quality scoring lowest.

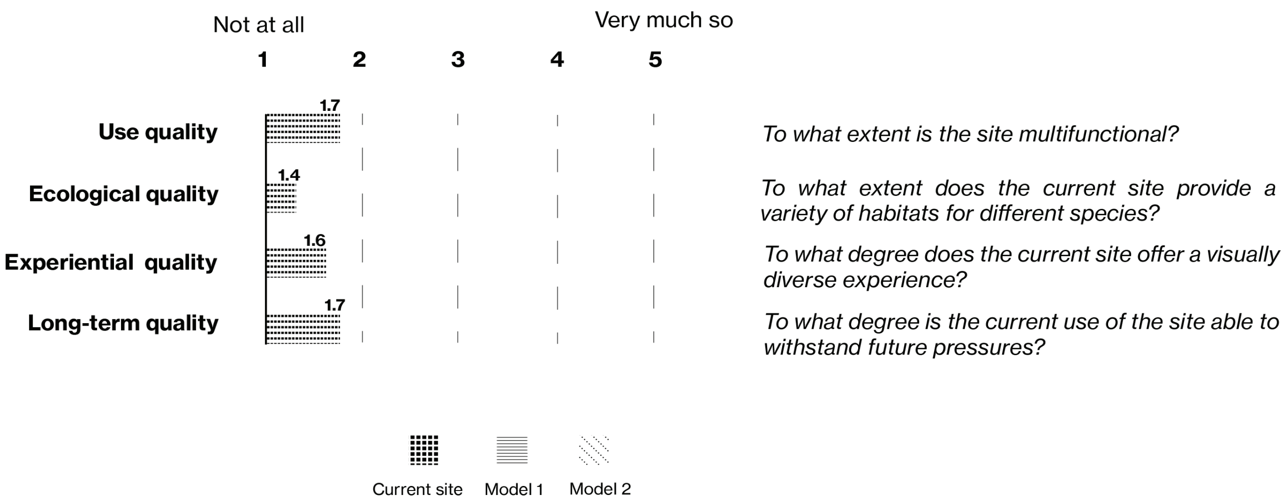


Figure 57: Outcome of the expert assessment of the current site (Westervoortsedijk) including the questions from the questionnaire

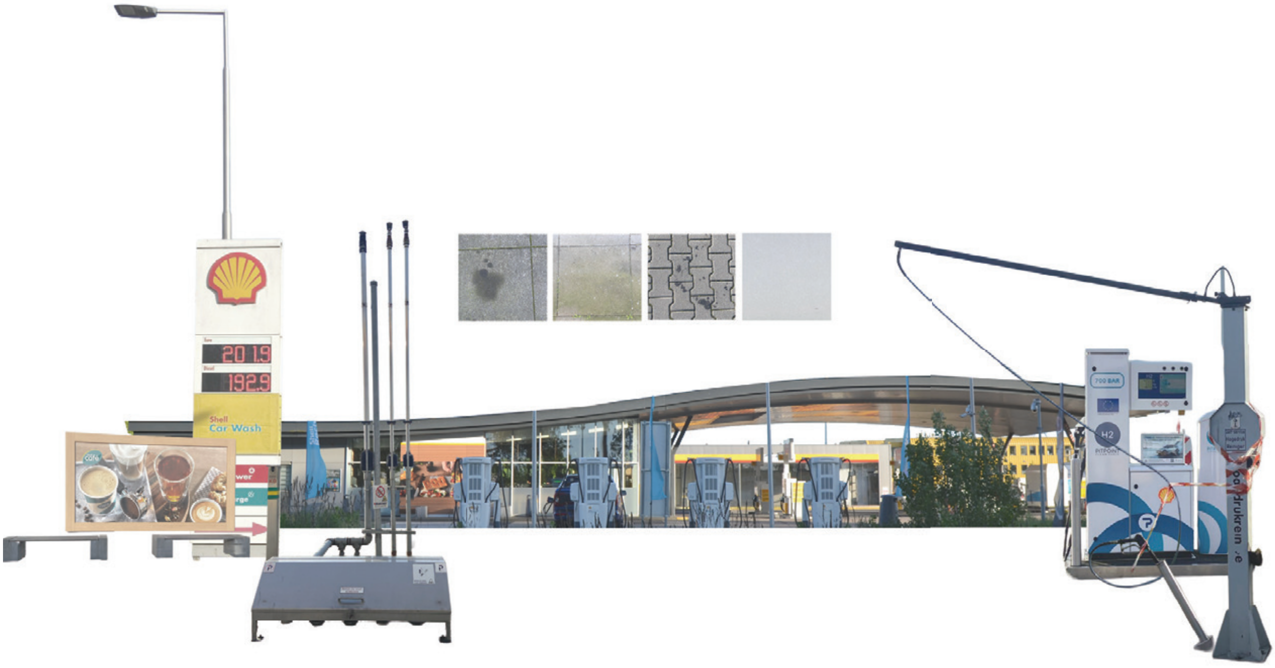


Figure 58: Silte collage

Westervoortsedijk first alternative: Park underneath

DESCRIPTION

The main ambition of the design models is to provide green space for the industrial area. This has been done in two ways.

The first model, shown in figures 59 and 61, illustrates how the site can be transformed into a park-like space featuring elevated solar arrays. Underneath the arrays, a recreational network can unfold to provide a space for people to walk and recreate. This space beneath the arrays can also serve as a temporary outdoor event space, bringing cultural activity into the area. The excavated space that is left by the removal of the tanks can become a pond, providing visual diversity and ecological value to the site. The strategy used in this model is the production of solar energy. The solar arrays in the model produce about 1131978 kWh of electricity per year, which is about the same amount as 468 households require per year. The wild flower meadow and the tree planting help to remove about 9.1 tons of CO_2 from the atmosphere per year.

The current site scores insufficiently in all four dimensions of spatial quality, with ecological quality scoring lowest. This was to be expected as the site does not offer any possibilities for ecology.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 60. The first model, which proposes elevated solar arrays above the path network, shows improvement across all four dimensions of spatial quality. All dimensions score higher than three. Experiential quality scores the highest. However, with a total score of 14.2, it scores lower than the second model. It only scores higher in the use quality when compared to the second model.

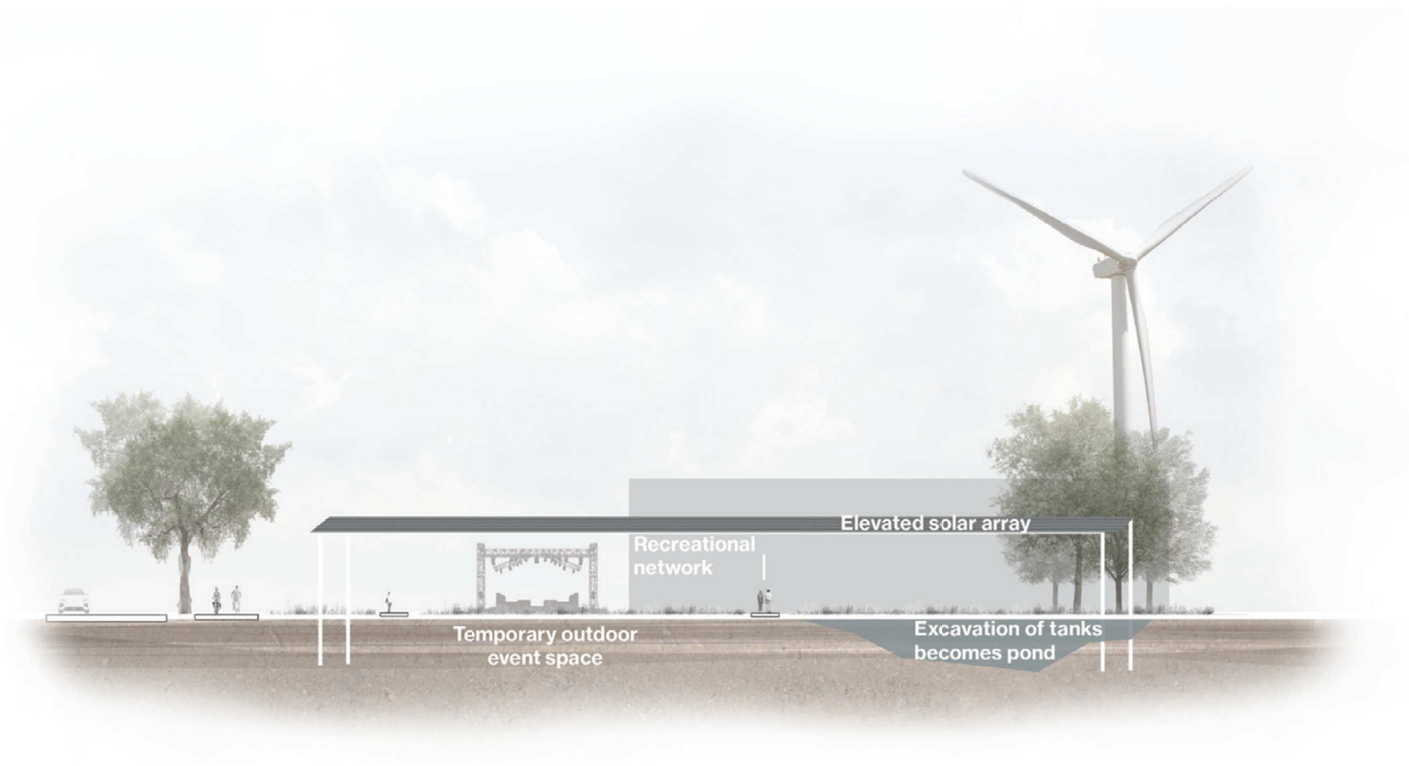


Figure 59: Section illustrating the design proposal of alternative model 1

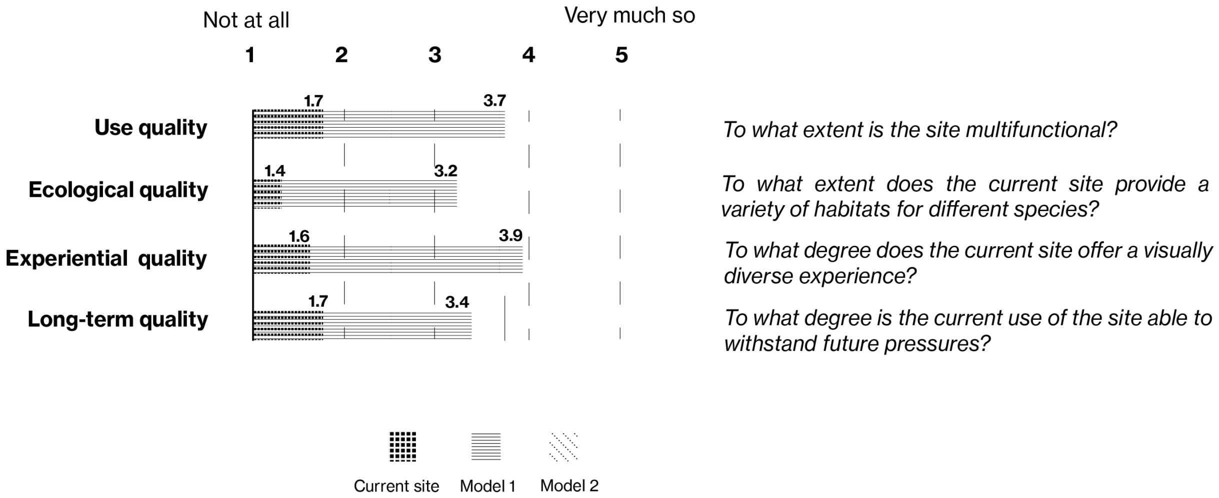


Figure 60: Outcome of the expert assessment of alternative model 1 including the questions from the questionnaire

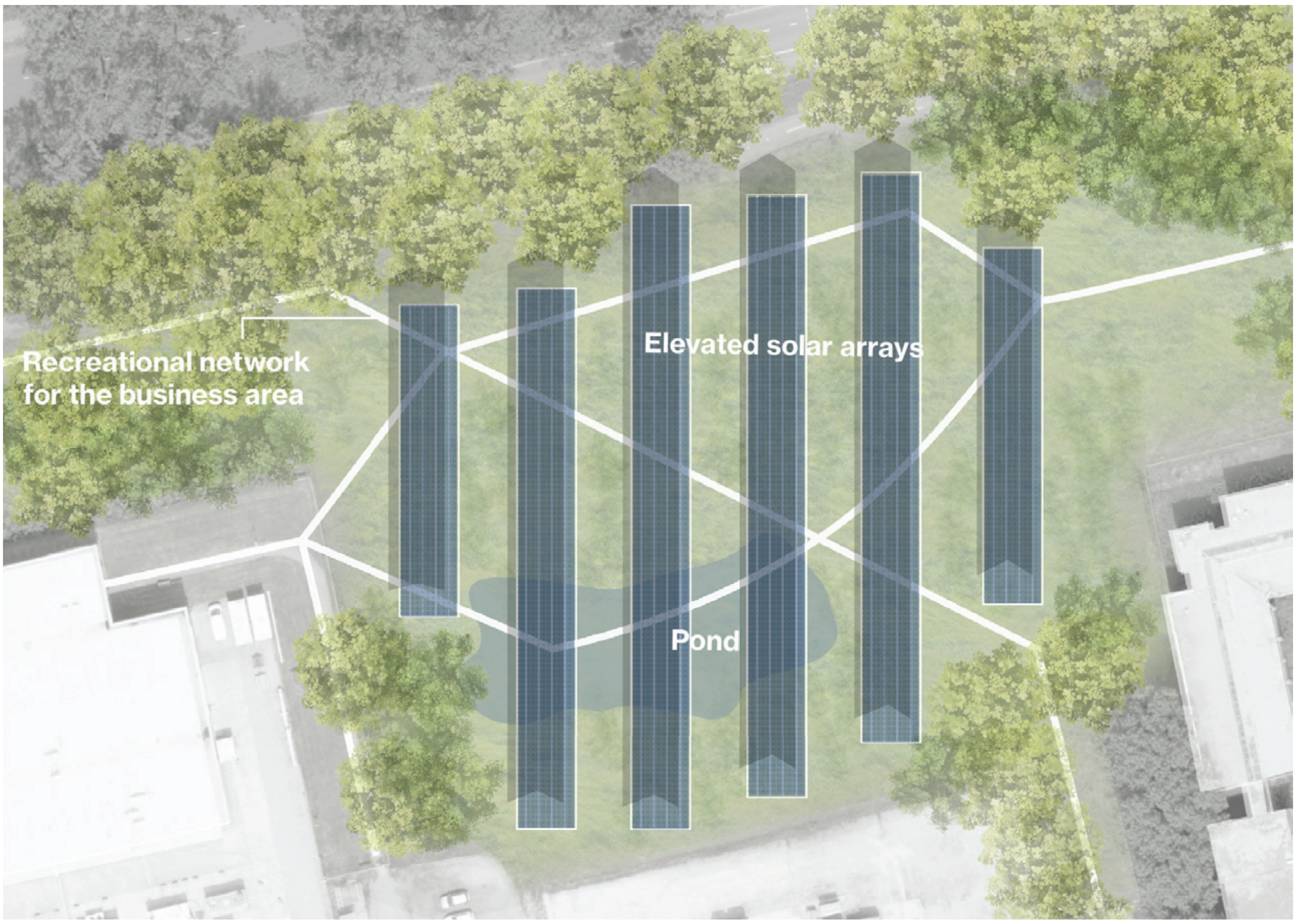


Figure 61: Plan view of alternative model 1

Westervoortsedijk second alternative: Carbon sink as a cultural connector

DESCRIPTION

The second model, shown in figures 62 and 64, transforms the site into a green space, defined by the bamboo plantation. This provides a visual contrast to the industrial area surrounding the site. The species used on the site can clean the soil through phytoremediation and are effective in producing a lot of biomass. The harvested biomass is a valuable resource for products or serves as an energy source. In this model, the former gas station building is transformed into an indoor event space. The strategy for climate neutrality used is the harvesting of biomass. Through the harvesting of bamboo biomass, the site will sequester about 97.7 tons of CO_2 per year.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 63. Based on the assessment, the second model has been chosen for the final design. To improve the final design, the implementation of energy production can be considered to further contribute to the improvement of the use quality dimension. As this model reuses the canopy construction, solar panels can be implemented on the roof of the event space.

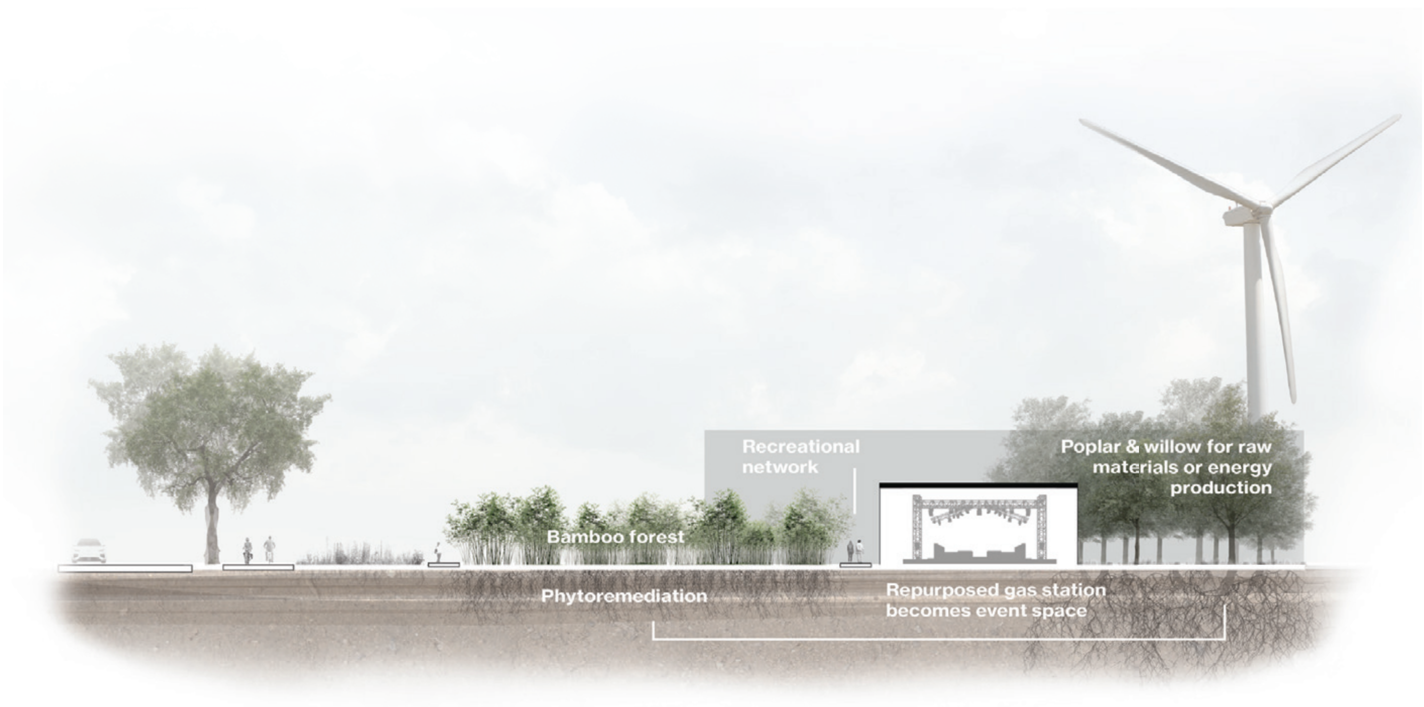
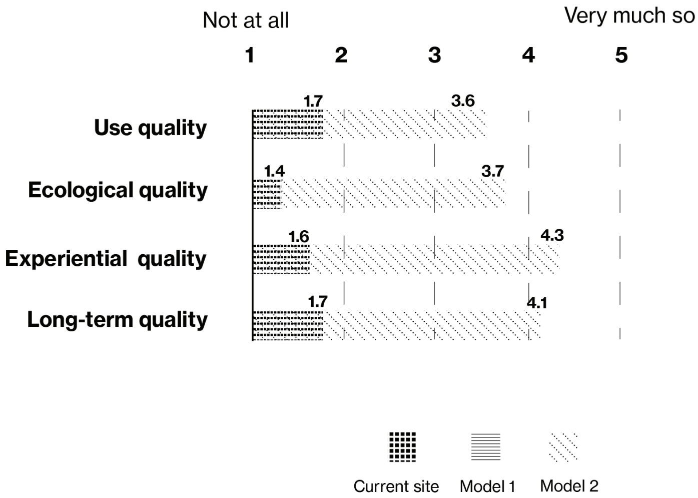


Figure 62: Section illustrating the design proposal of alternative model 2



To what extent is the site multifunctional?

To what extent does the current site provide a variety of habitats for different species?

To what degree does the current site offer a visually diverse experience?

To what degree is the current use of the site able to withstand future pressures?

Figure 63: Outcome of the expert assessment of alternative model 2 including the questions from the questionnaire

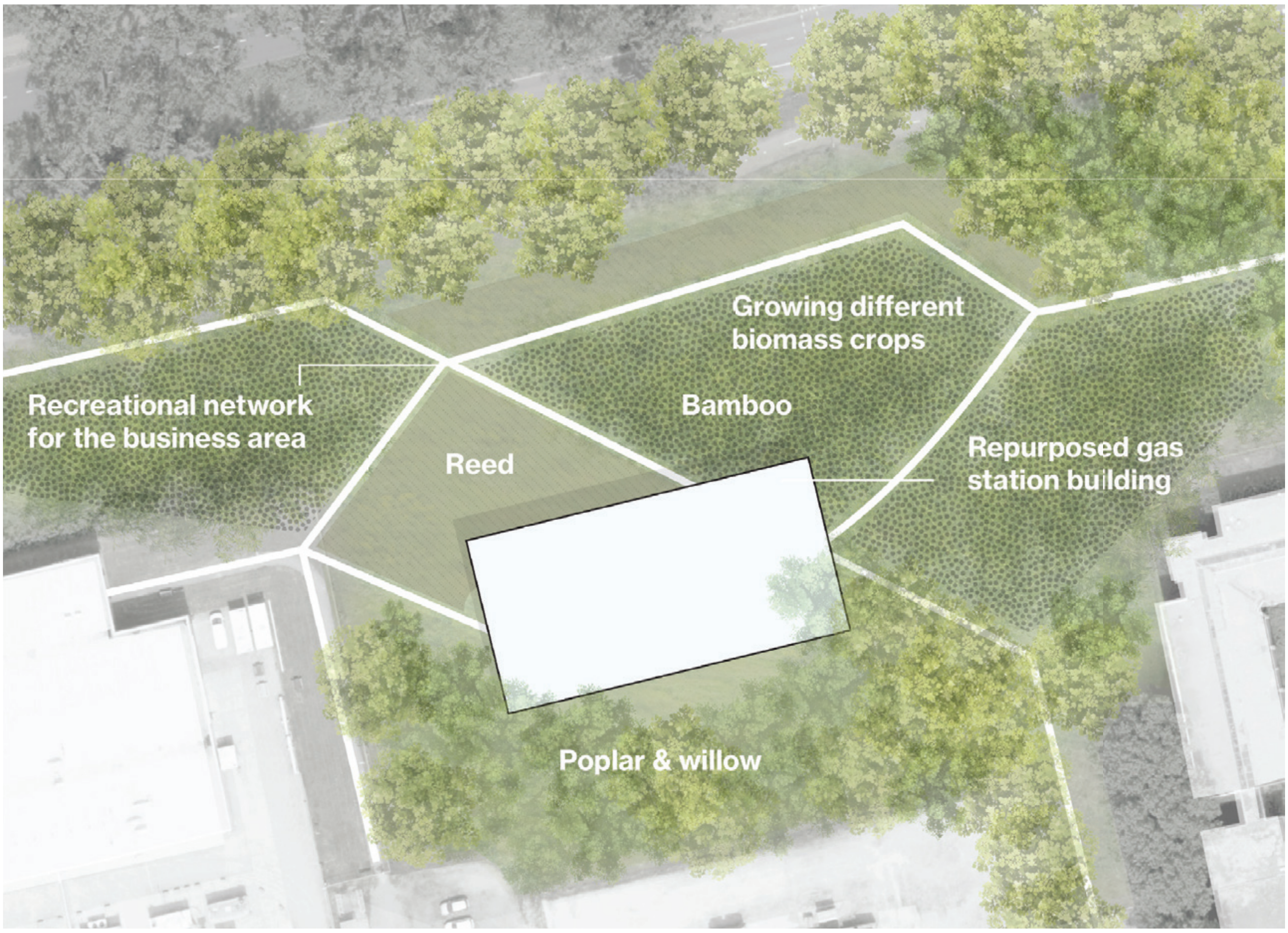


Figure 64: Plan view of alternative model 2

Westervoortsedijk

The following pages discuss the site design for the gas station at the Westervoortsedijk, Arnhem.


Power
Performance Fuels
Shell
V-Power
Performance Fuels
2
1
8
7
Voor uw veiligheid
PAK'N BAK

Natural connector

The conceptual diagram in figure 65 shows how the site is connected to the host landscape. Through the transformation of the site it becomes a new green connection space for the area. It is connected to a green network that spreads throughout the industrial area. The network consist of existing green spaces and adding new ones combined with a path system.

As can be seen in the visualization in figure 64, the final design for the station at the Westervoortsedijk repurposes the existing canopy construction. The canopy will be closed off on all sides and turned into a building. The path towards the building highlights the view onto the wind turbine and industrial buildings in the background. The canopy at the Westervoortsedijk is one of the largest in Arnhem, and the total building will have a footprint of about 1000 m2. This surface area can be turned into a space for connection and social interaction. The design proposes an event and exhibition space combined with a cafe. This can be used by companies near the site, and it also invites people from outside the area to come to this part of Arnhem. Through that interaction between innovative businesses and the residents can be fostered.

In the following pages, the design is presented through a master plan and a section.

Figure 65: Visualisation of the transformed gas station site

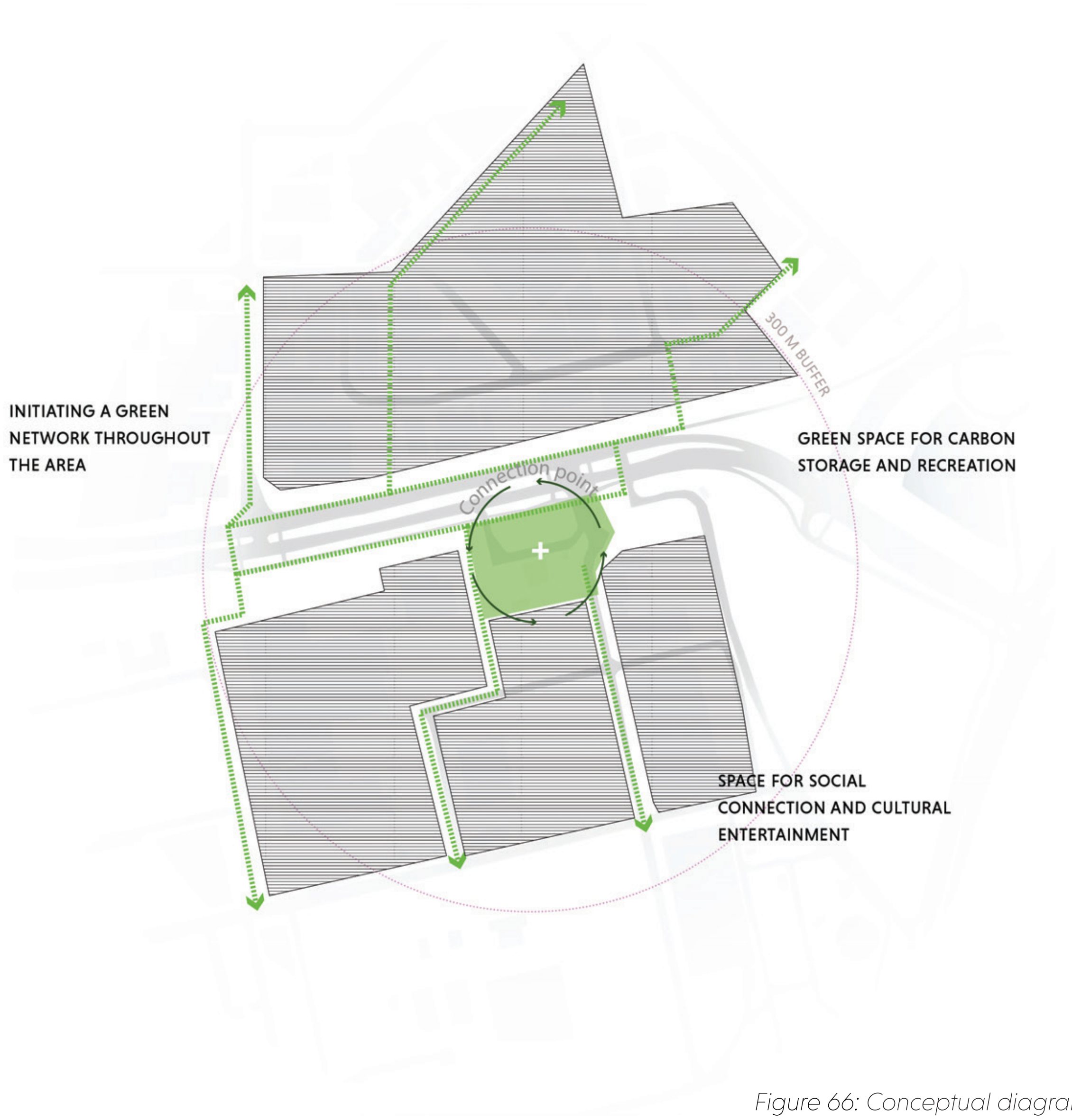


Figure 66: Conceptual diagram

Bamboo plantation

As can be seen in the site plan, the outside space of the site will be transformed into a park-like space that also has functional properties. The planting choice has been based on their potential to sequester carbon from the atmosphere and remediate the soil. For this site, bamboo has been chosen as the main species. It has the most promising CO_2 sequestration rate. After 8 years, about 275 t/ha/year can be removed from a bamboo plantation in temperate regions (Marchi et al., 2023). In comparison, a willow plantation only sequesters about 3.9 t/ha/y (Rytter et al., 2015).

The harvested biomass from a bamboo plantation can be used for manufacturing, such as the production of outdoor furniture for public spaces. However, it can also serve as an energy source for biomass power plants. In the design, the plantation frames the path system and creates a green space to roam during lunch break walks. The roof of the repurposed canopy hosts 500 solar panels, which can generate about 187178 kwh/y.

Repurposed canopy with solar panel roof

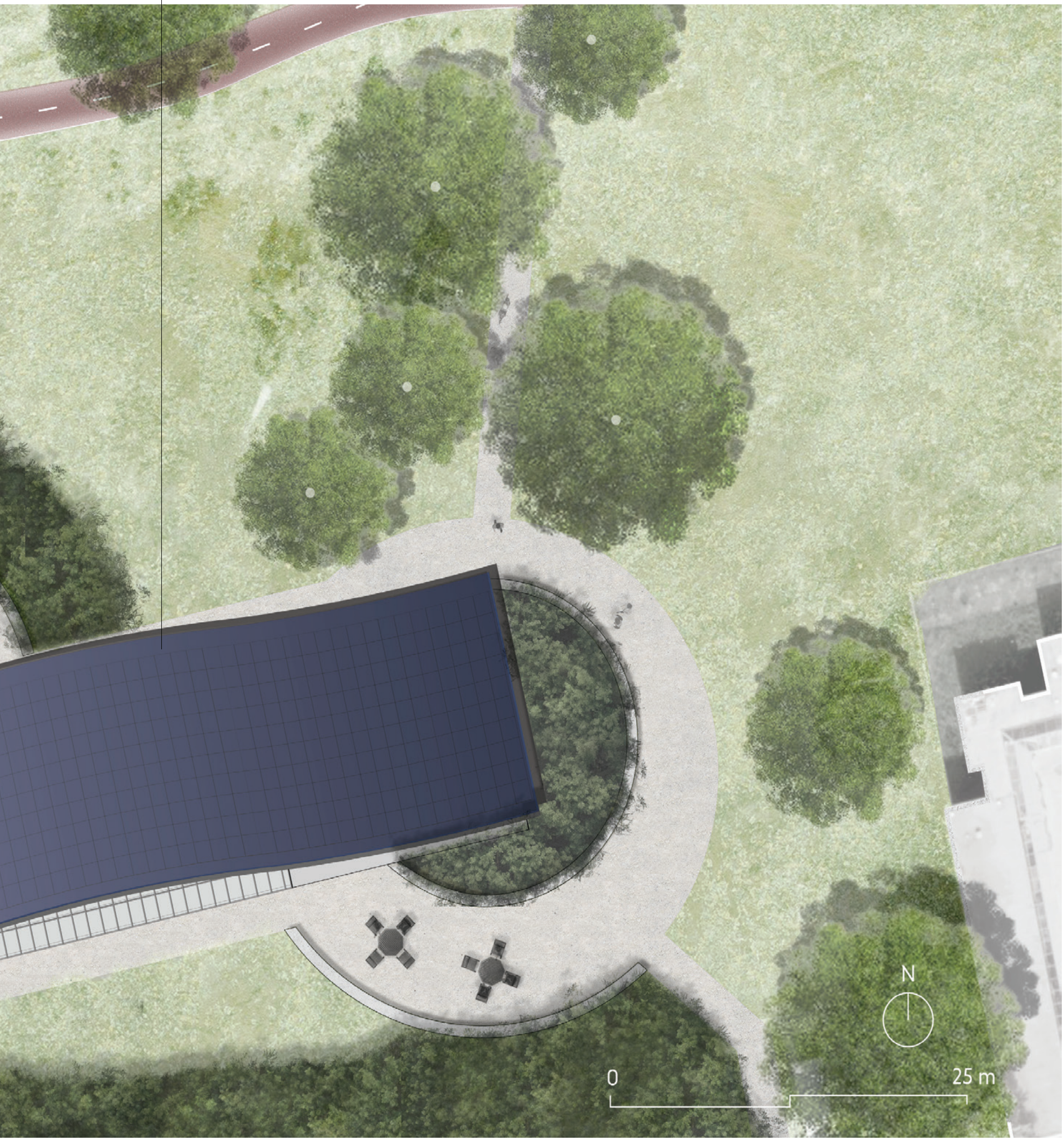


Figure 67: Site design master plan

The section shows how the converted canopy can be used inside. The design proposes a social space that can host small events such as concerts or exhibitions and meetings.

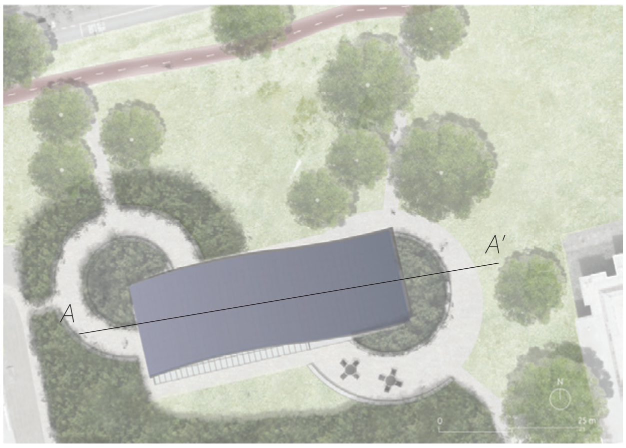
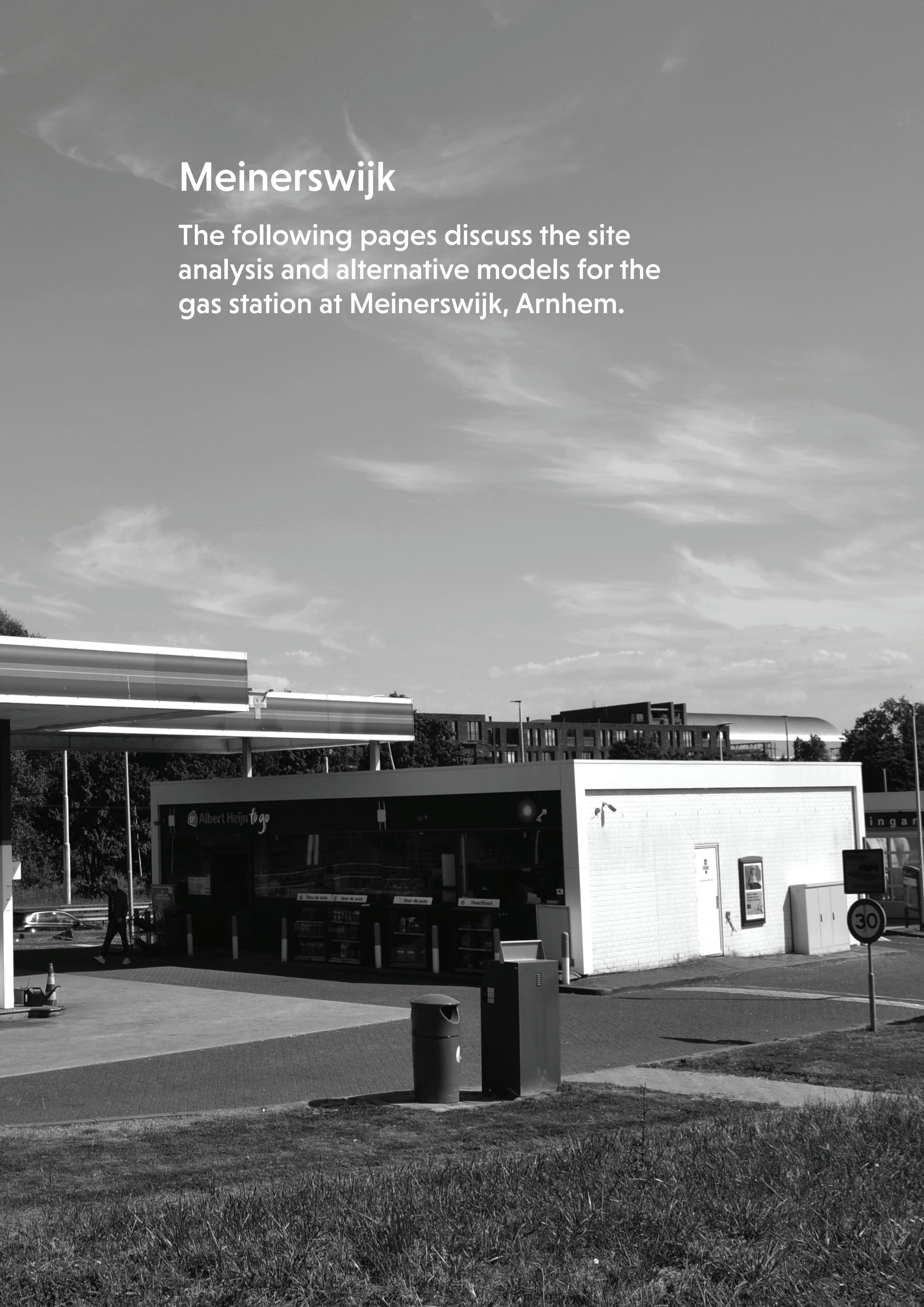


Figure 68: Site design section


autogas
ultimate
ongelood
diesel

Meinerswijk

The following pages discuss the site analysis and alternative models for the gas station at Meinerswijk, Arnhem.



5.3.3 Meinerswijk (GS20)

SITE ANALYSIS

The site belongs to the non-built host landscape type and is situated adjacent to the nature area of Meinerswijk in Arnhem.

The site itself is located along a dike between a residential neighbourhood to the east and a nature area to the west. The site is accessible via the bicycle path. The path runs along the dike and is used by recreationists visiting the nature area as well as by people commuting daily between the south of Arnhem and the city centre.

The experience of the site is influenced by the presence of the nature area. However, when cycling along the bicycle path that runs next to the site, you have a twofold experience. On the one hand, you enjoy being close to the nature area, but on the other hand, you cycle next to a busy road that is noisy and unpleasant. The road also makes accessing the nature area from the residential area on the opposite side of the road less intuitive. There are attempts to visually connect the residential area with the nature area through a viewing tower. The findings of the experience-based analysis, including photographs, can be found on the next page in the figure 75.

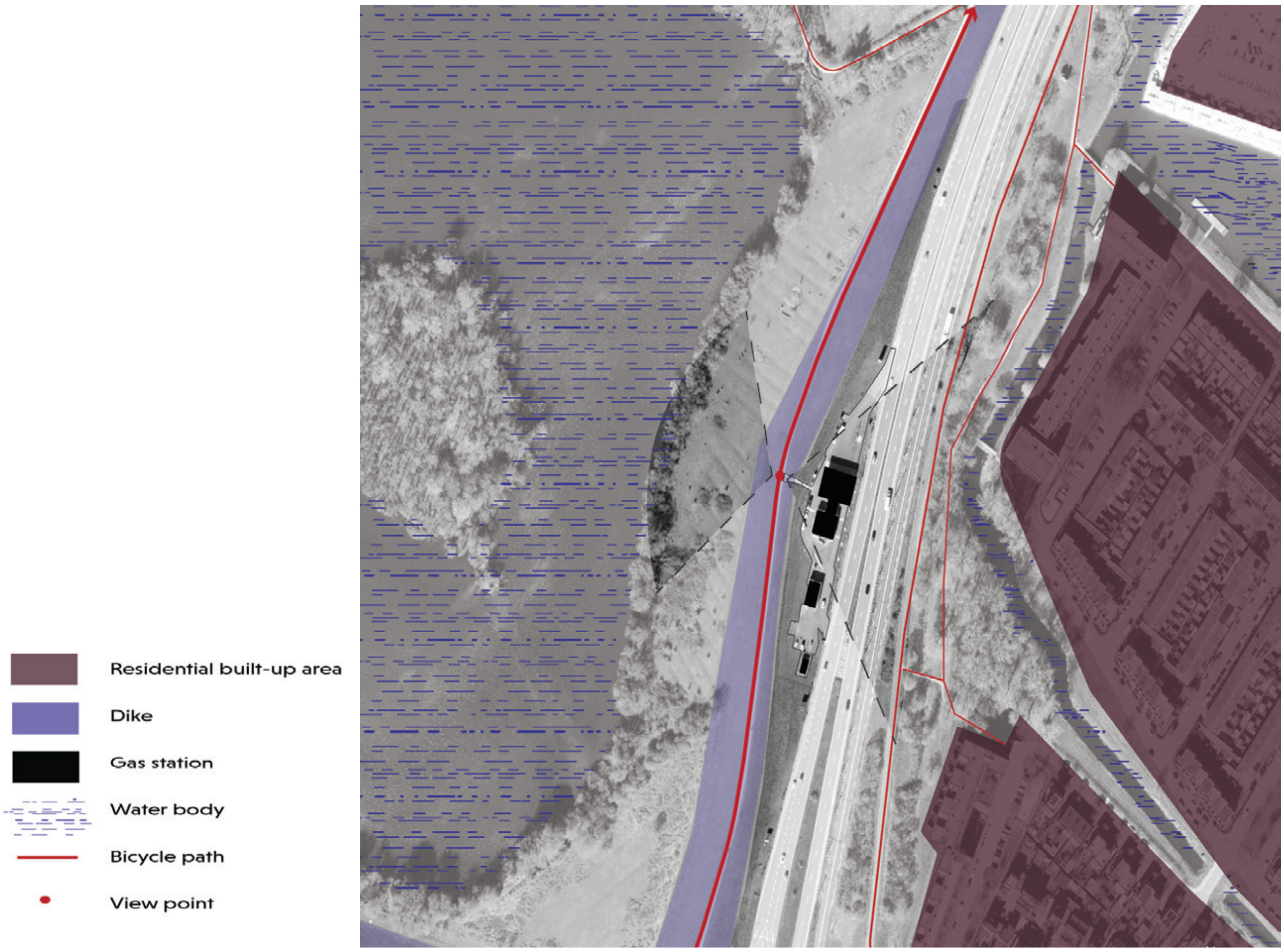


Figure 69: Host landscape analysis based on land use analysis

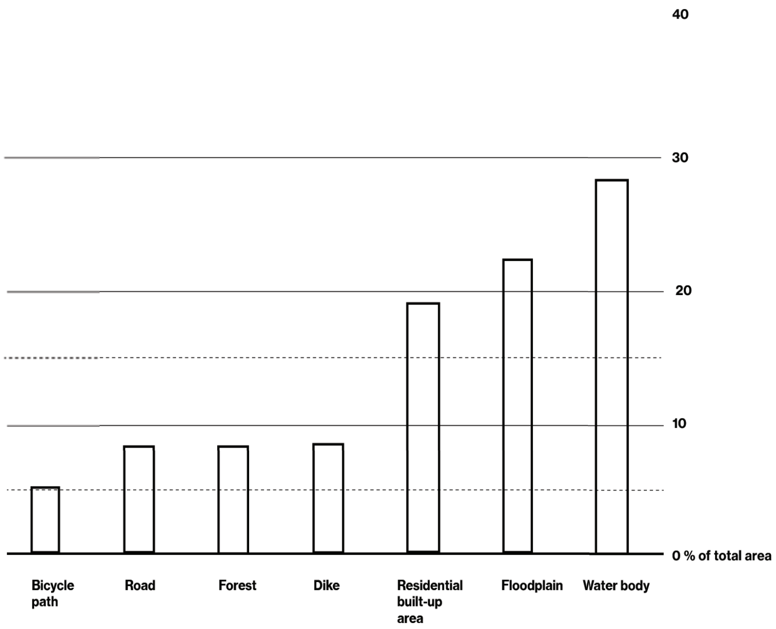


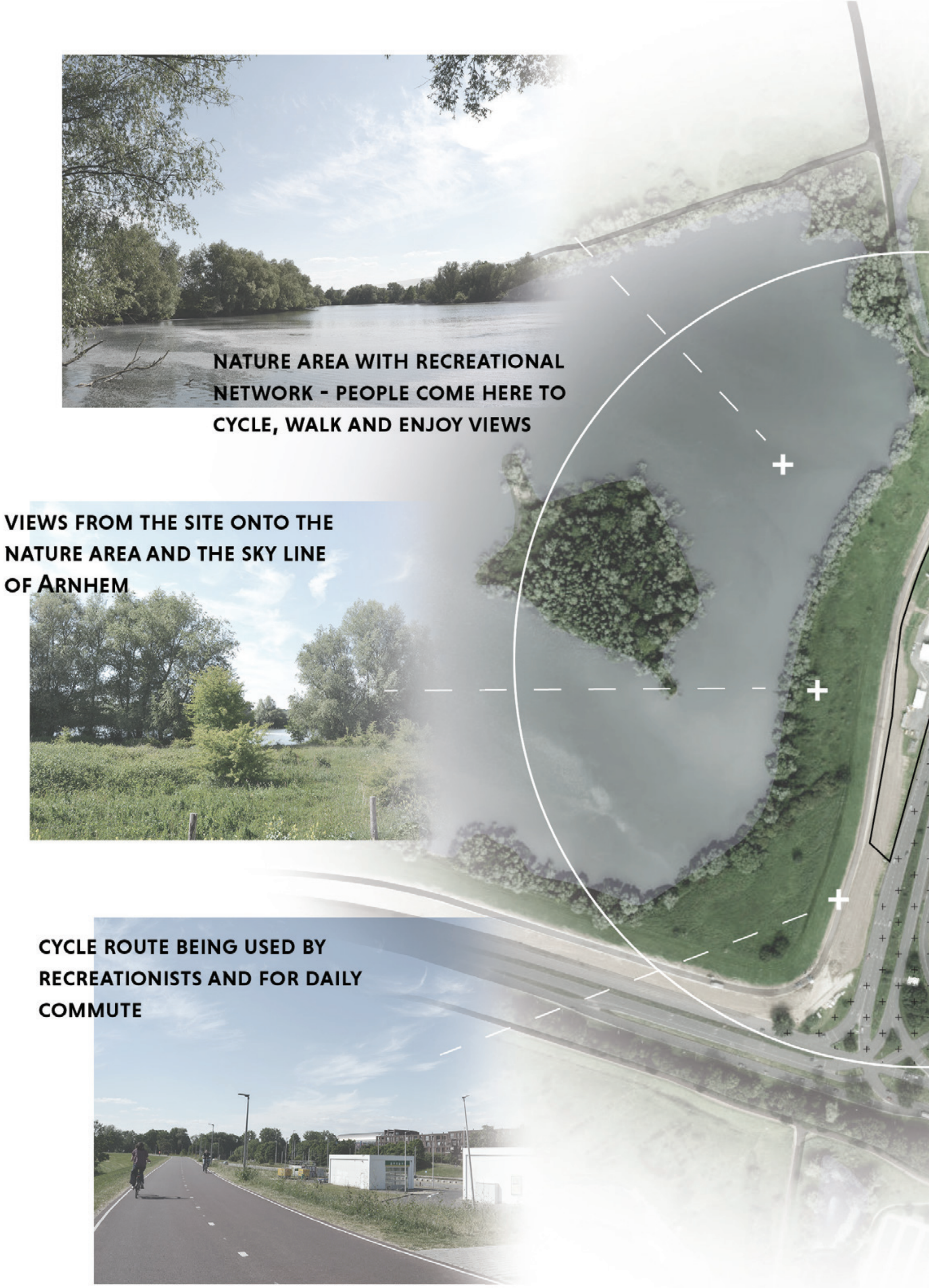
Figure 70: Graph summarizing the land use analysis of the host landscape of Meinerswijk

Figure 71 Photograph of view onto the nature area from the site

Figure 72: Photograph of the canopy

Figure 73: Photograph taken at the entrance of the nature area

Figure 74 Photograph of cycle path


NATURE AREA WITH RECREATIONAL NETWORK - PEOPLE COME HERE TO CYCLE, WALK AND ENJOY VIEWS
VIEWS FROM THE SITE ONTO THE NATURE AREA AND THE SKY LINE OF ARNHEM
CYCLE ROUTE BEING USED BY RECREATIONISTS AND FOR DAILY COMMUTE

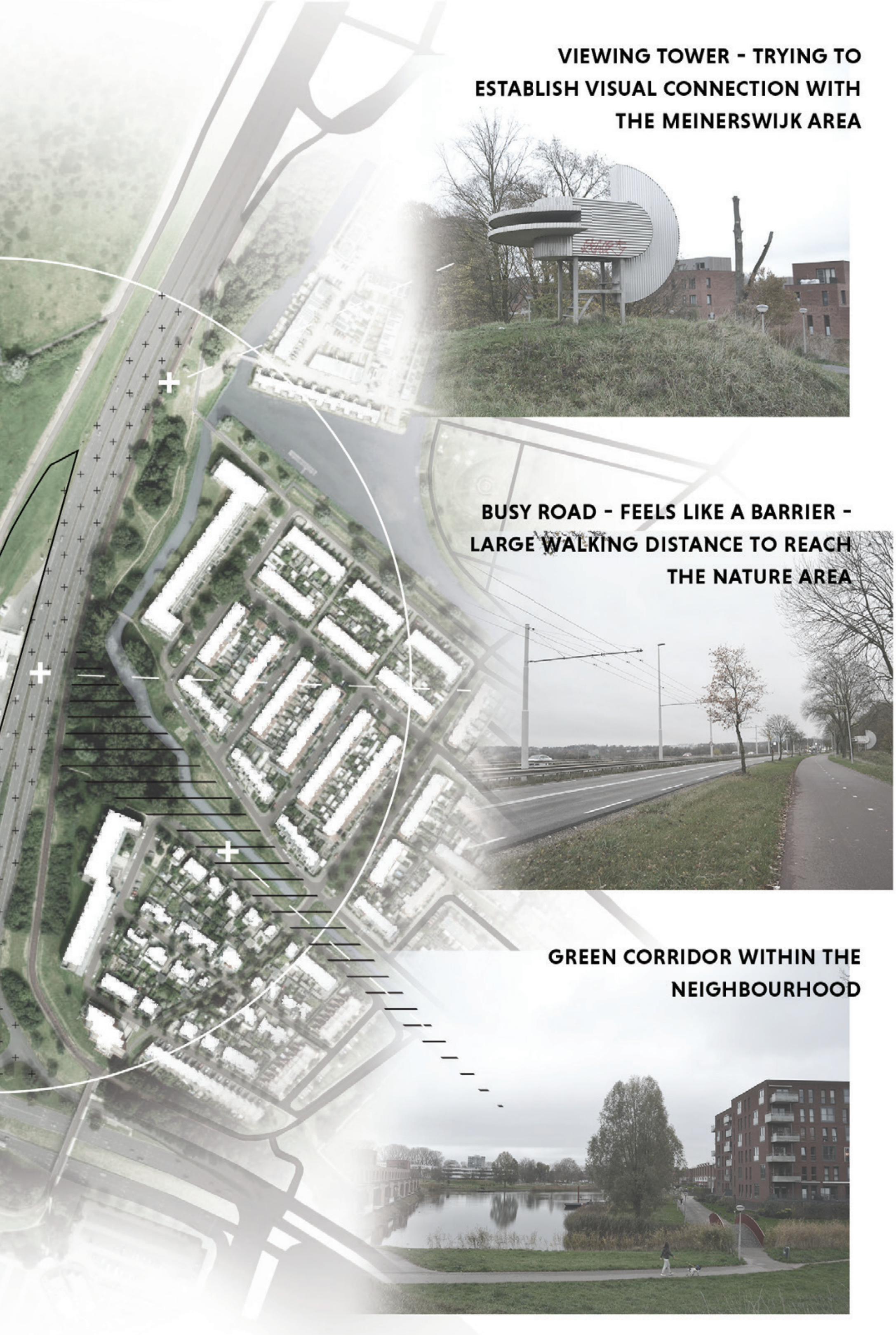


Figure 75: Summarizing the insights from the field visit/ qualitative host landscape analysis

What spatial qualities does the site hold?

EVALUATION RESULTS

To reveal existing spatial qualities of the site, the current sites have been evaluated by the 9 experts in the spatial quality assessment. The result of this evaluation is shown in the figure below. The figure on the next page shows a collage of the current site. Materials and individual elements have been collected in photographs to encapsulate the atmosphere of the site.

The third site also scores insufficiently in all four dimensions of spatial quality. Compared to the other sites, it scores highest in experiential, ecological, and long-term quality. This may be explained by the fact that the site is part of the dike and features some green space, as well as its location on the city's edge.

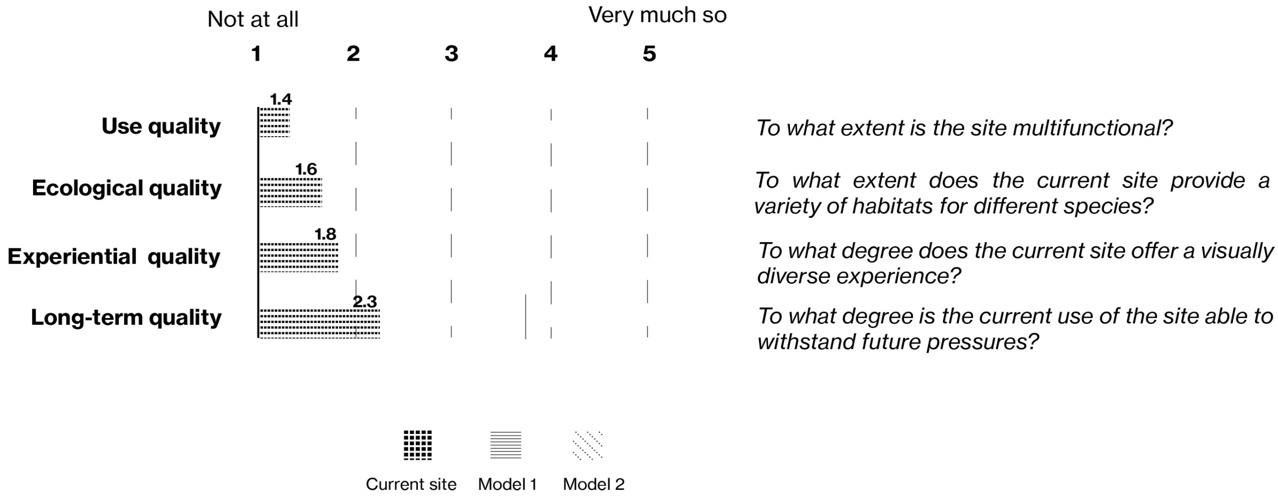


Figure 76: Outcome of the expert assessment of the current site (Meinerswijk) including the questions from the questionnaire

Figure 77: SIte collage

Meinerswijk first alternative: energy landscape experience

DESCRIPTION

The first alternative transforms the site into a resting stop with two viewpoints. One towards the solar arrays and the wind turbine, and another one onto the lake. This is illustrated in the section and plan view in figure 78 and 80 respectively.

The site will employ three strategies: solar arrays and wind turbines, which can produce about 384332 kWh per year (159 households), and a battery to store 60000 kWh on-site. The is covered with a wild flower meadow, which promotes the remediation of the soil and can sequester about 2.1 tons of CO_2 per year.

In the centre of the site, the elevated resting stop is located. The elevation of the dike is continued onto the site to create a half-circle. The resting stop consists of a flowerbed and a path that makes it accessible from the bicycle path. An elevated path crosses through it and connects the site with the nature area, creating another viewpoint.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 79. The first model, shows the greatest improvement in experiential and use quality. However, the ecological quality remains relatively low when compared to the second model. The total score of this model is 15.6.

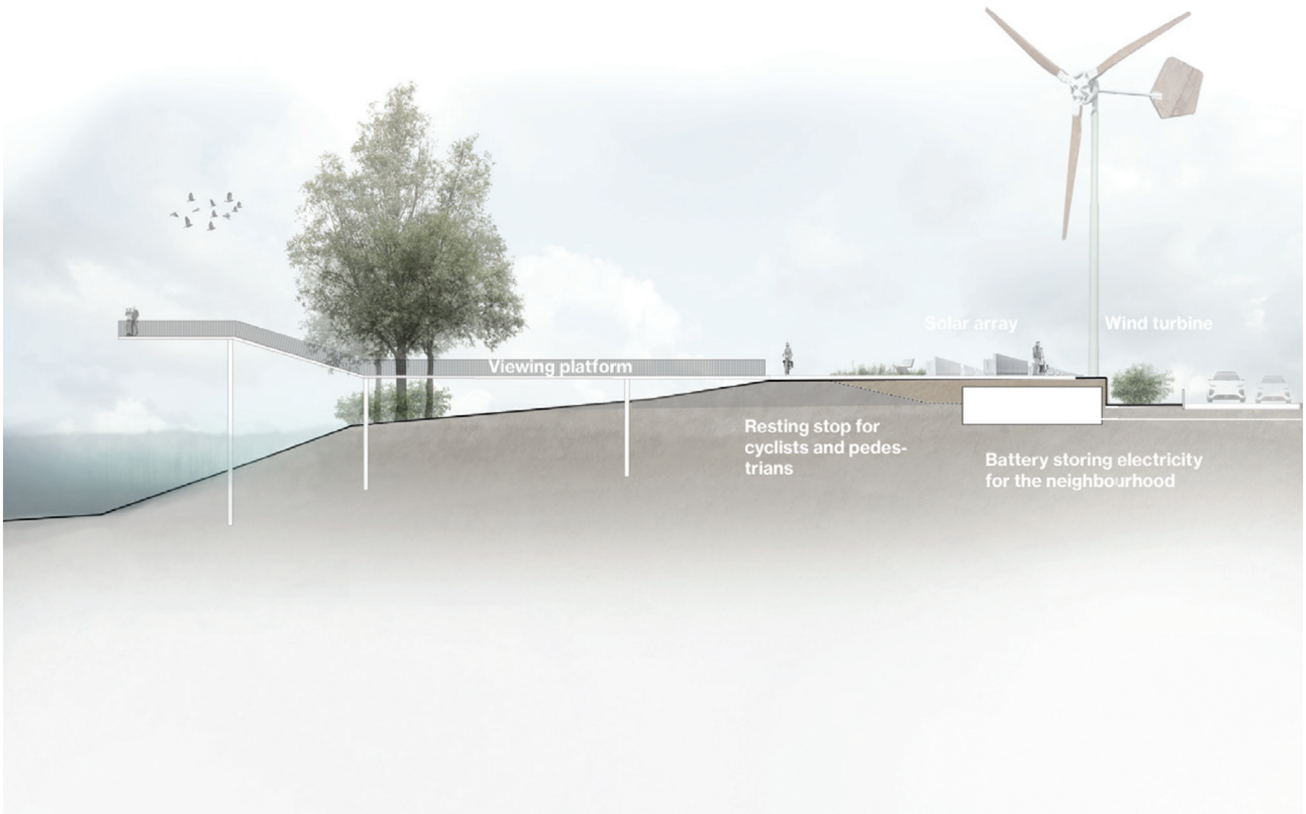


Figure 78: Section illustrating the design proposal of alternative model 1

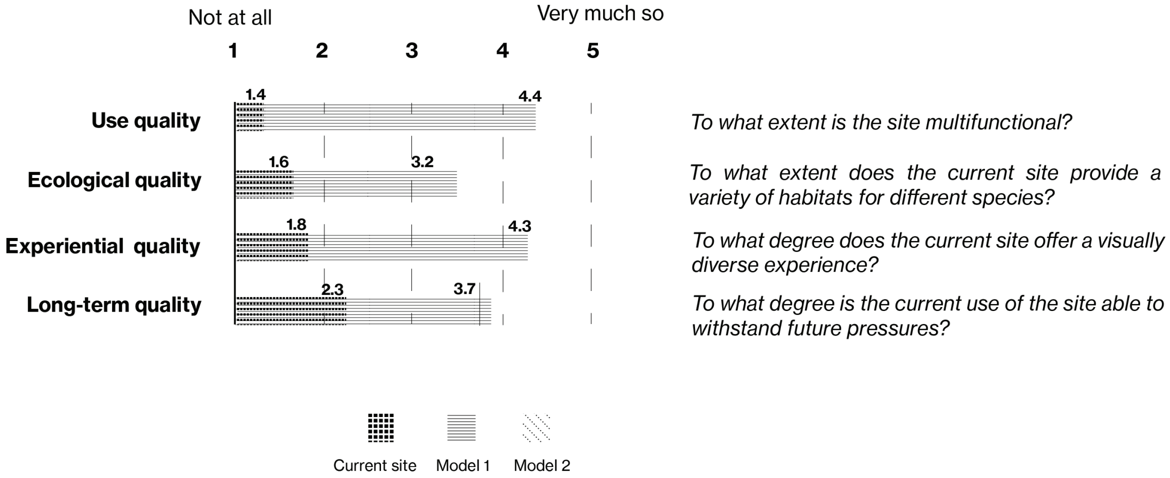


Figure 79: Outcome of the expert assessment of alternative model 1 including the questions from the questionnaire

Figure 80: Plan view of alternative model 1

Meinerswijk second alternative: forest as a barrier

DESCRIPTION

In the second model, a forest is being planted. The forest can create a visual barrier between the landscape user and the road, which creates a more pleasant and diverse cycling experience. This is illustrated in figure 81 and 83. It also functions as carbon capture, sequestering approximately 7.7 tons of CO2 per year, and creates possibilities for wildlife habitats. The resting stop and viewing platform remain unchanged from the first model. The strategy used in this model is Afforestation.

EVALUATION RESULTS

The results of the expert assessment of this model is visualized in figure 82. The second model for the site at Meinerswijk shows the highest improvement in ecological quality. However, the other dimensions score relatively low. The total score of this model is 15.2, which is lower than that of the first model. Based on that, the first model has been chosen for the site design.

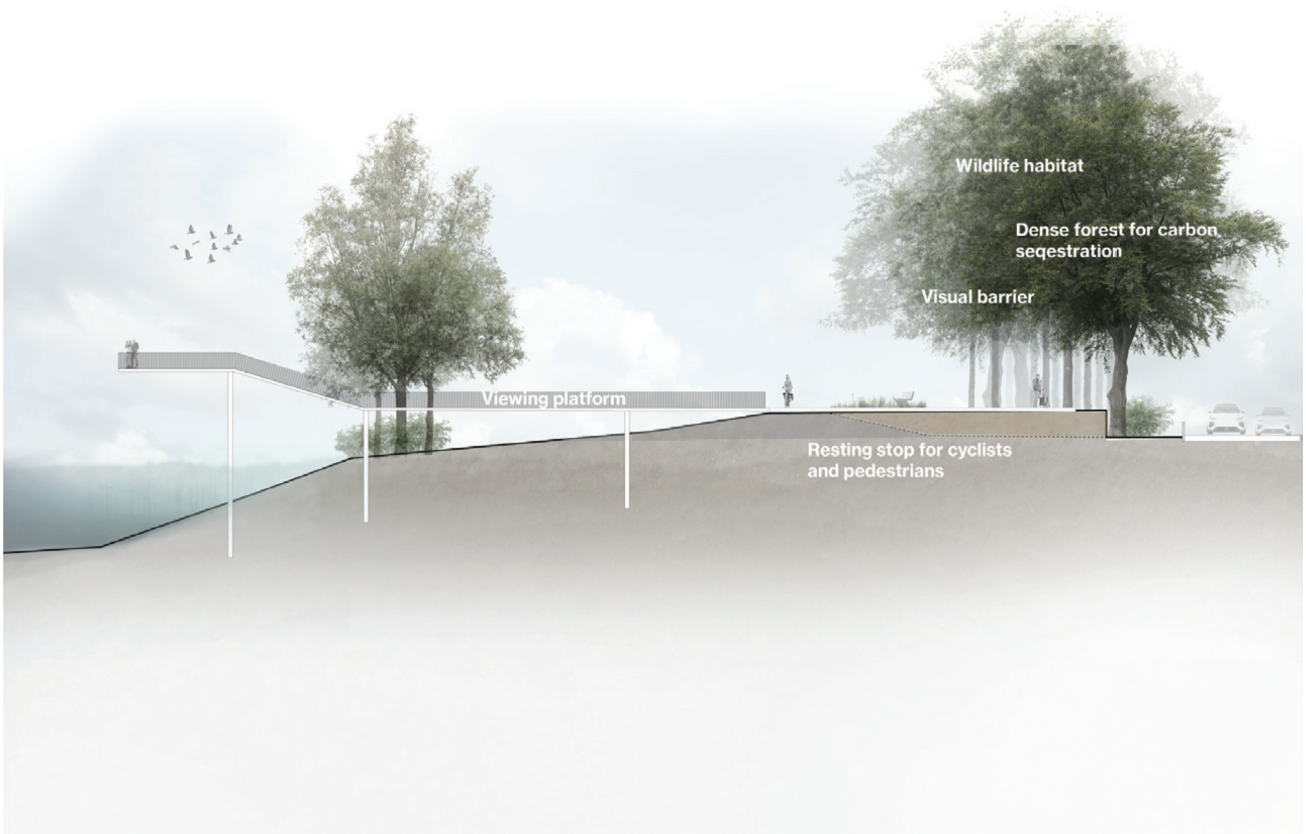


Figure 81: Section illustrating the design proposal of alternative model 2

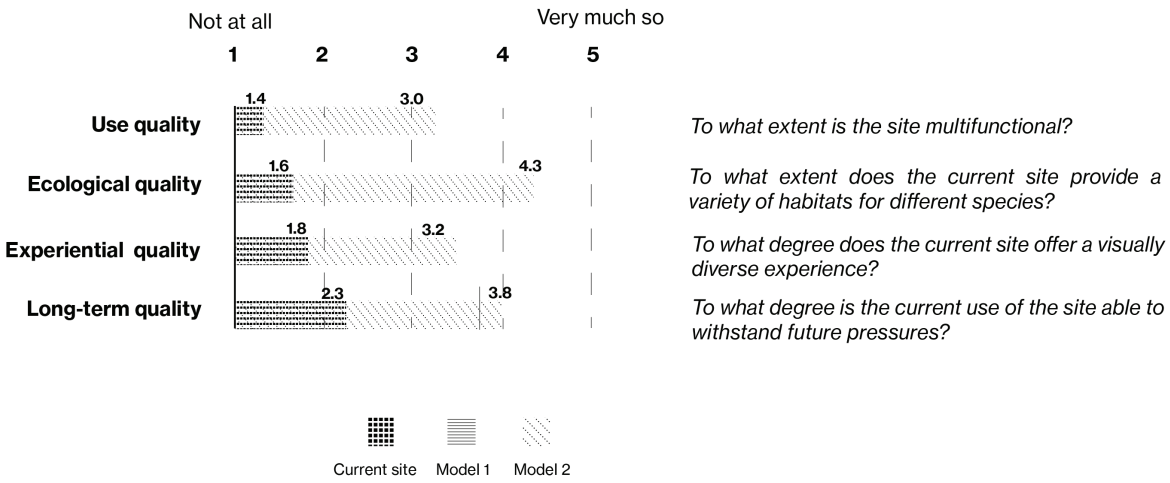


Figure 82: Outcome of the expert assessment of alternative model 2 including the questions from the questionnaire

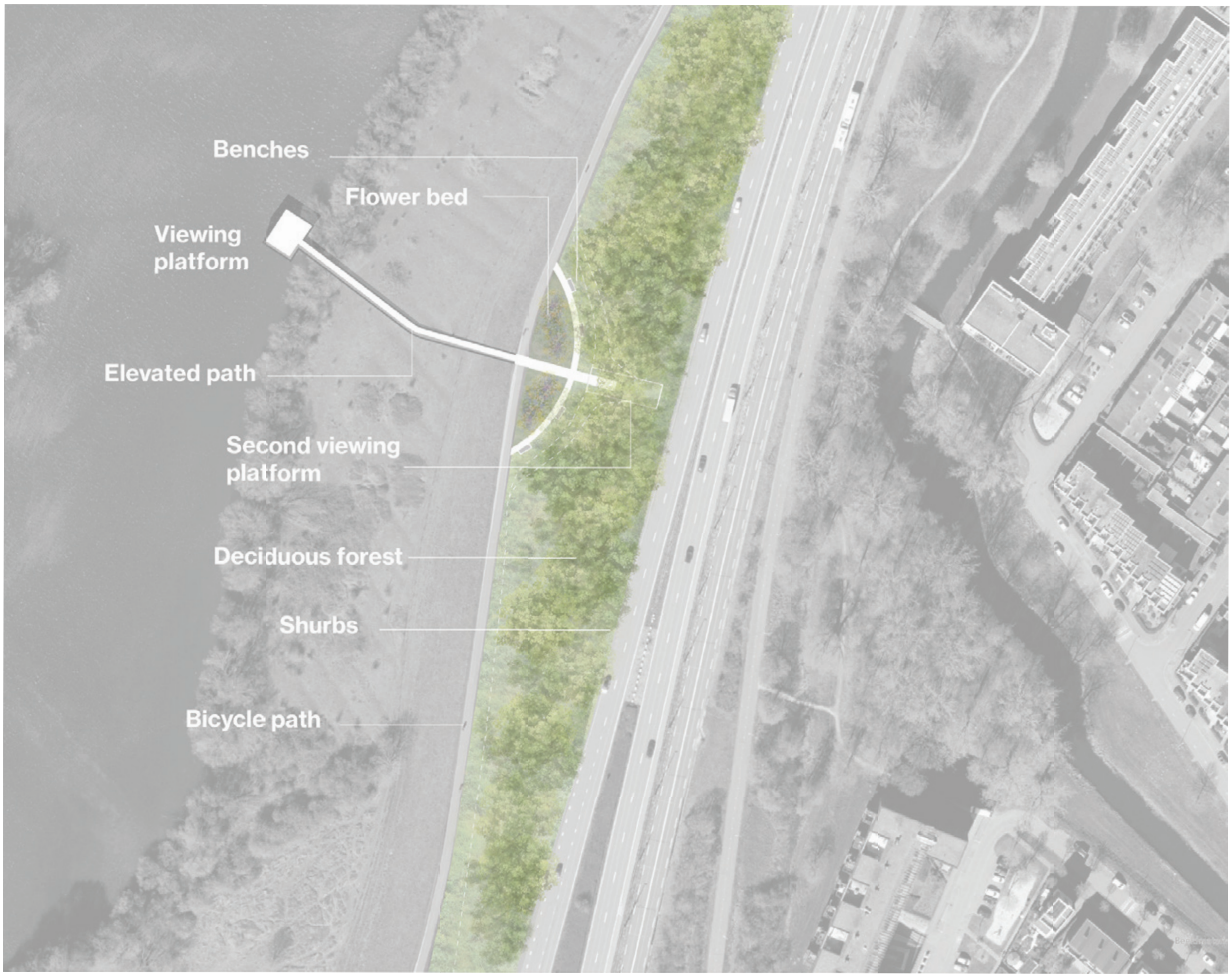


Figure 83: Plan view of alternative model 2

Meinerswijk

The following pages discuss the site design for the gas station at Meinerswijk, Arnhem.


Arnhem
Meinerswijk
- Vrij wandelen.
- Opengesteld van zonsopkomst tot zonsondergang
- Verboden voor gemotoriseerd verkeer behalve aanwonenden.
- Verboden voor honden.
- Naaktrecreatie verboden
- Overigens verboden toegang.
ART. 461 W.v.S.
Begrazingsgebied
Meinerswijk
Arnhem
In dit natuurgebied lopen vrij levende kuddes runderen en paarden. De dieren kunnen onvoorspelbaar reageren.
Voor uw eigen veiligheid en het welzijn van de dieren:
Honden niet toegestaan
25 meter
Houdt minimaal 25 meter afstand van de dieren
Doorkruis de kuddes niet
Voer of aai de dieren niet

Landscape link

The conceptual diagram in figure 48 shows how the site is connected to the host landscape. Through the transformation the site can become a landscape link linking the neighbourhood with the nature area. By bridging the road and creating a viewing platform enjoying the local landscape becomes more accessible for the residents. Additionally, the experience of cyclists is enhanced through a visually divers cycling experience featuring the renewable energy landscape, wind flower meadow and a resting stop inviting to visit the viewing platform. In figure 83 a visualization of the cyclist experience is presented.

In the following pages the site plan and section are presented which show the full transformation of the site.

Figure 84: Visualization of the landscape experience from bicycle path

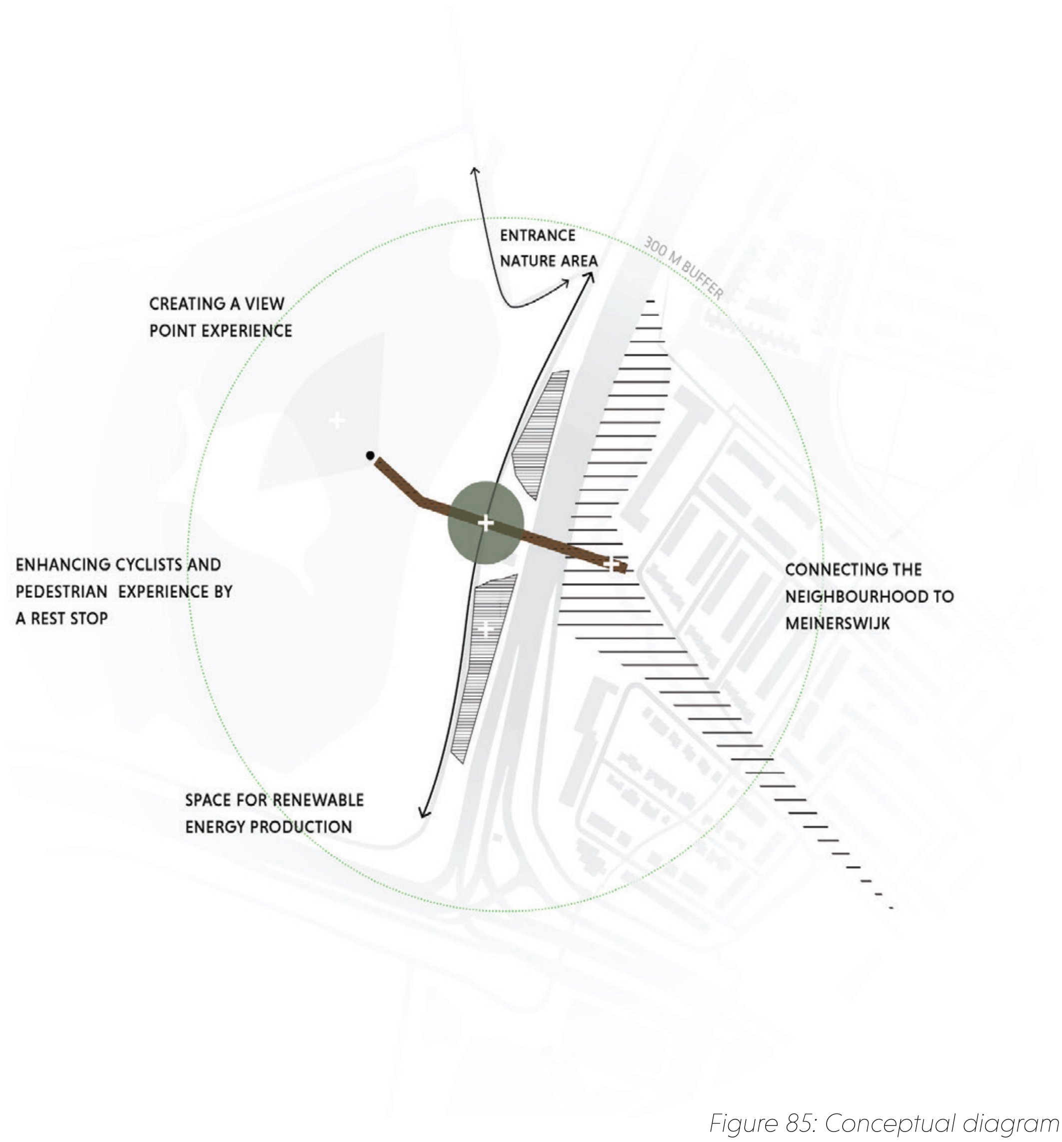


Figure 85: Conceptual diagram

The transformation of the station at Meinerswijk proposes a resting stop for cyclists and hikers. It is surrounded by a wildflower meadow that hosts vertical bifacial solar arrays and three small wind turbines. On the east side of the resting place, a small building provides a protected space for battery storage. The wooden construction is integrated into the elevation of the resting stop and extends the path on its roof. Here, visitors can enjoy the view of the solar arrays, which are oriented towards this point. The roof of the building transitions into a bridge connecting the neighbourhood to the site and the nature area. The resting stop includes wooden benches with taller backs to provide shelter from the noise, and a path system that crosses a flowerbed where wooden poles are placed. The poles serve as habitat for insects that can feed on the flowers. Extending from the resting place, a wooden elevated path offers a viewpoint onto the lake.

Through the addition of solar arrays and wind turbines, the site will be able to provide the neighbourhood with 384332 kWh of electricity per year. This is about the same amount as 159 households would use based on the current electricity demand. The storage capacity of the battery is estimated to be 60000 kWh. The wildflower meadow has the ability to sequester approximately 3 t of CO_2 per ha per year. Translated to the size of the site, the meadow stores about 2.1 t/y.

Figure 86: Site design master plan

The section shows how the elevated path extends towards the nature area proving a viewing point, how the resting stop extends the dike, as well as the wooden building that can host the battery storage.

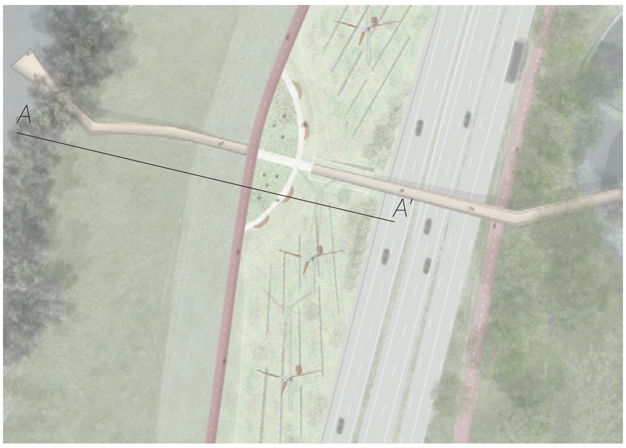


Figure 87: Site design section

5.4 Design principles

The design principles shown in the table summarise the outcome of the thesis. They show how gas stations in urban and peri-urban environments can be transformed to contribute to climate neutrality and the spatial quality of the site. The principles are subdivided into three columns and four rows. The columns indicate the functions that can be implemented, and the rows show which part of the gas station will be repurposed by each new function. The main components of the gas stations that are reusable are: the excavation of the tanks, the surface area that becomes available, the canopy/building and the location, including its site-specific characteristics.

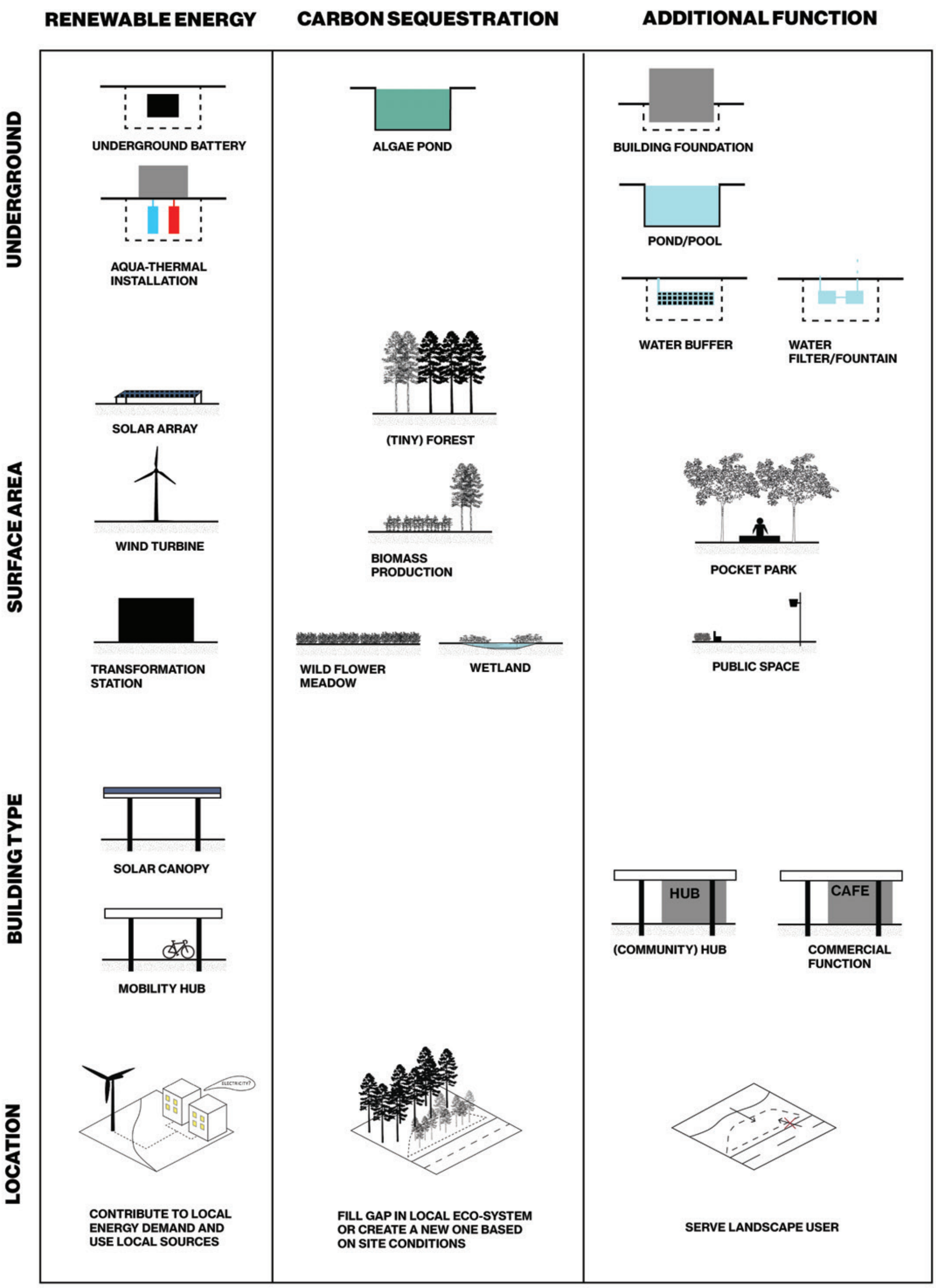


Table 9: Design principles

5.5 Generalizability and projection of results

GENERALIZABILITY

This section explores the application and capacity of the transformation approach for other sites in Arnhem. It discusses the generalizability of the proposed solutions and provides a quantitative estimation of the capacity of the 28 sites based on the number calculated for the three site designs.

Through the application of the typology, the following has become apparent: the host landscape type is not fine enough to provide a generalized approach. The type of residential area plays a big part in the type of solution that should be applied in residential gas station types. Denser urban areas have different requirements than lower-density neighbourhoods. Additionally, the kind of strategy that can be applied in different kinds of non-built areas also differs. If the site is located in a forest, it is challenging to implement solar arrays or wind turbines.

The landscape user is related to the host landscape but can have more specific needs based on site-specific characteristics that can be missed by the typology. This is why the landscape user's needs are included as a separate design principle. The same is true for the energy demand and supply. The host landscape can give an indication of this; however, individual characteristics that are not included in the typology should be considered in the choice of renewable energy strategy.

The transformation approach offers the most opportunities in residential and non-built host landscape types. There is less scarcity in space in industrial areas to implement measures for climate neutrality. However, it does offer the opportunity to add spatial qualities that are underrepresented in this type of environment, which can improve the work environment for people.

PROJECTION

To give a rough estimation of the capacity of the transformation of gas stations in the urban and peri-urban environment, a quantitative projection has been carried out. The projection has been calculated for the municipality of Arnhem and the Netherlands as a whole. The calculations of this estimation can be found in Appendix 4.4.

As mentioned in the introduction, there are about 4100 gas stations in the Netherlands. 3116 of the gas stations are located within urban and peri-urban areas (Mulder, 2025). This means that about 1212 ha of surface becomes available for contributing to the climate neutrality and spatial quality of urban areas. By using the three site designs as an estimation of how much renewable energy could be produced or CO2 sequestered, these numbers would be 462 GWh and 74057 t per year.
Estimating the potential contribution purely based on the amount of surface area, the numbers would be 1546 GWh per year for south-facing PV systems and 333239 t per year for bamboo monocultures.

When comparing the design solution to the potential contribution based on surface area, the design solutions score lower. What is missed by this comparison, however, is the qualitative contribution of the proposed solutions. By combining the functional aspects of the renewable energy production or carbon sequestration with other spatial qualities, such as biodiversity, a more diverse landscape experience can be created. By adding other spatial values, the transformation of a gas station can contribute to the living environment of people beyond functionality.

Figure 88: All location of gas stations in the Netherlands, map created using ArcGIS® software by Esri

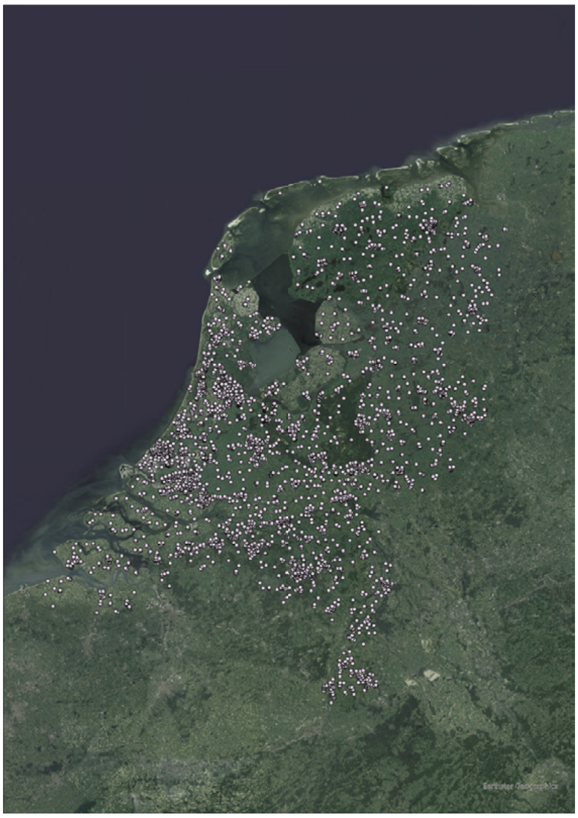


Figure 89: All location of gas stations in the Netherlands with in built environments, map created using ArcGIS® software by Esri

Figure 87: Photograph of the gas station signs appearing to be attached to the tree

Chapter 6: Discussion and conclusion

6.1 Discussion

This chapter reviews and discusses the methods used and results found. Furthermore, it offers recommendations on how future research can contribute to the pursuit of transforming fossil fuel land uses to contribute to climate neutrality.

TYPOLOGY

One of the results of this thesis is the typology of gas stations in Arnhem. In the following paragraphs, the results and methods of this part will be discussed.
This research did not study the entire population of gas stations. Still, within the municipality of Arnhem, the typology has proven useful as a distinction between different types. Within this municipality, several urban and peri-urban contexts are available, existing within different landscape types. This suggests that the typology can be useful for other cases and makes the findings of this study also relevant for other cities in the Netherlands. However, the application of the typology also revealed room for improvement. A generalizability of the transformation approach based on the types seems reasonable in only some cases. The three host landscape types seem too coarse to make a relevant distinction between the sites. For example, the type of residential area (high/low density) and type of non-built area (forest, meadow, etc.) might be a relevant addition.

Future research should investigate other cases throughout the Netherlands. Not only gas stations but also other fossil fuel land uses, and shed light on their post-carbon trajectory and spatial capacities.

DESIGN PRINCIPLES

Another outcome of this thesis is the design principles. The proposed design principles offer room to complement the generalized types with site-specific requirements in the transformation approach.
For example, the landscape user is related to the type of host landscape, but can have more specific needs based on site-specific characteristics that are overlooked by the typology. This is why it is included as a separate design principle. Fulfilling this principle might involve a more in-depth analysis than the one carried out in this research, for example, informed by landscape users through interviews.

The same is true for the energy demand and supply. The host landscape can give an indication of this; however, individual characteristics that are not included in the typology should be considered in the choice of renewable energy strategy. An in-depth energy demand and supply analysis informed by stakeholders might lead to a more substantiated proposal. However, this research gave prominence to the exploration of possible solutions and the construction of the typology rather than this particular aspect.

SCALE

The thesis focused on the scale of the gas station; however, to achieve climate neutrality, the whole system needs to be adapted. The gas station sites can only provide a piece of this system. Nevertheless, due to their prominence and widespread presence throughout the city, they offer opportunities to contribute to this system change.

DESIGN EXPLORATION AND STRATEGIES FOR CLIMATE NEUTRALITY

The design exploration has been carried out only with three sites. This means that other solutions might be thinkable with other sites. The design programming was limited to the key strategies outlined in the Dutch government's climate plans. These plans included limited real-life examples. By exploring international strategies and examples, the perspective could have been broader. However, by using the strategies from the climate plans, the applicability of a strategy for the study area could be ensured.

Furthermore, they are based on the policy ambitions of 3 municipalities and one province, which means that the list of possible solutions might not be complete, and other solutions might be thinkable or even desirable. The climate plans have been written from a policy perspective and not a spatial perspective. Strategies related to the spatial dimension have been selected as possible solutions; however, their translation into actual spatial interventions depended on the researcher's interpretation.

TESTING AND EVALUATION

For the evaluation of the alternative models, experts in landscape architecture have been chosen. However, as mentioned previously, the implementation of new land uses would benefit from input from landscape users, as this can increase social acceptance of the proposed intervention. Additionally, including landscape users in the analysis phase could have revealed the importance of certain functions the site provided that are invisible to outsiders.

Another aspect that is relevant to discuss is that landscape architects are not experts in ecology. For a more reliable evaluation of the effect of the interventions on the biodiversity, ecologists would be necessary. However, landscape architects are seen to have an understanding of a wide range of natural and social processes and can bridge the gap between science and practice (Nassauer, 2023). Additionally, the goal of the evaluation was not to fully understand the effect of the proposed interventions on biodiversity, but to discover the potential of each model to improve the spatial quality of the site. Furthermore, the timeframe of the research was restricted, and the decision was made to use accessible resources. For that reason, the choice of landscape architects and their overall understanding of landscapes and landscape interventions has been made.

This choice can result in potential biases. The experts consisted of students working on master's thesis topics related to energy/post-carbon landscapes and academic landscape architects researching them. This could mean they prefer energy- and post-carbon landscapes and would rate the transformation higher than the current situation based on this preference.

RELEVANCE

The outcome of this thesis is believed to be relevant to the wider field of (academic) landscape architecture based on the following reasoning:
By exploring alternatives for gas stations, awareness can be raised on the trajectory of this land use. Within the near future, these sites will lose their economic relevance and might become vacant. Vacancy contributes negatively to the community's well-being (Garvin, 2013). By offering options to transform these sites and give them a new, future-proof function, this threat can be mitigated. By connecting the need for spatial transformation with its effect on the perception of spatial quality, we can enhance people's living environments and create new, meaningful places.

Gas stations can be seen as part of the oil energy landscape, more specifically, the storage and distribution component of it (Pasqualetti & Smardon, 2025). In their paper, Pasqualetti and Smardon (2025) highlight the potential and necessity for recycling these energy landscapes. This thesis can add to the pursuit of identifying and transforming energy landscapes to contribute to the sustainable use of limited land resources. It should be further investigated how these landscapes can be transformed to contribute to climate neutrality.

Further studies should also put emphasis on translating climate plans into actual spatial interventions. By exploring it through a design study, the effect on spatial quality can be studied before the actual implementation. This enables the discovery of inventions that can enhance the living environment and foster public support. Through the translation of the policy strategies into actual spatial interventions, their limitations can be uncovered and recommendations for improvement made.

6.2 Conclusion

This section of the final chapter recapitulates the conclusions that can be drawn per sub-research question.

SRQ1: What are the locations and characteristics of gas stations in the urban and peri-urban environment of Arnhem?

The GIS analysis and field work have revealed 31 gas stations within the municipality of Arnhem. Of these 31, 28 have been classified as suitable for the research objective, as they are within municipal boundaries and not located along highways. These 28 together occupy about 7 ha of surface area. Common characteristics have been identified that have led to the construction of the three host landscape classes. These host-landscape classes entail information that can guide the transformation of the sites by revealing potential landscape users. It also contains information on energy demand and supply. The non-built class, for example, often includes waterbodies that can serve as heat sources for the heat network. The industrial classes have a high energy demand in their host landscape and may offer opportunities for denser energy solutions. The outcome of the analysis has been collected in an inventory that provides the necessary details to inform the second research question. The residential host landscape class, however, might demand greater attention to the site's accessibility and multifunctionality.

SRQ2: What typology of gas stations in the urban and peri-urban environment of Arnhem can be defined?

The study proposes a typology to distinguish between gas stations in the urban and peri-urban environments of Arnhem. The distinction is based on the host landscape types in which the gas station is situated. Secondly, for the size of the project extent, a distinction has been made between larger to medium-sized gas stations and smaller gas stations. The presence or absence of a canopy construction represents the third layer of distinction. This resulted in 12 different types in the municipality of Arnhem.

The proposed typology contains information that can guide the future use of the site through the host landscape types. These can indicate the demand and supply for renewable energy, the kind of solutions that can be applied, and the potential landscape users. The size is a relevant factor as it can determine the suitability for new functions, and the availability of a canopy or building on the site also provides opportunities for reuse.

SRQ3: Which strategies for climate neutrality can be used to transform which type of gas station?

To answer this research question, a suitability framework has been developed. This framework can be used to assess the suitability of each site. The strategies have been extracted from Dutch governmental climate plans and translated into three site designs. Based on this research, the strategies that seem most suitable for industrial sites are biomass plantations, which require limited maintenance and thus offer a way to integrate more greenery into industrial areas. They also offer multiple benefits, such as soil remediation, and can be used as an energy source. For the residential types, the mobility hub seems a suitable option. They are often located near bus stations or train stations and are easily accessible to pedestrians. Their surface area is smaller than that of the other two host landscape types, which limits the implementation of solutions for renewable energy. Non-built sites offer the greatest flexibility for implementing renewable energy strategies. They are more often located next to water bodies, which can be used for renewable heat extraction, and generally have a larger surface area, allowing the implementation of solar power plants or wind turbines.

SRQ4: How can the strategies for climate neutrality be applied in the transformation of gas stations to contribute to the climate neutrality of the city and the spatial quality of the site?

The effect of the transformation has been evaluated by experts based on criteria for spatial quality. The results show that gas station sites can be transformed using key strategies for climate neutrality outlined in governmental climate plans. It has also been demonstrated that these strategies can enhance the spatial quality of the site. On a larger scale, transforming gas stations in the urban and peri-urban environment of Arnhem could create a new layer of public spaces that contribute to climate neutrality and improve spatial quality.

MRQ: In what way can the transformation of gas stations in the urban and peri-urban environment contribute to the climate neutrality of Arnhem?

The proposed design solutions for the three sites together can produce enough electricity for 259 households. When using this number as an estimate for the other 25 sites, the electricity produced would be enough for 1106 households. The application of nature-based solutions for carbon sequestration that has been used to transform the sites could sequester about 428 t/y.
Thus, the sites can contribute quantitatively but also qualitatively as the results of the evaluations have shown. This has been done by putting emphasis on the experience of pedestrians and cyclists.

General conclusion

The main findings of the study are the mapping of gas station sites in the municipality of Arnhem. This results in the visibility of this fossil-fuel-based land use, which can be transformed to contribute to climate neutrality. The total area of the 28 gas stations in Arnhem in the municipality of Arnhem alone is 7 ha. When extrapolating this number to the other 3116 gas stations that are located within the urban and peri-urban environment of Dutch cities, the amount of space that becomes available is about 1212 ha. This shows the potential of transforming this land use to contribute to the climate neutrality of urban areas.

The transformation of gas stations is explorative and speculative in nature. This design study demonstrates how various types of gas stations can be transformed and how their potential for contributing to climate neutrality differs.

Furthermore, the study shows that spatial transformation to contribute to climate neutrality can be combined with an improvement in spatial quality. The proposed solutions show how qualities such as biodiversity, multifunctionality, maintainability, and visual diversity can be combined with post-carbon landscapes. This shows that the transition from a fossil fuel-based society brings not only challenges for our cities but also the opportunity to improve our living environment.

7. Reference list

Statement: No text, images, or data in this report have been generated using AI tools. Grammarly has been used for spelling and grammar checks.

Bakx, M., Stremke, S., & Lenzholzer, S. (2023). Beyond landscape experience: A systematic literature review on the concept of spatial quality in flood-risk management. *Wiley Interdisciplinary Reviews: Water*, 10(5). https://doi.org/10.1002/wat2.1669

Deming, M. E., & Swaffield, S. (2011). Landscape architectural research : inquiry, strategy, design. In Landscape architecture research. Wiley.

Garvin, E., Branas, C., Keddem, S., Sellman, J., & Cannuscio, C. (2013). More than just an eyesore: local insights and solutions on vacant land and urban health. Journal of urban health : bulletin of the New York Academy of Medicine, 90(3), 412–426. https://doi.org/10.1007/s11524-012-9782-7

Gurney, K. R., Kılkış, Ş., Seto, K. C., Lwasa, S., Moran, D., Riahi, K., Keller, M., Rayner, P., & Luqman, M. (2022). Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100. *Global Environmental Change*, 73, 102478. https://doi.org/10.1016/J.GLOENVCHA.2022.102478

Hein, C. (2018). Oil spaces: The global petroleumscape in the Rotterdam/The Hague area. *Journal of Urban History*, 44(5), 887–929. https://doi.org/10.1177/0096144217752460/FORMAT/EPUB

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. Environmental Advances, 8, 100203. https://doi.org/10.1016/J.ENVADV.2022.100203

Lenzholzer, S., Duchhart, I., & Koh, J. (2013). 'Research through designing' in landscape architecture. Landscape and Urban Planning, 113, 120–127. https://doi.org/10.1016/J.LANDURBPLAN.2013.02.003

Marchi, M., Marchettini, N., Neri, E., Esposito, G., Niccolucci, V., Pulselli, F. M., Lajo, M., Rissone, E., & Pulselli, R. M. (2023). Carbon Footprint offset of a managed Bamboo plantation in temperate regions. Sustainable Production and Consumption, 40, 220–235. https://doi.org/10.1016/j.spc.2023.05.025

Nassauer, J.I. (2023) "Transdisciplinarity and Boundary Work for Landscape Architecture Scholars," Landscape Journal: design, planning, and management of the land, 42(1), pp. 1–11

Pan, C., Zhou, G., Shrestha, A. K., Chen, J., Kozak, R., Li, N., Li, J., He, Y., Sheng, C., & Wang, G. (2023). Bamboo as a Nature-Based Solution (NbS) for Climate Change Mitigation: Biomass, Products, and Carbon Credits. Climate, 11(9), 175. https://doi.org/10.3390/cli11090175

Pasqualetti, M. J., & Smardon, R. C. (2025). Recycling energy landscapes: Addressing the sustainable legacy of the world's largest enterprise. Energy Research & Social Science, 120. https://doi.org/10.1016/j.erss.2024.103906

Pereira, P., Wang, F., Inacio, M., Kalinauskas, M., Bogdzevič, K., Bogunovic, I., Zhao, W., & Barcelo, D. (2024). Nature-based solutions for carbon sequestration in urban environments. Current Opinion in Environmental Science & Health, 37. https://doi.org/10.1016/j.coesh.2024.100536

Rytter, R.-M., Rytter, L., & Högbom, L. (2015). Carbon sequestration in willow (Salix spp.) plantations on former arable land estimated by repeated field sampling and C budget calculation. Biomass and Bioenergy, 83, 483–492. https://doi.org/10.1016/j.biombioe.2015.10.009

Stahlschmidt, P. (2017). Landscape analysis : investigating the potentials of space and place. Routledge.

Stremke, S., Dobbelsteen, A. Van Den, & Koh, J. (2011). Exergy landscapes: exploration of second-law thinking towards sustainable landscape design. International Journal of Exergy, 8(2), 148–174

Weustenenk, A. G., & Mingardo, G. (2023). Towards a typology of mobility hubs. Journal of Transport Geography, 106, 103514. https://doi.org/10.1016/J.JTRANGEO.2022.103514

GOVERMENTAL CLIMATE PLANS

Gemeente Amsterdam (2020, march 3) Nieuw Amsterdams Klimaat 2050 [PDF] Openresearch.amsterdam.nl. Retrieved from https://openresearch.amsterdam/nl/page/55055/nieuw-amsterdams-klimaat-2050

Gemeente Arnhem (2019, october), New Energy Made in Arnhem [PDF] Burgersgevenenergie.nl Retreieved from https://burgersgevenenergie.nl/wp-content/uploads/2021/03/Programmaplan-NemiA-2020-2030.pdf

Gemeente Groningen, (2018) Routekaart Groningen CO2 neutraal 2035 [PDF] Gemeente.groningen.nl Retrieved from https://gemeente.groningen.nl/groningen-co2-neutraal-2035

Provinciale staten, (2018, december 19). Omgevingsvisie Gaaf Gelderland [PDF], Gelderland.nl. Retrived from https://www.gelderland.nl/themas/omgeving/omgevingsvisie

GREY LITERATURE

Aquathermie (thermische energie uit water). (n.d.). NPLW. Retrieved July 10, 2025 from https://www.nplw.nl/warmtenet/warmtebronnen/aquathermie.

Banken.nl. (2024, July 11). Aantal tankstations halveert zelfstandige pomphouders hardst geraakt. banken.nl. Retrieved October 8, 2024 from https://www.banken.nl/nieuws/25401/aantal-tankstations-halveert-zelfstandige-pomphouders-hardst-geraakt

Centraal Bureau voor de Statistiek. (2025, September 8). Hernieuwbare energie in Nederland 2024. cbs.nl. Retrieved November 10, 2025, from https://www.cbs.nl/nl-nl/longread/rapportages/2025/hernieuwbare-energie-in-nederland-2024/samenvatting

European Environment Agency. (2025, November 6). New registrations of electric cars in Europe. Retrieved December 10 from eea.europa.eu. Retrieved Dezember https://www.eea.europa.eu/en/analysis/indicators/new-registrations-of-electric-vehicles

EXP. (2024, December 9). Place des Fleurs-de-Macadam. exp.com. Retrieved July 1st 2025 from https://www.exp.com/experience/place-des-fleurs-de-macadam/

Gas to Green (n.d.). Streetlifedesigncompetition.com Retrieved January 6, 2025, from https://streetlifedesigncompetition.com/gas-to-green/

Goldstein, J., & Brooker, N. (2022, October 11). The NTH Space: hybrid work and the future of gas stations. Gensler. Retrieved Janurary 15, 2025 from https://www.gensler.com/blog/the-nth-space-hybrid-work-and-the-future-of-gas-stations

Jordan, A. (2019, March 19). These are America's 7 Most Beautiful Gas Station Conversions. Architectural Digest.com Retrieved January 7, 2025 from https://www.architecturaldigest.com/gallery/americas-most-beautiful-gas-station-conversions

Mulder, D. (2025, September 16). ing.nl. Retrieved October 29, 2025, from https://www.ing.nl/zakelijk/sector/trade-retail/facts--figures-oliehandel---tankstations#:~:text=Van%20de%204.100%20Nederlandse%20tankstations,op%20transport%2C%20raffinage%20en%20verkoop.

Netbeheer Nederland, (2019). Basisinformatie over energie-infrastructuur Opgesteld voor de Regionale Energie Strategieën. [PDF]

SMUS. (n.d.). Methodologies for the Investigation Spatial Transformation Processes. gcsmus.org. Retrieved November 22, 2024, from https://gcsmus.org/conferences/botswana/sessions/12-methodologies-for-the-investigation-spatial-transformation-processes/

UN environment program. (n.d.). Cities and Climate change. unep.org. Retrieved December 8, 2025, from https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities-and-climate-change

United Nations Climate Change. (2021, February 26). A Beginner's Guide to Climate Neutrality. unfcc.int. Retrieved Novermber 22, 2024, from https://unfccc.int/news/a-beginner-s-guide-to-climate-neutrality

IMAGES

Bodeminformatie. (n.d.). https://arnhem.maps.arcgis.com. Retrieved October 29, 2025, from https://arnhem.maps.arcgis.com/apps/instant/sidebar/index.html?appid=1650b84f5ded4ac4b92a7a5ab2f0f980

Brent Cross Town Substation | IF_DO — Architecture & Design. (n.d.). ifdo.co. Retrieved July 15, 2025 from Https://Www.Ifdo.Co/Projects/Brent-Cross-Town-Substation.

EXP. (2024, December 9). Place des Fleurs-de-Macadam. exp.com. Retrieved July 1, 2025 from https://www.exp.com/experience/place-des-fleurs-de-macadam/

Roze Tanker - Noorderpark. (2024, March 21). Noorderpark.nl Retrived from https://noorderpark.nl/locaties/roze-tanker/

8. Appendix

Appendix 1: List of all gas station sites in Arnhem with numbering, name and address

Number	Name (from google maps or roadname)	Adress	
1	Kuster Energy Total Express Arnhem	Ingenieur J.P. van Muijlwijkstraat 175, 6828 BN Arnhem	
2	AVIA Xpress Arnhem	Graaf Lodewijkstraat 103, 6821 EC Arnhem	
3	Tango Arnhem Hommelseweg	Hommelseweg 399, 6821 LK Arnhem	
4	TinQ Kemperbergerweg	Eduard van Beinumlaan 2, 6815 GD Arnhem	
5	TotalEnergies Boszicht	Apeldoornseweg 300, 6815 AB Arnhem	
6	Shell Kramersgildeplein	Kramersgildeplein 92, 6826 KP Arnhem	
7	Haan Dr. C. Lelyweg	Doctor C. Lelyweg 31, 6827 BH Arnhem	
8	TotalEnergies Presikhaaf	IJsseloordweg 15, 6825 LG Arnhem	
9	Tango Vlamoven	Vlamoven 23, 6826 TM Arnhem	
10	Esso Ijsseloord	IJsseloordweg 42, 6825 LE Arnhem	
11	Shell Westervoortsedijk	Westervoortsedijk 71A, 6827 AV Arnhem	
12	ESSO Express Dr. C. Lelyweg	Doctor C. Lelyweg 13, 6827 BH Arnhem	
13	BP Snelliusweg	Snelliusweg 30-1, 6827 DH Arnhem	
14	Shell Salvatorplein	Salvatorplein 1, 6832 AB Arnhem	
15	Berkman	Malburgse Sluis 22, 6833 KB Arnhem	
16	ANAC Overmaat	De Overmaat 1, 6831 AE Arnhem	
17	Shell Marga Klompélaan	Marga Klompélaan 24, 6836 BH Arnhem	
18	TotalEnergies Marasingel	Marasingel 259, 6846 DX Arnhem	
19	BP Express Elderveld	Hollandweg 51, 6843 JN Arnhem	
20	BP Meinerswijk	Eldenseweg 2, 6841 HP Arnhem	
21	TinQ Kemperbergerweg	Kemperbergerweg 727, 6816 RV Arnhem	
22	TotalEnergies De leeren doedel	Amsterdamseweg 467A, 6816 VK Arnhem	
23	Shell Amsterdamseweg	N 224 258 Amsterdamseweg, NZ, 6816 VN Arnhem	
24	ESSO Overmaat	Burgemeester Matsersingel 30, 6831 ZA Arnhem	
25	TotalEnergies Express Van Dijkhuizen Elden	Klapstraat 32, 6842 AE Arnhem	
26	Tango Papenkamp	Papenkamp 3, 6836 BC Arnhem	
27	ESSO Express Lange Water	Bakenbergseweg 240, 6814 MT Arnhem	
28	Shell Barkenbergseweg	Lange Water 2, 6825 BA Arnhem	
29	ESSO Slenkweg	A12 E35 NZ, 6816 VZ Arnhem	excluded
30	Shell Europaweg	Slenkweg 1, 6816 VX Arnhem	excluded

Appendix 2: Inventory of all characteristics collected

Category	Spatial property	1. Kuster Energy Total	2. AVIA Xpress	3. Tango Arnhem Hommelseweg	4. TinQ Eduard van Beinumlaan	5. Total energies Boszicht	6. Shell Kramersgildeplein	7. Haan	8. Total energies Presikhaaf	9. Tango Vlamoven	10. Esso Ijsseloord	11. Shell Westervoortsedijk	12. ESSO Express Lelyweg	13. BP Snelliusweg	14. Shell Salvatorplein	15. Berkman	16. ANAC Overmaat	17. Shell Marga Klompélaan	18. Marasingel	19. BP Express Elderveld	20. BP Meinerswijk	21. TinQ Kemperbergerweg	22. Total energies De leeren doedel	23. Shell Amsterdamseweg	24. ESSO Overmaat	25. Total energies van Dijkhuizen Elden	26. Tango Papenkamp	27. Shell Barkenbergseweg	28. ESSO Express Lange Water
Canopy	Semi attached				x													x											
	Canopy	x		x		x	x	x	x	x	x	x	x	x	x	x			x	x	x		x	x		x	x	x	x
	No canopy		x																			x							
Accessability	Public transport	x	x				x					x	x		x		x			x								x	x
	Cyclists	x	x	x	x		x	x		x		x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
	Pedestian	x	x	x	x		x	x		x		x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
Amenities	Shop	x				x	x		x		x	x			x			x	x		x		x	x	x			x	x
	Bakery	x																											
	Ice cream shop						x																						
Residential	Vooroorlogse woonwijk																									x		x	
	Naoorloogse woonwijk				x					x					x			x							x	x	x	x	x
	Tuindorp														x														
	Tuinstad laagbouw																												x
	Tuinstad hoogbouw				x		x	x		x	x				x														x
	Hoogbouw	x					x								x					x									x
	Vernieuwd	x					x	x							x			x											
	Historische binnenstad	x	x																										
	Stedelijk bouwblok																												
	Villawijk		x	x	x																				x	x		x	
	Volkswijk		x	x																x									x
	Vinex-wijk					x									x			x	x		x				x	x	x		
	Bloemkoolwijk																			x						x			
Commercial	Shopping center						x																						x
	Shopping street	x													x														
	Retail centers												x	x															
Industrial	Production							x																					
	Storage													x															
	Logistics																												
	Energy production											x																	
Green space	Forest (decidiuous)			x	x	x											x				x								
	Forest (coniferous)				x																								
	Forest (mixed)																												
	Cemetery					x																							
	Allotment garden										x																		
	Sports field				x						x					x			x									x	
	Floodplain																				x								
	Grass field				x				x	x	x	x				x	x		x	x								x	
	Grass strips			x		x			x	x	x	x					x		x	x		x					x		
	Park			x		x	x																						x
	Park-like structure														x					x						x			
Agricultural	Cropland																		x										
	Grassland																												
Nature reserve (natura 2000)	Forest																					x	x	x				x	
	Grassland																						x	x					
	Cropland																							x					
	Floodplain															x													
Waterbody	River												x	x		x													
	Lake															x			x		x								x
	Ditch																		x										x
	Stream																												
Public facilities	Hospital				x						x						x	x							x		x		
	School		x	x			x		x	x									x	x						x			x
	Campus																												x
	Emplacement													x															
	Train station	x																											
	Tennis court																					x							
	Sports habour													x															
	Habour												x	x															
	Recycling center												x				x												
	Transformation station																x												
	Post office																												
	Police station	x					x																						
	Mosque/Church	x													x														x
	Swimming pool			x																									
	Trailerpark									x						x									x			x	
	Prison															x													
Car infrastructure	Main road																												
	Parking garage	x																											
	Parking lot	x					x								x					x									x
Soft mobility infrastructure	Bicycle path	x	x	x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Archeological artefacts	Burial mounds																						x						
Water management	Dike								x							x					x								

Appendix 3: Questionnaire used for the expert evaluation

Spatial Quality Assessment

Meinerswijk

Evaluating the current situation

Aerial image of the site

View from bicycle path

View from bicycle path onto the site

1. To what extent does the current site provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

2. To what extent is the site multifunctional?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

3. To what degree is the current use of the site able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

4. To what degree does the current site offer a visually diverse experience?

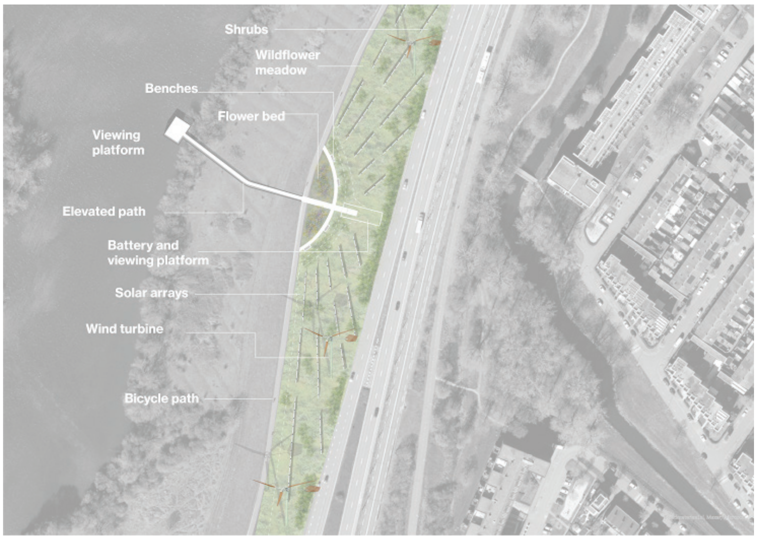
Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

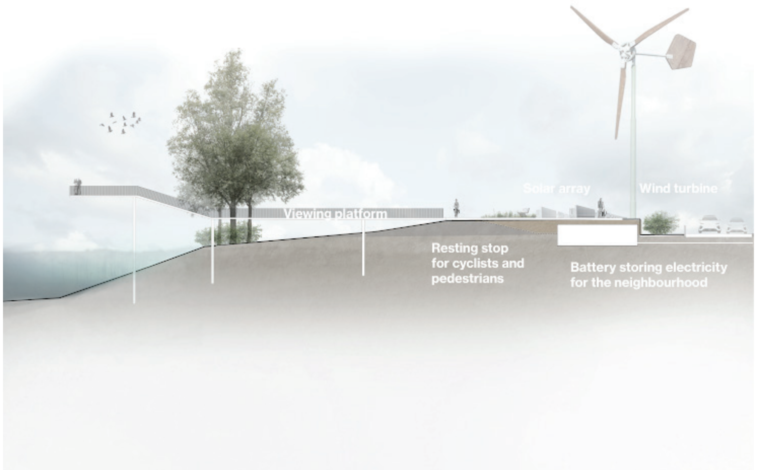
Meinerswijk design option 1

Here, please answer the questions for the design solution 1 presented in the images below.

Plan view of the proposed design solution 1



Section of the proposed design solution 1



5. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

6. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

7. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

8. To what degree does the proposed design solution offer a visually diverse experience of the site?

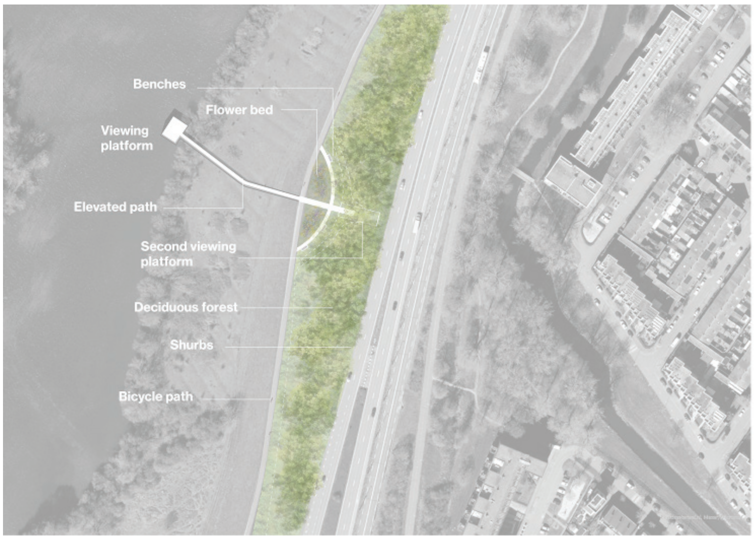
Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

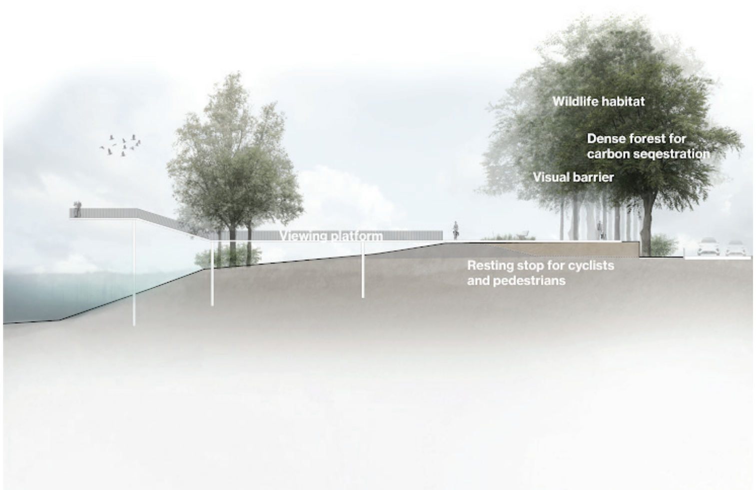
Meinerswijk design option 2

Here, please answer the questions for the design solution 2 presented in the images below.

Plan view of the proposed design solution 2



Section of the proposed design solution 2



9. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

10. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

11. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

12. To what degree does the proposed design solution offer a visually divers experience of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

Salvatorplein

Evaluating the current situation. Please use the images of the current site to answer the questions below.

View onto the site from the parking lot

Arial image of the site

13. To what extent does the current site provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

14. To what extent is the site multifunctional?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

15. To what degree is the current use of the site able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

16. To what degree does the current site offer a visually diverse experience?

Mark only one oval.

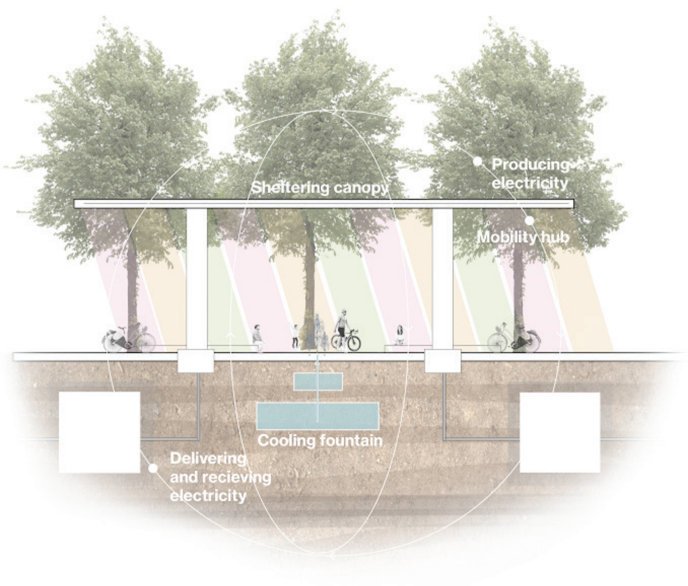
	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

Salvatorplein design option 1

Here, please answer the questions for the design solution 1 presented in the images below.

Plan view of the proposed design solution 1

Section of the proposed design solution 1



17. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

18. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

19. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

20. To what degree does the proposed design solution offer a visually divers experience of the site?

Mark only one oval.

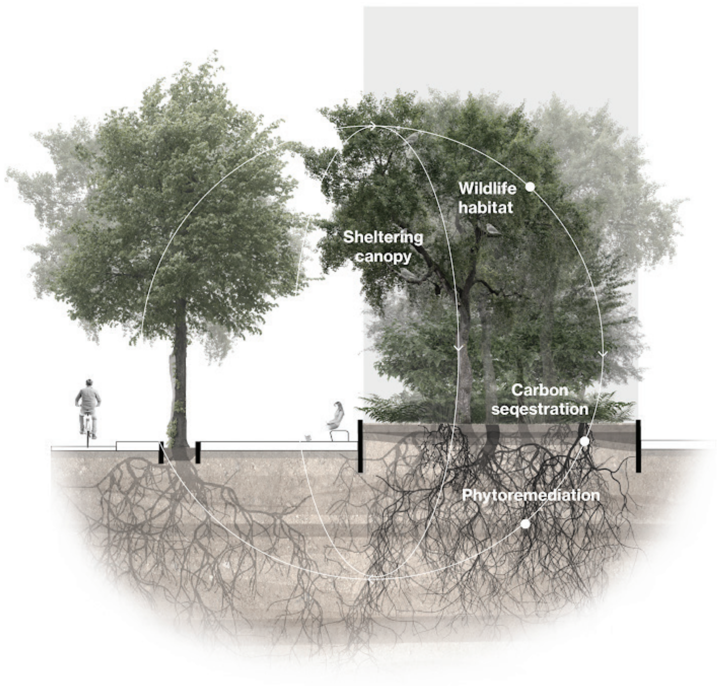
	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

Salvatorplein design option 2

Here, please answer the questions for the design solution 2 presented in the images below.

Plan view of the proposed design solution 2

Section of the proposed design solution 2



21. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

22. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

23. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

24. To what degree does the proposed design solution offer a visually divers experience of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

Westervoortsedijk

Evaluating the current situation

view on to the site from the bicycle path

side view of the gas station

Arial image of the site

25. To what extent does the current site provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

26. To what extent is the site multifunctional?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

27. To what degree is the current use of the site able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

28. To what degree does the current site offer a visually diverse experience?

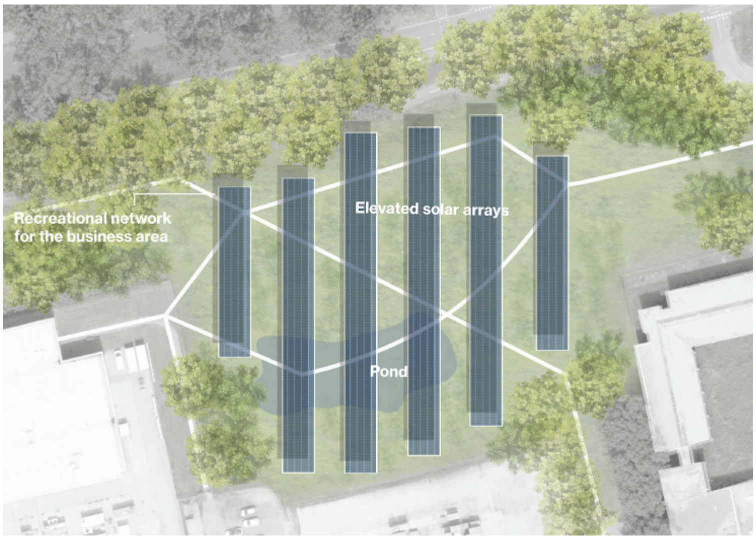
Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

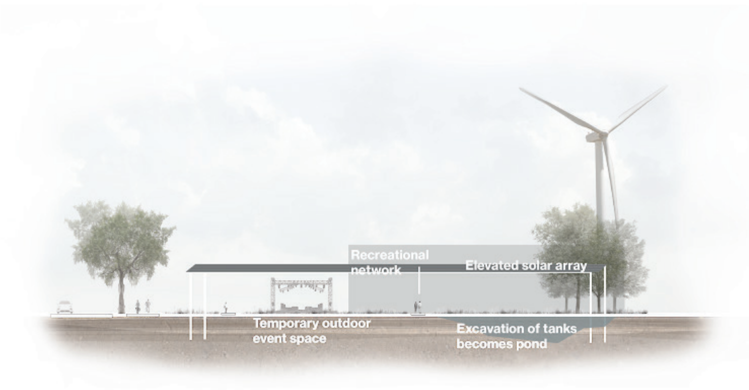
Design alternative 1

Here, please answer the questions for the design solution 1 presented in the images below.

Plan view of the proposed design solution 1



Section of the proposed design solution 1



29. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

30. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

31. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

32. To what degree does the proposed design solution offer a visually divers experience of the site?

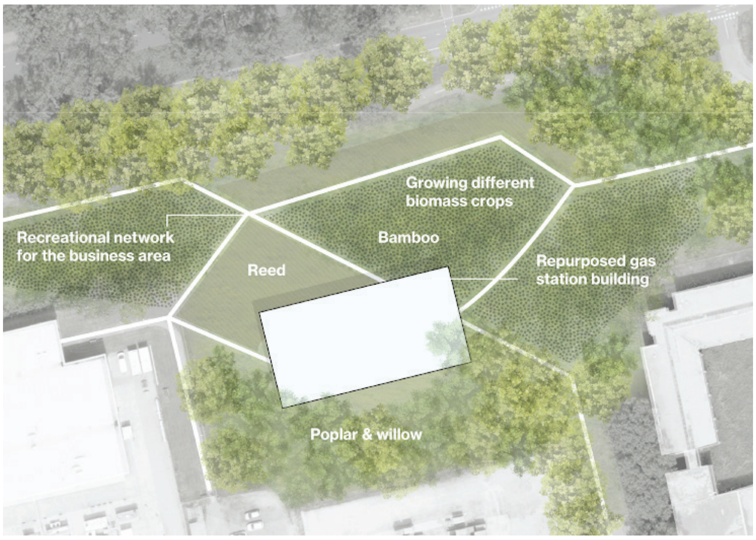
Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

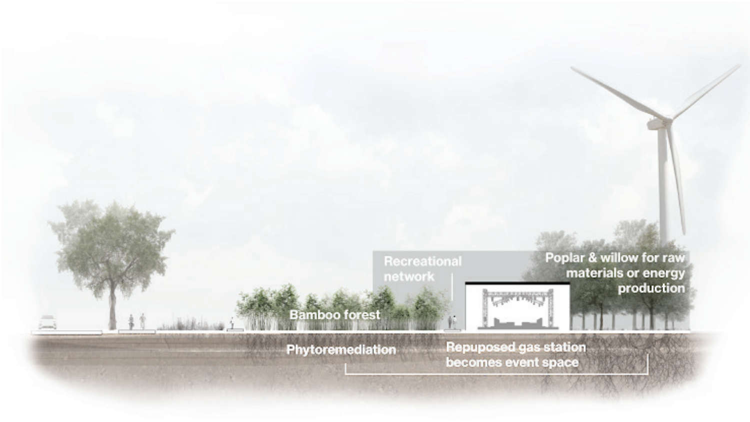
Westervoortsedijk design option 2

Here, please answer the questions for the design solution 2 presented in the images below.

Plan view of the proposed design solution 2



Section of the proposed design solution 2



33. To what extent does the proposed design solution provide a variety of habitats for different species?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

34. To what degree does the design solution contribute to a multifunctional use of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

35. To what degree does the design solution propose a land use that is able to withstand future pressures?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

36. To what degree does the proposed design solution offer a visually divers experience of the site?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very much so

Appendix 4: Calculations

4.1 Models carbon removal calculations

To calculate the carbon removal rate of the planting choice of the 6 different models, the surface area covered by the vegetation type has been multiplied by the carbon removal rate per m^2. The carbon removal rates are presented in Table 2 and have been taken from scientific literature or grey literature. For single trees, the rate of forests has been used as a simplification.

The results of this estimation are presented in the table below.

Carbon removal rate			
Meadow [1]	*Bamboo* [2]	*Forest* [3]	
3	275	11	t/ha/y
0.0003	0.0275	0.0011	t/m2/y

Model	*Size*		Surface area cover (m2) *Meadow*	*Bamboo*	*Forest /Trees*	*Total CO2 removal*	
Salvatorplein 1	820	m2			100	0.1	t/y
Salvatorplein 2	820	m2			500	0.6	t/y
Westervoortsedijk 1	8500	m2	8300		200	9.1	t/y
Westervoortsedijk 2	8500	m2	3000	3500	500	97.7	t/y
Meinerswijk 1	7100	m2	7000			2.1	t/y
Meinerswijk 2	7100	m2			7000	7.7	t/y

1: Wildflower Meadows & Carbon Offsetting Fight Climate Change (n.d.). meadowmania.co.uk Retrieved November 27, 2025, from https://meadowmania.co.uk/blogs/news/wildflower-meadows-amp-carbon-offsetting-how-native-flowers-help-fight-climate-change

2: Marchi, M., Marchettini, N., Neri, E., Esposito, G., Niccolucci, V., Pulselli, F. M., Lajo, M., Rissone, E., & Pulselli, R. M. (2023). Carbon Footprint offset of a managed Bamboo plantation in temperate regions. Sustainable Production and Consumption, 40, 220–235. https://doi.org/10.1016/j.spc.2023.05.025

3: A Supply Curve for Forest-Based CO2 Removal (n.d.). climate.mit.edu Retrieved November 28, 2025, from https://climate.mit.edu/posts/supply-curve-forest-based-co2-removal

4.2 Renewable energy calculations

4.2.1 Salvatorplein

To calculate the potential electricity output from PV panels on the repurposed canopy construction, the surface area has been divided by the surface area of one PV panel (288/2 = 144). This revealed that about 144 panels fit on the construction. The number of panels has then been multiplied by the nominal power output of one panel (450*144 = 64800 Wp 65 kWp), resulting in a nominal power output of 65 kWp. This number has been used to estimate the yearly output using the Photovoltaic Geographical Information System (PVGIS). This resulted in a yearly output of 54074 kWh.

Canopy size	Number of panels	Nominal power output	Yearly output*	Households
288 *m2*	144	64800 *Wp* 65 *kwp*	54074 *kWh*	22

4.2.2 Westervoortsedijk

MODEL 1

The first site alternative at Westervoortsedijk proposes an elevated PV installation. This construction covers 6384 m2, with panels tilted at an 35-degree angel, and an east-west orientation.

To calculate the output, the number of panels had to be calculated. For that, the surface area covered by the panels has been divided by 1.833 (3192/1.833 = 1741). This has been done because the panels are tilted by an angle of 35 degrees, which reduces the surface area covered. Then the nominal power output has been calculated by multiplying the number of panels by 450 Wp (output per panel). Then this has been divided by 1000 to get the kWp output. This number has been used in the PVGIS tool to get the yearly output. This has been done twice, once with an azimuth of -90 degrees and once with 90 degrees. By adding the two numbers, the total yearly output has been estimated to be 1270507 kW, which is about the same 525 households would require (1270507/2410 = 525).

East orientation	Number of panels	Nominal power output	Yearly output*	Total yearly output
3192 *m2*	1741	783633 *Wp* 784 *kWp*	642452 *kWh*	1270507 *kWh* 525 households
West orientation	**Number of panels**	**Nominal power output**	**Yearly output***	
3192 *m2*	1741	783633 *Wp* 784 *kWp*	628055 *kWh*	

FINAL DESIGN

The final design of the site at Westervoortsedijk repurposes the canopy construction. To calculate the potential electricity output from PV panels on the repurposed canopy construction, the surface area has been divided by the surface area of one PV panel (1000/2 = 500). This revealed that about 500 panels fit on the construction. The number of panels has then been multiplied by the nominal power output of one panel (450 Wp), resulting in a nominal power output of 225 kWp (450*500 = 225000 Wp = 225 kWp). This number has been used to estimate the yearly output using the Photovoltaic Geographical Information System (PVGIS). This resulted in a yearly output of 187178 kWh.

Canopy size	Number of panels	Nominal power output	Yearly output*	Households
1000 *m2*	500	225000 *Wp* 225 *kwp*	187178 kWh	77

4.2.3 Meinerswijk

WIND TURBINES

To calculate the potential electricity output from the proposed wind turbines at Meinerswijk, the yearly output provided by the manufacturer has been multiplied by the number of turbines, resulting in a yearly output of 135000 kWh (3*45000 = 135000 kWh).

Wind turbine output***	Number of turbines	Yearly output	Households
45000 *kWh/y*	3	135000 *kWh*	56

PV PANELS

To calculate the potential electricity output from the vertical bifacial PV panels, the number of panels has been calculated by measuring the length of the rows and dividing it by the width of the panels (1m). 538 panels fit in the design, which is equal to 242 kWp nominal power output (538*450 = 242100 Wp = 242 kWp).

In the second step, the yearly output has been calculated using the PVGIS tool. This has been done twice, once using an azimuth of 90 degrees and once using an azimuth of -90 degrees. This resulted in a total yearly output of 249332 kWh.

Bifacial vertical solar arrays				
Azimuth	**Number of panels**	**Nominal power output**	**Yearly output***	**Households**
-90 *degree*	538	242100 *Wp* 242 *kwp*	126620 *kWh*	52
90 *degree*	538	242100 *Wp* 242 *kwp*	122712 *kWh*	51

Total yearly output
384332 *kWh*
159 households

**JRC Photovoltaic Geographical Information System (PVGIS) (n.d.). ec.europa.eu Retrieved November 27, 2025, from https://re.jrc.ec.europa.eu/pvg_tools/en/*

*** Gemiddeld energieverbruik in Nederland (n.d.). milieucentraal.nl Retrieved November 29, 2025, from https://www.milieucentraal.nl/energie-besparen/inzicht-in-je-energierekening/gemiddeld-energieverbruik/*

****Onze windmolen (n.d.). ecoways.nl Retrieved November 27, 2025, from https://ecoways.com/nl-be/kleine-windmolen*

4.3 Battery

For the battery storage, a value of 300 kWh/m3 has been estimated. This represents a battery pack with medium efficiency.*

To calculate the storage capacity of the designs, the volume of the battery space has been multiplied by the kWh/m3. For the neighbourhood battery at the Salvatorplein, this results in 30000 kWh (100*300 = 30000). For the battery storage at Meinerswijk, this results in 60000 kWh (200*300 = 60000).

**Pack Volumetric Energy Density (n.d.). Batterydesign.net Retrieved November 27, 2025, from https://www.batterydesign.net/pack-volumetric-energy-density/*

4.4 Projection

Arnhem

The three site designs have a combined yearly output of 625584 kWh. Dividing this output through the area of the three sites results in a yearly output per square meter (625584/1620 = 38). The total area of the 28 gas stations in Arnhem in the municipality of Arnhem is 7 ha (70000 m2). Multiplying the area by the average yearly output per square meter of the site designs the total yearly output for the 28 gas stations is 2666921 kWh/y (70000*38=2666921), enough for about 1102 households (2666921/2420 = 1102).

Total site designs		kWh/m2/y
16420	*m2*	38
625584	*kWh/y*	
259	*Households*	

Total Arnhem		Average size	
70000	*m2*	3889	*m2*
2666921	*kWh/y*		
1102	*Households*		

Total NL

There are 3116 gas stations located within urban and peri-urban areas in the Netherlands*. By multiplying the average surface area of gas stations in Arnhem by the number of all gas stations in urban and peri-urban environments, the total area is estimated to be 1212 ha (3116*3889 = 1211778 m2).

By multiplying this estimated area by the calculated kWh/m2 rate of the site designs, the estimated output for all gas station in the urban and peri urban environment of the Netherlands becomes 461673725 kWh/y (38*121177 = 461673725), enough for about 190774 households (461673725/2420 = 190774).

If the entire area of all gas stations in the urban and peri-urban environment of the Netherlands were covered with south-oriented solar arrays at a 35-degree tilt and a density of 50%, the amount of electricity that can be produced would be 1546484005, enough for about 639043 households.

The first step of this calculation was to multiply the total area by 0.5 to account for the density of the solar arrays (12117778*0.5 = 6058889 m2). Then this number has been divided by the surface area of the panels at a 35-degree tilt to get the number of panels (6058889 /1.8 = 3366049 m2). This has then been multiplied by 450 Wp (3366049*450 = 1514722222 Wp) and then divided by 1000 to get the kWp. This number has then been inserted in PVGIS together with the other relevant variables to estimate the total yearly output, which is 1546484005 kWh (1546 GWh). To estimate the number of households, the total yearly output has been divided by 2420 (1546484005/2420 = 639043).

Total NL projection	
3116	*Gas stations*
12117778	*m2*
461673725	*kWh/y*
190774	*households*

If only solar would be placed (south orientation, 35°)	
12117778	*m2*
6058889	*m2*
3366049	*panels*
1514722222	*Wp*
1514722	*kWp*
1546484005	*kWh*
639043	*households*

**Mulder, D. (2025, September 16). ing.nl. Retrieved October 29, 2025, from https://www.ing.nl/zakelijk/sector/trade-retail/facts--figures-oliehandel---tankstations#:~:text=Van%20de%204.100%20Nederlandse%20tankstations,op%20transport%2C%20raffinage%20en%20verkoop.*

Carbon

To provide an estimation for the carbon sequestration potential of all gas stations in Anrhem, based on the proposed solutions in the site designs, first, the sequestration rate per m2 per year has been calculated (t/m2/y). This has been done by dividing the total area of the three sites by the total CO2 removal calculated earlier (16420/100.4 = 0.0061). In the second step, this number has been multiplied by the total area of all gas stations in Arnhem (70000*0.0061 = 428 t/y).

The same has been done to estimate the carbon sequestration potential for all gas stations in the urban and peri-urban environment in the Netherlands (12117778*0.0061 = 74057 t/y).
Thirdly, it has been estimated how much could be sequestered if only bamboo were planted on these sites. For that, the area of all gas stations in the Netherlands has been multiplied by the carbon removal rate of bamboo per m2 (12117778*0.0275 = 333239 t/y).

Total Arnhem	Average size
70000 *m2* 428 *t/y*	3889 *m2*

Total site designs	t/y/m2
16420 *m2* 100.4 *t/y*	0.0061

Total NL
3116 *n* 12117778 *m2* 74057 *t/y*

If only bamboo was planted
333239 *t/y*