Aqua Thermal Energy for 5th Generation District Heating and Cooling Network in Vreeswijk

Advisory Report

Client: WarmVreeswijk

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Version 1.0

Colophon

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Summary

The Netherlands aims to transition from natural gas to renewable energy sources to mitigate carbon dioxide emissions and build a sustainable energy network. By 2030, 27% of energy production must be derived from renewable sources, with full capacity expected by 2050. In collaboration with the client WarmVreeswijk, this study aims to provide Vreeswijk with a sustainable aqua-thermal energy extraction (TEO) and heat storage (WKO) system for their potential 5GDHC network. The citizen-led initiative of WarmVreeswijk aims to reduce fossil-fuel reliance by harnessing heat from locally available heat sources for sustainable residential heating and cooling. Primary stakeholder interviews and literature research identified relevant information, energy data, and (TEO, WKO, Post-insulation) technologies. Data was utilised to develop a Multi-Criteria Analysis (MCA), an energy/financial inventory, and a dimensioning report.

MCA results depict Energy Sheet Pile walls (4.48) as the highest-scoring TEO techniques, and BTES (4.22) and ATES (3.44) as thermal energy storage technologies. Among post-insulation techniques, PUR Spray Foam Wall insulation (4.38) and floor insulation (3.98) were advised. However, data limitations and gaps (e.g. geohydrological and soil data) and methodology subjectivity must be accounted for within evaluation processes.

Energy inventory results estimated the yearly energy consumption for Vreeswijk as 24,461 MWh. The dimensioned generation potential of the suggested sheet pile wall system was approximately 24,607 MWh per year, indicating the ability to comply with energy needs. Estimated thermal energy storage was 13,833 MWh, requiring 5 ATES or 148 BTES systems. Moreover, the financial inventory depicted annual gas consumption of 1,214 m^3 (around €1,995.40). However, energy data estimates do not represent recent energy transition trends, and financial estimations are based on year-fixed contracts, inherently excluding potential energy price fluctuations, subsidies, or market volatilities.

Conclusively, the client is advised to adopt Energy Sheet Pile Walls as an energy extraction technique, combined with the ATES System for Seasonal storage. Both techniques depict high system efficiency and extraction rates, low GHG emissions and reduced ecological disruptions, while supplying sufficient energy to cover Vreeswijk's energy demand. Moreover, polyurethane spray foam for wall insulation is advised for household applications, based on its high-performance rate and cost-effectiveness with subsidies. The client is recommended to continuously gather and update energy data, conduct a geohydrological and (sub)soil surveys, and consult governmental and technical bodies to assist in project realisation. Mid-term actions entail securing permits and developing plans for the proposed technologies. Long-term monitoring and maintenance of installed systems is critical to ensure their efficiency and stable and continuous energy supply capabilities.

Contents

List of Acronyms

Abbreviation	Definition
5GDHC	5th Generation District Heating & Cooling
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CBS	Central Bureau of Statistics
GHG	Greenhouse Gas Emissions
GIS	Geographic Information System
HDSR	Hoogheemraadschap de Stichtse Rijnlanden
MCA	Multi-Criteria Analysis
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
STES	Seasonal Thermal Energy Storage
SWHP	Surface Heat Water Pump
TEO	Thermal Energy from Surface Water
TTES	Tank Thermal Energy Storage
WKO	Soil Heat-Cold Storage
WUP	Wijkuitvoeringsplan

1. Introduction

1.1 General Background

The Netherlands aims to transition from natural gas to renewable energy sources to mitigate carbon dioxide emissions and build a sustainable energy network. In 2022, the Dutch energy sector emitted 158 million tonnes of CO_2-equivalent emissions, with current reductions up to 25% due to the surge of renewable energy production. Aligned with the European Union's 2050 climate neutrality objectives, the country committed to a 55% reduction in greenhouse gas emissions by 2030 compared to 1990. The target is supported by 27% of energy production being derived from renewable sources by 2030, with full capacity expected by 2050 [1]-[3].

Coordinated efforts are required not only at the national level but also at the regional and local levels. Exemplar is WarmVreeswijk, a citizen-led initiative within the old village of Vreeswijk, Nieuwegein. Historically known as a harbour town, Vreeswijk is defined by its canal and river network, which covers 18 hectares (22%). The initiative aims to develop a collective 5th Generation District Heating and Cooling Network (5GDHC) to provide sustainable heating and cooling for the community by harnessing thermal energy from surface water (TEO) from possibly the Merwede Canal, Vaartsche Rijn or Lek Canal, and utilising seasonal soil heat-cold storage (WKO). The proposal strives to reduce fossil-fuel dependency, leverage local resources, and realise a sustainable heating and cooling solution for the village. [4], [5].

WarmVreeswijk is actively informing residents on TEO, WKO, and post-insulation (e.g. roof-, floor-, wall insulation) methods to expand the technology efficiency, foster community participation and facilitate a smooth energy transition. However, current efforts include researching TEO and WKO solutions while assessing their technical, ecological, and financial impacts on a local and individual level. [4], [6].

1.2 Problem Statement

Currently within its Social and Technical Development Phase, WarmVreeswijk faces gaps in identifying and classifying TEO and WKO technologies that are financially viable, feasible for adaptation, and with minimal ecological impacts. Additionally, gaps exist in translating these technologies into household-specific actions (considering their needs and the architectural and technical aspects of the house) for successful adaptation. [4], [5].

1.3 Project Goal

The research aims to provide WarmVreeswijk with a sustainable aqua-thermal energy extraction (TEO) and heat storage (WKO) system for Vreeswijk's potential 5GDHC network. The system must reduce the neighbourhood's reliance on natural gas for residential heating and cooling, and be considered feasible for local implementation.

Several subgoals have been established to address the primary goal:

- Conduct a literature review of 5GDHC Principles, TEO and WKO systems, other energy-sharing/saving opportunities, and related legislative/environmental frameworks.
- Depict the village's current energy demand in an Excel Energy Inventory to determine the energy-saving/coverage potential of applied TEO and WKO systems.

- Conduct a Multi-Criteria Analysis (MCA) to evaluate the financial, environmental, and social feasibility of six to nine TEO, WKO, and post-insulation techniques, supported by literature research and stakeholder collaboration.
- Dimension the solutions to the case study scale to assess their ability to meet the residential energy demand.
- Compile relevant legislative, environmental, financial, and background data within an Advisory Report, recommending the optimal combined TEO and WKO solution.
- Develop an information board for residents outlining the technology implementation process and the financial and sustainability aspects.

1.4 Project Boundaries

Key project boundaries within the research period include:

- The project is geographically limited to the neighbourhood of Vreeswijk, focusing on harnessing TEO from local water resources (Merwede Canal, Vaartsche Rijn, Lek Canal).
- The research project duration is 20 weeks, from February 3rd until June 30th, 2025
- Non-residential buildings are excluded from the proposed scenario.
- Another party assesses intake and outlet locations and WKO boreholes.
- The proposed solution is based on cost-effectiveness, environmental friendliness, and a mid-way approach. All methods must meet the necessary energy capacity/demand
- Technologies must adhere to national and local energy, heat, soil use, and sustainable construction regulations.
- Electricity consumption is not directly relevant for the report outcome, but can provide valuable insights for future references regarding electricity reduction

1.5 Client & Stakeholders

WarmVreeswijk is a citizen-led project based in the old historic village of Vreeswijk, Nieuwegein. The project aims to implement a collective 5th Generation District Heating and Cooling (5GDHC) Network that harnesses energy from local water resources to provide residential heating and cooling. The initiative was launched by resident concern over fossil fuel dependency, lack of use of regional water resources, and limitations within the current district heating network of Nieuwegein (overlooking housing composition diversity, and cooling demand) [4], [5].

Key project stakeholders include WarmVreeswijk (project client); Vreeswijk Residents (end users that require household-specific participation actions); the Municipality of Nieuwegein (planning and implementation partner); Hoogheemraadschap de Stichtse Rijnlanden (governmental body that regulates local and regional water management); and Volantis (engineering and technical consultancy office involved in the heating network design. Most stakeholders are in collaboration to develop a Neighbourhood Implementation Plan (Wijkuitvoeringsplan - WUP), describing and analysing the village's energy transition measures [7], [8], [9].

1.6 Reading Guide

Chapter 1 provides a brief context on the project's general background, defining key objectives and boundaries relevant to the project. Chapter 2, "Theoretical Background", explores the key

5GDHC Network principles, TEO, WKO, post-insulation techniques, and appropriate legislative frameworks. The following chapter depicts the data collection, analysis, and interpretation methods. The Results chapter provides an overview of the essential findings and insights of the key methodological activities. In contrast, the Discussion chapter evaluates the validity and credibility of the methodology and results. All crucial findings and key considerations are then summarised and/or concluded in the following chapter. Moreover, Chapter “7. Advice & Recommendations” depicts the key advice and recommendations provided to the client on Aqua thermal Energy Extraction & Storage. Lastly, the bibliography depicts the relevant sources utilised, whereas the Appendices provide secondary data pertinent to the project, excluded from the primary advisory report.

2. Theoretical Background

2.1 Thermal Energy Extraction

Heat extraction techniques primarily harness surface water (TEO) thermal energy. The primary method discussed within the report includes energy sheet pile walls, whereas surface water heat pumps and geothermal systems are depicted in Appendix II: Secondary Literature Research.

2.1.1 Energy Sheet Pile Walls

Energy sheet pile walls *(NL: Energie damwanden)* are interlocking steel sheet pile walls functioning as a structural (soil and water) barrier and heat exchanger. Energy sheet pile walls integrate a closed-loop configuration to extract heat from surrounding environments without injecting liquids or substances into soil or surface water ecosystems. [10]. There are two primary energy sheet pile wall configurations:

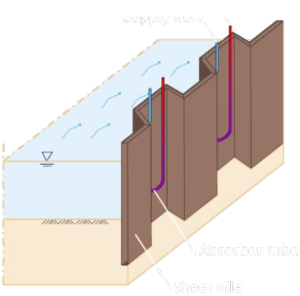


Figure 1: Energy Sheet Pile Wall Integrated Pipes [13]

Integrated Absorber Pipes

A common approach in new projects is welding heat exchanger pipes directly into or onto a steel sheet pile, see Figure 1. The direct contact between the steel sheets and pipes increases their heat exchange capacity compared to the modular element system. [11], [12].

Modular Energy Elements

Modular energy elements are retrofitted to match the wall box width dimensions *(Nl: kastbreedte)* of existing sheet pile walls, see Figure 2. This approach requires identifying the wall’s profile type and dimensions to create a modular element. If a concrete layer *(Nl: deksloof)* is present, the space under it is removed to install the element. A groove is cut on the wall's interior (land) side to install the piping network. [14], [11].

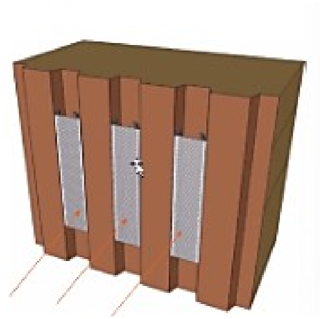


Figure 2: Modular Energy Elements [14]

Both systems are constructed with activation loops (absorber pipes) through which a heat carrier fluid circulates. The fluid extracts heat from the surrounding subsurface water bodies through conduction.[1] and convective[2] Heat transfer processes. The extracted heat can then be utilised to heat homes with heat pumps, while the system can also be reversed to provide residential cooling. The total amount of heat that can be extracted, known as the so-called heat extraction capacity, depends on various components [11]:

- Thermal Conductivity of Steel: Higher thermal conductivities enhance heat transfer potentials and extraction rates.
- Volumetric Flow Rate: Higher water flow rates simulate convective heat transfer through the supplementation of renewed water with a high thermal potential

[1] Conduction- heat transfer between solid materials- occurs primarily between the subsurface to the sheet pile wall, and between the sheet pile walls and its absorber pipes.

[2] Convection- heat transfer between fluids- occurs primarily within the flowing water and within the heat carrier fluid.

- Water Surface Area: A larger surface area between the sheet pile wall and water allows more heat exchange.
- Volumetric Heat Capacity & Temperature of Water: Water's total heat capacity (extraction potential) is impacted by the water depth and temperature.

Energy sheet pile walls offer ecological and technical benefits, potentially reducing carbon dioxide emissions by over 1 ton per meter length, based on the equivalent gas energy saved. Its closed-loop configuration ensures low to negligible thermal heat pollution in adjacent waters of the sheet pile wall. Moreover, energy extraction can occur throughout the year, operating without natural gas consumption. However, the installation process of energy sheet pile walls can have higher attached costs due to the preliminary investigations (existing or new sheet piles) and labour, materials, and equipment required. [15], [11].

2.1.2 Ecological Impacts

Assessing the thermal energy extraction techniques requires an overview of the potential ecological implications associated with these systems. Particularly, the emphasis is on thermal pollution, a temperature difference in the subsurface waters due to cooled or heated water discharge. Increased water temperatures affect gas and chemical solubility, affecting pH levels, oxygen solubility, nutrient availability, and the behaviour of chemicals/metals in water. [15].

Lower temperatures and nutrient availability reduce phytoplankton photosynthetic and enzymatic activity. The cold can also impact macrofauna growth and development, particularly in stagnant waters, where cold dumping can increase individual size but decrease reproductive cycles. Moreover, temperature fluctuations delay aquatic plants' development, shortening their growth season and limiting biomass production, reducing their ability to withstand harsh (winter) conditions. Additionally, lower water temperatures may alter the suitability of fish breeding grounds, shift reproduction periods, and impact fish migration behaviour. [15].

2.2 Thermal Energy Storage

2.2.1 Aquifer Thermal Energy Storage

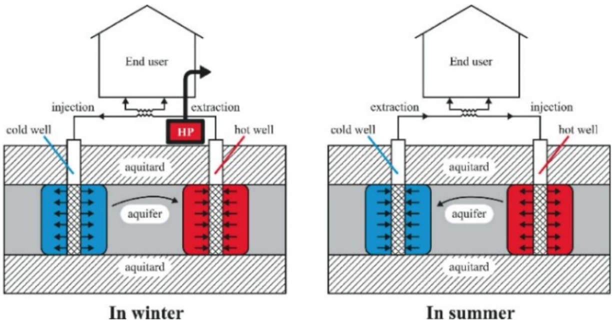
Aquifer Thermal Energy Storage (henceforth, ATES) is a thermal energy storage system that utilises subsurface aquifers to store, distribute, and recover thermal energy for heating and cooling demands. As a form of seasonal thermal energy storage (STES), ATES is already commonly implemented within district heating and cooling systems and is recognised as a promising low-carbon solution for sustainable energy regulation and storage. [16], [17].

ATES systems capture and store thermal energy in underground aquifers, porous water-bearing rock layers. The system is based on water's high heat capacity and energy potential, allowing it to be an effective medium for thermal energy storage. Other factors that may impact ATES's extraction and storage capacity include the thermal and hydraulic conductivity, with lower values minimising heat loss. Moreover, aquifer permeability will impact the ease of water flow throughout these sedimentary formations. Lastly, thermal stratification- the natural water separation based on temperature differences- can minimise the general energy loss. [16], [17].

An ATES System contains heat exchangers and heat pumps to transport/exchange thermal energy between water bodies and the built environment. Excess heat from the summer is captured and stored for potential winter heating demand, whereas cool water from the ATES system is utilised for the cooling demand in the summer, see Figure 3. The capacities of ATES systems range from 0.33 MW to 20 MW. [18], [19].

Figure 3: ATES System

Their ability to store and release excess energy allows for seasonal energy storage and demand balancing, effectively reducing fossil fuel dependency and improving energy efficiency. Moreover, integration with renewable energy sources further reduces energy-related carbon emissions. However, ATES are at risk of groundwater contamination and thermal breakthrough (risk of thermal interference between both wells), requiring adherence to strict environmental, legislative, and spatial planning frameworks. The systems tend to have higher capital and operational costs due to high initial investments and ongoing maintenance. [16].

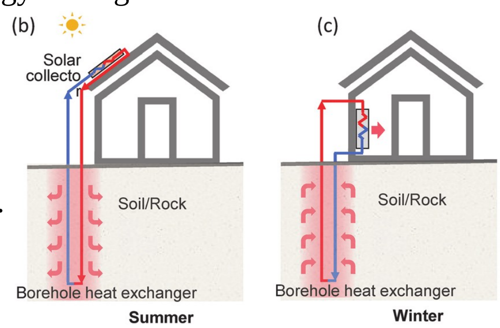


Modern monitoring and control systems are essential for an ATES system’s efficiency. Automated systems that adjust the thermal input/output can balance energy demands, while monitors/sensors can regulate flow rates, the system’s efficiency, and water temperatures [18].

2.2.2 Borehole Thermal Energy Storage

Borehole Thermal Energy Storage (BTES) systems (Figure 4) utilise vertical boreholes and geothermal heat pumps for heat storage, transfer, and recovery within the underground thermal mass; the soil that can hold and release heat. BTES- typically ranging from depths of 50 to 200 metres in depth- are closed-loop configurations, with piping systems circulating a heat-transfer fluid within the network. Thermal energy is collected and stored within the surrounding soil and gradually released over time, providing long-term stable energy storage with minimal environmental impact. [18]. Unlike ATES, BTES does not rely on nearby water bodies, making it ideal for locations lacking suitable and/or accessible aquifers. However, their disadvantage lies in their high initial capital costs for preliminary soil investigations, drilling and installation, and their limits for cooling capacities [18].

Figure 4: BTES System



2.3 Post-Insulation Techniques

Post-insulation methods diminish heat loss within residential houses, improving energy efficiency and thermal comfort. Typical and reliable post-insulation methods entail wall, floor, roof, and window upgrades. [20], [21].

Wall Insulation aims to minimise heat loss through the building's structure by filling air cavities within the wall structure. It is achieved through injecting insulation materials within the cavities, including examples of blown-in fibreglass, expanded polystyrene (EPS) beads, or polyurethane (PUR) spray foam. The materials limit the thermal conductivity of the wall, increasing the thermal resistance against heat loss. [20], [22].

Floor Insulation involves minimising heat loss through the housing floors by applying insulating materials beneath the floors. Typical materials utilised for floor insulation include expanded polystyrene (EPS) beads, polyurethane (PUR) spray foam, or mineral wool material. However, the costs depend on the surface area, insulation material type and thickness, and accessibility to the crawling area. Floor insulation has a dual function: reducing heat loss while enhancing the thermal comfort of residential houses. [20], [23].

Roof Insulation requires placing insulation materials either above or underneath the attic ceiling. Proper insulation allows for stable indoor temperatures, as significant amounts of heat are released from improper or uninsulated roofs. [21].

Window Upgrades to HR++ glass (triple glass) in residential houses effectively reduce heat loss. The system comprises three glass panes with air-filled cavities to reduce conductive and convective heat loss. [20], [21].

2.4 Legislation

Energy extraction, storage, and distribution systems must consider various legal, regulatory, and normative frameworks. The frameworks mainly relate to system design, construction, organisation quality assurance, and long-term performance monitoring. Key legislative considerations are stated below.

Certifications and Quality Standards to ensure sustainability, safety, and quality:

- BRL (Beoordelingsrichtlijn): Technical evaluation guidelines for construction and installation processes [24].
- ISO: International standards for environmental, quality, and energy management systems [25].
- SKIB (Stichting Infrastructuur Kwaliteitsborging Bodembeheer) Protocols: Dutch protocols concerning soil and groundwater management [25].

Laws and Regulations to guide the legal and environmental conformity of thermal energy systems:

- Environmental and Planning Act (Omgevingswet): Law that integrates spatial and environmental regulations focusing on the physical living environment [26].
- Dutch Heat Act (Warmtewet): Regulations on energy transport and pricing [27].

- Gas-Free Districts Policy: National regulations regarding the transition towards natural gas-free districts [28].
- Soil Usage Regulations: Regulations on the usage and ecological safeguarding of the subsurface [25].
- Sustainable Construction Framework: Guidelines for sustainable and responsible energy-efficient building practices [25], [29].

Permits that must be obtained to undertake specific actions:

- Environmental permit (Omgevingsvergunning): Permits that cover construction, zoning and environmental impacts within the living environment [27].
- Water Permit (Watervergunning): Permit for activities impacting water bodies [30].
- Roadworks Permit (Wegopbreking): Permit required for excavation and/or obstruction of street access.
- Environmental Activity Permit (Milieuvergunning): Permit intended for actions with potential (harmful) environmental effects [31], [32].
- Local Permits and Regulations: Further additional rules and permits established by local municipalities and/or the governing province.

Lastly, NEN (Nederlandse Norm) standards are considered as they contain specifications for technical safety, quality and dependability. [25], [29]. Specific norms and certifications applicable to the installation of heat grids, aqua thermal heat extraction techniques, thermal energy storage systems and heat pumps are depicted in Appendix II: Secondary Literature Research.

3. Methods

3.1 Primary Research & Stakeholder Collaboration

Primary research data involved data collection and input from relevant stakeholders, including stakeholder interviews and report reviews. A stakeholder is an individual, organisation, or group that can either (1) affect, (2) be affected by, or (3) perceive itself to be affected by an action or programme. A stakeholder assessment was conducted utilising a Scholar-provided Excel tool to identify, evaluate, and categorise key stakeholders based on initial client meetings and literature research. Stakeholders were mapped in a stakeholder matrix, a diagram reflecting their categorisation based on their interest/influence and participation level. The matrix allowed each party to select and employ effective and targeted collaboration strategies, ensuring active engagement through the research period.

Stakeholders were divided into three categories, ranging from Level I, II, or III, based on their direct or indirect involvement (participation level) in the project. Level I were directly involved with the project, actively managed and informed. Literature research, continuous emails and interviews were the basis of engagement (Appendix I: Primary Research & Stakeholder Collaboration). Level II stakeholders were not directly managed but could be impacted by the advice. Level III were stakeholders solely relevant for their expertise, but not managed or contacted. These two levels solely focused on literature research to gather relevant data. Moreover, participation levels were also evaluated on a scale: (1) inform, (2) consult, (3) advise, (4) co-create, and (5) co-decide, further reflecting their degree of involvement.

3.2 Secondary Research

Secondary literature research was conducted to gather relevant data for the project. Data gathering involved reviewing scientific or governmental reports (e.g. RIVM, WarmteAtlas, Rijkswaterstaat), technical documents (e.g. Aquathermie Viewer, Datavoorziening VNG), and stakeholder-provided reports (e.g. HDSR, Volantis). Research topics included (Warm)Vreeswijk, 5GDHC networks, TEO-, WKO-, post-insulation techniques, legislative frameworks, and additional heat mechanisms (e.g. heat pumps and block heating).

The collected data- covering technological, environmental, and financial aspects, as well as energy use, efficiency, and emission calculations- were compiled within a literature report and an Excel Spreadsheet (see Appendix II: Secondary Literature Research). The components were utilised to develop the energy inventory and Multi-Criteria Analysis (MCA).

3.3 Energy Inventory

An Energy Inventory was developed to establish a general overview of Vreeswijk's current gas consumption. It served as a basis for dimensioning the advised TEO and WKO systems to ensure compliance with residential heating and cooling demand. The inventory was developed utilising gas and electricity consumption data derived from ArcGIS data from the Central

Bureau of Statistics (CBS). Figure 5 Highlights Vreeswijk's scope, with all datapoints (raster cells) extracted and compiled within an Excel Sheet (Appendix III: Energy Inventory). Figure 6 Illustrates an example of the provided data per raster cell, sorted by number of households, gas and electricity consumption. Total heat and cooling demand were calculated by summing up the gas consumption of all rasters and comparing them to the concept design provided by Volantis to assess the inventory's accuracy and reliability. [33], [21].

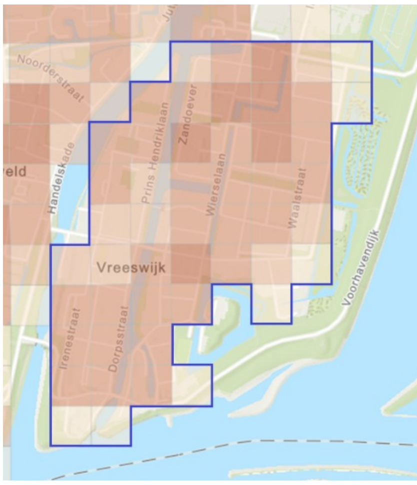


Figure 5: Boundaries Scope Vreeswijk ArcGIS [33]

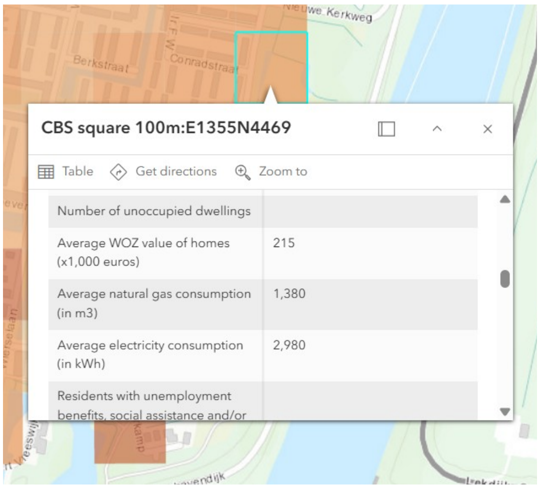


Figure 6: Snapshot CBS Data Table ArcGIS [33]

3.4 Financial Inventory

The financial inventory was based on the current tariffs provided by Stedin (grid manager) and Eneco (energy supplier). Table 1 Depicts the grid management, delivery, and gas prices, including taxes and VAT, whereas the electricity prices are described in Appendix IV: Financial Inventory. Financial data was categorised into fixed and variable costs based on household gas consumption. Fixed household costs were calculated by multiplying monthly fees by 12, while variable gas costs were determined by multiplying the gas price by average household consumption (Equation 1).

$$Gas\ Price\left(\frac{€}{\frac{m^3}{y}}\right)=Gas\ Price\left(\frac{€}{m^3}\right)*Average\ Gas\ Use\ per\ Household\left(\frac{m^3}{y}\right)$$

Equation 1: Yearly Gas Price per m³

Table 1 Provides an overview of gas expenditure at the individual and neighbourhood levels. The inventory was created to facilitate future comparison of current costs with sustainable scenarios. If desired, the total gas (and electricity) costs can be calculated using the Excel model provided in Appendix IV: Financial Inventory.

Table 1: Monthly Gas and Electricity Costs

Gas Prices

Post:	*Amount:*
Fixed Costs	
Grid Management	€ 70.91
Delivery Costs (Lowest)	€ 203.32
Measurement Costs	€ 39.69
Variable Costs	
Gas Price per m3	€ 1.43

3.5 Multi-Criteria Analysis

Multi-Criteria Analysis (Henceforth, MCA) is an assessment framework that evaluates and compares TEO, WKO, and post-insulation systems based on qualitative and quantitative criteria. The development began with a stakeholder analysis, depicting key actors, their relevance to the project, and what information can be extracted from them (Appendix V: Multi-Criteria Analysis). Secondly, an evaluation criteria list was established based on stakeholder input, project relevance, and literature research. Criteria were categorised by social-, environmental-, technical-, and financial aspects, with each criterion having a particular indicator; a conversion unit which provided the capability of comparison between and among scenarios.

The following step involved researching literature to select technologies and quantify their relevant data. Relevant data on cost-effectiveness, environmental impact, energy efficiency, scalability, and long-term sustainability were established (depicted in the Excel Sheet in Appendix V: Multi-Criteria Analysis). The quantified data was assigned a respective legend, converting the data to rated scores from 1 (poor performance) to 5 (best performance). Consequently, a standardisation process occurred within the MCA to compare the technologies. Scores were assigned weights based on relative importance, determined through expert consultation and stakeholder input. The primary stakeholders, depicted in Chapter 4.1 Stakeholder Interviews and the complete elaborated list within Appendix I: Primary Research & Stakeholder Collaboration, are WarmVreeswijk (project client), Volantis (Energy & Technical Consultant), HDSR (water and quantity manager), and Gooimeer (Energy Sheet Pile Walls Specialist). Criteria were divided into four groups, with group 1 being the most important and group 4 the least important and given an overall scoring percentage (weight). Lastly, the ratings were multiplied by their respective weights and summed, with a higher score signifying higher feasibility.

3.6 Scenario Development

3.6.1 Thermal Energy Extraction

Assessment of the feasibility of implementing thermal heat extraction methods requires scenario development based on the MCA results. The dimensioning method for energy sheet pile walls is depicted below. The approach involved estimating the potential number of energy sectors (sheet pile walls) that could be installed based on the canal wall length (measured with Google Maps) and the total annual heat that could be generated. The red lines in Figure 7 Indicate the potentially suitable canal segments, excluding non-applicable structures like boat locks. Moreover, technical data of the generation capacity and length per energy sector were derived through expert interviews, see Table 2 (Appendix I: Primary Research & Stakeholder Collaboration) [34], [35].

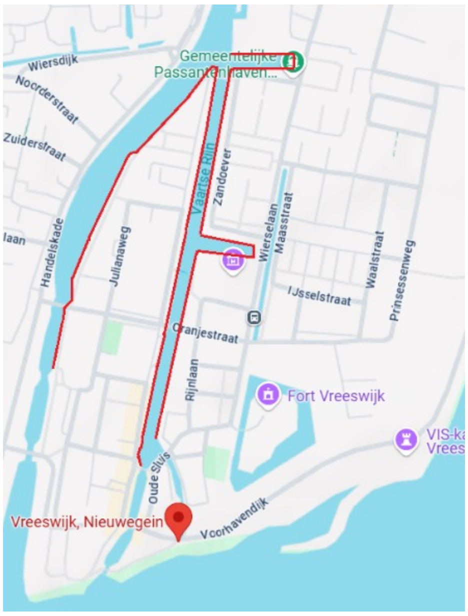


Figure 7: Potential Instalment Areas Red Line [34]

Table 2: Data Energy Sectors for Energy Sheet Pile Walls [35]

Post	Amount	Unit
Length per Sector	1.3	m
Heating Capacity per Sector	1.33	kW
COP	5	-
CAPEX	1600-2300	€/kW

3.6.2 Thermal Energy Storage

To evaluate the suitability of thermal energy storage systems, the energy inventory's heating demand and the required storage capacity to cover this demand in colder months were utilised. It was assumed that heat extracted during summer should be stored to cover the demand of the colder months (October – April), accounting for 56.6% of the total heating and cooling demand according to the data provided by Volantis (Figure 8). [21].

Underground storage volume and maximum storage capacity values were retrieved from MCA results. With these factors, the number of storage systems for ATES and BTES was determined, and the feasibility of each option was analysed based on their potential capacity. [36]-[38].

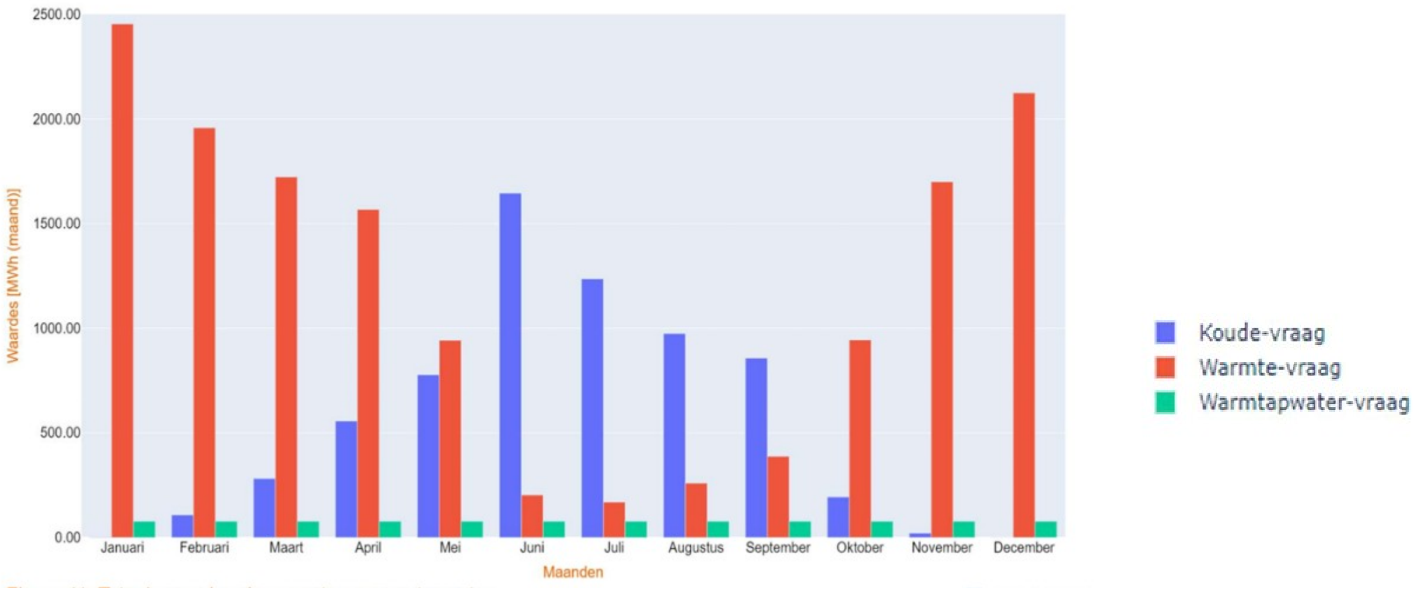


Figure 8: Monthly Heating and Cooling Demand [21]

3.6.3 CAPEX Thermal Energy Storage Systems

The potential CAPEX for the implementation of the chosen energy extraction and storage system will be estimated based on the CAPEX per kW and the generated energy, as depicted in Error: Reference source not found.

$$CAPEX\left(€\right)=CAPEX\ per\ kW\left(\frac{€}{kW}\right)\times Energy\ Generated/Stored\left(kW\right)$$

Equation 2: CAPEX Energy Systems

4. Results

4.1 Stakeholder Interviews

Several stakeholder interviews were conducted to gather primary data concerning the proposed technologies' technical, financial, and ecological implications. Key stakeholders that were interviewed include WarmVreeswijk, HDSR, Volantis, and Gooimeer.

WarmVreeswijk

The focus is on low-temperature 5th Generation District Heating and Cooling, considering using local water resources as a heat generation/extraction technique. Three different stakeholders own the three relevant canals. The Municipality of Nieuwegein owns the Vaartsche Rijn, HDSR owns the Merwede Canal, and Rijkswaterstaat owns the Lek Canal. Key figures are depicted in Table 3.

Table 3: Key Figures WarmVreeswijk Interviews

Factor	Description	Value
Lifetime Goal	Durability of the Project	>50 years
Temperature	Average water temperature in summer	27 Degrees Celsius
Subsidies	Insulation techniques subsidised by Nationaal Insulatie Programma	-
BTES	Borehole Wells (BH) for BTES system	10 houses/2 BH
Water Flow	Water flows back and forth in the canal. Thus, their heat stream would then be reused.	-
Lek Heat	The Lek Canal can be used as a potential heat source. However, it requires crossing a dike to extract energy.	-
Pilot	Theyhuis Pilot requires 9 panels to generate 12 kW	1 kW/panel

The ATES system implementation faces challenges of strong groundwater movement (diffuses adequate thermal storage), large pump (4/5 pumps of 6x2 metres) area requirements, and a lack of geohydrological study to depict the feasibility and locations of ATES implementation (which will be conducted in the coming months). Moreover, the difference in sheet pile wall types and dimensions supplements additional investigations and costs for Vreeswijk. Other considerations are using heat generated from sewage water treatment plants, drinking water plants, or the data centre nearby Vreeswijk to provide heat for 1700 residential houses. The heat could be utilised to rebalance the ATES system.

HDSR

HDSR, represented by Jeroen Bernhard, are involved in water quality and quantity management. Ecological impacts, discharge patterns, and the navigability of the canal must be considered to receive HDSR permits. A notable insight from HDSR is the concept of a 'sloshing basin'; the canal (particularly the Vaartsche Rijn) likely does not have a continuous (flow rate) current, but instead moves back and forth, likely due to the sluice systems in the area around Vreeswijk. This behaviour significantly impacts the thermal capacity of the canal, as there is no water refreshment for heat dispersion. Depending on the chosen technique, water stagnation can lead to unnaturally high temperature differences (thermal loading), disrupting the local ecosystems.

Moreover, temperature fluctuations can obstruct critical growth phases of organisms and impact fish migration. These fluctuations impact pH levels, oxygen, chemical solubility, and biological and chemical processes within water and aquatic life bodies. Open heat extraction systems filter the water, potentially killing water organisms or removing food for the microorganisms. Lastly, HDSR emphasised that there is still insufficient knowledge on the ecological impacts of aqua thermal energy extraction. Water authorities must still get accustomed to the new use of aquathermal energy and its environmental/technical implications.

Volantis

Volantis is the technical agency involved in the gas/energy transition design. With a developed concept note, their current tracks involve considering the technologies implemented within Vreeswijk to promote their plans. It was noted that energy labels are a classification that indicates how energy efficient a home is. However, they are not a good measure of energy consumption as they do not consider simultaneity and how a house is utilised. Factors that must be considered include 1) the way energy is generated, 2) the consumption of energy, and 3) the type of home (heat loss).

Gooimeer

Gooimeer, with Patrick Stoelhorst as co-owner and director, specialises in the trade and installation of steel sheet piles. The walls serve a dual function as a structural barrier and an energy source. Installation of energy sheet pile walls includes assessing the sheet pile wall type (new or existing) and dimensions (profile type, width, depth). Modular energy elements are created based on and fitted within the frame's box width, with elements placed underneath the top concrete cap layer (if present) and grooves cut for pipework. There is no aboveground space pollution. However, an adequate area is required for the pipe network (considering pipe bending and thermal efficiency).

The energy and output requirements depend on the availability of sheet pile walls, energy demand, and water depth. These energy sheet pile walls can be scaled along entire canal banks, complying with the ability to grow simultaneously as the growing energy demand. Key values are further depicted in Table 4.

Table 4: Key Figures Gooimeer Interview

Factor	Description	Value
Energy Output	Energy generation of a singular element	1 kW
COP	Coefficient of Performance	5
Sheet	Thickness (length) of sheet pile walls. Thicker profiles tend to	1.2 – 1.4 m

Thickness	have high energy potential output (limited by pipe installation constraints)	
Lifetime	Durability of Sheet Pile Walls	50 years
Seasonal Stability	Ability to work in all seasons	100%
CAPEX	Initial investment costs	€1600-2300/kW
OPEX	Operational costs are low as a closed system (Maintenance for the heat pump)	Low
Construction	Construction time (digging, installation, and closure). Low noise pollution due to specialised technology used	24 elements in 1.5 weeks
Ecology	Low impact due to closed system (diffused temperature difference, with adjacent waters experiencing drops of 1/10)	1/10 Degrees Drop
Emissions	Carbon dioxide reduction based on energy output-to-gas equivalent. Further use of recycled/electro steel may reduce GHG emissions.	

Lastly, elaborate stakeholder interview results are depicted in Appendix I: Primary Research & Stakeholder Collaboration.

4.2 Energy Inventory

Energy inventory results were based on data from CBS and ArcGIS. The number of residents, households, and average annual gas and electricity consumption were noted for each postal code area within the defined scope. This data was utilised to calculate the total energy consumption of all postal code areas. The combined yearly energy usage amounts to 22,857 MWh, as shown in Table 5.

Table 5: Total Gas and Electricity Use for Vreeswijk in 2021

Subject	Amount	Unit
Gas Use	1,782,103	m³
Electricity Use	40,559,323	kWh
Gas Use (Converted)	18,801	MWh
Electricity Use (Converted)	4,056	MWh
Total Energy Use	22,857	MWh

The calculated energy use was translated into future heating and cooling demand aspects. Natural gas consumption was assumed to represent the heating of buildings and the production of warm tap water, accounting for 18,801 MWh annually. Additionally, the future cooling demand was estimated to entail 30% of the total energy demand, in compliance with assumptions from Volantis Concept Design [21]. Combining the estimated warming and cooling demands established the assumed total future energy demand, resulting in 24,461 MWh annually for Vreeswijk. Furthermore, the average energy consumption per household was calculated by dividing the total energy consumption by the number of households, as shown in Table 6.

Table 6: Total Annual Energy Demand and Energy Demand per Household

Subject	Amount	Unit

Warming Demand	18,801	MWh
Cooling Demand	5,660	MWh
Total Energy Demand	24,461	MWh
Number of Households	1,468	-
Average Energy Demand per Household	16.67	MWh

4.3 Financial Inventory

To estimate the current expenditures related to gas consumption, the variable costs were multiplied by the previously established gas usage per year (as depicted in Appendix IV: Financial Inventory). This result, in addition to the fixed annual costs, indicated residents' current energy consumption expenditures. The total cost of gas consumption yearly amounts to € 2,049.88, as described in Table 7.

Table 7: Average Gas Consumption Prices per Household

Yearly Average per Household (Gas)	
Post:	*Amount:*
Fixed Annual Costs	
Total	€ 313.91
Variable Costs	
Total for average gas use	€ 1,735.97
TOTAL Costs	€ 2,049.88

4.4 Multi-Criteria Analysis

Resulting from the MCA are the highest scoring TEO, WKO, and post-insulation methods based on the environmental, technical, financial, and social feasibility dimensions. The highest scoring thermal extraction technique (Table 8) is Energy Sheet Pile walls, with a score of 4.48. This is followed by Surface Water Heat Pumps with 3.57 and Geothermal Heat Pumps with 3.15. Energy Sheet Pile Walls scored higher than the other two techniques within all four dimensions. Surface Water Heat Pump follows the same pattern, but scores lower on social feasibility (0.20) than Geothermal Pump (0.33).

Table 8: Thermal Energy Extraction Technique MCA Results

Thermal Energy Extraction Techniques			
Dimension	**Energy Sheet Pile Walls**	**Surface Water Heat Pump**	**Geothermal Heat Pump**
Environmental Impacts	0.97	0.59	0.59
Technical Feasibility	2.78	2.53	2.13
Financial Feasibility	0.40	0.25	0.10

Social Feasibility	0.33	0.30	0.33
Total Score	4.48	3.67	3.15

For the Thermal Energy Storage Techniques (Table 9) The highest scoring methods were BTES (4.22), TTES (3.80), and lastly ATES (3.44). BTES scored highest within technical and financial feasibility (3.14 and 0.33, respectively), whereas TTES scored highest in environmental aspects (0.58). ATES had lower scores due to its associated environmental impacts (0.43) and higher financial implications (0.26).

Table 9: Thermal Energy Storage Technique MCA Results

Thermal Energy Storage Techniques			
Dimension	**ATES**	**BTES**	**TTES**
Environmental Impacts	0.43	0.50	0.58
Technical Feasibility	2.50	3.14	2.67
Financial Feasibility	0.26	0.33	0.3
Social Feasibility	0.25	0.25	0.25
Total Score	3.44	4.22	3.80

Lastly, several post-insulation techniques were assessed within the MCA, see Table 10. The floor and wall insulation depict the highest scores, with averages of 3.98 and 3.90, respectively. Wall Insulation consists of PUR Spray Foam (4.38), EPS Material (3.83), and Blown-in Fibreglass (3.51). Following this are roof insulation, with a score of 3.70, and window upgrades, scoring 3.33. Floor insulation scores higher in the environmental aspect (1.35), roof insulation in technical elements (1.25), while all insulation methods except window upgrades dominate the financial aspect (1.26, 1.30, and 1,31, respectively).

Despite a higher TTES score than ATES, ATES was selected as the most suitable technique next to BTES due to client preferences.

Table 10: Post Insulation MCA Results

Post Insulation Techniques						
	Wall Insulation			**Roof Insulation**	**Floor Insulation**	**Window Upgrade**
Dimension	**Blown-in Fiberglass**	**EPS**	**PUR Spray Foam**			
Environmental Impacts	0.90	1.35	1.35	0.90	1.35	1.20
Technical Feasibility	1.18	0.93	1.48	1.25	1.08	1.10
Financial	1.18	1.31	1.31	1.30	1.31	0.78

Feasibility						
Social Feasibility	0.25	0.25	0.25	0.25	0.25	0.25
Total Score	3.51	3.83	4.38	3.70	3.98	3.33

The criteria list utilised for technology assessment is depicted in Table 24, Table 25, and Table 26, whereas detailed descriptions on ratings, raw data, weights, and individual component results can be found in Appendix V: Multi-Criteria Analysis.

4.5 Dimensioning

As a result of the MCA, the most optimal techniques were identified for local energy generation and storage. Energy sheet pile walls emerged as the optimal energy production option, while ATES and BTES systems were the preferred solution for thermal energy storage. The following paragraphs estimate the space and number of systems required to meet the total energy demand.

4.5.1 Energy Generation Technique

One sector of sheet pile wall, with an average length of approximately 1.3 metres, can produce up to 1.33 kW. Utilising Google Maps, the total length of the canals was determined, amounting to 2,738.7 metres (Table 11).

Table 11: Input Data Energy Sheet Pile Walls

Data Energy Sheet Pile Walls		
Post	*Amount*	*Unit*
Canal Wall Length	2,738.7	m
Sector Capacity	1.33	kW
Sector Length	1.3	m

Table 12 Depicts the calculation results; the number of sectors required over the canal length, and their absolute sector capacity. The capacity is scaled up to a yearly production basis of 24,607 MWh annually. The calculated capacity theoretically covers Vreeswijk's required energy production (24,461 MWh per year).

Table 12: Potential Energy Generation Energy Sheet Pile Walls

Energy Production Calculations		
Post	amount	*unit*
Number of Sectors	2,107	-
Total Capacity	2,809	kW
Total Annual Capacity	24,607	MWh/y

Legislation

Besides compliance with general legislation, including the Environmental and Planning Act (Omgevingswet) and the Sustainable Construction Framework, see Appendix II: Secondary

Literature Research. The implementation of energy sheet pile walls requires the norms and certifications named in Table 13. These legislative aspects apply to installing the components impacting the water body and soil.

Table 13: Relevant Legislation Regarding Energy Sheet Pile Walls

Law, Regulation or Norm	Description
SIBK	
SIBK 11000	Certification of the underground part of soil energy systems
NEN	
NPR 7171-2:2025 nl	Ordening van ondergrondse netten
NEN 2767-2:2022 Ontw. nl	Conditiemeting van bouw- en installatiedelen
NEN 5743	Monsterneming van grond en sediment voor de bepaling van vluchtige verbindingen
NEN-EN-ISO 22475-1	Methoden voor monsterneming en grondwatermeting — Deel 1: Technische grondslagen voor de uitvoering
NPR 5741:2015 nl	Richtlijn voor de keuze en toepassing van boortechnieken en monsternemingstoestellen voor grond, sediment, slib en grondwater bij milieuonderzoek
NEN-EN-ISO 22282-1:2012 en	Geotechnisch onderzoek en beproeving - Geohydrologische beproeving - Deel 1 : Algemene regels
NEN-EN 14996:2006 en	Water - Richtlijn voor de kwaliteitsborging van biologische en ecologische beoordelingen in het aquatische milieu

CAPEX Energy Sheet Pile Walls

The estimated CAPEX for the implementation of energy sheet pile walls amounts to €5,477,560, see Table 14.

Table 14: CAPEX Energy Sheet Pile Walls

CAPEX		
post	*amount*	*unit*
CAPEX	1950	€/kW
Total Capacity	2809	kW
Total CAPEX	5,477,560	€

4.5.2 Energy Storage Techniques

The number of systems needed for the two thermal energy storage techniques, ATES and BTES, is shown in the following sections. Based on the monthly energy demand derived from the Concept Design, the systems must store up to 13,833 MWh.

The number of systems needed for the two thermal energy storage techniques, ATES and BTES, is shown in the following sections. The systems should have the capacity to store up to 13,833 MWh. This number was determined based on the monthly energy demand, derived from the Concept Design, see Appendix VI: Dimensioning For the various calculation steps.

ATES System

The maximum storage capacity of an ATES system is approximately 0.02 MWh of energy per m^3. Based on this efficiency, the total volume of 691,644 m^3 is required to meet the neighbourhood's projected storage demand. Given that the average capacity of a single system is around 150,000 m^3, it is calculated that five such systems are required to fulfil the storage demand (Table 15).

BTES System

Data on the spatial and storage capacities of BTES systems are presented in Table 15. A volume of approximately 1,383,288 m^3 is needed to meet the total storage demand, based on an average storage capacity of 0.01 MWh per cubic meter. As a single BTES system typically has a size of 9,350 m^3, 148 systems would be necessary to satisfy the complete annual storage requirement.

Table 15: Data Storage Capacity ATES and BTES Systems

Data Energy Storage Systems			
post	*Amount ATES*	*Amount BTES*	*Unit*
Energy Storage Demand	13,833	13,833	MWh
Space Capacity per System	150,000	9,350	m^3/system
Max. Capacity per m3	0.02	0.01	MWh/m^3
Amount of Space Required for Storage Demand	691,644	1,383,288	m^3
Number of Systems (Rounded Up)	5	148	

Legislation

The implementation of thermal energy storage systems requires geohydrological investigation and mechanical drilling. The necessary certifications and norms for these actions are described in The implementation of thermal energy storage systems requires geohydrological investigation and mechanical drilling. Table 16.

Table 16: Relevant Legislation Regarding Thermal Energy Storage Systems

Law, Regulation or Norm	Description
BRL	
BRL 6000-21	Certification of the above-ground part of soil energy systems (by Kiwa)
SIBK	
SIBK 11000	Certification of the underground part of soil energy systems
SIKB 2100	Mechanical drilling version 4.1 -1 January 2024 (by SIKB)
NEN	
NEN 7125:2017 nl	Energieprestatienorm voor maatregelen op gebiedsniveau (EMG)
NPR 7171-2:2025 nl	Ordening van ondergrondse netten
NEN 2767-2:2022 Ontw. nl	Conditiemeting van bouw- en installatiedelen
NEN-EN 17522:2023 en	Ontwerp en realisatie van gesloten bodemenergiesystemen (verticale bodemwarmtewisselaars)
NEN 5743	Monsterneming van grond en sediment voor de bepaling van vluchtige verbindingen
NEN 5744:2021 nl	Monsterneming van grondwater
NEN-EN-ISO 22475-1	Methoden voor monsterneming en grondwatermeting — Deel 1: Technische grondslagen voor de uitvoering
NPR 5741:2015 nl	Richtlijn voor de keuze en toepassing van boortechnieken en monsternemingstoestellen voor grond, sediment, slib en grondwater bij milieuonderzoek
NEN-EN-ISO 22282-1:2012 en	Geotechnisch onderzoek en beproeving - Geohydrologische beproeving - Deel 1 : Algemene regels

CAPEX ATES Systems

For the implementation of ATES systems with the storage capacity of 2719 kW, a CAPEX of €1,196,239 is estimated, as shown in Table 17.

Table 17: CAPEX ATES System

CAPEX		
post	*Amount*	*Unit*
CAPEX	440	€/kW
Required Energy Storage	2719	kW

Total CAPEX	1,196,239	€

5 Discussion

5.1 Primary & Secondary Literature Research

Primary research consisted of stakeholder collaboration and interviews. As depicted in Chapter 4.1 Stakeholder Interviews, Key players were identified and approached for project collaboration. It must be noted that the Municipality of Nieuwegein and Rijkswaterstaat, despite being essential stakeholders, were deliberately not contacted for interviews, as those were limited to those directly involved/engaged with the technical designs of the project. Both players were considered more governmental and must be contacted at later stages concerning relevant legislative and regulatory approvals and planning.

Interviews revealed that several stakeholders held slightly conflicting opinions regarding the feasibility of specific techniques. An example is the TEO techniques, in which the client preferred surface heat water pumps and solely slight support for energy sheet pile walls. In contrast, Gooimeer strongly proposed energy sheet pile walls. Varying stakeholder opinions, data gaps (e.g. ecological and technical data), and a lack of input from other stakeholders highlight the complexity of scenario development and uncertainty about whether all demands were met. Both techniques were implemented within the Advice and Recommendations chapter to ensure most needs are met.

To develop the MCA and energy/financial inventories, credible sources, scientific and governmental reports related to the project were utilised. However, differences in methodologies, assumptions, or report scales must be acknowledged, as they do not fully address local variations within Vreeswijk (e.g., geohydrological conditions, water quality, or infrastructure composition and diversity). Thus, client-provided reports must stand as a base for evaluating the applicability of techniques to Vreeswijk's scale.

5.2 Energy & Financial Inventory

Results were compared between our calculated outcomes and those within the Concept Note. However, the varying methodological approaches between the two analyses must be acknowledged. Volantis based their energy estimates on the energy use of various residential archetypes (year of construction, degree of insulation, and ownership situation). Our results were based on calculations utilising ArcGIS and CBS data. Their data depicts more detailed insights on energy, heat flow, and individual energy behaviour, whereas our results represent a more general, data-driven energy consumption overview. Thus, limitations must be considered, and comparisons must be adapted accordingly.

The ArcGIS data utilised to create the current energy inventory was based on secondary data from CBS, dating back to 2021. The data was employed with the authorisation of the client and stakeholders, as no other recent gas data was available. As a result, this does not reflect the most recent or realistic annual gas consumption per household, nor the ongoing energy transition trends within Vreeswijk. Furthermore, the raster cells in ArcGIS do not specify the sources of gas or electricity consumption, aggregating data of individual households or streets. For example, some households may produce electricity or use heat pumps, meaning their energy use does not contribute to Vreeswijk's heating demand. Nevertheless, the heating demand calculated in this study, 24,461 MWh, differs by only 2,356 MWh from the 22,104 MWh estimated in the concept design by Volantis.

The financial inventory is based on the assumption of a one-year fixed energy contract using the cheapest available package, with Stedin as the grid operator and Eneco as the gas and electricity supplier. It does not account for potential energy price fluctuations, subsidies' impact, or market volatilities. Moreover, since not all households may be connected to the grid and each can choose its supplier, the financial overview may differ from the actual average consumption patterns in Vreeswijk. This research determined about 1,214 m^3 of annual gas consumption, costing approximately €1,995, which aligns with the national average in the Netherlands, which ranges between 1,100 and 2,000 m^3 per year, depending on the type of house [39].

Lastly, an assumption was made regarding the cooling demand, depicting it at 30% of the total current energy use. The assumptions were based on the estimations within the Volantis concept design and reflect the increased demand due to cooling comfort and anticipated climate trends. Reviews of literature studies depict cooling projections ranging between 15% and 35% of total energy use. However, the cooling demand depends on the house's insulation level, ventilation mechanisms (building characteristics), and the regional climate. Well-insulated buildings can reduce cooling demand by preventing heat from entering but can increase demand by allowing heat to leave without adequate ventilation. Thus, the assumption can be used as a scenario prediction, rather than a definite baseline [40].

5.3 Multi-Criteria Analysis

Briefly described within Chapter 5.1 Primary & Secondary Literature Research, Utilising both Dutch and non-Dutch sources with varying methodological approaches may reduce the accuracy and applicability of technologies to the local conditions of Vreeswijk. Moreover, the risk of introducing subjectivity and bias is present when assigning weights to criteria, as they are grouped on the contextual importance of indicators to the project (Appendix V: Multi-Criteria Analysis). Recognising the subjectivity in observations is crucial, as it can inherently affect the scoring of all techniques.

The subjectivity was also faced while quantifying and rating options. Quantifiable scores categorised under all three technologies included (e.g.) "Impact on Carbon Footprint", "System Efficiency", "System Lifespan", Space Requirements", "CAPEX", "OPEX", and "Thermal Resistance". However, "Ecological Disruption", "Adaptability to evolving energy demands", "Seasonal Stability", and "Compatibility with Existing Infrastructure", were qualitative assessments, depicted as a qualitative scale or with a binary score (yes/no).

An essential distinction within the individual MCA criteria results must be considered. The ultimate score does not indicate a dominant preference among all requirements and dimensions. Key factors to consider include:

- A high score may result from outliers (heavily weighted criteria), despite lower scores for all other criteria.
- A method may depict an average ultimate score, due to consistent average criteria scores.

An exemplar of the first consideration is the score of Window Upgrades. The total score of 3.33 is attributed to significant scores across “Heat Loss Reduction”, “Impact on Carbon Footprint”, and “Thermal Resistance”, all scoring 0.60. Other criteria scored below 0.33, with the lowest score being 0.07. Polyurethane (PUR) spray form (wall insulation) is an example of the second consideration. It scored 4.38, with individual criteria ranging from 0.25 to 0.75, with a general even variance.

The financial dimension of the MCA results is also needed to be looked at more closely, with the focus on thermal storage techniques. In this project, ATES scored the lowest in financial feasibility score (0.25) among the three: BTES (0.48) and TTES (0.37). Therefore, while being a stronger competitor in terms of technical aspects, ATES shows more significant financial and environmental obstacles due to higher long-term system management (OPEX) (0.04 vs 0.16 and 0.12) and less favourable for ecological disruption (0.23 vs 0.30 and 0.38). BTES scored the highest in this dimension due to its relatively simple and lower-cost infrastructure. These findings highlight that financial feasibility can heavily influence overall MCA performance, and lower-scoring techniques may still be favourable in other dimensions if cost can be addressed through subsidies, scale, or regulatory incentives.

Another point is the assessment of both the impacts and the risks of implementing these optimal technologies. Based on the Physical Climate Risk Metrics, qualitative and quantitative criteria cover financial, technical, and environmental implications and risks. Risks- including regulations and adaptability to future demands, which are difficult to quantify but relevant for the (current and future) project's outcome, are addressed within the framework. However, the framework does not depict vulnerabilities to physical climate variations, e.g., climate change, extreme weather events, or shifts within (geo)hydrological systems [41].

Within the project, three MCAs were developed and conducted for TEO, WKO, and post-insulation techniques. The approach was selected as each group had distinct energy functions, impacts, and operational mechanisms, requiring varying (technical-, environmental-, social-, and financial) criteria lists with minimal oversimplification. The approach allows for context-specific evaluation of all grouped technologies but limits direct comparison across all individual options. It is best to utilise these outputs to depict all scenarios' strengths and weaknesses, rather than solely use them to aggregate each group into a proposed scenario. Based on our analysis, a combined approach to the two technologies is possible for future studies. However, further literature research and expert opinion are required to confirm this hybrid approach's technical feasibility.

Lastly, while the MCA provides ultimate scores to suggest the most optimal outcomes, these outcomes are not guaranteed to be applicable/feasible in reality. The lack of geohydrological and (sub)soil investigations, potential social discouragement, or financial implications may impact the practical implementation of proposed solutions. Thus, the selection of technologies must be based on complete preliminary investigations and implementation advice from specialised institutes/companies.

5.4 Dimensioning

In the heat extraction design of the energy sheet pile walls, the assumed total length (2,738.7 metres) of the canal wall includes sections of the Vaartse Rijn and the Koniginnesluis originating from the Lek, excluding the ship locks due to the fluctuating water levels that may hinder heat extraction feasibility, see Figure 7. However, it should be noted that not all canal walls are currently equipped with sheet pile walls to install the energy sheets. Additional sheet pile walls would need to be installed to use the full extent of the proposed wall sections for heat generation. The designed heat extraction system meets Vreeswijk's annual heat demand of 24,461 MWh, which is dimensioned to extract up to 24,607 MWh annually.

The sizing of the seasonal thermal energy storage system is based on the heat demand during the coldest period of the year, estimated from October to April. To close the gap between summer production and winter demand, it is assumed that 13,833 MWh of heat generated in the warmer months should be stored for late use in autumn and winter. This assumption is based on and Volantis is considered a credible source, as it relies on modelling approaches that offer a reliable estimation of the seasonal demand.

The size was determined for both ATES and BTES systems for comparison based on the MCA outcomes and the required storage. An ATES system with a volume of 150,000 m³ and storage capacity of 0.02 MWh. Or a BTES systems of 9350 m³ with a capacity of 0.01 MWh/m³. This translates to a need for 5 ATES systems and 148 BTES systems. A limitation of BTES is its low connection capacity, typically supporting only 5-20 households per system. Under the assumption that each BTES unit in Vreeswijk can serve 10 families, 158 systems would be needed to cover the estimated 1,579 households. The proposed 148 systems would therefore be insufficient, serving only 1,480 households. However, if it is feasible to connect 20 households per BTES system, the current design would be capable of covering the entire heating demand of Vreeswijk [42].

6 Conclusion

This research investigated the feasibility of local and sustainable energy generation (TEO) and storage (WKO) techniques for Vreeswijk's potential 5GDHC network. The citizen-led initiative of WarmVreeswijk aims to reduce fossil-fuel reliance by utilising locally available heat sources for sustainable residential heating and cooling.

Primary stakeholder collaboration, interviews, and secondary literature research allowed for identifying relevant energy data, background information, and technologies with their associated technical, financial, social and environmental implications. Data was utilised to conduct an MCA, develop an energy/financial inventory, and a dimension report, depicting scale-based implementation of the proposed solutions.

The MCA results depicted that Energy Sheet Pile walls (4.48) scored the highest among TEO techniques, followed by Surface Water Heat Pumps (3.57), and Geothermal Heat Pumps (3.15). Energy Sheet Pile Walls showed a dominant preference across all criteria/dimensions. Among the WKO options, BTES (4.22) scored the highest, particularly in technical and financial feasibility, whereas TTES (3.80) and ATES (3.44) follow. Lastly, post-insulation techniques, including PUR Spray Foam Wall Insulation (4.38) and floor insulation (3.98) depict the highest scores. Wall Insulation consists of PUR Spray Foam (4.38), EPS Material (3.83), and Blown-in Fibreglass (3.51). Closely following are roof insulation (3.70) and window upgrades (3.33). However, subjectivity within methodology, limitations and gaps within data (e.g. geohydrological assessments) must be accounted for when assessing these techniques individually.

The financial inventory depicted about 1,214 m^3 of annual gas consumption, costing approximately €2,049.88. This aligns with the national average in the Netherlands, which ranges between 1,100 and 2,000 m^3 per year (depending on the type of house). However, energy data estimates do not depict recent energy transition trends, and financial estimations are based on year-fixed contracts, inherently excluding potential energy price fluctuations, subsidies, or market volatilities.

Derived from ArcGIS data from CBS, the predicted yearly energy consumption for Vreeswijk was determined, amounting to 24,461 MWh. The energy generation potential of the suggested sheet pile wall system was scaled to the possible implementation scale, resulting in 2,107 energy sectors along 2,739 metres with an annual generation capacity of approximately 24,607 MWh. Additionally, the estimated thermal energy storage capacity was approximately 13,833 MWh. An average of 5 ATES systems or around 148 BTES systems would need to be installed to meet this storage demand.

7 Advice & Recommendations

7.1 Advice

To implement a 5th Generation District Heating and Cooling Network, the client is advised to leverage Energy Sheet Pile Walls as the primary energy extraction technique (TEO) and an ATES system (WKO) for energy storage.

Energy Sheet Pile Walls are depicted as promising TEO technologies, with minimal environmental disruptions and no direct carbon dioxide emissions. It depicts high system efficiency and heat extraction rates. Moreover, dimensioned results of 24,607 MWh represent the ability to cover the total heating demand of Vreeswijk, accounting for up to 24,461 MWh. The system is combined with an Aquifer Thermal Energy Storage (ATES) system, requiring solely 5 systems to meet the energy demand. ATES is advised in favour of previous client case studies and its commercial availability in the Netherlands. The system can extract and store (heating and cooling) thermal energy, depicting a high seasonal stability, and the ability to cover peak load demand hours. These features are critical to the project's objective of providing a sustainable and financially feasible heating and cooling solution for Vreeswijk.

For household-oriented actions, the advisable post-insulation strategy is the application of PUR (polyurethane) spray foam in the absence of proper wall insulation. The system consistently scores high in heat loss reduction, system efficiency, lifespan, and positive impact on carbon footprint. Moreover, adequate subsidies cover a significant portion of the expenditures, making them a financially viable option for residents. Otherwise, household investigations should be conducted to determine which infrastructure components can be further isolated.

7.2 Recommendations

Short-term recommendations (1-12 months)

It is recommended that the client retrieve primary data on household energy consumption in Vreeswijk to accurately determine the theoretical heat demand that the proposed extraction and storage systems must cover. The data could be retrieved from consumption bills in consideration of relevant privacy legislation.

Moreover, a geohydrological and (sub)soil inspection must be conducted in Vreeswijk to determine the locations of the underground storage systems and their connections. A certified third party must assess the location of the energy sheets and boreholes. A Klic-melding (excavation notification) must be reported to Kadaster between 3 and 20 workdays before (sub) drilling. If the client prefers the Surface Heat Water Pumps as a TEO extraction method, strict adherence to legislative standards is required based on potential hydrological/ecological-associated impacts. Preliminary investigations are thus crucial for storage and extraction techniques.

Moreover, the residents of Vreeswijk must be informed about the heat transition plan of this project. Prior or recent insulation of buildings, supported by municipal subsidies, is vital to minimise heat loss within the systems (lower energy demand and increased efficiency), ultimately reducing the future heat demand.

It is recommended that relevant technical and governmental bodies be consulted for project realisation within the brainstorming phase and before decision-making. These companies, e.g. Gooimeer, could deliver expert perspectives on possible solutions, whether advantageous or disadvantageous. However, it is also necessary to determine the role of water authorities within the heating transition. The action could decide whether they could have a position as project initiator, facilitator (governmental or technical), and resource manager, potentially allowing for smoother network development.

Mid-term recommendations (1 - 3 years)

Specific permits and regulations must be considered or requested to start constructing a heat extraction technique, such as energy sheet pile walls or a different system, if preferred, such as surface water heat pumps. These include an Environmental (and Planning) Permit, a Water Permit, a Roadworks Permit, BRL and ISO Certifications, and the Dutch Heat Act. NEN standards with specific norms and certification for aqua thermal heat extraction, storage, and heat grids must be considered.

Moreover, it must be acknowledged that, in the case of energy sheet pile walls, not all canal sections contain a suitable sheet pile structure, requiring the construction of additional sheets. This impacts the duration of construction and must be assessed with detailed design planning. Lastly, if energy sheet pile walls are depicted to be impractical and costly applications, other alternatives must be considered. There is potential to utilise “waste” heat from a nearby data centre, sewage plants, or drinking water plants, to provide heat to housing (and balance the WKO system). Therefore, it is advised to consult the data centre for this opportunity and determine its potential within this project. [43].

Long-term recommendations (3 - 7 years)

It is expected that the techniques will be realised or are already operating. In this case, monitoring and maintenance should happen frequently based on the advice of the construction companies and regulations.

References

[1] Rijksoverheid Nederland, "How long can I continue to cook and heat with gas?" 2025. Available: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/vraag-en-antwoord/hoe-lang-kan-ik-nog-koken-op-gas#:~:text=De%20Rijksoverheid%20wil%20de%20CO,alleen%20nog%20met%20duurzame%20installaties.

[2] CBS, "Decrease in greenhouse gas emissions levelled off in 2024," 2025. Available: https://www.cbs.nl/en-gb/news/2025/11/decrease-in-greenhouse-gas-emissions-levelled-off-in-2024.

[3] European Union. *2050 long-term strategy - European Commission*. Available: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en .Retrieved on Jun 72025.

[4] Avans University, "Assignment - WarmVreeswijk.nl," unpublished.

[5] WarmVreeswijk. *Vreeswijk aardgasvrij*. Available: https://warmvreeswijk.nl/ .Retrieved on Feb 202025.

[6] RVO. *Transitievisie Warmte en Wijkuitvoeringsplan*. Available: https://www.rvo.nl/onderwerpen/aardgasvrij/transitievisie-warmte-en-wijkuitvoeringsplan .Retrieved on Feb 202025.

[7] Hoogheemraadschap De Stichtse Rijnlanden. *Our work*. Available: https://www.hdsr.nl/werk/ .Retrieved on Feb 212025.

[8] Rijkswaterstaat. *About us*. Available: https://www.rijkswaterstaat.nl/over-ons .Retrieved on Feb 212025.

[9] Volantis. *Ingenieurs-, architectuur- en consultancygroep*. Available: https://volantis.nl/ .Retrieved on Feb 212025.

[10] Anonymous *Sheet Pile Walls: Learn Definition, Types, Importance & Selection*. Available: https://testbook.com/civil-engineering/sheet-pile-walls-types .Retrieved on Apr 252025.

[11] Jacco Haasnoot *et al*, "Energy quay walls," 2020Available: https://pure.tudelft.nl/ws/portalfiles/portal/85734488/e3sconf_icegt2020_06002.pdf.

[12] M Ziegler *et al*, "Energy sheet pile walls - Experimental and numerical Investigation of innovative energy geostructures," 2019. Available: https://www.ecsmge-2019.com/uploads/2/1/7/9/21790806/0932-ecsmge-2019_ziegler.pdf.

[13] Energie-Damwanden, "De voordelen van Energiedamwanden zijn o.a. gratis energie," Available: https://energie-damwanden.nl/voordelen-energiedamwanden/.

[14] Gooimeer. *Steel sheet piles from Gooimeer | Sales and rental*. Available: https://gooimeer.nl/ .Retrieved on Jun 72025.

[15] STOWA, "Handreiking voor beoordeling van ecologische effecten van TEO-systemen," 2023Available: https://www.stowa.nl/sites/default/files/2024-01/STOWA%202023-40%20WEB.pdf.

[16] P. Ocłoń, "Storage of thermal energy in the ground," in *Renewable Energy Utilisation using Underground Energy Systems*, P. Ocłoń, Ed. 2021, Available: https://doi.org/10.1007/978-3-030-75228-6_2.

[17] M. Bakr, N. van Oostrom and W. Sommer, "Efficiency of and interference among multiple Aquifer Thermal Energy Storage systems; A Dutch case study," *Renewable Energy*, vol. 60, pp. 53–62, 2013. Available: https://www.sciencedirect.com/science/article/pii/S0960148113002097. DOI: 10.1016/j.renene.2013.04.004.

[18] V. Rostampour *et al*, "Aquifer Thermal Energy Storage (ATES) smart grids: Large-scale seasonal energy storage as a distributed energy management solution," *Applied Energy*, vol. 242, pp. 624–639, 2019. Available: https://www.sciencedirect.com/science/article/pii/S0306261919305197. DOI: 10.1016/j.apenergy.2019.03.110.

[19] M. Bloemendal, M. Jaxa-Rozen and T. Olsthoorn, "Methods for planning of ATES systems," *Applied Energy*, vol. 216, pp. 534–557, 2018. Available: https://www.sciencedirect.com/science/article/pii/S0306261918301958. DOI: 10.1016/j.apenergy.2018.02.068.

[20] AAglass, "HR Glass - The difference between HR, HR+, HR++ and HR+++ glass," Available: https://en.aaglas.nl/alles-over-glas/het-verschil-tussen-verschillende-soorten-hr-glas.

[21] Tom Wijnen and Nadeche van de Braak, "Concept Ontwerpnota," unpublished, private communication, January 16.

[22] Tom Wijnen and Nadeche van de Braak, "Concept OntwerpNota," 2025. Available: https://file:///C:/Users/Etty/Downloads/20240675-090-RA-001%20-%20Concept%20ontwerpnota%20(16-01-2025)%20(1)%20(1).pdf.

[23] M. Lee. *9 Best Insulation Options for Under Floors*. Available: https://www.rmax.com/blog/underfloor-insulation .Retrieved on Jun 82025.

[24] BoVal. *Beoordelingsrichtlijnen (BRL's)*. Available: https://boval.nl/preventie-veiligheid-en-bedrijfscertificering/bedrijfscertificeringen/beoordelingsrichtlijnen/#:~:text=Beoordelingsrichtlijnen%20%28BRL%E2%80%99s%29%20zijn%20extra%20eisen%20om%20de%20kwaliteit,en%20eisen%20tot%20aan%20de%20praktische%20implementatie%20hiervan.

[25] Informatiepunt Leefomgeving. *Into Dutch Soils*. Available: https://iplo.nl/@281038/into-dutch-soils/ .Retrieved on Jun 82025.

[26] M. v. B. Z. e. Koninkrijksrelaties. *Omgevingswet*. Available: https://wetten.overheid.nl/BWBR0037885/2024-01-01 .Retrieved on Jun 82025.

[27] Omgevingsvergunning, "Alles Wat Je Moet Weten Over Omgevingsvergunningen," 2023. Available: https://omgevingsvergunning.net/omgevingsvergunningen/.

[28] European Commission. *BUILD UP*
The European portal for energy efficiency and renewable energy in buildings. Available: https://build-up.ec.europa.eu/en/resources-and-tools/articles/districtees-district-energy-efficiency-subscriptions-project-supports .

[29] NEN, "NEN," Available: https://www.nen.nl/.

[30] Rijkswaterstaat - Ministerie van Infrastructuur en Waterstaat. *Vergunningen Rijkswateren*. Available: https://www.rijkswaterstaat.nl/water/wetten-regels-en-vergunningen/vergunningen-rijkswateren .

[31] Anonymous *NEN*. Available: https://www.nen.nl/ .

[32] Omgevingsdienst. *Milieuvergunningen*. Available: https://omgevingsdienstnederland.nl/milieuvergunningen/ .

[33] CBS. *Kaart CBS Thema's Verbruik Gas & Elektriciteit*. Available: https://www.arcgis.com/home/item.html?id=f0bff57b428d41b8be304a9274e5bca1 .Retrieved on 06/062025.

[34] Google Maps. *Vreeswijk, Nieuwegein*. Available: https://www.google.com/maps/place/Vreeswijk,+Nieuwegein/@52.0098404,5.0700263,13.02z/data=!4m10!1m2!2m1!1svreeswijk!3m6!1s0x47c665006c77b8fd:0xbc91f3b53765069e!8m2!3d52.0037775!4d5.0966477!15sCgl2cmVlc3dpamtaCyIJdnJlZXN3aWprkgESdG91cmlzdF9hdHRyYWN0aW9umgEkQ2hkRFNVaE5NRzluUzBWSlEwRm5TVU5RTkhKdFdXbDNSUkFCqgFBEAEqDSIJdnJlZXN3aWprKAIyHxABIhu3H5cKfLLmpFrgPNZwBrbfCH65Hr_83K8j4FgyDRACIgl2cmVlc3dpamvgAQD6AQQIABBK!16s%2Fg%2F11lnddfnmd?entry=ttu&g_ep=EgoyMDI1MDYwMy4wIKXMDSoASAFQAw%3D%3D .Retrieved on 06/062025.

[35] Energie-damwanden NL. *Onze partners in energiedamwanden*. Available: https://energie-damwanden.nl/partners/ .Retrieved on 06/062025.

[36] M. Bloemendal, M. Jaxa-Rozen and T. Olsthoorn, "Methods for planning of ATES systems," *Applied Energy,* 2018. Available: https://www.sciencedirect.com/science/article/pii/S0306261918301958?via%3Dihub. DOI: https://doi.org/10.1016/j.apenergy.2018.02.068.

[37] T. Schmidt, D. Mangold and H. Müller-Steinhagen, "Seasonal Thermal Energy Storage in Germany," *ISES Solar World Congress,* 2003. Available: https://www.igte.uni-stuttgart.de/veroeffentlichungen/publikationen/publikationen_03-06.pdf.

[38] ECTP Innovative built environment, "Guideline for seasonal thermal energy storage systems in the built environment," 2016. Available: https://www.ectp.org/fileadmin/user_upload/documents/BED/EINSTEIN/einstein-guidelines_stes-tanks-del-38.pdf.

[39] Nibud. *Kosten van energie en water*. Available: https://www.nibud.nl/onderwerpen/uitgaven/kosten-energie-water/ .Retrieved on 08/062025.

[40] Sustainalytics, "Evaluate the physical climate risks facing your portfolio companies," 2023. Available: https://www.sustainalytics.com/investor-solutions/climate-solutions/physical-climate-risk-metrics.

[41] E. Ekmekci, Z. Ozturk Faith and A. Sisman, "Collective behavior of boreholes and its optimization to maximize BTES performance," *Applied Energy*, vol. 343, 2023. Available: https://www.sciencedirect.com/science/article/pii/S030626192300572X#:~:text=In%20this%20study%2C%20a%20small,the%20field%20at%20the%20lowest.

[42] Kadaster. *Klic-melding graafmelding*. Available: https://www.kadaster.nl/producten/woning/klic-melding?gad_source=1&gad_campaignid=20336815652&gbraid=0AAAAADqvNe84mZl-QZ54cu0dgWPIclxFm&gclid=CjwKCAjw6ZTCBhBOEiwAqfwJdzRSxlctnJuRBtQwqDejKZy0WSJe7WNmqvumYy-LIkrSn227JYk9cRoCTvQQAvD_BwE .Retrieved on 08/062025.

Appendices

Appendix I: Primary Research & Stakeholder Collaboration

As depicted in Chapter 3.1 Primary Research & Stakeholder Collaboration, stakeholder interviews were conducted to gather relevant primary data for the project. The stakeholder analysis was developed using an Excel sheet provided by Avans University of Applied Sciences. Figure 9 Depicts the stakeholders, their potential relevance to the project, and their assigned participation level.

Note: think in terms of a representative of the stakeholder.

Highlight	Stakeholder	Stakes (personal or professional)	Expertise added value	Expertise crucial or formally needed	Key role in implementation of the final plan	Should co-finance the final plan	#	Minimal participation level	Personal remarks
	Insert a new stakeholder Move stakeholder up Move stakeholder down Remove empty rows	*The person or organization has a stake in this project, i.e. is affected by the implementation of the actions of the final plan.*	*The stakeholder's expertise provides added value for the development of the plan.*	*The stakeholder's expertise is crucial or even formally obliged for the development of the plan.*	*Stakeholder is responsible for the implementation of actions of the final plan, i.e. as a "project manager", rather than as an individual actor who*	*Stakeholder should co-finance (a substantial amount of) the actions of the final plan.*		*1 - inform* *2 - consult* *3 - advise* *4 - co-create* *5 - co-decide*	
0	WaterNet (studying heat transfer sy	no	maybe	maybe	no	no	1	Inform	
0	Volantis	yes	yes	yes	maybe	no	4	Co-create	
0	HDSR	maybe	yes	yes	no	no	2	Consult	
0	Rijkswaterstaat	maybe	yes	maybe	no	no	2	Consult	
0	Hollandse Waterlinie	maybe	no	no	no	no	1	Inform	
0	Municipality	yes	yes	maybe	yes	yes	4	Co-create	
0	WarmVreeswijk/Berry	yes	yes	yes	yes	no	4	Co-create	
0	Citizens of Vreeswijk	yes	no	no	no	no	2	Consult	
0	Owners of non-residential buildings	yes	no	no	no	no	2	Consult	
0	Current Energy Provider (Eneco)	yes	maybe	no	no	no	2	Consult	
0	Government	maybe	no	no	no	no	1	Inform	
0	Partners that provide the technique:	maybe	yes	yes	maybe	no	3	Advise	
0	Deltares	no	yes	yes	no	no	2	Consult	
0	WarmingUp	no	yes	yes	no	no	2	Consult	
0	Key Residents	yes	no	no	no	maybe	##	#REF!	
0	Environmental Organizations	no	maybe	no	no	no	2	Consult	
0	HetEnergieBureau	no	yes	yes	no	no	1	Inform	
0	CodeGroenCommunicatie	no	yes	yes	no	no	2	Consult	
0	Consultancies	no	yes	maybe	no	no	2	Consult	
0	Other Environmental Researchers/A	maybe	no	no	no	no	2	Consult	
0	Other Municipalities	maybe	maybe	no	no	no	1	Inform	

Figure 9: Stakeholder Analysis (Excel Tool)

As depicted above, stakeholders were assigned to 5 degrees of Participation levels, based on their contextual importance to the project (elaborated in Table 18).

Table 18: Participation Levels Stakeholders

Participation Level	Description
1 – Inform	The stakeholder is informed of the proceedings of the process.
2 – Consult	The stakeholder is informed of the proceedings and can phrase their concerns, but these concerns cannot be guaranteed to be considered.
3 – Advise	The stakeholder is asked for his advice on the project.
4 – Co-Create	The stakeholders are invited to actively work on developing the plan with the project team and other stakeholders.
5 – Co-Decide	The stakeholder can steer the process of developing the plan. Stakeholders are active in deciding the plan's contents and/or budget.

Stakeholders were assigned Stakeholder Levels (Level I, II, III) based on literature research, client wishes, and 5 degrees of Participation. The final list (directly involved or researched) is depicted in Table 19, whereas all potential participants are depicted in the MCA link provided below.

Table 19: Stakeholder Engagement Summary

Stakeholder Level I		
Stakeholder	**Participation**	**Description**

	Level	
WarmVreeswijk	4 – Co-Create	-Project Client -Directly impact the project's direction & outcome with input and opinions -Goal: Constant collaboration & Input
Municipality of Nieuwegein	4 – Co-Create	-Planning & Implementation Partner -WUP Development & Energy transition -Owner of Vaartsche Rijn -Goal: Obtain technical/legal expertise for aquathermy systems
Rijkswaterstaat	4 – Co-Create	-A governmental body that regulates local and regional water management -Governmental Role in Permits -Owner of the Lek Canal -Goal: Obtain technical/legal expertise for the aquathermy systems
HDSR	4 – Co-Create	-Water quality & quantity management -Environmental Impact of aquathermy -Governmental Role in Permits -Owner of Merwede & Moat Fort Vreeswijk -Goal: Obtain ecological-, hydrological-, and legal expertise
Volantis	4 – Co-Create	-Engineering & Technical Agency -Goal: Obtain technical expertise for energy inventory
Deltares	3 – Advise	-Access to data on water management & aquathermy systems -Goal: Obtain hydrological, technical, and environmental expertise in aquathermy systems
Stakeholder Level II		
Stakeholder	**Participation Level**	**Description**
Residents Vreeswijk	2 - Consult	-Directly impacted when implementing the project's final actions -Goal: Receive acceptance and participation in the project
Current Energy Provider (Stedin)	4 – Co-Create	-Knowledge of current energy systems and infrastructure -Goal: Obtain Vreeswijk Energy Data
Stakeholder Level III		
Stakeholder	**Participation Level**	**Description**
WaterNet	2 – Consult	-Studies heat transfer systems -Knowledge of the technical aspects of systems -Goal: Obtain technical knowledge & data
WarmingUp	2 – Consult	-Relevant data on heating and energy systems -Goal: Obtain relevant knowledge on energy and heating systems

The following table (Table 20) results in a stakeholder matrix, which is the diagram categorising stakeholders based on their power/interest and participation level. After thorough Team discussions, the matrix was slightly adjusted to consider the stakeholder relevance and their direct involvement in the project.

Table 20: Stakeholder Matrix based on Participation Level.

Consult	Co-Create
- Residents Vreeswijk - WaterNet - WarmingUp	- WarmVreeswijk - Municipality of Nieuwegein - Rijkswaterstaat - HDSR - Volantis - Stedin
Inform	**Advise** - Deltares

The following link depicts summaries of key results and data obtained from stakeholder interviews and research.

SPSERR03 Stakeholder Summaries.docx

Appendix II: Secondary Literature Research

The following link contains additional literature on 5GHDC, other TEO and WKO technologies, and legislation relevant to the project.

SPSERR03 Literature Research.docx

Appendix III: Energy Inventory

The energy demand for building heating and cooling depends on several factors, including insulation levels, building characteristics, and residential behaviour. Table 21 presents the average annual energy requirements for heating, cooling, and domestic hot water across all residential units combined, provided by Volantis [21].

Table 21: Annual Energy Demand

Subject	Energy Demand
Heat Demand	14.441 MWh
Warm Tap Water Demand	1.009 MWh
Cooling Demand	6.654 MWh

The energy inventory was developed within an Excel file, depicting all secondary data, values, and calculations regarding Vreeswijk's current energy demand. The link for the energy inventory is depicted below:

SPSERR03 Energy Inventory.xlsx

Appendix IV: Financial Inventory

As depicted in Chapter 3.4 Financial Inventory, The financial inventory was developed utilising the energy inventory results and indicative current energy prices. Table 22 Entails the potential fixed and variable costs associated with electricity provision, based on the current tariffs provided by Stedin (grid manager) and Eneco (energy supplier), under the assumption of a one-year fixed contract.

Table 22: Indication Electricity Prices

Electricity Costs	
Post	*Amount*
Fixed Annual Costs	
Grid Management	€ 65.16
Delivery Costs (Lowest)	€ 453.87
Measurement Costs	€ 54.26
Variable Costs	
Electricity Price per kWh	€ 0.13

The average household electricity consumption costs, including taxes and VAT, were calculated with Equation 3.

$$Electricity\ Price\left(\frac{€}{\frac{kWh}{y}}\right) = Electricity\ price\left(\frac{€}{kWh}\right) * Average\ Electricity\ Use\ per\ Household\left(\frac{kWh}{y}\right)$$

Equation 3: Yearly Electricity Price per kWh

The total annual electricity costs per household amounted to approximately € 921.02. The values are depicted in Table 23.

Table 23: Average Electricity Consumption Prices per Household

Yearly Average per Household (Electricity)	
Post:	*Amount:*
Fixed Monthly Costs	
Total	€ 573.29
Variable Costs	
Total for Average Electricity Use	€ 347.74
TOTAL	€ 921.02

Appendix V: Multi-Criteria Analysis

An MCA was developed to depict the financial, social, environmental, and technical aspects of TEO, WKO, and post-insulation techniques. Table 24, Table 25, and Table 26 Depict the criteria, indicators, and selection motives for these technologies.

Table 24: TEO Extraction Criteria

Aqua Thermal Energy Extraction Criteria	**Indicator**	**Motivation**
Environmental Impact		
Ecological Disruption	Qualitative Scale (Low/Medium/High)	Measures the aqua thermal extraction impact on local aquatic ecosystems
Impact on Carbon Footprint	kg $CO_{2\,eq}$ /MWh	Measures CO_2 emission reduction from energy extraction
Legal Water Extraction Limits	Binary (Yes/no)	Measures passible water extraction rates to measure regulatory compliance
Technical Feasibility		
Adaptability to Evolving Energy Demands	Binary (Yes/no)	Focus on Sustaining the Evolving Energy Growth
Scalability (Output)	MWh/year	Maximum Energy Generation
Heat Extraction Rate	kW/ m^3h	Measures how effectively thermal energy can be extracted from water sources per unit volume
System Efficiency (COP)	Dimensionless	How effectively the system converts energy into usable heat/cooling
System Lifespan	Years	Durability of the system
Seasonal Stability	%	Assesses system performance year-round despite temperature fluctuations
Required Space	m^3 or m^2	Evaluates spatial requirements for the technology
Compatible with existing infrastructure	Binary (Yes/no)	Assess the compatibility with existing infrastructure
Financial Feasibility		
CAPEX	Euro	Upfront investments for installation and infrastructure modification
OPEX	Euro/year	Ongoing costs for maintenance, repairs, etc.
Citizen & Social Feasibility		
Noise Pollution/Impact	Decibels (dB)	Evaluate the impact of noise from construction/operation
Construction Duration	Years	Assess the length of construction (impact on residents and surroundings)

Table 25: Aqua Thermal Energy Storage Criteria

Aqua Thermal Energy Storage Criteria	**Indicator**	**Motivation**
Environmental Impact		
Ecological Disruption	Qualitative Scale (Low/Medium/High)	Measures the aqua thermal storage impact on local ecosystems
Impact on Carbon Footprint	kg $CO_{2\,eq}$ /MWh	Measures CO_2 emission reduction from energy storage
Technical Feasibility		
Adaptability to Evolving Energy Demands	Binary (Yes/no)	Focus on Sustaining the Evolving Energy Growth
System Efficiency (COP)	Dimensionless	How effectively the system converts energy into usable heat/cooling (final energy)
Storage Capacity	kWh/m^3	The amount of energy it can store
Ability to Store Cool & Heat	Binary (Yes/no)	Ability to store both cooling and heating
Peak Load Handling/Coverage	Binary (Yes/no)	Ability to meet heat/cool demands during peak usage hours
System Lifespan	Years	Durability of the technology
Seasonal Stability	%	Assesses system performance year-round despite temperature fluctuations
Required Aboveground Space	m^2	Evaluates spatial requirements for the technology
Required Underground Space	m^2	Evaluates spatial requirements for the technology
Compatible with existing infrastructure	Binary (Yes/no)	Assess the compatibility with existing infrastructure
Financial Feasibility		
CAPEX	Euro	Upfront investments for installation and infrastructure modification
OPEX	Euro/year	Ongoing costs for maintenance, repairs, etc.
Potential Revenue Generation (ROI)	Years	Assess how aqua thermal systems lower heating/cooling costs over time
Citizen & Social Feasibility		
Noise Pollution/Impact	Decibels (dB)	Evaluates the impact of noise from construction/operation
Construction Duration	Years	Assess the length of construction (impact on residents

		and surroundings)

Table 26: Post-Insulation Methods Criteria

Post-insulation Methods	**Indicator**	**Motivation**
Environmental Impact		
Heat Loss Reduction	W/m^2K	Measures the effectiveness of minimising energy waste
Impact on Carbon Footprint	Ton $CO_{2\ eq}$/kg	Measures CO_2 emission reduction from post-insulation methods
Technical Feasibility		
Thermal Resistance ®	m^2K/W	Measures insulation materials' resistance (checking energy efficiency and heat loss)
System Lifespan	Years	Durability of the technology
Compatible with existing infrastructure	Binary (Yes/no)	Assess the compatibility with existing infrastructure
Financial Feasibility		
CAPEX	Euro	Upfront investments for installation and infrastructure modification
OPEX	Euro/year	Ongoing costs for maintenance, repairs, etc.
Energy Price Reduction	Euro/year	Assess how insulation can reduce the energy costs for residents
Payback Period	Years	Assess the effectiveness of investment over time
Citizen & Social Feasibility		
Installation Duration	Days	Assess how long installation takes (disrupting residents)

The following link depicts the MCA, containing all individual measures taken and raw data collected to develop a final score.

SPSERR03 MCA.xlsx

Appendix VI: Dimensioning

An Excel link is provided, detailing the calculation steps conducted to estimate the necessary capacities of the energy generation and storage technologies:

SPSERR03 Dimensioning.xlsx

Appendix VII: Client-Specific Criteria

The client-specific product includes an informative brochure developed within Canva to inform residents and interested individuals on potential aqua thermal extraction and storage technologies. It aims to enhance awareness of the possible strategies and implementation implications of potential solutions.

The client-specific product can be found in Figure 10.

Figure 10: Client-Specific Product