# Report of Cavern and Subsurface Storage

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# Managerial Summary


Underground hydrogen storage (UHS) plays a pivotal role in enabling the large-scale integration of green hydrogen and accelerating the transition toward zero-emission energy systems. Among the various UHS technologies, salt caverns stand out due to their technical reliability, operational safety, and relatively low cost. As hydrogen demand increases across sectors such as industry, heating, and transport, developing a robust and flexible storage infrastructure becomes essential to balance the spatial and temporal mismatches between hydrogen production and consumption.

This research investigates the techno-economic feasibility of establishing an underground hydrogen storage network in the Northern Netherlands (NN) by linking potential salt cavern sites with projected hydrogen demand for 2050. The Northern Netherlands is a strategic location for such an assessment, as it combines favorable geological conditions with an emerging hydrogen ecosystem that includes major industrial clusters, renewable energy sources, and planned hydrogen infrastructure.

A Facility Location Problem (FLP) model was developed to determine the cost-optimal configuration of hydrogen storage and transport networks under three alternative demand scenarios (low, medium, and high). The modeling approach was complemented by expert interviews with key stakeholders from research, industry, and government to ensure realistic assumptions regarding technical feasibility, infrastructure planning, and policy dynamics. This integrated methodology bridges a key gap in hydrogen infrastructure planning by analyzing how demand uncertainty, capacity limitations, and cost dynamics interact to shape regional network design.

The results show that hydrogen demand levels decisively influence the structure and feasibility of UHS systems. Under a low-demand scenario, a single site at Zuidwending can accommodate all regional storage needs, whereas medium- and high-demand scenarios require up to nine of the ten candidate salt cavern sites. Although higher demand improves cost efficiency through economies of scale, the limited practical storage capacity of 15.2 TWh compared with a theoretical potential of 43.3 TWh presents a significant constraint for long-term scalability. These findings underscore the need for additional storage solutions, such as depleted gas fields or cross-border integration with German caverns, to ensure system flexibility and resilience.

The analysis further emphasizes the importance of proactive, long-term planning that integrates domestic and international storage strategies. Early inclusion of alternative storage options and clear coordination between public and private stakeholders are crucial to prevent future capacity shortages. Policy stability, well-designed investment incentives, and harmonized regulatory mechanisms will also be essential to accelerate infrastructure deployment and reduce uncertainty for investors.

From a governance perspective, three strategic actions are recommended: (i) introducing phased investment incentives to stimulate early-stage UHS development, (ii) establishing harmonized cross-border regulatory frameworks, particularly with Germany, and (iii) aligning regional storage capacity targets with verified industrial and mobility demand milestones. Implementing these measures can support a coordinated and adaptive rollout of hydrogen infrastructure across Northwest Europe.

By integrating quantitative modeling with stakeholder-informed governance insights, this study provides a decision-support framework for sequencing hydrogen infrastructure investments, aligning storage capacity with projected demand, and informing policy design. The results offer actionable evidence to guide the Northern Netherlands and other hydrogen regions in developing cost-effective, scalable, and resilient underground hydrogen storage systems.

# Structuring Hydrogen Storage Networks: Matching Geological CapacitywithFutureDemandintheNorthernNetherlands

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ABSTRACT

Undergroundhydrogenstorage(UHS)playsapivotalroleinenablingthelarge-scaleintegration ofgreenhydrogenandadvancingthetransitiontowardzero-emissionenergysystems.Amongthe variousUHStechnologies,saltcavernsemergeasaparticularlyattractiveoptionduetotheirtechnical reliability,operationalsafety,andrelativelylowcost.Ashydrogendemandgrowsacrosssectorssuch asindustry,heating,andtransportation,arobuststorageinfrastructureisessentialtoaddressthespatial andtemporalmismatchesbetweenproductionandconsumption.Thisstudyexplorestheoptimal designofahydrogenstoragenetworkintheNorthernNetherlands(NN)bylinkingpotentialUHS sites with projected hydrogen demand for the year 2050. A facility location problem (FLP) model is developed and applied to three demand scenarios (low, medium, and high) to determine cost-optimal configurations that minimize transport and storage costs. The model results indicate that under a low- demand scenario, only one storage site is utilized, whereas up to nine out of ten candidate sites are selected under high-demand conditions. However, the available salt cavern capacity proves inadequate in medium and high-demand scenarios, underscoring the need for complementary storage solutions such as depleted gas fields or above-ground tanks. These findings highlight the importance of scenario- based planning and accurate demand forecasting in guiding hydrogen infrastructure investments. Additionally, qualitative insights from five expert interviews inform key model assumptions and scenario development. Aligning UHS strategically with spatially distributed demand centers enhances system flexibility and cost-effectiveness, offering valuable guidance for regional hydrogen network planning.

## 1. Introduction

Decarbonizing global energy systems is imperative for mitigating greenhouse gas (GHG) emissions and addressing the escalating impacts of climate change. Energy production and consumption currently account for over 70% of global GHG emissions, and demand is projected to rise substan- tially in the coming decades [62]. According to the Inter- national Renewable Energy Agency (IRENA), low-carbon energy sources could supply up to 86% of final energy demand by 2050, a dramatic increase from 17% in 2015 [38]. Achieving this transformation requires the widespread adoption of renewable technologies and low-carbon energy carriers, most notably solar photovoltaics, batteries, heat pumps, and hydrogen [70, 27].

Hydrogen, particularly green hydrogen produced via electrolysis powered by renewable electricity, has gained significant attention as a versatile energy vector capable of decarbonizing hard-to-abate sectors, including heavy indus- try, long-distance transport, and high-temperature heating [1, 8]. Its potential for large-scale deployment has been reflected in policy and industrial initiatives such as the Clean Hydrogen Partnership [14]. However, the intermittent nature of renewable energy generation poses a major challenge for ensuring the reliability and continuity of hydrogen supply, thereby necessitating large-scale, long-duration energy stor- age solutions [61].

While hydrogen exhibits a high gravimetric energy density of about 120 MJ/kg, its volumetric energy density is considerably lower than that of conventional fossil fuels [51]. For comparison, natural gas provides approximately 40 MJ/m3, whereas hydrogen delivers only about 9.9 MJ/m3 [40, 49]. This discrepancy requires substantially larger stor- age volumes, presenting a major barrier to hydrogen's widespread adoption as an energy carrier [45]. When com- bined with the intermittency of renewable energy sources that supply green hydrogen, it becomes evident that large- scale and long-term applications demand significant storage capacity. As a result, underground geological formations such as salt caverns, saline aquifers, and depleted reservoirs have been identified as promising options for bulk hydrogen storage [46, 32, 81, 45, 47, 82].

Among various storage technologies, underground hy- drogen storage (UHS) in salt caverns stands out for its sim- plicity, high capacity, flexibility, and long-duration storage potential [73, 62, 52]. The Northern Netherlands (NN) offers favorable geological conditions for salt cavern development, alongside a strategic position within the broader European hydrogen network [10]. While prior studies [69, 5, 26, 12, 80] have investigated the technical feasibility of UHS, there is a notable gap in understanding how storage capacity, cost-effectiveness, and spatial network configurations evolve under varying and uncertain hydrogen demand.

While hydrogen supply chain optimization and storage planning have been examined in the literature, most studies focus on national-level system design or techno-economic comparisons of storage technologies rather than the spatial allocation of storage sites. For example, Almansoori and

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Shah (2009) [3] and Almansoori et al. [2] developed optimization models for hydrogen supply chains emphasiz- ing cost and carbon trade-offs, while Seo et al. [68] com- pared centralized and decentralized storage configurations, highlighting resilience–cost trade-offs. Other contributions have modeled hydrogen logistics and distribution pathways [57, 16], assessed the techno-economics of storage and pro- duction systems [32, 73, 46, 17], or provided reviews of geological storage potential [82], but few explicitly address the spatial placement of UHS facilities.

Applications of facility location models (FLP) to subsur- face storage remain scarce. Some relevant analogues exist in natural gas networks, where FLP-based approaches have been used to optimize storage and pipeline infrastructure [13, 22]. However, to the best of our knowledge, this study presents the first application of an FLP framework to eval- uate cost-optimal configurations of UHS in salt caverns, explicitly considering alternative and uncertain hydrogen demand scenarios at a regional scale.

This research advances prior modeling by integrat- ing projected regional hydrogen demand for the Northern Netherlands, the technical constraints of salt cavern storage, and the spatial optimization of the hydrogen network. Expert interviews complement the modeling by refining assump- tions and guiding scenario development. In doing so, the study offers new insights into infrastructure requirements for a cost-effective and scalable hydrogen system in the Northern Netherlands, within the broader Hydrogen Energy Applications in Valley Environments for Northern Nether- lands (HEAVENN) initiative [15].

The results reveal that while increasing hydrogen de- mand enhances cost-efficiency through economies of scale, it also introduces capacity constraints that challenge the feasibility of certain network configurations. These findings underscore the need for proactive strategic planning, early policy intervention, and the integration of alternative and cross-border storage solutions. They also highlight critical limitations in current infrastructure planning, particularly the long development timelines for salt caverns and the lack of integration with existing gas networks.

The remainder of this paper is organized as follows. Section 2 presents a review of relevant literature. Section 3 outlines the methodology and FLP model formulation. Section 4 introduces the case study and datasets. Section 5 presents the modeling results, followed by a discussion in Section 6. Section 7 concludes the paper by highlighting policy implications, limitations, and directions for future research.

## 2.TheoreticalBackground

Thissectionpresentsthetheoreticalandpracticalfoun- dations of UHS within the context of regional hydrogen economies, with a focus on the Northern Netherlands. It highlights key challenges in hydrogen distribution and stor- age, emphasizing the potential of salt caverns for large-scale applications and contrasting centralized with decentralized approaches.

### 2.1. HydrogenasanEnergyCarrierintheSupply Chain

Hydrogen is increasingly recognized as a flexible and low-carbon energy carrier, capable of supporting decar- bonization across electricity generation, transport, heating, and hard-to-abate industrial sectors. It is particularly relevant where direct electrification is technically or economically infeasible. In alignment with national climate ambitions, the Dutch Climate Agreement emphasizes the role of green hydrogen, produced via electrolysis powered by renewable electricity, as a cornerstone of the energy transition [19]. Electrolysis continues to gain traction in the Netherlands and across Europe as the primary technology for clean hydrogen production [1, 8].

However, the widespread deployment of hydrogen is constrained by infrastructure related challenges along the supply chain, particularly in the domains of distribution and storage [57, 56]. Hydrogen demand is projected to expand across multiple sectors including industry, mobility, energy, and the built environment driving the need for integrated and regionally tailored supply chain solutions [65, 54, 9, 11]. Although transportation by tube trailers is currently employed for short distances and pilot projects, long-term distribution is expected to rely heavily on pipeline networks. Recent studies indicate that up to 50% of the existing natural gas infrastructure in the Netherlands could be repurposed for hydrogen transport with limited modifications [64, 61, 6]. Nonetheless, the technical feasibility of such repurposing depends on key factors such as pipeline pressure ratings, material compatibility, and susceptibility to hydrogen em- brittlement [20].

Designing efficient hydrogen supply chains requires a careful balance between technical feasibility, economic via- bility, safety, and environmental performance. Recent mod- eling efforts emphasize the importance of optimizing hydro- gen logistics by integrating these multidimensional criteria [68, 57]. This need becomes even more pronounced at the re- gional level, where localized demand profiles, infrastructure availability, and sectoral priorities can differ substantially from national averages.

Although several national-level studies identify the in- dustrial, transport, and heating sectors as key drivers of future hydrogen demand in the Netherlands [67, 23, 25, 76], they typically lack the spatial and sectoral resolution re- quired for infrastructure planning at the regional or munici- pal level. Berenschot [7] report is a rare exception, offering detailed, sector-specific hydrogen demand projections disag- gregated by municipality. This study builds on such localized forecasts to address a critical gap in the literature: the lack of regionally tailored hydrogen supply chain analysis. By focusing on the Northern Netherlands, it enables a spatially and sectorally responsive design of hydrogen infrastructure aligned with regional development needs.

## 2.2. Centralized vs. Decentralized Storage Configurations

The spatial variability of renewable energy resources has accelerated the shift from centralized to decentralized energy systems [48]. Electrolyzers are increasingly colocated with renewable generation units, resulting in geographically distributed hydrogen production and storage networks [53, 8].

Comparative analyses show that centralized hydrogen storage configurations are generally more cost-efficient and require fewer storage sites at the national scale [2, 68]. However, their feasibility is constrained by the regional availability of suitable geological formations, such as salt caverns, and by the infrastructure required to transport hy- drogen over long distances. In contrast, decentralized storage systems provide greater operational flexibility and system resilience but typically incur higher capital and operational costs. Therefore, the selection of an optimal storage configu- ration is highly dependent on regional conditions and system objectives.

Despite these insights, notable gaps remain in integrating geological feasibility with spatially distributed hydrogen demand in infrastructure planning. This study addresses this issue by modeling centralized and decentralized hydrogen storage network configurations in the Northern Netherlands, where favorable salt formations coincide with strong regional hydrogen policy targets.

## 2.3. Hydrogen Storage Potential in Northern Netherlands

### 2.3.1. Salt Cavern Storage Potential in the Northern Netherlands

Salt caverns in the Northern Netherlands (NN) present a technically and economically viable solution for large-scale underground hydrogen storage, owing to their impermeabil- ity, self-healing characteristics, and proven mechanical sta- bility under cyclic loading conditions [50]. These favorable properties are complemented by the region's access to exist- ing pipeline infrastructure and renewable electricity sources, which are critical for enabling a flexible and integrated hydrogen system.

The regional underground hydrogen storage potential in salt caverns is estimated at approximately 43.4 TWh, based on around 321 identified caverns distributed across ten locations in the Northern Netherlands [75, 39]. However, only a subset of these sites is expected to be technically and economically feasible for development. Practical constraints including surface space limitations, risks of land subsidence, availability of leaching water, and brine disposal require- ments, reduce the realistically developable capacity to about 15 TWh by 2050, corresponding to roughly 60 caverns [78, 58]. This practically achievable capacity reflects current technological, spatial, and regulatory conditions, whereas the 43.4 TWh estimate serves as the theoretical upper bound that could become attainable as technologies, permitting processes, and deployment strategies evolve toward 2050.

Experience from global frontrunners supports the feasibility of this trajectory. Currently, four salt cavern hydrogen storage facilities are operational worldwide. The earliest, in Teesside (UK), has been active since 1972. In the United States, Clemens Dome (since 1983), Moss Bluff (2007), and Spindletop (2016) — all located in Texas — are integrated into industrial hydrogen pipeline networks [20, 59, 41, 43]. Their long-term performance underlines the suitability of salt formations for storing high-purity hydrogen, supported by favorable thermomechanical properties such as low per- meability and structural integrity under cycling [34, 71].

A key project in the Dutch context is the Zuidwending site in Groningen, now under development as the Nether- lands' first hydrogen-specific salt cavern storage facility. With operations expected to commence in 2026, the site serves as a pilot for hydrogen injection and withdrawal and will inform future large-scale deployment [33, 24].

On a broader scale, international initiatives such as the Advanced Clean Energy Storage (ACES) project in Utah, USA (planned capacity: 300 GWh), and the HyPSTER project in Étrez, France, aim to demonstrate the techno-economic viability of salt cavern storage for green hydrogen [42, 72]. These efforts reinforce the strategic value of salt cavern storage in achieving dispatchability, seasonal balancing, and scalability of hydrogen systems—principles equally relevant to the Northern Netherlands.

### 2.3.2. Strategic Role of the Northern Netherlands

Hydrogen is increasingly central to national and Euro- pean decarbonization strategies, with many countries inte- grating it into their 2030 and 2050 climate frameworks [36, 27, 35, 38]. The Netherlands has committed to becoming a frontrunner in the European hydrogen economy, positioning hydrogen as a core pillar of its energy transition [29, 30].

Within this national context, the Northern Netherlands (NN) plays a particularly strategic role. It has been des- ignated by the Clean Hydrogen Partnership as the EU's flagship "Hydrogen Valley" through the HEAVENN project, which aims to demonstrate an integrated hydrogen value chain from production to distribution and end use [31, 55].

The region's strategic importance stems from several structural advantages. It has direct access to offshore wind energy from the North Sea, a well-developed energy and industrial base, and proximity to domestic and cross-border demand centers. The NN's central location within the Eu- ropean energy network enhances its function as a potential hydrogen corridor for Northwest Europe.

Crucially, the Netherlands also benefits from extensive experience in managing natural gas infrastructure, much of which can be repurposed for hydrogen transport and system balancing [23, 25]. This legacy infrastructure provides a foundation for hydrogen network integration and supports the region's ambitions to facilitate large-scale hydrogen deployment both nationally and at the European level.

Taken together, these attributes make the NN a strategi- cally positioned hub for hydrogen innovation, infrastructure development, and cross-sectoral integration in support of a broader climate-neutral energy system.

### 2.3.3. *Hydrogen Infrastructure and Network Feasibility*

A fully integrated hydrogen network, including storage and distribution infrastructure, is not yet in place in the NN. The absence of such a network represents a major barrier to the widespread adoption of hydrogen technologies. Crucially, demand must precede infrastructure development to justify investment and reduce risk [10].

Studies suggest that approximately 50% of the existing Dutch natural gas network could be repurposed for hydrogen transport, depending on pipeline material and operating pressures [61]. Polyethylene pipes, commonly used in recent installations, are compatible with hydrogen and exhibit long lifespans of 50–100 years. Conversely, older steel pipelines may be susceptible to hydrogen embrittlement unless operated at low pressure [71, 20].

Retrofitting existing infrastructure presents an economically viable and environmentally favorable approach to hydrogen distribution [28]. Despite these advantages, large-scale pipeline construction has yet to begin, primarily due to high upfront costs and demand uncertainty. Establishing a robust hydrogen network thus hinges on long-term policy support and reliable demand projections [71, 20].

## 2.4. CostConsiderationsofSaltCavernHydrogen Storage

While salt caverns are widely regarded as one of the most technically suitable options for large-scale hydrogen storage, significant cost uncertainties continue to limit their commercial deployment. A widely used metric for eco- nomic assessment is the Levelized Cost of Storage (LCOS), which encompasses capital expenditure (CAPEX), opera- tional expenditure (OPEX), infrastructure requirements, and energy losses incurred over the facility's operational lifetime [63]. However, the absence of standardized cost estimation methodologies across studies has resulted in a broad spec- trum of LCOS values reported in the literature [43, 68, 34].

The major cost components of UHS in salt caverns in- clude cavern development, compression and pressurization infrastructure, and gas purification systems such as drying units and pressure swing adsorption (PSA) technologies. Early cost estimates by Lord et al. [43] suggest that total cap- ital costs, inclusive of surface and subsurface installations, could amount to approximately €1.54 per kilogram of hy- drogen . However, this figure is now considered outdated and highly sensitive to assumptions about plant size, geological conditions, and technology maturity.

Due to the site-specific nature of cavern construction and the technological complexity involved, the potential for cost reductions through economies of scale remains limited [44, 59]. This underscores the need for more robust and transparent component-level cost modeling.

More recent evaluations, such as those by Det Norske Veritas (DNV) [18], advocate for focusing on the most reliably estimable components of the hydrogen value chain, particularly storage and transport costs. These are summa- rized in Table 1.

Overall, while cost estimates for salt cavern-based hydrogen storage remain highly variable, a component-based approach enables more transparent and comparable evaluations. Such detail is critical for investment planning, project design, and policy support mechanisms aimed at scaling up UHS infrastructure.

## 2.5. Facility Location Optimization in Hydrogen Networks

While the optimization of natural gas infrastructure has been extensively investigated [4, 66], research on hydrogen network optimization remains at an early stage [16]. The development of an integrated hydrogen network—including the strategic allocation of storage facilities—can be con- ceptualized using the FLP framework. The FLP aims to determine the optimal siting and number of facilities that minimize total system cost or maximize service efficiency given spatially distributed demand [13].

In the context of hydrogen system planning, the FLP functions as a multi-criteria decision-making (MCDM) tool that incorporates both technical and policy-oriented con- straints [37]. It allows decision-makers to evaluate alterna- tive storage configurations under uncertainty and to align infrastructure development with long-term demand trajec- tories and governance objectives.

The model developed in this study applies the FLP framework to assess the optimal number and location of UHS sites in the Northern Netherlands, based on projected hydrogen demand through 2050. Multiple demand scenarios are explored to test the robustness of network configurations and to derive practical recommendations for infrastructure development. This study thus contributes to the growing body of literature on hydrogen infrastructure optimization and provides decision-support insights for initiatives such as HEAVENN, where aligning geological potential with spatial demand is a key planning challenge.

Although the mathematical structure of the FLP employed here follows the conventional formulation established in natural gas infrastructure studies, its application is specifically adapted to the hydrogen context and the regional characteristics of the Northern Netherlands. The model integrates hydrogen demand projections, salt cavern capacity constraints, and policy-relevant capacity targets to identify cost-optimal configurations under varying long-term scenarios. The contribution of this work therefore lies not in developing a new optimization algorithm but in contextualizing and applying the FLP approach to a real-world hydrogen valley setting. Future research should extend the model to incorporate hydrogen-specific operational aspects—such as material embrittlement, cyclic injection and withdrawal behavior, and hybrid storage systems combining salt caverns with depleted reservoirs.

## 2.6. Contribution

This study makes several key contributions to the litera- ture on hydrogen infrastructure planning and regional energy system modeling.

Table 1
Levelized Cost of Underground Hydrogen Storage and Transportation

| Function | Item | Cost (EUR/kg) |
|---|---|---|
| Levelized cost of hydrogen storage | Pressur ization<br>Storage CAPEX (cushion gas)<br>Storage OPEX<br>Losses | ± €0.32/kg |
| Levelized cost of transportation | Transportation CAPEX<br>Transportation OPEX | ± €0.004/kg per 1 km |
| **Total** | | **± €0.324/kg** |

First, it advances the methodological frontier by being, to the best of our knowledge, the first to apply a facility location problem (FLP) framework to the spatial placement of underground hydrogen storage (UHS) sites. The proposed model integrates salt cavern storage capacities and regional hydrogen demand within a unified location–allocation framework, addressing a critical gap in existing studies. Whereas prior research has typically examined storage feasibility and demand distribution separately, this study captures their spatial interdependencies through expert-validated, scenario-based analyses, providing a more realistic foundation for regional-scale hydrogen storage planning.

Second, the study enhances the modeling framework with insights derived from expert interviews. These inputs refine key assumptions, clarify technical and policy con- straints, and contextualize the interpretation of results within real-world planning environments—thereby strengthening the model's practical relevance.

Third, it contributes to applied regional planning by producing spatially optimized deployment scenarios under alternative demand growth and policy trajectories. The re- sulting insights are particularly relevant for hydrogen valley initiatives such as HEAVENN and comparable European projects, where strategic investment decisions must consider both subsurface constraints and evolving demand patterns.

Taken together, these contributions establish an integrated decision-support framework that links expert knowledge, geological resource availability, spatial optimization, and long-term energy demand. The approach provides policymakers and regional planners with a tool to design scalable and resilient hydrogen infrastructure consistent with broader decarbonization objectives.

## 3. Research Methodology

### Mathematical Model

This study employs an FLP formulation for hydrogen infrastructure planning in the NN. Municipality-level demand projections are integrated with the optimization of both the number and placement of UHS facilities to determine the least-cost system configuration. The model minimizes total system cost, comprising CAPEX for UHS development and hydrogen transportation costs, while ensuring that regional demand is met within predefined capacity and service distance constraints. It also accounts for the limited availability of suitable salt cavern sites and the need for large-scale storage to balance intermittent renewable supply with end- use demand.

The FLP is formulated as a mixed-integer linear program that identifies the cost-optimal configuration of UHS sites and the associated pipeline network. The objective is to minimize total system cost, defined as the sum of (i) CAPEX for UHS development and (ii) transport cost from storage sites to demand nodes, capturing the economic trade-off between infrastructure investment and distribution.

***Objective Function***

$$\text{Minimize} \quad \sum CG_i z_i + \sum \sum V x_{ij} L_{ij} \quad (1)$$

The first term represents the fixed cost of constructing UHS facilities, where $C$ is the unit capital cost of storage development (€/TWh), $G$ is the storage capacity at site $i$, and $z_i$ isabinarydecisionvariableindicatingwhetherafacility $i$ is built. the second term represents the cost of hydrogen transmission through pipelines between storage and demand nodes, where $V$ is the unit transport cost per kilometer (€/TWh·km), $x_{ij}$ isthevolumeofhydrogentransportedfrom storagenode $i$ todemandnode $j$, and $L_{ij}$ isthedistance between them. Together, these terms capture the total economic cost of the storage network.

***Constraints***

$$\sum x_{ij} \leq G_i z_i \quad \forall i \in S \quad (2)$$

$$\sum_{i \in S} G_i z_i \geq T \quad (3)$$

$$z_i = 0,1 \quad \forall i \in S : L_{ij} \leq \delta \quad (4)$$

$$x_{ij} = 0 \quad \forall i \in S : L_{ij} > \delta \quad (5)$$

Constraint (2) ensures that the hydrogen delivered from any storage site does not exceed its capacity. Constraint (3) requires total installed storage capacity to meet or exceed total system demand $T$. Constraints (4) and (5) enforce the maximum allowable service distance $\delta$, ensuring that hydrogen is only supplied to demand nodes within a feasible range.

### *Model Components*

**Decision Variables**

- $z$ co$^{i}$:Bina ryvariable ,equals1ifaUHSfacilityis nstructedatnode$i$,0otherwise.
- $x$ no$^{ij}$:Qu antityofhydrogentransportedfromstorage de$i$todemandnode$j$.

**Sets and Indices**

- $S$: Set of potential storage (supply) nodes.
- $F$:Setofhydrogendemandnodes.

**Parameters**

- $C$: Unit capital cost of UHS development (€/TWh).
- $V$:Unittransportationcostperkilometer(€/TWh·km).
- $N_i$:Hydrogendemandatdemandnode$i$.
- $G_i$:Storagecapacityofnode$i$.
- $L$ no$^{ij}$:Di stancebetwe enstoragenode$i$anddemand de$j$.
- $T$ : Total hydrogen demand in the system.
- $\delta$: Maximum allowable service distance from storage to demand node.

### *Model Assumptions*

- Subsurface hydrogen pipelines are assumed to follow straight-line (bird-flight) distances between demand and storage nodes.
- All UHS facilities are assumed to have uniform technical characteristics.
- There is no upper limit on the number of UHS fa- cilities; capacity constraints determine the optimal number and placement.
- Only salt cavern locations are considered viable for UHS.
- Hydrogen demand must be served immediately upon need (no time delay).
- Aservicedistancethresholdlimitsthemaximumdis- tance between a storage facility and the demand it serves.

Hydrogen transport distances between storage and demand nodes are modeled using straight-line (Euclidean) distances. This simplification is common in strategic-level facility location analyses and provides a transparent approximation of routing at regional scale. Given the Netherlands' flat topography and relatively compact geography, the deviation between Euclidean and actual pipeline routes is expected to be minor. To evaluate the potential influence of this assumption, Section 5.5 includes a sensitivity analysis in which route multipliers of 1.2, 1.3, and 1.4 were applied to emulate more realistic routing conditions. The results show that although total system costs increase with longer effective routes, the spatial configuration of the least-cost hydrogen network remains stable. Incorporating route-specific pipeline data, repurposing feasibility, and detailed cost constraints represents a key avenue for future model refinement.

## 4.CaseStudyOverview

Toidentifytheoptimalhydrogenlocation-allocationnet-work, a case study was conducted in the NN. This analysis aims to determine the ideal number and configuration of UHS locations, with a focus on minimizing overall system costs while meeting regional hydrogen demand.

### 4.1. UHS Specifications

Hydrogen storage in salt caverns is increasingly rec- ognized as a technically viable and scalable solution for balancing supply-demand mismatches in renewable-based hydrogen systems. While the theoretical storage potential in the Netherlands is substantial, practical deployment is constrained by geological, spatial, and economic factors. Insights from both the literature and stakeholder interviews confirm that hydrogen demand is projected to grow signifi- cantly as the market matures [67, 76, 23].

The Northern Netherlands region has been identified as particularly promising for underground hydrogen storage due to its favorable subsurface geology. Gasunie, in collab- oration with Nobian, is currently developing the country's first hydrogen storage facility in Zuidwending [33]. The construction involves the development of caverns at depths of around 1,500 meters, with timelines ranging from 3 to 4 years for cavern formation and 6 to 8 years for full operational readiness [21].

According to TNO [77, 78], national storage capacity in salt caverns is estimated to range from a lower bound of approximately 1.3 to 4.3 TWh, requiring 17 to 34 caverns, up to an upper bound of 15 to 26 TWh under high-demand scenarios, which could necessitate nearly 200 caverns. These estimates are based on technical criteria, including geologi- cal spacing constraints of 100 to 150 meters between cavern walls and the top of the salt structure.

This range of potential capacity has informed the sce- nario development and spatial planning components of the present study, particularly in relation to the sizing and allo- cation of UHS facilities across the Northern Netherlands.

Table2
Levelizedcostsofundergroundhydrogenstorage(UHS)

| Function–CostUHS | Cost(EUR/kg) |
|---|---|
| *Levelized cost of hydrogen storage* | |
| Pressurization | ±0.32 |
| StorageCAPEX(cushiongas) | ±0.32 |
| StorageOPEX | ±0.32 |
| Losses | ±0.32 |
| *Levelizedcostoftransportation* | |
| TransportationCAPEX | ±0.004perkm |
| TransportationOPEX | ±0.004perkm |
| **Total** | **±0.324** |

## 4.2.CostAssumptionsandUncertainties

Cost estimations for hydrogen storage remain uncertain due to evolving technologies and limited empirical data. Moststakeholdersinterviewedduringthisstudywererelucatanttoprovidespecificfigures,underscoringsubstantialunknownsregardingcavernconstructionandtopsidefacilities. Onlystorageandpipelinetransportationcostswereincluded in the model, as these are more consistently reported across studies.

According to Det Norske Veritas (DNV) [18], the levelized cost of hydrogen storage in salt caverns—including pressurization,cushiongas,storageCAPEXandOPEX,and transportation—isapproximately€0.324perkg.Thisbenchmark,alsoreferencedinBerenschot[7],iswidelycitedinthe literature and was validated through stakeholder interviews asarealisticreflectionofcurrentindustrypractice.

The study area—Friesland, Groningen, and Drenthe—covers a geologically consistent region of roughly 11,400 km2 (about 27% of the Netherlands), where major subsurface heterogeneity is not expected. Consequently, applying a uniformbenchmarkcostacrosssitesrepresentsadeliberate andtransparentsimplificationsuitedtothemodel'sregional scope and comparative purpose, rather than an uncritical assumption.Thisapproachensuresmodeltransparencyand tractability while maintaining consistency with established datasources.
Nevertheless,weacknowledgethatreal-worldcostsmay vary due to site-specific geological, regulatory, and scale-related factors. To explicitly account for this uncertainty, Section 5.5 tests the influence of cost variation by adjusting underground hydrogen storage CAPEX by ±30% and pipeline routing factors between 1.2–1.4. The results show that UHS consistently remains an integral element of the least-costnetworkconfigurationacrossalltestedcases,confirmingthatthestudy'sprincipalconclusionsarerobustand policy-relevantevenundersubstantialparametervariation.

Table 2 summarizes the applied cost components and correspondingunitvaluesusedinthemodel.

Dataforthisstudywerecollectedfrommultiplesources, including peer-reviewed literature and technical reports (e.g., [39, 7]). These quantitative and documentary sources provided the basis for model parameters such as hydrogen demandprojections,potentialstoragecapacities,andcost assumptions.
Tocomplementthequantitativedataandincorporate real-world practitioner perspectives, five semi-structured interviews were conducted with stakeholders actively engaged inthehydrogentransitionintheNorthernNetherlands.Participantswereselectedbasedondomainexpertise,institutionalresponsibilities,andavailability.Table3summarizes anonymizedintervieweelabels(A–E),organizationalroles, sectoralaffiliations,andinterviewdurations.Thesample representsacross-sectionofactorsfromindustry,infrastructureoperators,andlocalgovernment.

Eachinterviewwasrecorded,transcribed,andthematically analyzed using an inductive coding framework to identify recurring technical, economic, and governance themes relevanttohydrogenstoragenetworkdesign.Theinterviews provided qualitative insights into issues such as permitting timelines, regulatory fragmentation, public acceptance, and infrastructurereadiness—factorsthatstronglyinfluencethe real-worldfeasibilityofUHSdeployment.

Althoughmostinterviewswereconductedpriortofinalizingthefacility-locationmodelandthereforedidnot directly influence its mathematical structure, they play a complementaryroleincontextualizingthequantitativeanalysis. Stakeholder input informed assumptions about realistic development timelines and institutional constraints, anditguidedtheframingofdemandscenariosbyhighlightingpracticallimitationsonhowquicklyUHScapacity canbescaled.Accordingly,themodelingandinterview components are designed as interconnected but distinct elements:theFLPmodelprovidesquantitativeinsightsinto cost-optimal network configurations, while the interviews interpret how these outcomes align with existing governance, permitting, and societal conditions in the Northern Netherlands.

Whilethestakeholderinterviewswereconductedprimarilybeforefinalizingthefacilitylocationmodel,their insights remain essential to interpreting and contextualizingthequantitativefindings.Theinterviewsilluminate practitioner perspectives on permitting delays, regulatory fragmentation,andpublicacceptance—factorsthatstrongly shapethefeasibilityofundergroundhydrogenstoragebut fall outside the scope of the optimization framework. Accordingly, the modeling and interview components are presented as complementary yet interdependent elements of the study: the FLP model quantifies cost-optimal network configurations, whereas the interviews situate these results within the broader implementation landscape. This integratedframingensuresthatthequalitativeevidenceenriches thestudy'spolicyandpracticalrelevance,eventhoughit doesnotdirectlyaltermodelparametersorstructure.

## 4.3.MappingofUHSNodes

ThetotalUHScapacityofapproximately43.4TWh presentedinTable4andvisualizedinFigure1corresponds to the cumulative potential of all identified salt cavern sites across the three provinces of the NN (Friesland, Groningen,

Table 3
Details of Stakeholder Interviews

| Label | Interviewee | Position | Organization Category | Duration (min) |
|---|---|---|---|---|
| A | Interviewee A | Principal Consultant Hydrogen in Energy Systems | Technical Consultancy | 59:43 |
| B | Interviewee B | Head Hydrogen | Gas Infrastructure Operator | 54:17 |
| C | Interviewee C | Principal Consultant Hydrogen in Energy Systems | Local Government | 41:47 |
| D | Interviewee D | CEO | Private Data Infrastructure | 31:14 |
| E | Interviewee E | Policy Officer for Energy Transition | Local Government | 45:03 |

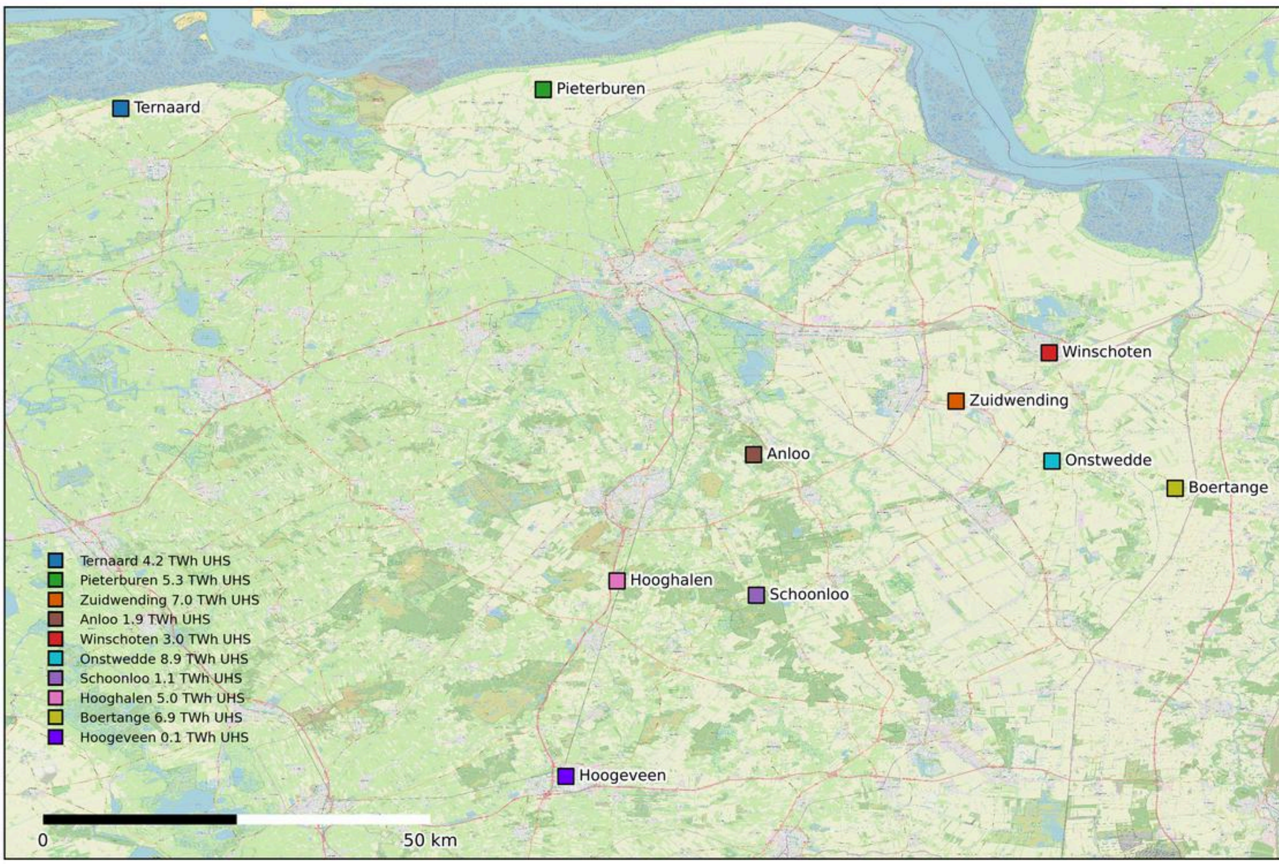



Figure 1: Spatial distribution of salt cavern UHS sites across Friesland, Groningen, and Drenthe with a combined theoretical storage capacity of 43.4 TWh

and Drenthe), as reported in TNO [75, 78], and Juez-Larre et al. [39]. These studies identify around 321 individual caverns, which together constitute the region's theoretical storage potential of 43.4 TWh. This theoretical value represents the upper bound of subsurface storage capacity in the NN and provides the basis for scenario development and system design in this study.

## 4.4. Identification of Hydrogen Demand Nodes

Hydrogen demand in the Northern Netherlands (NN) is anticipated to arise across three primary end-use sectors: industry, mobility, and spatial (residential) heating. However, consistent and disaggregated sector-specific data at the municipal level is currently lacking. To overcome this limitation, the present study draws on the regional hydrogen demand projections provided by Berenschot [7], which offer detailed, municipality-level estimates for the year 2050.

Within the modeling framework, each of the 49 municipalities in the NN is treated as a unique demand node, collectively constituting the set $F$. These nodes represent the spatial distribution of hydrogen demand and are integrated into the FLP model. A full list of the identified demand nodes is provided in Appendix A. The corresponding distances between each demand node $F_j$ and potential underground hydrogen storage location $S$, expressed in kilometers ($L_{ij}$) are presented in Appendix C, forming the set of realizable arcs within the model.

Table 4
Set of UHS nodes $S$ and the capacity $G_i$ of every node in the set $S$

| Salt Cavern Location | # Caverns | Capacity (TWh) |
|---|---|---|
| **Groningen** | **230** | **31.1** |
| Zuidwending | 52 | 7.0 |
| Winschoten | 22 | 3.0 |
| Pieterburen | 39 | 5.3 |
| Onstwedde | 66 | 8.9 |
| Boer tange | 51 | 6.9 |
| **Friesland** | **31** | **4.2** |
| Ternaard | 31 | 4.2 |
| **Drenthe** | **60** | **8.1** |
| Anloo | 14 | 1.9 |
| Hooghalen | 37 | 5.0 |
| Hoogeveen | 1 | 0.1 |
| Schoonloo | 8 | 1.1 |
| **Total** | 321 | 43.4 |

## 4.5. Scenario Framework and Demand Modeling

To address long-term uncertainty in hydrogen infrastruc- ture planning, this study develops three overarching demand scenarios: Low, Medium, and High, each featuring four governance-based sub-scenarios. These sub-scenarios incor- porate four future energy system scenarios developed under the Integrale Infrastructuurverkenning 2030–2050 (II3050) framework: *Regional Control*, *National Control*, *European Control*, and *International Control* [74].

The four II3050 scenarios reflect different governance approaches to the energy transition. In the Regional Con- trol scenario, local communities take the lead, prioritizing circularity, decentralized renewable generation (solar, wind, geothermal), and reduced industrial activity, resulting in near self-sufficiency with green gas and hydrogen used to cover peak demand. The National Control scenario features strong central government coordination, the largest build- out of solar and wind capacity, and extensive electrification across sectors, with imports and green hydrogen supporting a stable industrial base. The European Control scenario is driven by EU-wide carbon pricing, leading to industrial growth through hybrid electrification, CCS, and a mix of blue and green hydrogen, alongside increased imports and continued gas use in various sectors. In the International Control scenario, market forces dominate, favoring cost- effective global hydrogen imports over domestic production, with hydrogen playing a key role in hybrid energy systems and supporting industry, while the role of green gas is minimal.

Demand projections for Friesland, Drenthe, and Gronin- gen provinces under each sub-scenario were derived from the Berenschot (2020) study [7] and are presented in Table 5. All the scenarios, sub-scenarios and demand per municipal- ity can be found in Appendix B.

# 5. Results

The results and outputs of the FLP model simulations un- der each predefined demand scenario are presented and dis- cussed in this section. For each sub-scenario within the low, medium, and high demand trajectories, a distinct hydrogen storage network configuration is derived. The analysis dif- ferentiates between the theoretical storage potential and the practically achievable capacity, acknowledging both techni- cal feasibility and real-world implementation constraints.

## 5.1. Results Low-demand Scenario 2050

In the 2050 low-demand scenario, annual hydrogen de- mand in the Northern Netherlands is projected to range from 0.31 TWh under the regional sub-scenario to 5.5 TWh un- der the international sub-scenario (Table 6). Notably, these demand levels remain well below the total storage capacity of the Zuidwending facility, which is estimated at 7 TWh. Consequently, Zuidwending is the sole underground hydro- gen storage site utilized across all sub-scenarios in this low-demand case.

Consequently, the overall network structure and associ- ated storage costs remain unchanged across all sub-scenarios (regional, national, European, and international) within the low-demand scenario. Since the same UHS location is used and its capacity is fixed, the levelized storage cost remains constant. However, the hydrogen distribution cost varies between sub-scenarios, reflecting differences in total de- mand volumes and the distances over which hydrogen must be transported. This spatial variation in transport cost is illustrated in Figure 2.

As a result, the spatial configuration of the hydrogen network remains identical across the regional, national, Eu- ropean, and international sub-scenarios in the low-demand case, as illustrated in Figure 3.

## 5.2. Results Medium Demand Scenario 2050

In the medium demand scenario for 2050, the demand for hydrogen in the NN increases and is expected to vary between 13.41 and 35.70 TWh. The number of UHS fa- cilities increases, resulting in significantly higher hydrogen demand, as the hydrogen market and developments begin to mature. The results are shown in Table 7. The increase in demand is directly reflected in the costs. The total cost of the national medium-demand sub-scenario amounts to approximately 376 million euros, whereas the total cost of the national sub-scenario in the low-demand scenario was 83 million euros, even though the demand has increased nearly ninefold. This cost reduction indicates that as demand increases, the ratio of demand to cost becomes more favor- able because the costs of storing and distributing hydrogen decrease significantly for every sub-scenario in the medium demand scenario.

The service distance in kilometers in the medium de- mand scenario decreased by more than 50% compared to the low demand scenario. This can be explained by the fact that the overall demand for hydrogen has increased, necessitating more UHS to supply the demand locations. The addition of

Table 5
Hydrogen demand per province in 2050 based on Berenschot (2020) and II3050 scenarios

| Scenario | Friesland(TWh) | Drenthe(TWh) | Groningen(TWh) | Total NN (TWh) |
|---|---|---|---|---|
| | | **Low demand scenario** | | |
| Regional | 0.11 | 0.09 | 0.11 | 0.31 |
| National | 0.98 | 0.85 | 1.26 | 3.09 |
| European | 1.24 | 1.05 | 1.71 | 4.00 |
| Inter national | 1.62 | 1.64 | 2.44 | 5.70 |
| | | **Medium demand scenario** | | |
| Regional | 4.83 | 3.87 | 4.71 | 13.41 |
| National | 8.86 | 7.75 | 11.46 | 28.08 |
| European | 9.69 | 8.19 | 13.38 | 31.25 |
| Inter national | 10.16 | 10.26 | 15.28 | 35.70 |
| | | **High demand scenario** | | |
| Regional | 9.55 | 7.64 | 9.32 | 26.52 |
| National | 16.75 | 14.65 | 21.66 | 53.06 |
| European | 18.13 | 15.33 | 25.05 | 58.51 |
| Inter national | 18.70 | 18.89 | 28.12 | 65.71 |

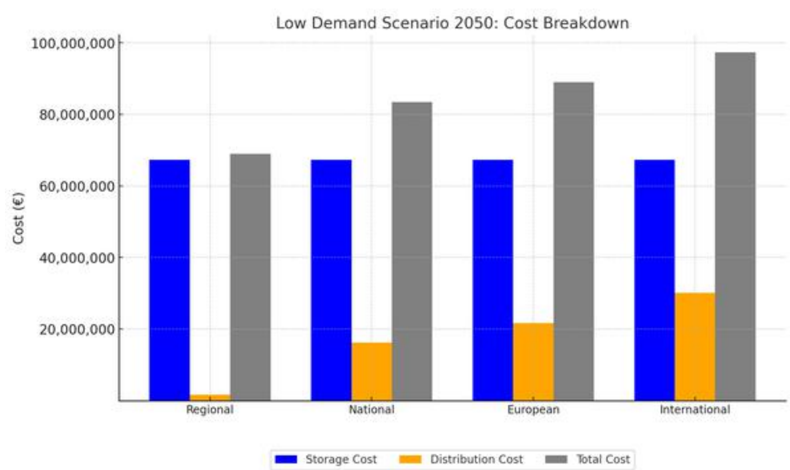



Figure 2: FLP Model Results of Low Demand Scenario

Table 6
Results for the low demand scenario

| Scenario | Hydrogen Demand (TWh) | Service Distance (km) | Storage Facilities | Storage Cost (€) | Distribution Cost (€) | Total Cost (€) |
|---|---|---|---|---|---|---|
| Regional | 0.31 | 125.73 | 1 | 67,267,267.27 | 1,683,974.40 | 68,951,241.67 |
| National | 3.09 | 125.73 | 1 | 67,267,267.27 | 16,177,016.55 | 83,444,283.81 |
| European | 4.00 | 125.73 | 1 | 67,267,267.27 | 21,704,195.36 | 88,971,462.62 |
| Inter national | 5.70 | 125.73 | 1 | 67,267,267.27 | 30,077,585.43 | 97,344,852.70 |

Table 7
Results for the medium demand scenario

| Scenario | Hydrogen Demand (TWh) | Service Distance (km) | Storage Facilities | Storage Cost (€) | Distribution Cost (€) | Total Cost (€) |
|---|---|---|---|---|---|---|
| Regional | 13.41 | 66.62 | 4 | 136,456,456.46 | 47,979,093.10 | 184,435,549.55 |
| National | 28.08 | 66.64 | 6 | 283,483,483.48 | 92,616,330.54 | 376,099,814.02 |
| European | 31.25 | 60.13 | 7 | 320,960,960.96 | 106,191,095.90 | 427,152,056.86 |
| Inter national | 35.70 | 59.76 | 8 | 349,789,789.79 | 125,027,308.45 | 474,817,098.24 |

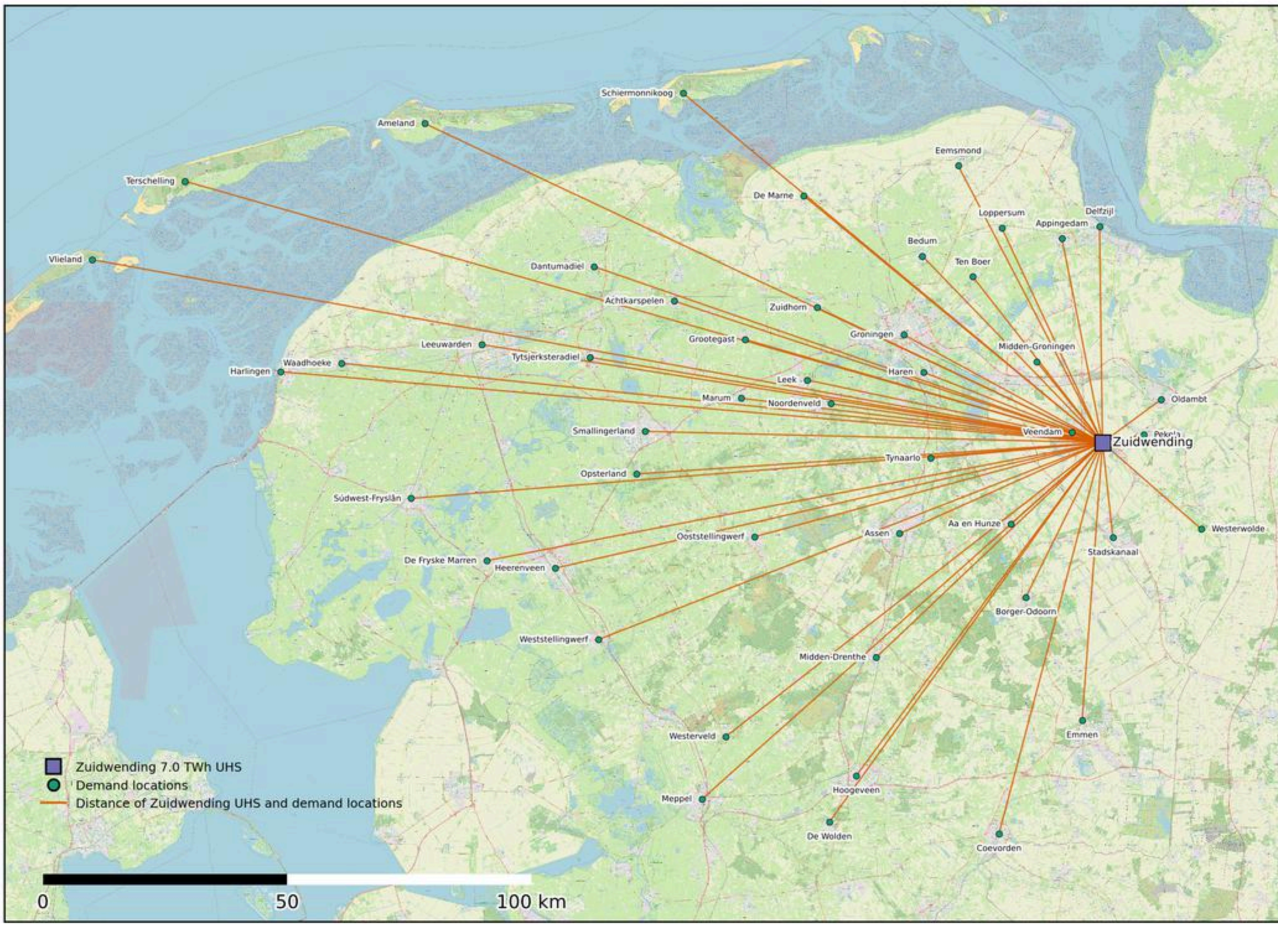



Figure 3: Results of Low Demand Scenario

more UHS locations results in a broader distribution, thereby shortening the distances to demand locations. Despite the shorter distances, the increase in transport costs can be explained by the larger volumes of hydrogen that need to be transpor ted.

The hydrogen network structure and UHS locations for the different sub-scenarios in the medium demand scenario can be seen in Figures 5, 6, 7, 8, and the associated cost in Figure 4. Looking at the demand and available capacity, only the regional sub-scenario in the medium demand scenario is feasible with the practical capacity of 15 TWh. The other three sub-scenarios in the medium demand scenario have too high demand, exceeding the 15 TWh capacity. In these three sub-scenarios, the combined capacity of the UHS is insufficient to meet the demand.

### 5.3. Results High Demand Scenario 2050

In the high-demand scenario, the hydrogen market is assumed to be well-developed and completely mature by 2050. The hydrogen demand is expected to vary between 26.52 and 65.71 TWh. The number of UHS increases further, and three of the four sub-scenarios within the higher demand scenarios become infeasible because demand exceeds the available capacity at the UHS locations. The constraint $\sum i \in F\ N x_{ij} \leq$

$G_{iz}$he$^{i}$i snolongersatisfiedinthesethreesub-scenarios. required UHS facilities ranges from seven to nine across all sub-scenar ios

As the model seeks to satisfy as much hydrogen demand as possible at minimal total system cost, it continuously optimizes the trade-off between opening additional storage facilities and extending service distances. With increasing demand, the cost-efficiency of the system improves, re- flected in a more favorable demand-to-cost ratio, although the marginal gains diminish as total demand rises.

As expected, the total costs increase substantially under high demand conditions. The international sub-scenario, for example, reaches a total cost of approximately 732 million euros, nearly double that of the highest-cost medium demand scenario (474 million euros). This increase is primarily driven by the larger volume of hydrogen handled and the longer transport distances, particularly evident in the European sub-scenario, where the average service distance exceeds 125 km. Compared to the low demand scenario, which had a maximum total cost of 148 million euros, the cost increase in the high demand scenario is nearly fivefold.

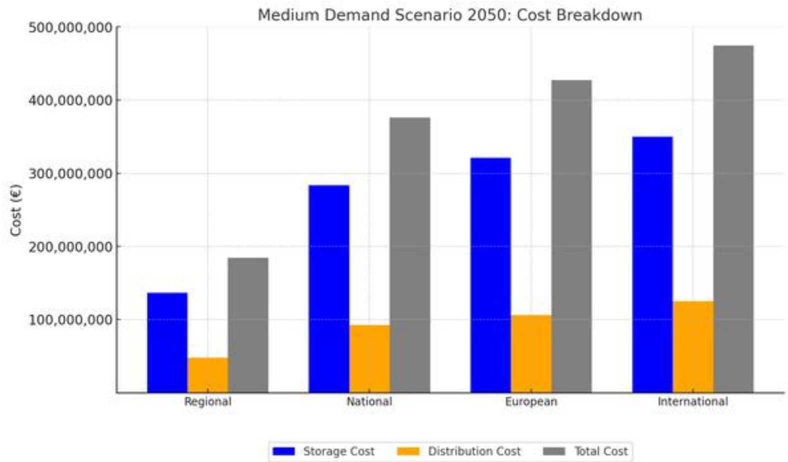



Figure 4: FLP Model Results of Medium Demand Scenario

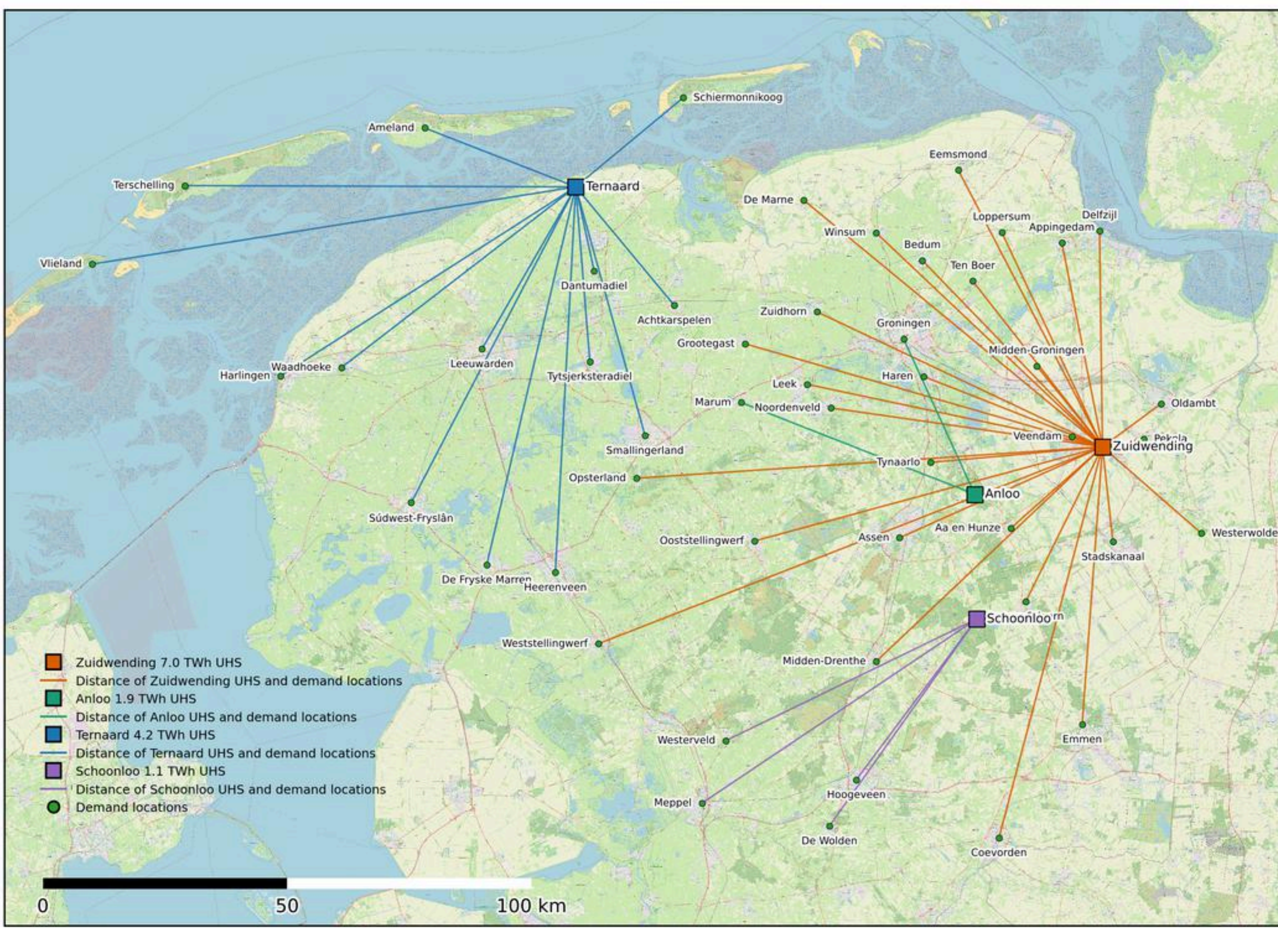



Figure 5: Results of Medium Demand Scenario-Regional

Despite the increase in absolute costs, the results indicate that economies of scale continue to moderate cost intensity. The cost per unit of hydrogen stored and transported does not increase proportionally with demand. For instance, while the international sub-scenario's demand is nearly twice that of the medium regional sub-scenario, its total cost is only about four times higher. This demonstrates that, as infrastructure scales, cost-efficiency per TWh improves, especially when UHS facilities are strategically located to optimize network per for mance.

However, the increase in service distances, particularly in the European scenario, suggests a growing geographical

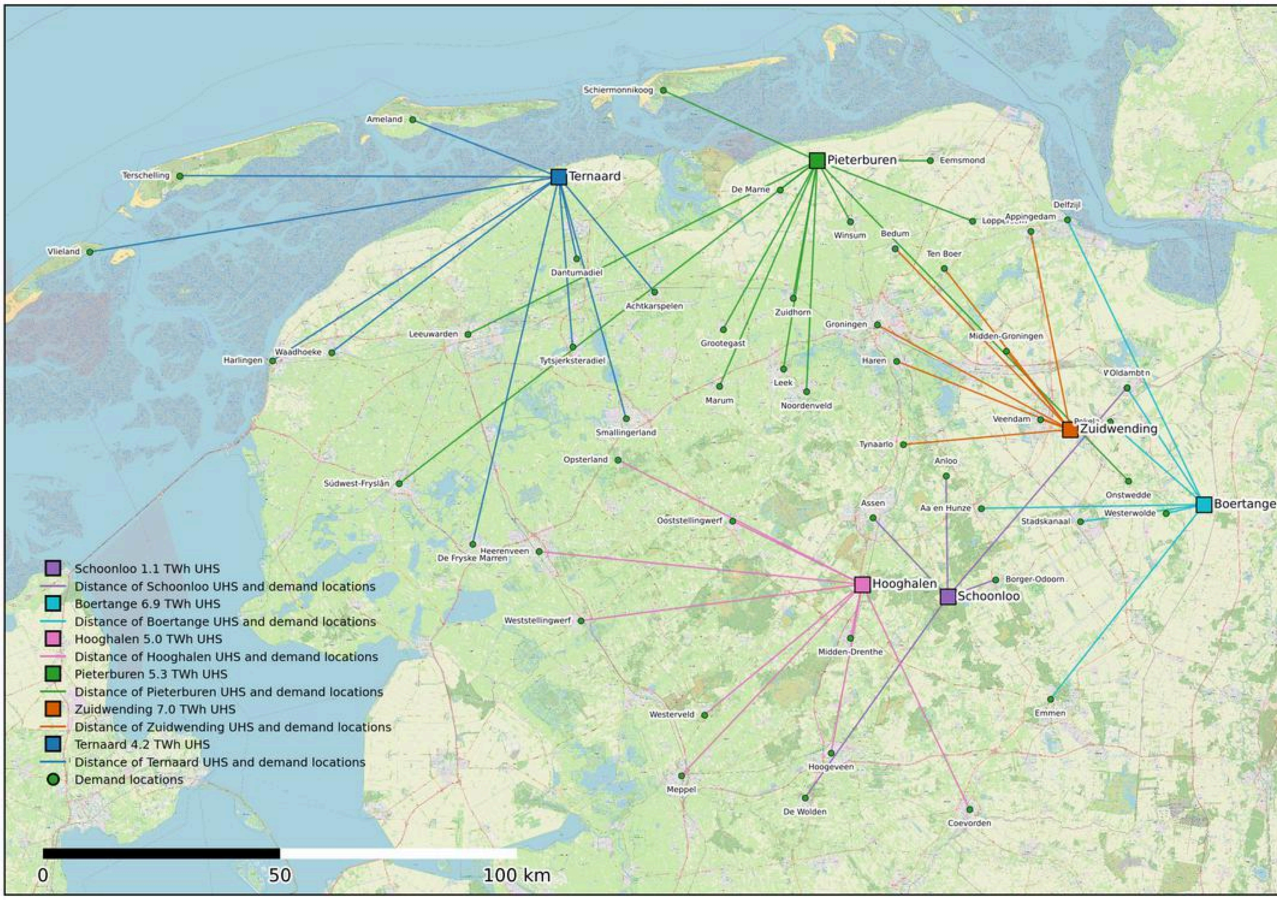



Figure 6: Results of Medium Demand Scenario-National

Table 8
Results for the high demand scenario

| Scenario | Hydrogen Demand (TWh) | Service Distance (km) | Storage Facilities | Storage Cost (€) | Distribution Cost (€) | Total Cost (€) |
|---|---|---|---|---|---|---|
| Regional | 26.52 | 69.02 | 7 | 267,627,040.87 | 84,264,240.04 | 351,891,280.91 |
| National | 53.06 | 83.56 | 9 | 416,096,096.10 | 235,307,264.96 | 651,403,361.05 |
| European | 58.51 | 125.21 | 9 | 416,096,096.10 | 273,710,718.25 | 689,806,814.35 |
| Inter national | 65.71 | 73.10 | 9 | 416,096,096.10 | 316,358,662.64 | 732,454,758.74 |

mismatch between UHS locations and hydrogen demand centers. This stands in contrast to the medium demand scenario, where shorter average service distances (as low as 59.76 km) were achievable due to a denser and more regionally distributed network of storage facilities. Under high demand, maintaining spatial optimization becomes more difficult, highlighting the increasing importance of integrated spatial planning for hydrogen infrastructure.

A crucial finding is that three of the four sub-scenarios in the high demand case become infeasible under the current theoretical storage capacity constraints. Specifically, the constraint $\sum Nx_{ij} \leq C_i z_i$ is violated in the national, European, and international sub-scenarios, due to demand exceeding the available UHS capacity. Only the regional sub-scenario remains feasible within the defined storage limits.

The infeasibility of these sub-scenarios aligns with insights from the literature and expert interviews. TNO [78] and an interview with Company X both emphasized that the available UHS capacity in salt caverns is unlikely to be sufficient to meet future hydrogen demand alone. Company X explicitly noted: “To offer flexibility and cover the future hydrogen demand, many salt caverns, and possibly depleted gas fields as strategic storage facilities are needed.” This implies that in addition to expanding the UHS network, the integration of repurposed natural gas infrastructure or cross-border coordination particularly with Germany, which reportedly has a higher availability of salt cavern storage is essential. According to Company X, several German storage

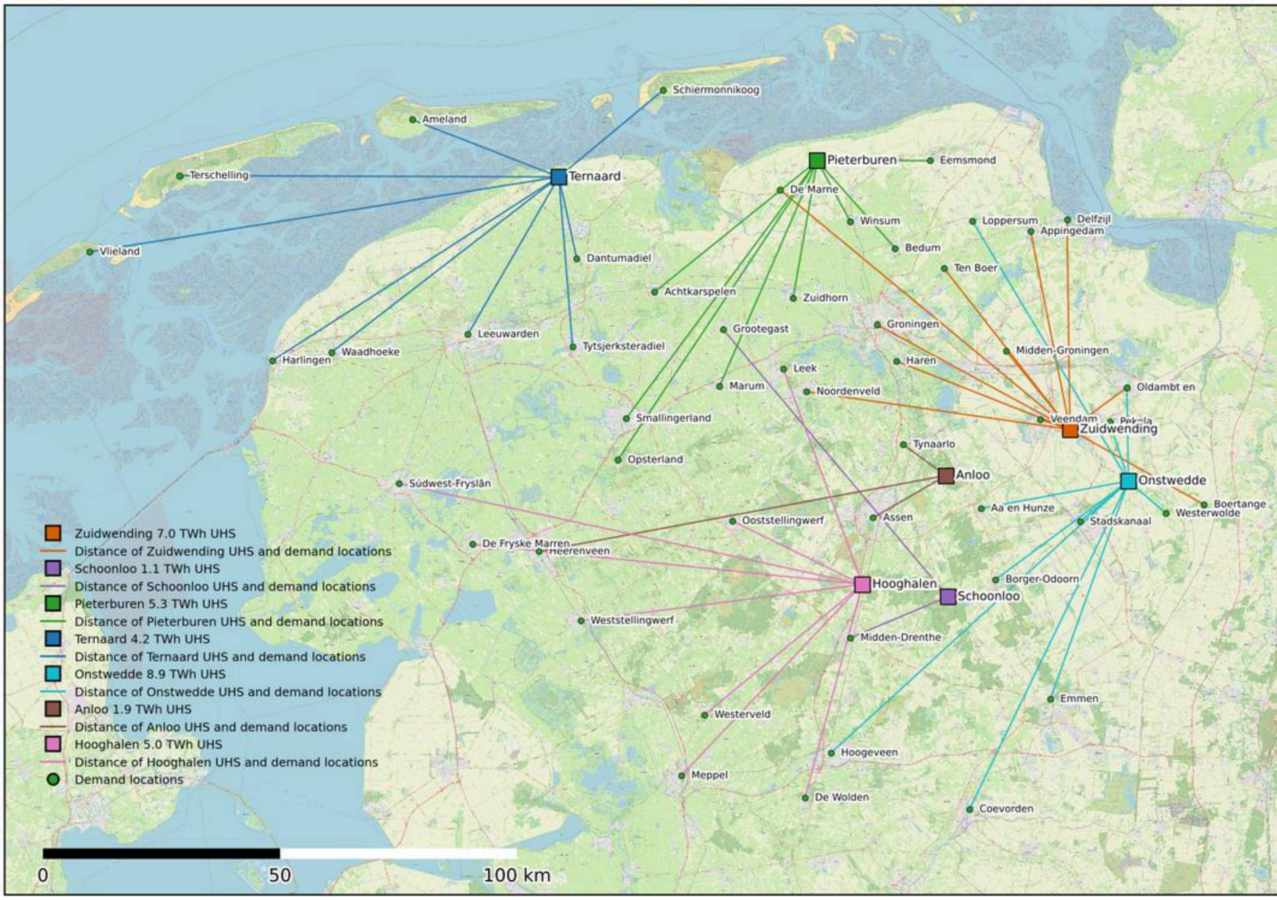



Figure 7: Results of Medium Demand Scenario-European

fields have already been leached and could potentially offer a near-term solution.

Figures 10 through 13 present the FLP model results for each sub-scenario, and the associated costs are visualized in Figure 9.

## 5.4. Relation between Hydrogen Demand and Total Cost

As hydrogen demand increases, the combined cost per TWh for storage and transport decreases significantly. This trend reflects the presence of economies of scale in hydrogen infrastructure development. Specifically, the cost of storage at a UHS location is largely fixed and determined by the facility's maximum capacity. When the actual hydrogen demand served is below this capacity, the cost per TWh increases, as the infrastructure is underutilized. Conversely, higher utilization of each UHS facility leads to a lower unit cost of storage and distribution.

Importantly, storage costs are incurred upon commissioning a UHS facility, regardless of the volume of hydrogen it ultimately stores. Therefore, lower demand leads to higher cost per unit of hydrogen. This effect is clearly illustrated in Table 9, which presents the cost per TWh of hydrogen for each scenario. For example, in the low demand scenario, the unit cost can exceed 220 million euros per TWh in the regional sub-scenario. In contrast, under high demand conditions, this value drops below 12 million euros/TWh in the international sub-scenario.

These results underline a critical insight: the development of a hydrogen backbone is most cost-effective under conditions of high and sustained demand. When demand is low, the fixed costs of infrastructure are spread over a smaller volume of hydrogen, making such investments economically unattractive. Therefore, from a techno-economic standpoint, large-scale hydrogen infrastructure becomes increasingly viable and financially justified as demand scales up.

## 5.5. SensitivityAnalysisandModelValidation

To strengthen the credibility of the FLP model and validate its predictive performance, we complement our optimization results with a structured sensitivity analysis and benchmarking against existing studies (e.g., [75, 39, 78]). The sensitivity analysis is conducted on the *Medium De- mand Scenario – National* configuration, which serves as the reference case, to evaluate how variations in key parameters affect the structure and cost of the hydrogen storage network. This approach allows us to verify the robustness of the model's outcomes and assess whether the main findings remain stable under parameter uncertainty.

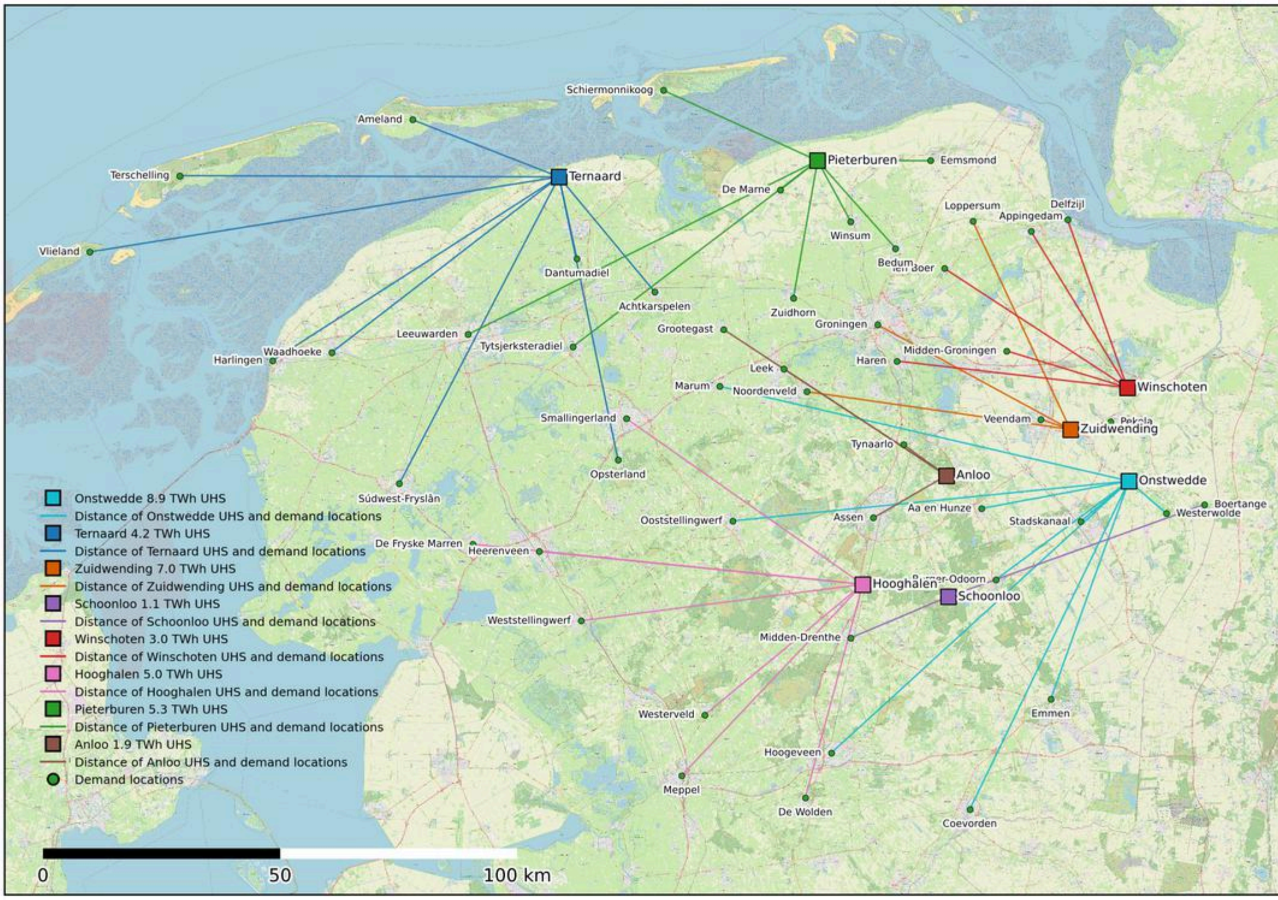



Figure 8: Results of Medium Demand Scenario-International

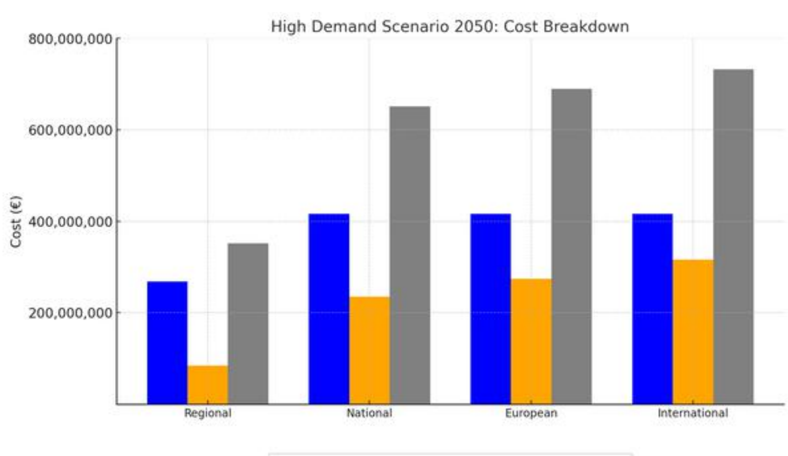



Figure 9: FLP Model Results of High Demand Scenario

The analysis focuses on two critical parameters: (i) pipeline routing distance and (ii) UHS CAPEX. While the base model assumes straight-line (Euclidean) distances and nominal storage costs, actual routing often deviates due to spatial constraints, and storage costs vary depending on cavern size and number. To capture these uncertainties, route factors of 1.2, 1.3, and 1.4 are applied to simulate increas- ingly indirect routing, and UHS CAPEX is varied by – 30%, 0%, and +30% to reflect cost uncertainty. Additionally, both the theoretical storage potential (43.4 TWh) and the practically achievable capacity (15 TWh) are considered as

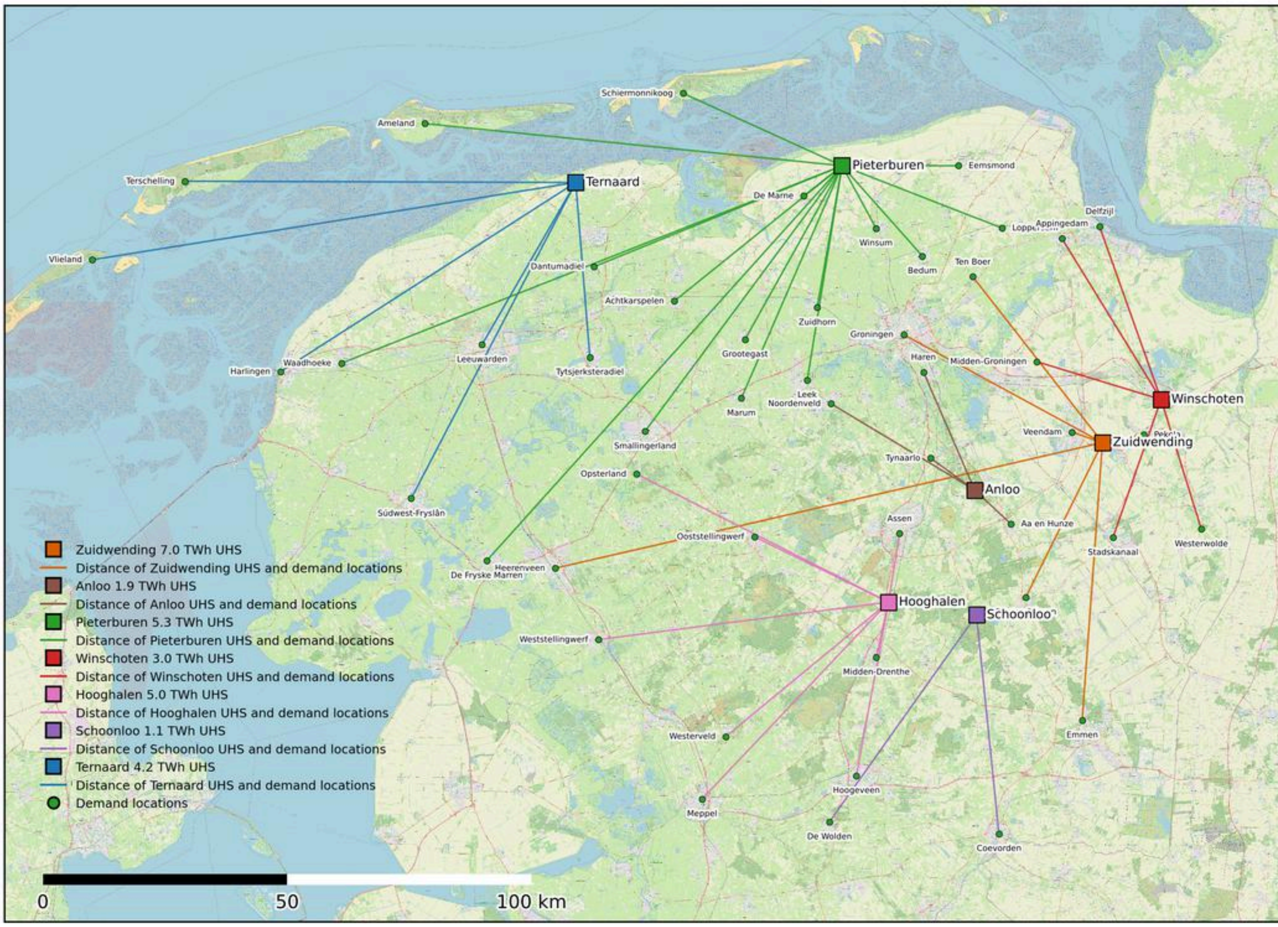



Figure 10: Results of High Demand Scenario – Regional

Table 9
Cost per TWh of hydrogen (storage & transportation)

| Scenario | € |
|---|---|
| **Low demand** | |
| Regional | 222,423,360.21 |
| National | 27,004,622.59 |
| European | 22,242,865.66 |
| Inter national | 17,078,044.33 |
| **Medium demand** | |
| Regional | 13,750,975.03 |
| National | 13,396,149.93 |
| European | 13,667,214.78 |
| Inter national | 13,299,072.82 |
| **High demand** | |
| Regional | 13,268,901.99 |
| National | 12,276,731.27 |
| European | 11,789,554.17 |
| Inter national | 11,146,777.64 |

boundary conditions to account for the range between technical potential and real-world deployment. These variations result in 12 distinct sensitivity scenarios.

Table 10 summarizes the results for all scenarios. Across all twelve cases, UHS remains an integral part of the least- cost system configuration, with between five and seven fa- cilities consistently deployed, even under the most unfavor- able conditions (+30% CAPEX). This outcome highlights the structural robustness of UHS integration. In contrast, pipeline routing assumptions emerge as a significant cost driver. Increasing the route factor from the baseline (1.0) to more realistic values (1.3–1.4) increases total system costs by approximately 30–40 million €, depending on storage cost levels.

The total system cost ranges from 295.37 million € in the lowest-cost scenario (route factor = 1.0, CAPEX = –30%) to 505.98 million € in the most expensive scenario (route factor = 1.3, CAPEX = +30%). The cost per unit of hydrogen stored ranges from approximately 10.52 million €/TWh to 18.02 million €/TWh. Demand coverage remains constant at 28.08 TWh in all scenarios, while the maximum service distance (≤187.6 km) remains far below the conventional 1000 km constraint, indicating that distance is not a limiting factor. The network structure adapts slightly across cases, with total storage capacity fluctuating between 28.4 TWh

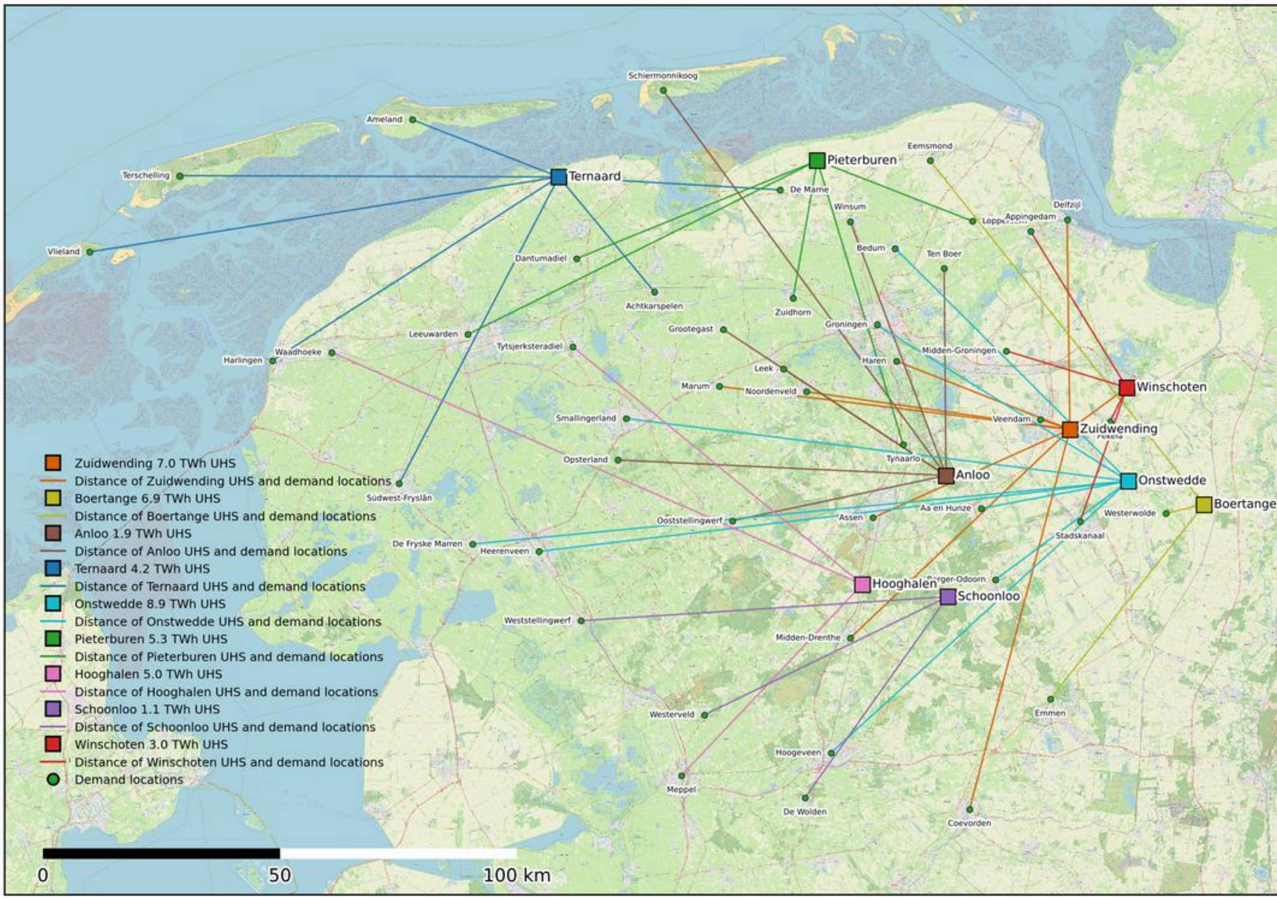



Figure 11: Results of High Demand Scenario – National

and 31.4 TWh as the FLP locally optimizes capacity and site selection in response to parameter changes.

These findings confirm that UHS is a robust and indispensable component of the hydrogen energy system design. Even with a 30% increase in CAPEX, UHS remains part of the least-cost solution. By contrast, pipeline routing uncertainty exerts a strong influence on system costs, underscoring the importance of careful spatial planning, permitting, and integration with existing infrastructure. The incorporation of both practical capacity (15 TWh) and technical potential (43.4 TWh) as boundary conditions further enhances the realism of the system assessment. The results of the sensitivity analysis are illustrated in Figure 14, which visualizes how these variations influence total system costs relative to the base case.

## 6.Discussion

TheresultsoftheFLPmodelingforthehydrogen storage network in the Northern Netherlands (NN) reveal key insights into the techno-economic dynamics of large-scale hydrogen infrastructure deployment by 2050. The scenario-based approach—ranging from low to high de- mand—provides a comprehensive view of how hydrogen de- mand interacts with UHS configuration, costs, and feasibility constraints.

Although uniform cost assumptions were necessary for model tractability, their implications were explicitly tested through sensitivity analysis. Varying UHS CAPEX by ±30% and pipeline routing multipliers by 1.2–1.4 resulted in only moderate changes in total system cost and did not alter the spatial configuration of the least-cost network. This indi- cates that the principal insights of the study—specifically, the centrality of underground storage and the importance of spatially optimized deployment—remain robust under substantial cost uncertainty.

A strong correlation emerges between hydrogen demand and network cost efficiency. As demand increases, the levelized cost per TWh of hydrogen storage and transport decreases markedly, reflecting economies of scale. Fixed infrastructure costs are distributed more efficiently across higher throughput volumes. In the low-demand regional scenario, unit costs exceed €220 million per TWh, while in the high-demand international scenario this figure drops below €12 million per TWh. This highlights the economic inefficiency of underutilized infrastructure and underscores

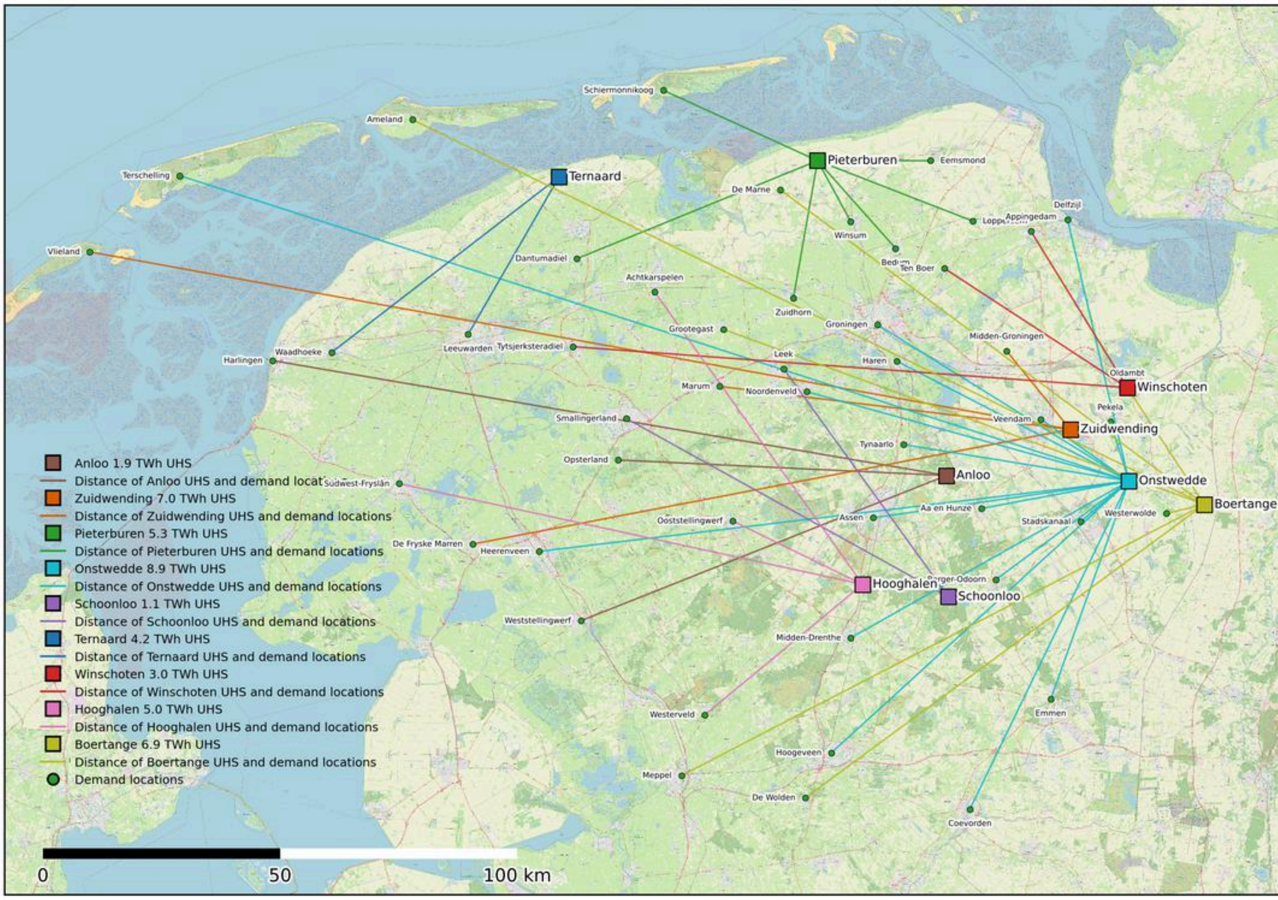



Figure 12: Results of High Demand Scenario – European

Table 10
Sensitivity analysis results for the Medium Demand Scenario – National.

| Scenario | Description | UHS Costs [€] | Distribution Costs [€] | Total Cost [€] | Capacity [TWh] | Cost/TWh | Facilities | Demand [TWh] | Distance [km] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Routefactor 1.0, UHS cost -30% | 211,219,219.22 | 84,149,444.29 | 295,368,663.50 | 31.4 | 10,518,827.05 | 7 | 28.08 | 100.52 |
| 2 (Base) | Base scenario | 283,483,483.48 | 92,616,330.54 | 376,099,814.02 | 29.5 | 13,393,868.02 | 6 | 28.08 | 66.64 |
| 3 | Routefactor 1.0, UHS cost +30% | 368,528,528.53 | 90,319,089.43 | 458,847,617.96 | 29.5 | 16,340,727.14 | 6 | 28.08 | 65.09 |
| 4 | Routefactor 1.2, UHS cost -30% | 203,819,819.82 | 107,938,998.87 | 311,758,818.69 | 28.4 | 11,102,522.03 | 6 | 28.08 | 103.06 |
| 5 | Routefactor 1.2, UHS cost base | 279,639,639.64 | 119,586,969.79 | 399,226,609.43 | 29.1 | 14,217,471.85 | 7 | 28.08 | 120.63 |
| 6 | Routefactor 1.2, UHS cost +30% | 363,531,531.53 | 119,301,528.23 | 482,833,059.77 | 29.1 | 17,194,909.54 | 7 | 28.08 | 127.65 |
| 7 | Routefactor 1.3, UHS cost -30% | 191,039,039.04 | 119,384,196.79 | 310,423,235.83 | 28.4 | 11,054,958.54 | 5 | 28.08 | 86.63 |
| 8 | Routefactor 1.3, UHS cost base | 283,483,483.48 | 115,243,516.52 | 398,727,000.00 | 29.5 | 14,199,679.49 | 6 | 28.08 | 95.03 |
| 9 | Routefactor 1.3, UHS cost +30% | 392,264,264.26 | 113,717,571.70 | 505,981,835.96 | 31.4 | 18,019,296.15 | 7 | 28.08 | 187.64 |
| 10 | Routefactor 1.4, UHS cost -30% | 211,219,219.22 | 121,993,835.04 | 333,213,054.26 | 31.4 | 11,866,561.76 | 7 | 28.08 | 120.23 |
| 11 | Routefactor 1.4, UHS cost base | 283,483,483.48 | 124,170,684.50 | 407,654,167.98 | 29.5 | 14,517,598.57 | 6 | 28.08 | 102.34 |
| 12 | Routefactor 1.4, UHS cost +30% | 368,528,528.53 | 124,931,393.22 | 493,459,921.75 | 29.5 | 17,573,359.04 | 6 | 28.08 | 114.07 |

that large-scale UHS development becomes financially viable only once demand reaches a critical threshold.

However, higher demand levels also introduce feasibility constraints. Under the high-demand scenario, three out of four sub-scenarios become infeasible given the assumed total salt cavern capacity of 15 TWh. Even with optimal facility siting, the available or planned storage capacity in NN is insufficient to meet future hydrogen demand. Only the regional sub-scenario remains within feasible limits, suggesting that substantial expansion or diversification of storage capacity will be required to support a mature hydro- gen economy.

This finding aligns with warnings from industry and prior studies, such as Van Gessel et al. [79], which emphasize the need for complementary storage solutions. Stakeholder interviews also confirmed that repurposing depleted gas fields or integrating cross-border storage (e.g., in Germany) will be essential for long-term system resilience. Papadias and Ahluwalia [60] similarly argue that growing hydrogen demand will necessitate multiple storage types to ensure supply security and operational flexibility.

Across the twelve modeled scenarios, consistent structural patterns emerge. In the low-demand case, a single facility—Zuidwending—meets the region's storage needs. Its

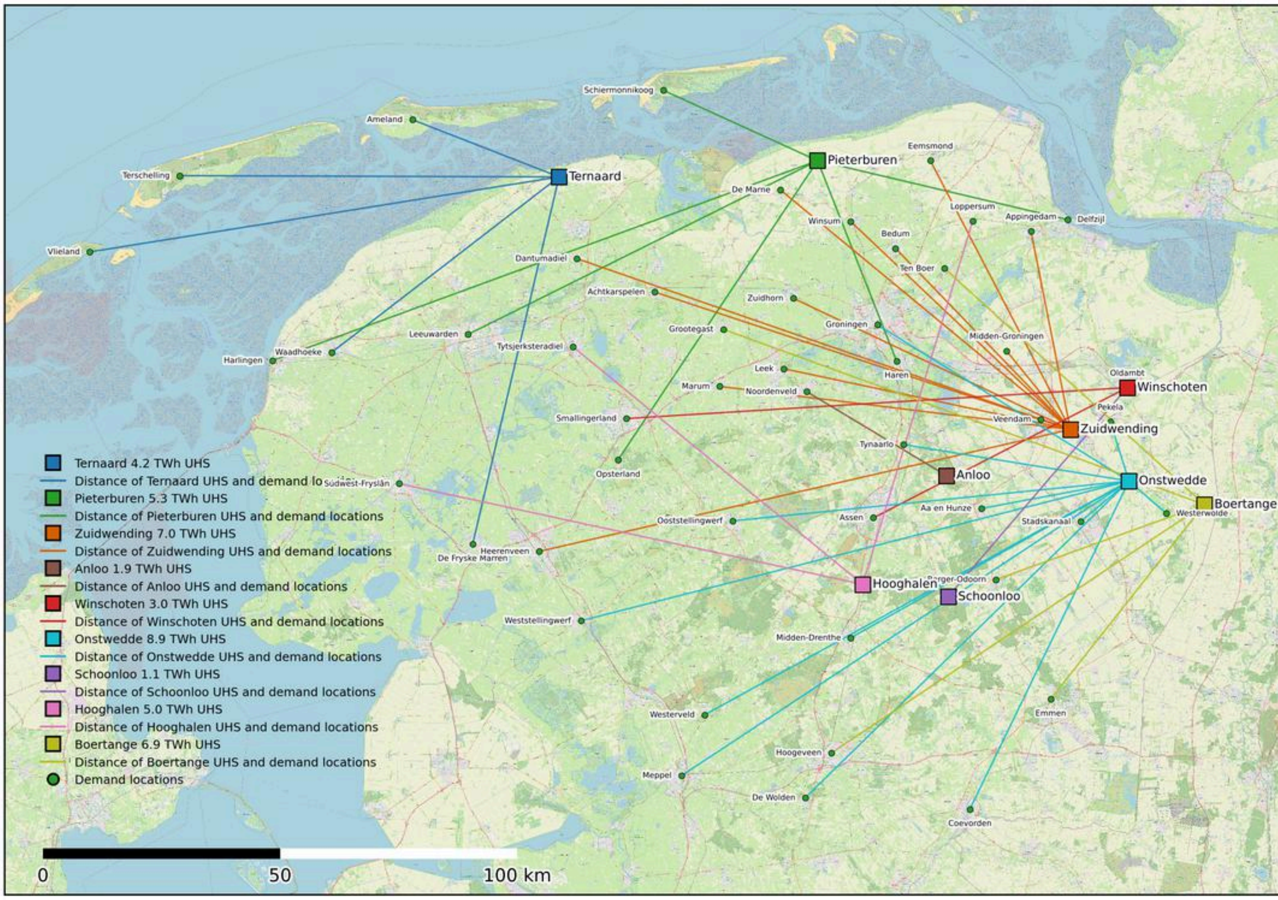



Figure 13: Results of High Demand Scenario – International

7 TWh capacity is sufficient across all sub-scenarios, underscoring its strategic role in early deployment. In the medium-demand scenario, four to eight UHS sites are required, improving the balance between supply and demand and yielding a more favorable cost-to-demand ratio. In contrast, the high-demand scenario exceeds the combined capacity of all candidate sites, necessitating either additional cavern development beyond NN or the repurposing of depleted gas reservoirs.

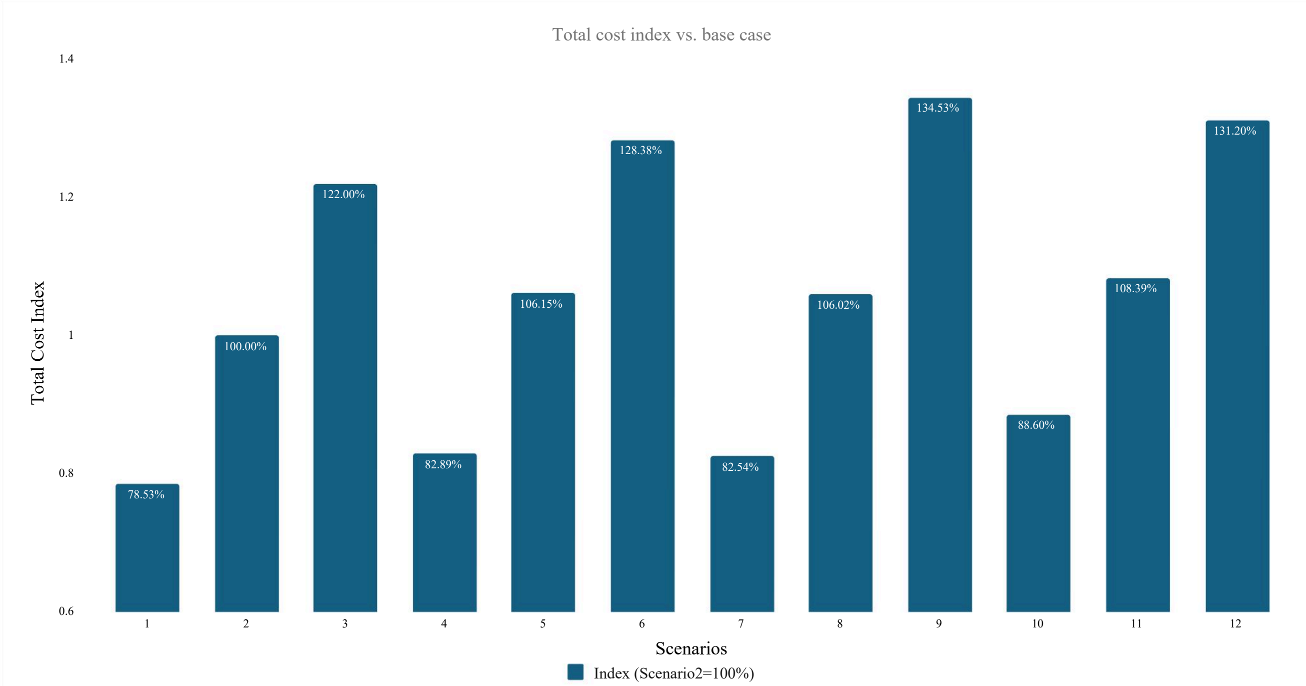
The consistent exclusion of the Hoogeveen site from all model outcomes also warrants attention. With a maxi- mum capacity of just 0.1 TWh, Hoogeveen is not selected under any scenario, indicating that small-capacity sites are economically inefficient even when located closer to demand centers. The model systematically favors larger, more cost-effective facilities, emphasizing the importance of economies of scale in UHS planning.

Spatial optimization patterns further illustrate how network design evolves with demand. In the medium-demand scenario, the average service distance decreases by more than 50% compared to the low-demand case, indicating improved geographic coverage and distribution efficiency. However, in the high-demand scenario—particularly under the European sub-scenario—service distances increase again, reflecting the growing difficulty of maintaining spatial efficiency as the network expands to meet dispersed demand hotspots. These results suggest that spatial optimization yields diminishing returns as the system scales, reinforcing the need for future UHS development near industrial demand clusters.

Stakeholder interviews also highlighted that cavern development is both time- and resource-intensive. Construct- ing a single salt cavern can take up to a decade due to ge- ological logging, permitting, topside installation, and brine disposal requirements [58]. TNO [79] estimates that no more than 60 caverns can realistically be developed by 2050, emphasizing the urgency of early strategic siting decisions. Furthermore, societal resistance linked to historical gas ex- traction in NN could present additional challenges to timely implement ation.

These practitioner perspectives complement the quantitative results by highlighting real-world constraints—such as permitting delays, regulatory fragmentation, and public acceptance—that shape the feasibility of hydrogen storage deployment beyond purely techno-economic considerations.

These findings carry several policy and planning implications. First, early and coordinated policy action is essential



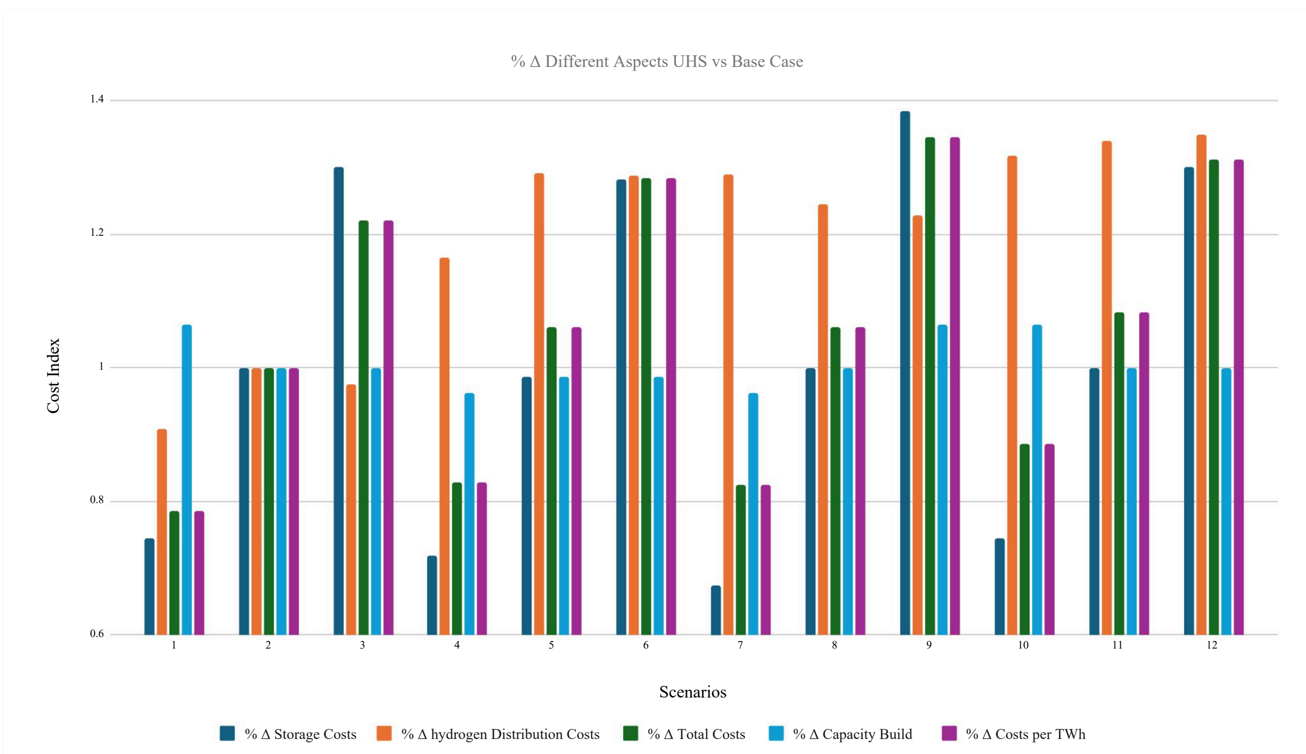




Figure 14: Total system cost index across 12 sensitivity scenarios relative to the base case (top) and percentage deviation of total system cost from the base scenario (bottom).

to align storage capacity expansion with projected hydrogen demand. Second, cost efficiency improves markedly at higher demand levels, supporting policies that promote hydrogen adoption in industry and heavy transport. Third, addressing feasibility constraints requires both technological and regulatory interventions, such as enabling storage in depleted gas fields and fostering cross-border UHS integration.

Uncertainty in future hydrogen demand remains a major barrier to effective infrastructure planning. Current projections for 2030 and 2040 are fragmented and lack governance clarity across regional, national, and EU levels. Stakeholders emphasized the need for an authoritative roadmap to prevent misaligned investments and ensure coherent development of hydrogen infrastructure.

Finally, the consistent underutilization of small-capacity sites suggests the need for a differentiated infrastructure hi- erarchy. Large-scale sites should serve as strategic backbone nodes, while smaller facilities could play niche roles—for example, in balancing local grids, providing emergency re- serves, or supporting decentralized hydrogen ecosystems.

Assumptions regarding straight-line routing were tested using route multipliers up to 1.4, confirming that while total system costs increase, the least-cost network configuration remains stable. This supports the validity of using simplified distance assumptions for strategic-scale analyses. Future research should incorporate detailed pipeline routing data, repurposing costs, and dynamic flow modeling to better capture temporal variability and operational constraints.

## 7.Conclusion

Thisstudyassessedthetechno-economicfeasibilityof developing an UHS network in the NN under alternative hydrogen demand scenarios for 2050. By extending a FLP model with region-specific demand projections and insights from literature and stakeholder consultations, the research addresses a critical gap in hydrogen infrastructure plan- ning—namely, the interaction between demand uncertainty, storage capacity constraints, and cost-optimal network con- figuration.

The results demonstrate that future hydrogen demand levels will decisively shape the structure, feasibility, and cost efficiency of UHS networks. Under low-demand condi- tions, a single facility at Zuidwending is sufficient; however, medium- and high-demand scenarios require a substantially expanded network, activating up to nine of the ten candi- date sites. Although higher demand enhances cost efficiency through economies of scale, the limited capacity of salt caverns emerges as a major bottleneck, rendering several configurations infeasible without supplementary storage so- lutions.

These findings highlight the need for proactive, long- term planning that integrates both domestic and cross-border storage strategies. Early inclusion of alternative storage op- tions—such as depleted gas fields or cavern facilities in neighboring regions like Germany—will be essential to en- sure adequate system flexibility and resilience. Coordinated policy support and strong public–private collaboration are likewise critical to reduce investment uncertainty and accel- erate infrastructure deployment.

Beyond reaffirming established relationships between scale economies and storage capacity constraints, this study contextualizes them within the specific regional and policy environment of the Northern Netherlands—a key hub in Europe's emerging hydrogen economy. By quantifying these dynamics within a spatially explicit network framework, the research provides actionable, region-specific evidence to guide investment sequencing and infrastructure rollout.

The integration of stakeholder perspectives further grounds the analysis in practical governance and regulatory contexts, underscoring that technical feasibility must be accompanied by institutional readiness. Accordingly, the findings point to three strategic recommendations for policymakers: (i) im- plementing phased investment incentives to stimulate early- stage UHS development; (ii) establishing harmonized regu- latory mechanisms for cross-border storage integration, par- ticularly with Germany; and (iii) aligning regional storage capacity targets with verified industrial and mobility demand milestones. Together, these measures translate model in- sights into a concrete roadmap for achieving a cost-effective and resilient hydrogen storage system in Northwest Europe. The study's scope is limited to the Dutch context and does not account for potential international hydrogen flows that could influence network design. Future research should therefore examine integration with existing natural gas in- frastructure and explore the scalability of UHS networks across transnational hydrogen corridors.

This analysis focused primarily on salt caverns due to their technological maturity and data availability. Future re- search should extend the assessment to include other poten- tial underground hydrogen storage formations, such as de- pleted gas reservoirs and deep saline aquifers. The Northern Netherlands hosts several depleted hydrocarbon fields that could provide substantial additional storage capacity and seasonal flexibility. However, their suitability depends on factors such as caprock integrity, residual gas composition, and geochemical reactivity. A comparative techno-economic and risk-based evaluation of these alternatives would provide valuable insights for developing an integrated and resilient hydrogen storage portfolio for the region.

The present study applies a conventional FLP frame- work, with its main contribution lying in the contextual adaptation of this approach to hydrogen storage network planning in the Northern Netherlands. The model captures spatially explicit hydrogen demand patterns, geological con- straints, and policy-relevant capacity considerations, while intentionally simplifying transport routing and omitting time-dependent storage dynamics consistent with the study's strategic scope. Future work should extend the framework to include (i) material embrittlement and the associated retrofit costs of repurposed infrastructure, (ii) dynamic injection and withdrawal constraints reflecting cyclic operation of salt caverns and depleted reservoirs, and (iii) hybrid storage configurations that combine multiple geological formations. Integrating these elements would enhance the model's tech- nical realism and provide deeper insights into the operational design of hydrogen storage networks.

Advancing the practical implementation of UHS in a decarbonizing Europe will require close alignment between technical modeling, regulatory development, and societal engagement. By integrating quantitative modeling with stakeholder-informed governance insights, this study pro- vides a decision-support framework for sequencing hydro- gen infrastructure investments, coordinating cross-border regulation, and aligning regional storage capacity with verified demand trajectories. Overall, the scenario-based modeling approach presented here offers a flexible, data-driven framework to support adaptive hydrogen infrastruc- ture planning consistent with long-term energy transition and climate neutrality objectives.

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# Appendices

## A. Set of Demand Nodes

**Table 11:** Demand Nodes (Municipalities)

| ID | Municipality | ID | Municipality |
|---|---|---|---|
| 1 | Achtkarspelen | 26 | Noordenveld |
| 2 | Ameland | 27 | Tynaarlo |
| 3 | Dantumadiel | 28 | Westerveld |
| 4 | DeFryskeMarren | 29 | DeWolden |
| 5 | Harlingen | 30 | Delfzijl |
| 6 | Heerenveen | 31 | Appingedam |
| 7 | Leeuwarden | 32 | Loppersum |
| 8 | Ooststellingwerf | 33 | Groningen |
| 9 | Opsterland | 34 | Bedum |
| 10 | Schiermonnikoog | 35 | Haren |
| 11 | Smallingerland | 36 | Midden-Groningen |
| 12 | Súdwest-Fryslân | 37 | Oldambt |
| 13 | Terschelling | 38 | Pekela |
| 14 | Tytsjerksteradiel | 39 | Stadskanaal |
| 15 | Vlieland | 40 | Veendam |
| 16 | Waadhoeke | 41 | Zuidhorn |
| 17 | Weststellingwerf | 42 | Westerwolde |
| 18 | AaenHunze | 43 | TenBoer |
| 19 | Assen | 44 | DeMarne |
| 20 | Borger-Odoorn | 45 | Grootegast |
| 21 | Coevorden | 46 | Marum |
| 22 | Emmen | 47 | Eemsmond |
| 23 | Hoogeveen | 48 | Leek |
| 24 | Meppel | 49 | Winsum |
| 25 | Midden-Drenthe | | |

## B. Total Demand (T) in PJ, TWh, and kg for Each Demand Node in the Set of F

**Table 12:** Total hydrogen demand per node under Low Demand Scenario (Friesland)

| Municipality | BuurtCode | PJ | | | | TWh | | | | kg | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Achtkarspelen | GM0059 | 0.02 | 0.20 | 0.24 | 0.32 | 0.01 | 0.06 | 0.07 | 0.09 | 166833.50 | 1668335.00 | 2002002.00 | 2669336.00 |
| Ameland | GM0060 | 0.00 | 0.01 | 0.03 | 0.06 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 83416.75 | 250250.25 | 500500.50 |
| Dantumadiel | GM1891 | 0.01 | 0.06 | 0.08 | 0.15 | 0.00 | 0.02 | 0.02 | 0.04 | 83416.75 | 500500.50 | 667334.00 | 1251251.25 |
| De Fryske Marren | GM1940 | 0.03 | 0.31 | 0.45 | 0.60 | 0.01 | 0.09 | 0.13 | 0.17 | 250250.25 | 2585919.25 | 3753753.75 | 5005005.01 |
| Harlingen | GM0072 | 0.01 | 0.07 | 0.12 | 0.15 | 0.00 | 0.02 | 0.03 | 0.04 | 83416.75 | 583917.25 | 1001001.00 | 1251251.25 |
| Heerenveen | GM0074 | 0.04 | 0.20 | 0.43 | 0.52 | 0.01 | 0.06 | 0.12 | 0.14 | 333667.00 | 1668335.00 | 3586920.25 | 4337671.00 |
| Leeuwarden | GM0080 | 0.08 | 0.84 | 0.72 | 0.89 | 0.02 | 0.23 | 0.20 | 0.25 | 667334.00 | 7007007.01 | 6006006.01 | 7424090.76 |
| Ooststellingwerf | GM0085 | 0.02 | 0.08 | 0.13 | 0.25 | 0.01 | 0.02 | 0.04 | 0.07 | 166833.50 | 667334.00 | 1084417.75 | 2085418.75 |
| Opsterland | GM0086 | 0.02 | 0.10 | 0.14 | 0.17 | 0.01 | 0.03 | 0.04 | 0.05 | 166833.50 | 834167.50 | 1167834.50 | 1418084.75 |
| Schiermonnikoog | GM0088 | 0.00 | 0.00 | 0.05 | 0.07 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 417083.75 | 583917.25 |
| Smallingerland | GM0090 | 0.04 | 0.20 | 0.22 | 0.33 | 0.01 | 0.06 | 0.06 | 0.09 | 333667.00 | 1668335.00 | 1835168.50 | 2752752.75 |
| Súdwest-Fryslán | GM1900 | 0.06 | 0.55 | 0.72 | 0.90 | 0.02 | 0.15 | 0.20 | 0.25 | 500500.50 | 4587921.25 | 6006006.01 | 7507507.51 |
| Terschelling | GM0093 | 0.00 | 0.02 | 0.04 | 0.07 | 0.00 | 0.01 | 0.01 | 0.02 | 0.00 | 166833.50 | 333667.00 | 583917.25 |
| Tytsjerksteradiel | GM0737 | 0.02 | 0.45 | 0.48 | 0.55 | 0.01 | 0.13 | 0.13 | 0.15 | 166833.50 | 3753753.75 | 4004004.00 | 4587921.25 |
| Vlieland | GM0096 | 0.00 | 0.00 | 0.11 | 0.14 | 0.00 | 0.00 | 0.03 | 0.04 | 0.00 | 0.00 | 917584.25 | 1167834.50 |
| Waadhoeke | GM1949 | 0.03 | 0.33 | 0.30 | 0.43 | 0.01 | 0.09 | 0.08 | 0.12 | 250250.25 | 2752752.75 | 2502502.50 | 3586920.25 |
| Weststellingwerf | GM0098 | 0.02 | 0.09 | 0.20 | 0.23 | 0.01 | 0.03 | 0.06 | 0.06 | 166833.50 | 750750.75 | 1668335.00 | 1918585.25 |
| **Total** | | 0.40 | 3.51 | 4.46 | 5.83 | 0.11 | 0.98 | 1.24 | 1.62 | 3336670.00 | 29279279.28 | 37203870.54 | 48631965.30 |

Table 13
Total hydrogen demand per node under Low Demand Scenario (Drenthe)

| Municipality | BuurtCode | PJ | | | | TWh | | | | kg | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Aa en Hunze | GM1680 | 0.02 | 0.58 | 0.46 | 0.54 | 0.01 | 0.16 | 0.13 | 0.15 | 166834 | 4838172 | 3837171 | 4504505 |
| Assen | GM0106 | 0.05 | 0.26 | 0.35 | 0.60 | 0.01 | 0.07 | 0.10 | 0.17 | 417084 | 2168836 | 2919586 | 5005005 |
| Borger-Odoorn | GM1681 | 0.02 | 0.08 | 0.11 | 0.23 | 0.01 | 0.02 | 0.03 | 0.06 | 166834 | 667334 | 917584 | 1918585 |
| Coevorden | GM0109 | 0.02 | 0.12 | 0.19 | 0.33 | 0.01 | 0.03 | 0.05 | 0.09 | 166834 | 1001001 | 1584918 | 2752753 |
| Emmen | GM0114 | 0.06 | 0.34 | 0.46 | 0.94 | 0.02 | 0.09 | 0.13 | 0.26 | 500501 | 2836169 | 3837171 | 7841175 |
| Hoogeveen | GM0118 | 0.04 | 0.57 | 0.57 | 0.79 | 0.01 | 0.16 | 0.16 | 0.22 | 333667 | 4754755 | 4754755 | 6589923 |
| Meppel | GM0119 | 0.02 | 0.26 | 0.51 | 0.70 | 0.01 | 0.07 | 0.14 | 0.19 | 166834 | 2168836 | 4254254 | 5839173 |
| Midden-Drenthe | GM1731 | 0.02 | 0.49 | 0.40 | 0.51 | 0.01 | 0.14 | 0.11 | 0.14 | 166834 | 4087421 | 3336670 | 4254254 |
| Noordenveld | GM1699 | 0.02 | 0.11 | 0.39 | 0.58 | 0.01 | 0.03 | 0.11 | 0.16 | 166834 | 917584 | 3253253 | 4838172 |
| Tynaarlo | GM1730 | 0.02 | 0.12 | 0.09 | 0.22 | 0.01 | 0.03 | 0.03 | 0.06 | 166834 | 1001001 | 750751 | 1835169 |
| Westerveld | GM1701 | 0.01 | 0.06 | 0.13 | 0.24 | 0.00 | 0.02 | 0.04 | 0.07 | 83417 | 500501 | 1084418 | 2002002 |
| De Wolden | GM1690 | 0.02 | 0.08 | 0.11 | 0.21 | 0.01 | 0.02 | 0.03 | 0.06 | 166834 | 667334 | 917584 | 1751752 |
| **Total** | | 0.32 | 3.07 | 3.77 | 5.89 | 0.09 | 0.85 | 1.05 | 1.64 | 2669336 | 25608942 | 31448115 | 49132466 |

Table 14
Total hydrogen demand per node under Low Demand Scenario (Groningen)

| **Municipality** | **BuurtCode** | **PJ** | | | | **TWh** | | | | **kg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Delfzijl Appingedam | GM0010 | 0.01 | 0.06 | 0.09 | 0.20 | 0.00 | 0.02 | 0.03 | 0.06 | 83417 | 500501 | 750751 | 1668335 |
| Loppersum | GM0003 | 0.01 | 0.07 | 0.21 | 0.26 | 0.00 | 0.02 | 0.06 | 0.07 | 83417 | 583917 | 1751752 | 2168836 |
| Groningen | GM0024 | 0.01 | 0.03 | 0.06 | 0.10 | 0.00 | 0.01 | 0.02 | 0.03 | 83417 | 250250 | 500501 | 834168 |
| Bedum | GM0014 | 0.14 | 1.68 | 1.80 | 2.71 | 0.04 | 0.47 | 0.50 | 0.75 | 1167835 | 14014014 | 15015015 | 22605939 |
| Haren Midden- | GM0005 | 0.01 | 0.33 | 0.28 | 0.32 | 0.00 | 0.09 | 0.08 | 0.09 | 83417 | 2752753 | 2335669 | 2669336 |
| Groningen Oldambt | GM0017 | 0.01 | 0.07 | 0.10 | 0.17 | 0.00 | 0.02 | 0.03 | 0.05 | 83417 | 583917 | 834168 | 1418085 |
| Pekela | GM1952 | 0.04 | 0.37 | 0.46 | 0.68 | 0.01 | 0.10 | 0.13 | 0.19 | 333667 | 3086419 | 3837171 | 5672339 |
| Stadskanaal | GM1895 | 0.02 | 0.15 | 0.18 | 0.34 | 0.01 | 0.04 | 0.05 | 0.09 | 166834 | 1251251 | 1501502 | 2836169 |
| Veendam | GM0765 | 0.01 | 0.08 | 0.33 | 0.40 | 0.00 | 0.02 | 0.09 | 0.11 | 83417 | 667334 | 2752753 | 3336670 |
| Zuidhor n | GM0037 | 0.02 | 0.10 | 0.09 | 0.21 | 0.01 | 0.03 | 0.03 | 0.06 | 166834 | 834168 | 750751 | 1751752 |
| Westerwolde | GM0047 | 0.02 | 0.09 | 0.08 | 0.20 | 0.01 | 0.03 | 0.02 | 0.06 | 166834 | 750751 | 667334 | 1668335 |
| Ten Boer | GM0056 | 0.01 | 0.06 | 0.56 | 0.70 | 0.00 | 0.02 | 0.16 | 0.19 | 83417 | 500501 | 4671338 | 5839173 |
| De Marne | GM1950 | 0.02 | 0.92 | 0.75 | 0.84 | 0.01 | 0.26 | 0.21 | 0.23 | 166834 | 7674341 | 6256256 | 7007007 |
| Grootegast | GM0009 | 0.00 | 0.03 | 0.04 | 0.07 | 0.00 | 0.01 | 0.01 | 0.02 | 0 | 250250 | 333667 | 583917 |
| Mar um | GM1663 | 0.01 | 0.03 | 0.04 | 0.08 | 0.00 | 0.01 | 0.01 | 0.02 | 83417 | 250250 | 333667 | 667334 |
| Eemsmond | GM0015 | 0.01 | 0.06 | 0.07 | 0.12 | 0.00 | 0.02 | 0.02 | 0.03 | 83417 | 500501 | 583917 | 1001001 |
| Leek | GM0025 | 0.01 | 0.11 | 0.70 | 0.84 | 0.00 | 0.03 | 0.19 | 0.23 | 83417 | 917584 | 5839173 | 7007007 |
| Winsum | GM1651 | 0.01 | 0.18 | 0.17 | 0.24 | 0.00 | 0.05 | 0.05 | 0.07 | 83417 | 1501502 | 1418085 | 2002002 |
| | GM0022 | 0.01 | 0.07 | 0.05 | 0.13 | 0.00 | 0.02 | 0.01 | 0.04 | 83417 | 583917 | 417084 | 1084418 |
| | GM0053 | 0.01 | 0.05 | 0.10 | 0.16 | 0.00 | 0.01 | 0.03 | 0.04 | 83417 | 417084 | 834168 | 1334668 |
| **Total** | | 0.39 | 4.54 | 6.16 | 8.77 | 0.11 | 1.26 | 1.71 | 2.44 | 3,253,253 | 37,871,205 | 51,384,718 | 73,156,490 |

Table 15
Total hydrogen demand per node under Medium Demand Scenario (Friesland)

| **Municipality** | **BuurtCode** | **PJ** | | | | **TWh** | | | | **kg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Achtkarspelen | GM0059 | 0.87 | 1.82 | 1.88 | 2.01 | 0.24 | 0.50 | 0.52 | 0.56 | 7256829.84 | 15163361.89 | 15652704.87 | 16742414.33 |
| Ameland | GM0060 | 0.00 | 0.09 | 0.23 | 0.38 | 0.00 | 0.03 | 0.07 | 0.10 | 0.00 | 758168.09 | 1956588.11 | 3139202.69 |
| Dantumadiel | GM1891 | 0.43 | 0.55 | 0.63 | 0.94 | 0.12 | 0.15 | 0.17 | 0.26 | 3628414.92 | 4549008.57 | 5217568.29 | 7848006.72 |
| De Fryske Marren | GM1940 | 1.30 | 2.82 | 3.52 | 3.76 | 0.36 | 0.78 | 0.98 | 1.05 | 10885244.77 | 23503210.94 | 29348821.63 | 31392026.87 |
| Harlingen | GM0072 | 0.43 | 0.64 | 0.94 | 0.94 | 0.12 | 0.18 | 0.26 | 0.26 | 3628414.92 | 5307176.66 | 7826352.44 | 7848006.72 |
| **Total** | | 17.40 | 31.90 | 34.87 | 36.57 | 4.83 | 8.86 | 9.69 | 10.16 | 145136596.89 | 266117001.25 | 290879432.18 | 305025861.13 |

Table 16
Total hydrogen demand per node under Medium Demand Scenario (Drenthe)

| **Municipality** | **BuurtCode** | **PJ** | | | | **TWh** | | | | **kg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Aa en Hunze | GM1680 | 0.87 | 5.27 | 3.60 | 3.39 | 0.24 | 1.46 | 1.00 | 0.94 | 7,256,829.84 | 43,973,749.49 | 30,001,017.67 | 28,252,824.19 |
| Assen | GM0106 | 2.17 | 2.36 | 2.74 | 3.76 | 0.60 | 0.66 | 0.76 | 1.05 | 18,142,074.61 | 19,712,370.46 | 22,826,861.27 | 31,392,026.87 |
| Borger-Odoorn | GM1681 | 0.87 | 0.73 | 0.86 | 1.44 | 0.24 | 0.20 | 0.24 | 0.40 | 7,256,829.84 | 6,065,344.76 | 7,174,156.40 | 12,033,610.30 |
| Coevorden | GM0109 | 0.87 | 1.09 | 1.49 | 2.07 | 0.24 | 0.30 | 0.41 | 0.57 | 7,256,829.84 | 9,098,017.14 | 12,391,724.69 | 17,265,614.78 |
| Emmen | GM0114 | 2.61 | 3.09 | 3.60 | 5.90 | 0.72 | 0.86 | 1.00 | 1.64 | 21,770,489.53 | 25,777,715.22 | 30,001,017.67 | 49,180,842.10 |
| Hoogeveen | GM0118 | 1.74 | 5.18 | 4.46 | 4.95 | 0.48 | 1.44 | 1.24 | 1.38 | 14,513,659.69 | 43,215,581.40 | 37,175,174.07 | 41,332,835.38 |
| Meppel | GM0119 | 0.87 | 2.36 | 3.99 | 4.39 | 0.24 | 0.66 | 1.11 | 1.22 | 7,256,829.84 | 19,712,370.46 | 33,261,997.85 | 36,624,031.35 |
| Midden-Drenthe | GM1731 | 0.87 | 4.45 | 3.13 | 3.20 | 0.24 | 1.24 | 0.87 | 0.89 | 7,256,829.84 | 37,150,236.64 | 26,087,841.45 | 26,683,222.84 |
| Noordenveld | GM1699 | 0.87 | 1.00 | 3.05 | 3.64 | 0.24 | 0.28 | 0.85 | 1.01 | 7,256,829.84 | 8,339,849.04 | 25,435,645.41 | 30,345,625.98 |
| Tynaarlo | GM1730 | 0.87 | 1.09 | 0.70 | 1.38 | 0.24 | 0.30 | 0.20 | 0.38 | 7,256,829.84 | 9,098,017.14 | 5,869,764.33 | 11,510,409.85 |
| Westerveld | GM1701 | 0.43 | 0.55 | 1.02 | 1.51 | 0.12 | 0.15 | 0.28 | 0.42 | 3,628,414.92 | 4,549,008.57 | 8,478,548.47 | 12,556,810.75 |
| De Wolden | GM1690 | 0.87 | 0.73 | 0.86 | 1.32 | 0.24 | 0.20 | 0.24 | 0.37 | 7,256,829.84 | 6,065,344.76 | 7,174,156.40 | 10,987,209.41 |
| **Total** | | 13.92 | 27.90 | 29.48 | 36.94 | 3.87 | 7.75 | 8.19 | 10.26 | 116,109,277.51 | 232,757,605.08 | 245,877,905.68 | 308,165,063.81 |

Table 17
Total hydrogen demand per node under Medium Demand Scenario (Groningen)

| **Municipality** | **BuurtCode** | **PJ** | | | | **TWh** | | | | **kg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Delfzijl Appingedam | GM0010 | 0.43 | 0.55 | 0.70 | 1.25 | 0.12 | 0.15 | 0.20 | 0.35 | 3,628,414.92 | 4,549,008.57 | 5,869,764.33 | 10,464,008.96 |
| Loppersum | GM0003 | 0.43 | 0.64 | 1.64 | 1.63 | 0.12 | 0.18 | 0.46 | 0.45 | 3,628,414.92 | 5,307,176.66 | 13,696,116.76 | 13,603,211.65 |
| Groningen | GM0024 | 0.43 | 0.27 | 0.47 | 0.63 | 0.12 | 0.08 | 0.13 | 0.17 | 3,628,414.92 | 2,274,504.28 | 3,913,176.22 | 5,232,004.48 |
| Bedum | GM0014 | 6.09 | 15.27 | 14.07 | 17.00 | 1.69 | 4.24 | 3.91 | 4.72 | 50,797,808.91 | 127,372,239.91 | 117,395,286.53 | 141,787,321.38 |
| Haren Midden- | GM0005 | 0.43 | 3.00 | 2.19 | 2.01 | 0.12 | 0.83 | 0.61 | 0.56 | 3,628,414.92 | 25,019,547.13 | 18,261,489.02 | 16,742,414.33 |
| Groningen Oldambt | GM0017 | 0.43 | 0.64 | 0.78 | 1.07 | 0.12 | 0.18 | 0.22 | 0.30 | 3,628,414.92 | 5,307,176.66 | 6,521,960.36 | 8,894,407.61 |
| Pekela | GM1952 | 1.74 | 3.36 | 3.60 | 4.27 | 0.48 | 0.93 | 1.00 | 1.18 | 14,513,659.69 | 28,052,219.50 | 30,001,017.67 | 35,577,630.46 |
| Stadskanaal | GM1895 | 0.87 | 1.36 | 1.41 | 2.13 | 0.24 | 0.38 | 0.39 | 0.59 | 7,256,829.84 | 11,372,521.42 | 11,739,528.65 | 17,788,815.23 |
| Veendam | GM0765 | 0.43 | 0.73 | 2.58 | 2.51 | 0.12 | 0.20 | 0.72 | 0.70 | 3,628,414.92 | 6,065,344.76 | 21,522,469.20 | 20,928,017.92 |
| Zuidhor n | GM0037 | 0.87 | 0.91 | 0.70 | 1.32 | 0.24 | 0.25 | 0.20 | 0.37 | 7,256,829.84 | 7,581,680.95 | 5,869,764.33 | 10,987,209.41 |
| Westerwolde | GM0047 | 0.87 | 0.82 | 0.63 | 1.25 | 0.24 | 0.23 | 0.17 | 0.35 | 7,256,829.84 | 6,823,512.85 | 5,217,568.29 | 10,464,008.96 |
| Ten Boer | GM0056 | 0.43 | 0.55 | 4.38 | 4.39 | 0.12 | 0.15 | 1.22 | 1.22 | 3,628,414.92 | 4,549,008.57 | 36,522,978.03 | 36,624,031.35 |
| De Marne | GM1950 | 0.87 | 8.36 | 5.86 | 5.27 | 0.24 | 2.32 | 1.63 | 1.46 | 7,256,829.84 | 69,751,464.71 | 48,914,702.72 | 43,948,837.62 |
| Grootegast | GM0009 | 0.00 | 0.27 | 0.31 | 0.44 | 0.00 | 0.08 | 0.09 | 0.12 | 0.00 | 2,274,504.28 | 2,608,784.15 | 3,662,403.14 |
| Mar um | GM1663 | 0.43 | 0.27 | 0.31 | 0.50 | 0.12 | 0.08 | 0.09 | 0.14 | 3,628,414.92 | 2,274,504.28 | 2,608,784.15 | 4,185,603.58 |
| Eemsmond | GM0015 | 0.43 | 0.55 | 0.55 | 0.75 | 0.12 | 0.15 | 0.15 | 0.21 | 3,628,414.92 | 4,549,008.57 | 4,565,372.25 | 6,278,405.37 |
| Leek | GM0025 | 0.43 | 1.00 | 5.47 | 5.27 | 0.12 | 0.28 | 1.52 | 1.46 | 3,628,414.92 | 8,339,849.04 | 45,653,722.54 | 43,948,837.62 |
| Winsum | GM1651 | 0.43 | 1.64 | 1.33 | 1.51 | 0.12 | 0.45 | 0.37 | 0.42 | 3,628,414.92 | 13,647,025.70 | 11,087,332.62 | 12,556,810.75 |
| | GM0022 | 0.43 | 0.64 | 0.39 | 0.82 | 0.12 | 0.18 | 0.11 | 0.23 | 3,628,414.92 | 5,307,176.66 | 3,260,980.18 | 6,801,605.82 |
| | | 0.43 | 0.45 | 0.78 | 1.00 | 0.12 | 0.13 | 0.22 | 0.28 | 3,628,414.92 | 3,790,840.47 | 6,521,960.36 | 8,371,207.17 |
| **Total** | GM0053 | 16.96 | 41.26 | 48.16 | 55.01 | 4.71 | 11.46 | 13.38 | 15.28 | 141,508,181.97 | 344,208,315.00 | 401,752,758.35 | 458,846,792.81 |

Table 19
Total hydrogen demand per node under High Demand Scenario (Drenthe)

| Municipality | Code | PJ | | | | TWh | | | | kg | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regional | National | European | Int'l | Regional | National | European | Int'l | Regional | National | European | Int'l |
| Aa en Hunze | GM1680 | 1.72 | 9.96 | 6.73 | 6.23 | 0.48 | 2.77 | 1.87 | 1.73 | 14346826.19 | 83109327.48 | 56164864.83 | 52001143.87 1.92 |
| Assen | GM0106 | 4.30 | 4.47 | 5.12 | 6.93 | 1.19 | 1.24 | 1.42 | 0.74 | [illegible] | [illegible] | [illegible] | [illegible] |
| Borger-Odoorn | GM1681 | 1.72 | 1.37 | 1.61 | 2.66 | 0.48 | 0.38 | 0.45 | 3.01 | | | | |
| Coevorden | GM0109 | 1.72 | 2.06 | 2.78 | 3.81 | 0.48 | 0.57 | 0.77 | 2.53 | [illegible] | [illegible] | [illegible] | [illegible] |
| Emmen | GM0114 | 5.16 | 5.84 | 6.73 | 10.85 | 1.43 | 1.62 | 1.87 | 1.64 | [illegible] | [illegible] | 48839012.90 | [illegible] |
| Hoogeveen | GM0118 | 3.44 | 9.79 | 8.34 | 9.12 | 0.96 | 2.72 | 2.32 | [illegible] | [illegible] | [illegible] | [illegible] | |
| Meppel | GM0119 | 1.72 | 4.47 | 7.46 | 8.08 | 0.48 | 1.24 | 2.07 | | [illegible] | [illegible] | [illegible] | 67408890.20 |
| Midden-Drenthe | GM1731 | 1.72 | 8.42 | 5.85 | 5.89 | 0.48 | 2.34 | 1.63 | | | | | |
| Noordenveld | GM1699 | 1.72 | 1.89 | 5.71 | 6.70 | 0.48 | 0.52 | 1.59 | | | | | |
| Tynaarlo | GM1730 | 1.72 | 2.06 | 1.32 | 2.54 | 0.48 | 0.57 | 0.37 | 0.71 | 14346826.19 | 17195033.27 | 10988777.90 | 21185651.21 |
| Westerveld | GM1701 | 0.86 | 1.03 | 1.90 | 2.77 | 0.24 | 0.29 | 0.53 | 0.77 | 7173413.09 | 8597516.64 | 15872679.19 | 23111619.50 |
| DeWolden | GM1690 | 1.72 | 1.37 | 1.61 | 2.42 | 0.48 | 0.38 | 0.45 | 0.67 | 14346826.19 | 11463355.51 | 13430728.55 | 20222667.06 |
| **Total** | | 27.52 | 52.74 | 55.18 | 68.00 | 7.64 | 14.65 | 15.33 | 18.89 | 229549219.02 | 439906267.88 | 460307696.57 | 567197661.83 |

Table 20
Total hydrogen demand per node under High Demand Scenario (Groningen)

| **Municipality** | **BuurtCode** | **PJ** | | | | **TWh** | | | | **kg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Reg | Nat | EU | Int | Reg | Nat | EU | Int | Reg | Nat | EU | Int |
| Delfzijl Appingedam | GM0010 | 0.86 | 1.03 | 1.32 | 2.31 | 0.24 | 0.29 | 0.37 | 0.64 | 7,173,413.09 | 8,597,516.64 | 10,988,777.90 | 19,259,682.91 |
| Loppersum | GM0003 | 0.86 | 1.20 | 3.07 | 3.00 | 0.24 | 0.33 | 0.85 | 0.83 | 7,173,413.09 | 10,030,436.08 | 25,640,481.77 | 25,037,587.79 |
| Groningen | GM0024 | 0.86 | 0.52 | 0.88 | 1.15 | 0.24 | 0.14 | 0.24 | 0.32 | 7,173,413.09 | 4,298,758.32 | 7,325,851.93 | 9,629,841.46 |
| Bedum | GM0014 | 12.04 | 28.86 | 26.35 | 31.28 | 3.34 | 8.02 | 7.32 | 8.69 | 100,427,783.32 | 240,730,465.81 | 219,775,558.04 | 260,968,703.49 |
| Haren Midden- | GM0005 | 0.86 | 5.67 | 4.10 | 3.69 | 0.24 | 1.57 | 1.14 | 1.03 | 7,173,413.09 | 47,286,341.50 | 34,187,309.03 | 30,815,492.66 |
| Groningen Oldambt | GM0017 | 0.86 | 1.20 | 1.46 | 1.96 | 0.24 | 0.33 | 0.41 | 0.55 | 7,173,413.09 | 10,030,436.08 | 12,209,753.22 | 16,370,730.48 |
| Pekela | GM1952 | 3.44 | 6.36 | 6.73 | 7.85 | 0.96 | 1.77 | 1.87 | 2.18 | 28,693,652.38 | 53,018,019.26 | 56,164,864.83 | 65,482,921.91 |
| Stadskanaal | GM1895 | 1.72 | 2.58 | 2.63 | 3.93 | 0.48 | 0.72 | 0.73 | 1.09 | 14,346,826.19 | 21,493,791.59 | 21,977,555.80 | 32,741,460.95 |
| Veendam | GM0765 | 0.86 | 1.37 | 4.83 | 4.62 | 0.24 | 0.38 | 1.34 | 1.28 | 7,173,413.09 | 11,463,355.51 | 40,292,185.64 | 38,519,365.83 |
| Zuidhor n | GM0037 | 1.72 | 1.72 | 1.32 | 2.42 | 0.48 | 0.48 | 0.37 | 0.67 | 14,346,826.19 | 14,329,194.39 | 10,988,777.90 | 20,222,667.06 |
| Westerwolde | GM0047 | 1.72 | 1.55 | 1.17 | 2.31 | 0.48 | 0.43 | 0.33 | 0.64 | 14,346,826.19 | 12,896,274.95 | 9,767,802.58 | 19,259,682.91 |
| Ten Boer | GM0056 | 0.86 | 1.03 | 8.20 | 8.08 | 0.24 | 0.29 | 2.28 | 2.24 | 7,173,413.09 | 8,597,516.64 | 68,374,618.06 | 67,408,890.20 |
| De Marne | GM1950 | 1.72 | 15.80 | 10.98 | 9.70 | 0.48 | 4.39 | 3.05 | 2.69 | 14,346,826.19 | 131,828,588.42 | 91,573,149.19 | 80,890,668.24 |
| Grootegast | GM0009 | 0.00 | 0.52 | 0.59 | 0.81 | 0.00 | 0.14 | 0.16 | 0.22 | 0.00 | 4,298,758.32 | 4,883,901.29 | 6,740,889.02 |
| Mar um | GM1663 | 0.86 | 0.52 | 0.59 | 0.92 | 0.24 | 0.14 | 0.16 | 0.26 | 7,173,413.09 | 4,298,758.32 | 4,883,901.29 | 7,703,873.17 |
| Eemsmond | GM0015 | 0.86 | 1.03 | 1.02 | 1.39 | 0.24 | 0.29 | 0.28 | 0.38 | 7,173,413.09 | 8,597,516.64 | 8,546,827.26 | 11,555,809.75 |
| Leek | GM0025 | 0.86 | 1.89 | 10.25 | 9.70 | 0.24 | 0.52 | 2.85 | 2.69 | 7,173,413.09 | 15,762,113.83 | 85,468,272.57 | 80,890,668.24 |
| Winsum | GM1651 | 0.86 | 3.09 | 2.49 | 2.77 | 0.24 | 0.86 | 0.69 | 0.77 | 7,173,413.09 | 25,792,549.91 | 20,756,580.48 | 23,111,619.50 |
| | GM0022 | 0.86 | 1.20 | 0.73 | 1.50 | 0.24 | 0.33 | 0.20 | 0.42 | 7,173,413.09 | 10,030,436.08 | 6,104,876.61 | 12,518,793.89 |
| | GM0053 | 0.86 | 0.86 | 1.46 | 1.85 | 0.24 | 0.24 | 0.41 | 0.51 | 7,173,413.09 | 7,164,597.20 | 12,209,753.22 | 15,407,746.33 |
| **Total** | | 33.54 | 77.99 | 90.16 | 101.24 | 9.32 | 21.66 | 25.05 | 28.12 | 279,763,110.68 | 650,545,425.47 | 752,120,798.64 | 844,537,095.79 |

## C. Distance in km between demand node $Fi$ and storage node $S_i$

**Table 21:** Pairwise distances (km) between demand locations $F$ and storage locations $S$.

| Distance in km | Storage location $S$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Demand location** $F$ | Zuidwending | Winschoten | Pieterburen | Onstwedde | Boertange | Ternaard | Anloo | Hooghalen | Hoogeveen | Schoonloo |
| Achtkarspelen | 55.26 | 60.82 | 26.32 | 64.48 | 74.46 | 18.84 | 43.52 | 45.37 | 62.55 | 53.51 |
| Ameland | 91.59 | 96.09 | 51.11 | 101.13 | 111.01 | 19.75 | 80.86 | 81.65 | 96.02 | 90.54 |
| Dantumadiel | 65.89 | 71.28 | 32.67 | 75.15 | 85.12 | 10.52 | 54.09 | 54.79 | 70.43 | 63.49 |
| De Fryske Marren | 77.08 | 85.20 | 65.09 | 83.56 | 92.91 | 47.62 | 60.67 | 49.77 | 52.80 | 60.72 |
| Harlingen | 101.19 | 107.99 | 73.10 | 109.35 | 119.27 | 42.86 | 86.44 | 79.92 | 86.64 | 90.63 |
| Heerenveen | 69.02 | 77.27 | 60.55 | 75.27 | 84.55 | 47.34 | 52.49 | 41.26 | 45.14 | 52.22 |
| Leeuwarden | 77.02 | 83.49 | 49.13 | 85.56 | 95.55 | 22.89 | 63.04 | 59.13 | 70.30 | 69.25 |
| Ooststellingwerf | 44.33 | 52.73 | 46.70 | 50.49 | 59.86 | 48.62 | 27.71 | 18.38 | 32.06 | 29.01 |
| Opsterland | 57.36 | 65.04 | 45.35 | 64.74 | 74.48 | 36.46 | 41.62 | 34.80 | 46.04 | 45.31 |
| Schiermonnikoog | 66.71 | 69.34 | 21.28 | 76.58 | 85.88 | 17.00 | 60.22 | 67.21 | 86.41 | 73.31 |
| Smallingerland | 56.17 | 63.43 | 40.45 | 64.09 | 73.98 | 31.61 | 41.14 | 36.59 | 49.80 | 46.61 |
| Súdwest-Fryslân | 85.20 | 92.87 | 66.64 | 92.40 | 102.03 | 43.62 | 69.29 | 60.13 | 64.70 | 71.07 |
| Terschelling | 116.73 | 122.31 | 80.14 | 125.77 | 135.78 | 47.65 | 103.83 | 100.53 | 110.19 | 110.68 |
| Tytsjerksteradiel | 63.73 | 70.20 | 38.70 | 72.33 | 82.34 | 21.44 | 49.97 | 47.46 | 61.09 | 57.11 |
| Vlieland | 125.73 | 131.94 | 92.22 | 134.35 | 144.34 | 59.76 | 111.77 | 106.38 | 113.40 | 116.97 |
| Waadhoeke | 93.83 | 100.55 | 65.76 | 102.10 | 112.03 | 36.16 | 79.26 | 73.36 | 81.25 | 83.96 |
| Weststellingwerf | 66.62 | 75.26 | 65.36 | 71.75 | 80.49 | 56.15 | 49.89 | 36.09 | 36.05 | 46.75 |
| Aa en Hunze | 15.06 | 23.96 | 48.49 | 19.01 | 28.27 | 67.75 | 6.08 | 17.88 | 36.45 | 11.97 |
| Assen | 27.33 | 36.09 | 45.60 | 32.70 | 41.98 | 58.52 | 10.68 | 8.55 | 30.35 | 13.79 |
| Borger-Odoorn | 21.22 | 29.45 | 57.48 | 20.98 | 28.10 | 75.04 | 14.61 | 16.94 | 30.41 | 6.46 |
| Coevorden | 49.92 | 57.16 | 84.36 | 46.38 | 48.91 | 95.52 | 42.54 | 31.72 | 19.08 | 27.20 |
| Emmen | 34.31 | 40.68 | 74.19 | 29.42 | 31.50 | 90.72 | 31.32 | 28.01 | 28.77 | 18.43 |
| Hoogeveen | 51.06 | 59.65 | 74.95 | 51.21 | 56.96 | 80.64 | 38.14 | 21.80 | 0.00 | 24.80 |
| Meppel | 66.12 | 75.01 | 79.71 | 68.08 | 74.88 | 77.37 | 50.86 | 33.51 | 19.33 | 40.85 |
| Midden-Drenthe | 38.39 | 47.26 | 60.44 | 40.52 | 47.98 | 68.95 | 23.91 | 6.96 | 14.84 | 13.43 |
| Noordenveld | 33.66 | 40.49 | 29.12 | 42.29 | 52.30 | 41.30 | 20.61 | 25.41 | 45.95 | 31.55 |
| Tynaarlo | 21.20 | 29.19 | 37.38 | 28.91 | 38.86 | 54.99 | 6.70 | 18.45 | 40.21 | 20.10 |
| Westerveld | 58.87 | 67.79 | 71.53 | 61.52 | 68.88 | 70.51 | 43.19 | 26.05 | 16.85 | 34.40 |
| De Wolden | 57.66 | 66.22 | 80.68 | 57.58 | 62.99 | 84.59 | 44.72 | 28.13 | 6.63 | 31.40 |
| Delfzijl | 26.47 | 22.48 | 32.27 | 33.89 | 39.91 | 64.14 | 35.73 | 52.87 | 73.86 | 50.00 |
| Appingedam | 25.49 | 23.15 | 28.25 | 33.87 | 40.87 | 59.72 | 32.63 | 49.44 | 70.74 | 47.38 |
| Loppersum | 29.03 | 28.65 | 20.91 | 38.28 | 46.23 | 52.29 | 32.28 | 47.97 | 69.68 | 47.58 |
| Groningen | 27.74 | 32.53 | 21.96 | 37.44 | 47.19 | 44.17 | 20.97 | 32.92 | 54.61 | 35.58 |
| Bedum | 31.76 | 34.09 | 14.74 | 41.61 | 50.68 | 43.26 | 29.39 | 42.68 | 64.43 | 44.55 |
| Haren | 23.60 | 29.32 | 27.11 | 33.07 | 42.96 | 48.42 | 15.79 | 28.60 | 50.39 | 30.55 |
| Midden-Groningen | 12.80 | 15.94 | 33.74 | 22.59 | 31.69 | 60.45 | 17.49 | 34.71 | 55.62 | 32.00 |
| Oldambt | 8.93 | 0.00 | 48.35 | 11.82 | 17.72 | 76.34 | 25.43 | 41.76 | 59.65 | 34.88 |
| Pekela | 5.15 | 4.83 | 49.44 | 7.84 | 15.85 | 76.04 | 21.83 | 37.54 | 54.96 | 30.23 |
| Stadskanaal | 11.75 | 17.97 | 56.35 | 8.01 | 15.85 | 78.90 | 17.97 | 28.76 | 43.20 | 19.31 |
| Veendam | 3.93 | 11.62 | 43.06 | 13.60 | 23.33 | 67.99 | 13.91 | 30.78 | 50.01 | 25.37 |
| Zuidhorn | 38.69 | 43.61 | 17.58 | 48.27 | 58.12 | 33.21 | 29.58 | 37.23 | 57.82 | 42.53 |
| Westerwolde | 16.15 | 16.67 | 62.58 | 6.27 | 4.96 | 87.61 | 28.27 | 39.56 | 52.34 | 29.64 |
| Ten Boer | 25.79 | 27.51 | 20.94 | 35.54 | 44.35 | 49.84 | 26.14 | 41.26 | 63.03 | 41.52 |
| De Marne | 47.41 | 50.30 | 5.94 | 57.28 | 66.62 | 27.87 | 41.67 | 50.90 | 71.56 | 55.59 |
| Grootegast | 45.62 | 51.51 | 24.31 | 54.73 | 64.73 | 28.21 | 33.71 | 36.78 | 55.43 | 44.22 |
| Marum | 44.64 | 51.47 | 30.98 | 53.11 | 63.11 | 33.27 | 30.80 | 30.92 | 48.61 | 39.32 |
| Eemsmond | 38.19 | 37.84 | 14.16 | 47.52 | 55.46 | 46.69 | 39.75 | 54.18 | 75.97 | 55.11 |
| Leek | 37.02 | 43.45 | 26.54 | 45.90 | 55.91 | 37.21 | 24.60 | 29.08 | 49.11 | 35.59 |
| Winsum | 38.18 | 40.69 | 8.67 | 48.05 | 57.22 | 37.06 | 34.28 | 45.90 | 67.35 | 49.02 |