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Long Duration Energy Storage in The Netherlands

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ABSTRACT

Developments for two key options for long duration energy storage in The Netherlands are explored, including green hydrogen and sustainable heat. The Netherlands faces significant challenges in meeting its ambitious target of 8 GW hydrogen electrolysis capacity by 2032. Domestic production is hindered by supply chain issues, increased costs, and high grid tariffs, making Dutch green hydrogen expensive compared to foreign alternatives. Meanwhile, direct electrification has become more attractive due to falling costs for renewables and batteries. Blue hydrogen emerges as a cost-efficient alternative, with extensive CO_2 storage capacity available in depleted North Sea gas fields and major projects like Porth's and Aramis underway.

The 8 GW target could be split, reverting to the Climate Agreement's 3-4 GW goal for green hydrogen while formulating a separate objective for sustainable heat supply and storage. Thermal energy storage, both short-term and long-term, offers promising solutions for system flexibility and seasonal demand. High-temperature thermal storage in deep aquifers (HT-ATES) is particularly promising, with costs below €15 per GJ for large systems. A target for sustainable heat supply and storage should be supported by a coherent policy framework considering all societal benefits, including CO_2 reduction and system flexibility.

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Background

A national roadmap for energy storage

Energy systems of the future will rely heavily on long duration energy storage (LDES), defined as storage systems capable of discharging over periods exceeding 10 hours [1]. Three interconnected storage domains will have a role in sustainable energy systems: electricity, molecules, and heat, which complement each other in terms of power capacity, duration, and functionality. These domains can be integrated through various conversion pathways, including power-to-gas, power-to-heat, power-to-fuels, gas-to-power, and gas-to-heat technologies.

In general, the applications of energy storage span multiple critical functions: balancing supply and demand across various timescales, managing peak heat demand, alleviating grid congestion, and maintaining strategic reserves. While these functions are essential for both current energy system operations and the ongoing energy transition, the market value of energy storage often fails to reflect its broader societal benefits.

Like other countries, The Netherlands faces unique opportunities and challenges in implementing various LDES solutions. In response, the Dutch government published a comprehensive energy storage roadmap outlining strategic actions through 2035 and beyond for each of these storage domains [2]. The roadmap emphasizes several key priorities. Both small-and large-scale battery storage systems, whether installed behind or in front of the meter, show significant potential and are considered crucial for future energy infrastructure. Molecule storage has a role in particular for long term storage yet faces considerable uncertainties requiring urgent strategic decisions. Additionally, the thermal storage sector requires enhanced knowledge development and exchange to achieve necessary scale-up objectives.

Hydrogen and thermal storage as key LDES options

The Netherlands' transition to renewable energy requires careful consideration of long duration storage options that align with its geographic characteristics, existing infrastructure, and specific energy needs. Among the range storage options available, hydrogen storage and thermal energy storage (TES) have emerged as particularly promising solutions for the Dutch context.

Hydrogen is an excellent storage medium and a good raw material for the production of iron, ammonia and methanol, important to several Dutch industries. In addition, during periods without wind or solar production strategic hydrogen reserves may be converted in fuel cells to produce electricity, although this implies conversion losses. Natural gas pipelines are repurposed to enable hydrogen transport. Since green hydrogen production is challenging. The Netherlands have started the production of blue hydrogen, which is hydrogen produced from natural gas steam reforming and subsequent CO_2 storage, to promote initial hydrogen demand and fill hydrogen infrastructure.

Thermal energy storage presents another particularly compelling option for the Netherlands. It includes short term power-to-heat options enhancing flexibility of the energy system and providing balancing or grid congestion services, as well as long term options to provide seasonal storage, often underground in open aquifers or confined systems at a variety of depths and temperatures. These systems can effectively address seasonal energy demand variations.

Other long duration storage technologies are feasible as well in the Dutch context including flow batteries and compressed air energy storage. Yet, hydrogen and heat storage have emerged as the most promising LDES solutions for the Netherlands [3]. Therefore, developments in these two key technologies will be examined in this article.

In the next chapter the role of green hydrogen production and storage will be discussed, while chapter 3 describes the role of sustainable heat supply and storage. The rational for a focus on green hydrogen in Dutch climate policies will be discussed (section 2.1), followed by challenges for introducing and scaling green hydrogen production (2.2), and the present policy framework for green hydrogen. Next, an outline will be provided of potential heat sources in The Netherlands (3.1), thermal storage options (3.2), and desired policies to help unlock national potentials for heat supply and storage in The Netherlands. Chapter 4 concludes.

Green hydrogen production and storage

Since 2019 The Netherlands has progressively scaled up its ambitions for green hydrogen production. While the 2019 national Climate Agreement set a target of 3-4 GW electrolysis capacity by 2030, this goal was later expanded to 8 GW by 2032 [4]. This ambitious target is closely tied to the planned expansion of offshore wind capacity in the North Sea, which must reach 21 GW to support green hydrogen production.

Rational for green hydrogen in The Netherlands

The Netherlands has positioned green hydrogen development as a cornerstone of its climate policy strategy, driven by several interconnected factors that reflect both domestic needs and international opportunities. The emergence of green hydrogen as a strategic priority aligns with multiple national objectives and leverages existing industrial strengths.

The primary driver is the Netherlands' commitment to ambitious climate targets: a 55% reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050, in accordance with the European Green Deal and Paris Agreement. Green hydrogen offers a viable pathway to decarbonize hard-to-electrify sectors, particularly heavy industry and transportation, which are crucial for meeting these targets.

The country's expanding offshore wind capacity in the North Sea presents a strategic opportunity for green hydrogen production. This geographical advantage enables the integration of renewable energy sources with hydrogen production, providing a solution for energy storage during periods of low wind or solar generation. The ability to convert excess renewable electricity into hydrogen addresses intermittency challenges while maximizing the utilization of offshore wind resources. By 2032 around 21 GW of offshore wind capacity would need to be realized to support the 8 GW electrolysis ambition.

The Netherlands' existing industrial infrastructure further strengthens the case for green hydrogen adoption. Major industrial clusters in Rotterdam, Zeeland, and the Chemelot region currently rely on grey hydrogen produced from fossil fuels. Transitioning these clusters to green hydrogen not only supports decarbonization efforts but also maintains their economic competitiveness. Moreover, this transition aligns with the country's ambition to establish itself as a principal hydrogen hub for Northern Europe, leveraging its strategic location and extensive port infrastructure.

Challenges for green hydrogen

While green hydrogen is considered by many as a key energy carrier for a carbon-free future, several barriers need to be overcome.

Levelized costs

For a start, green hydrogen will remain far more expensive than previously thought for the coming decades. Recently, production costs have experienced a marked increase, attributed to multiple factors, including higher interest rates, raw material costs, and energy prices [5]. Next to this, higher network tariffs and limited industrial exemptions in The Netherlands negatively impact levelized cost of domestic green hydrogen. Analysis indicates current levelized cost of green hydrogen in The Netherlands on the order of 12 to 14 euro/kg H_2 [6].

Recent analysis by Elzenga and Strengers comprehensively evaluated low-carbon hydrogen procurement costs in The Netherlands until 2040 (Table 1) [7]. In the near term, domestic blue hydrogen production emerges as the most economically viable option. Ship-based green hydrogen imports (via NH3), averaging costs across eight overseas nations, present significant competition to domestic electrolysis operations. Pipeline imports potentially offer even greater cost advantages, contingent upon infrastructure availability. Long-term projections (2040) indicate pipeline imports as the most cost-effective pathway for green hydrogen procurement.

Table 1: Projected costs (€/kg H_2) for domestic production of green and blue hydrogen, and for imported hydrogen by ship (using NH3) and pipe [7].

	2030	2040
Domestic production, green	6.3 – 9.1	5.6 – 8.0
Domestic production, blue	1.8 – 3.0	1.9 – 3.1
Import by ship	7.3 - 7.9	5.3 – 5.6
Import by pipe	4.1 – 7.3	3.5 – 5.3

The European hydrogen subsidy auction in April 2024 provided empirical support for these cost differences. From a competitive field of 132 bids, seven projects across Spain, Portugal, Norway and Finland were selected. These successful projects collectively proposed 1.58 Mt of green hydrogen production over a decade, projecting CO_2 emissions reduction exceeding 10 Mt. Winning bids requested subsidies ranging from €0.37 to €0.48 per kg of green H2. Production costs demonstrated significant regional variation, with projects in the four countries ranging from €5.3 to €5.8 per kg H2, compared to approximately €10 per kg in The Netherlands [8].

Given these cost estimates and the economic landscape, policy framework recalibration may be warranted to increase the role of blue hydrogen. The Porthos project, for which a final investment decision has been taken and scheduled for 2026 commissioning, will enable annual storage of 2.5 Mt CO_2 for 15 years beneath the North Sea. In addition, the Aramis project is an initiative for large scale CO_2 storage and will be designed to eventually transport and store 22 Mt CO_2 under the North Sea every year. It should become operational towards 2030. This is more than enough to at least store CO_2 from the production of blue hydrogen for industrial purposes, which is 180 PJ or 1.5 Mt H2 per year [7]. The production of this amount through steam reforming, producing CO_2 and H_2 in a stoichiometric ratio of 1:4, results in 5.5 Mt CO2 every year.

Supply chain coordination

The development of domestic production capacity for green hydrogen is further constrained by challenges in demand-supply coordination. The Renewable Energy Directive III (article 22a) establishes progressive targets for Renewable Fuels of Non-Biological Origin (RFNBO, mostly green hydrogen) in industrial applications, mandating 42% green hydrogen usage by 2030 and 60% by 2035. The Dutch government has explored transferring this Member State obligation to hydrogen-consuming industries through a purchase obligation mechanism, supported by production and demand subsidies, but this appeared premature [9]. Even a moderate mandatory offtake of 24% seemed to present significant challenges under base scenario conditions. Instead, a coordinated approach combining supply and demand subsidies appears optimal for supply chain development prior to implementing purchase obligations [10]. Like other countries, The Netherlands intends to support counting the use of green hydrogen in refineries towards purchase obligations by the transport sector.

As a matter of fact, this coordination challenge is not unique to domestic markets. Global low-carbon hydrogen production in 2023 reached less than 1 Mt against a demand of 97 Mt. Projections indicate a fivefold increase in global production by 2030, distributed equally between green and blue hydrogen (1.9 and 1.5 Mt per year respectively) [5]. However, implementation rates for announced projects remain low, with less than one-third of 1,600 proposed projects proceeding to development. Global electrolyser capacity could reach 95 GW, but around 58 GW still critically depends on policy implementation, introducing uncertainty regarding implementation [11].

Safe hydrogen storage

Another challenge regards the safe underground storage of hydrogen. This may well present the largest technical, spatial and societal challenge for national policies, compared to other forms of underground energy storage [3]. While hydrogen storage in salt caverns is technically feasible, risks-especially for fast-cycle storage-must be better understood. Large-scale hydrogen storage in gas fields still needs to be proven, with ongoing studies in Austria and Argentina. The market for commercial hydrogen storage is currently insufficient, requiring innovative business models to align storage capacity with energy infrastructure demands. To successfully implement hydrogen storage, early attention must be given to legal, policy, and social aspects, including public participation, policy design, and clear permitting procedures.

Policy framework green hydrogen

To facilitate the development of a green hydrogen supply chain, the Dutch government has implemented a National Hydrogen Program and a Roadmap Hydrogen, which outlines plans for production, infrastructure, and imports, and the development of a hydrogen backbone network to connect industrial clusters by repurposing existing gas pipelines [12].

As part of this policy framework the OWE subsidy for upscaling fully renewable hydrogen production via electrolysis has been introduced. In the first round, nearly 0.25 million euro was awarded to 7 projects with a total capacity of 101 MW [13]. The second funding round has been substantially increased to approximately 1 billion euros. For subsequent years €3.9 bln and €1.8 bln has been reserved for onshore and offshore electrolysis respectively [4].

Apart from this hydrogen policy framework a national innovation fund, Groenvermogen NL, was put in place. The fund includes €150 mln to support the development of electrolysers, and it will also pay for R&D programs amounting to €75 mln and involving 60 companies and 20 knowledge institutes. On top of these 10 demonstration projects have received subsidies to test innovations, and learning communities were started to support collaborations with knowledge/educational institutes.

Sustainable heat supply and storage

The Dutch government considers collective heat systems important for a climate neutral economy in 2050 [14]. In the 2023 National Energy Plan it is anticipated that 15-45% of the built environment would be linked eventually to some form of collective heat supply. Including heat demand for horticulture this would max 250 PJ of sustainable sources, up from 20 PJ today. Around 50-150 PJ would be accounted for by low and medium temperature networks and 15-25 PJ for very low temperature networks. In its vision on sustainable collective heating, the government calculates with a maximum of 250 PJ of collective heating, including 60 PJ for greenhouse horticulture and 9 PJ for e-boilers, and including transport losses [2].

A variety of sustainable heat sources is available, including geothermal, aqua thermal, solar thermal, aerothermal and residual heat. These sources typically match a continuous demand for baseload heat. A good use of domestic options for thermal storage will help to match supply of these sources with demand over longer time spans. In addition, such options may reduce the importance of strategic reserves. Import and storage of molecules is no longer necessary if good use can be made of sustainable heat sources in the domestic environment.

Sustainable heat sources in The Netherlands

A variety of sustainable heat sources is available in The Netherlands. Table 2 indicates their potentials plus maximum contributions to heat supply in 2050. These are indicative numbers that do not reflect national targets. Mind also that these potentials cannot be added. If one sources is applied more often, another source may have a less important role. Yet, these estimates indicate the vast potentials for heat sources, notably geothermal and aqua thermal energy. While aqua thermal energy comes at lower temperatures and will require the use of heat pumps, geothermal energy is available at higher temperatures.

Table 2: Estimated potentials of heat sources contribution to national heat supply of 250 PJ in 2050, including losses. Potential solar thermal includes individual systems. Aerothermal energy has been excluded. Soil refers to shallow geothermal systems. Source: KGG [14]

	Geothermal	Residual	Solar	Aqua	Soil	E-Boiler
Potential	210	100	107	211	108	n.a.
Max Contribution	125	100	25	60	50	38

Local needs and opportunities will be decisive for the preferred heat source. Typically, a heat strategy is based on a generic outlook on available sources and a clear view on the desired network temperature. This will be a basis for a future-proof decision, while it may allow for adjustments and developments along the way. For instance, a heat strategy may be based on the availability of residual heat and an existing high-temperature heat network, while including pathways for developing and integrating low temperature aqua thermal energy.

The choice for a network temperature is critical for a sustainable heat system. Low to medium temperatures will limit transportation losses, but heat pumps may be required to boost such temperatures to higher levels. This holds in particular for aqua thermal and aerothermal energy, which typically come at max 10-15°C, but also for heat from shallow geothermal systems or data centers. The need for heat pumps may be inconvenient as these typically require new or upgraded grid connections, which as a result of widespread grid congestion in The Netherlands are often not readily available.

Status of thermal storage

Heat may be stored from days to many months or longer. On a daily basis, thermal storage can help to provide heat flexibly to homes and business. Colder spells of weeks to months may be overcome by long term thermal storage options. Table 3 presents an overview of short- and long-term options. While not all of these are applied at large scale, most of these options are sufficiently mature to start market introduction.

Short term heat storage may be based on phase change materials (PCM), thermochemical materials (TCM), tank thermal storage (TTES) with sensible heat stored in water or solids, e.g. sand, stone, or salts or redox heat storage (in iron). These options help to store excess electricity and may contribute to a flexible heat supply while mitigating grid congestion, provided that a grid connection is available. Short term storage often happens at very high temperatures (over 100°C) and may make smart use of dynamic electricity prices. For some of these options (notably PCM, TCM) longer term storage is being explored too [15].

Long term storage of heat and/or cold may cover a week to several months, and contribute to national strategic reserves. Much of this happens underground. Storage capacity underground is typically a lot bigger than storage above ground. This makes it an attractive solution in densely populated areas with high heat demands. Various technologies are available including storage in aquifers (aquifer thermal energy storage, ATES) and in closed systems (borehole thermal energy storage, BTES), either shallow individual systems, or deep collective systems. Closed systems do not depend on the availability of aquifers, and therefore their technical potential is larger.

Next to this, seasonal heat storage may occur above or near the surface in pits (PTES), mines (MTES) or tanks (TTES). For larger versions of these storage systems investment cost are typically lower (Figure 1). In addition, no drilling is needed, which reduces costs. On the other hand, larger surfaces must be available, in particularly for pit storage, and in populated countries this is a drawback.

Existing models do not sufficiently take into account the added value of using large-scale thermal storage. Assumptions about the availability of green gas and hydrogen drive model outcomes [3]. Yet, underground heat buffering can play an important role in a more efficient large-scale use of constant and seasonal heat sources such as residual heat, geothermal energy, solar thermal energy.
In particular high temperature aquifer thermal energy storage (HT-ATES) is important in The Netherlands. In a benchmark study of potential HT-ATES systems in The Netherlands Zwamborn et al. concluded that the cost price of heat from a HT-ATES system can be lower than €15 per GJ, if the stored water volume exceeds 300.000 m3 [16]. In addition, several formations in the Netherlands are potentially suitable for high-temperature aquifer storage. Large parts of the west of the Netherlands have a favorable location for HT-ATES. South Holland (e.g. the Rotterdam-The Hague region) stands out. Of the potentially interesting areas, most parts require more research to be able to remove (or confirm) one or more possible barriers. A small part of the Netherlands, especially towards the eastern border, seems unsuitable for HT-ATES [17].

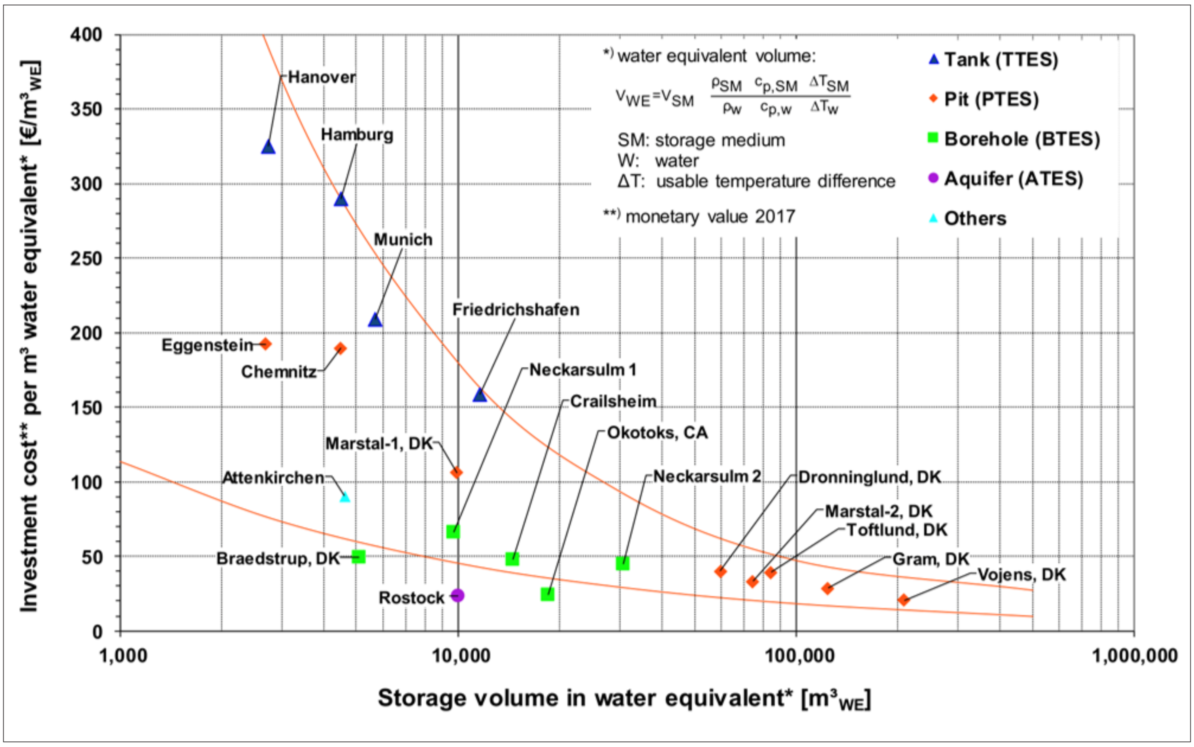

Figure 1: Investment costs for various thermal storage technologies [18].

Table 3: Temperature, technology readiness level and market penetration in The Netherlands for thermal storage technologies [2].

	Depth	Duration	Temp	TRL	Penetration NL
ATES					
LT (heat & cold)	10-100	Long	<25	9	>3000
MT open system	10-500	Long	25-60	7-8	A few
HT open system	10-500	Long	60-90	7-8	1
BTES	0-500		<90		
LT		Long		9	>10 000
HT		Long		7-8	A few
MTES	10-800	Long	<90	7-8	A few
PTES	0-10	Long	<90	7-9	A few*
TTES seasonal	n.a.	Long	<90	6-7	A few
TTES water	n.a.	Short - medium	<90	9	>500
TTES solid	n.a	Short - medium	<1200	6-7	A few
PCM	Na	Short - medium	Various	6-7	A few
TCM	Na	Medium-long	Various	4-6	Experiments
Redox	Na		75-650	4-6	A few

* or deeper
** incl Denmark

Currently, several deep geothermal projects are ongoing in The Netherlands, one of which is combined with high temperature storage in a deep aquifer.

- ECW Agriport is large industrial estate with horticulture, agribusiness, logistics and data centers, equipped with a heating network and connected to a geothermal source for baseload heating. Three doublets were installed with a depth of 2,250 m reaching water of 92°C. In a nearby village two more doublets with a slightly shallower depth were installed, where the water has a temperature of 84°C. The heat produced could support 1,500 home equivalents. This project was part of the Heatstore project within the EU Geothermic program [19].
- Haagse Aardwarmte Leyweg is a geothermal project in The Hague, the first to exclusively supply heat to the built environment. Two wells have been drilled to a depth of over 2,000 meters and tapping into water of 75°C. In 2022, the project would supply to 1,800 to 2,000 home equivalents via a heating network. In the long term, enough heat will be produced for approximately 4,000 home equivalents. Two other geothermal projects in The Hague are being investigated too in view of the large potential for HT-ATES in the region [20,21].
- The Geothermie Delft project aims to provide sustainable heating to both the TU Delft university campus and the surrounding neighborhoods. Two wells have been to a depth of approximately 2.5 km in a sandstone reservoir. Water at 85°C is being pumped up to heat university buildings and up to 10,000 nearby homes, while cooled water is being pumped back to maintain the process. The pilot is investigating whether excess geothermal heat in the summer (at 80°C, originating from a depth of 4 km) can be stored in an aquifer at a depth of 100 m, with an intended storage capacity of 25-50 TJ [22].

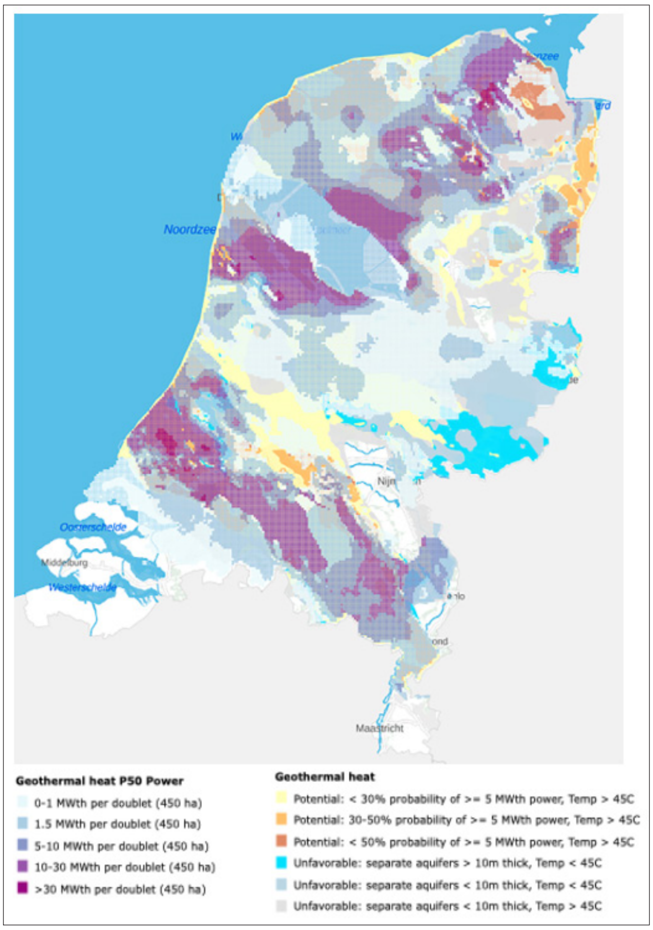

Figure 2: Potential for geothermal energy. "P50 power" presents the probability of 50% on realizing the power indicated. Source: Warmteatlas [17].

Policies for sustainable heat and thermal storage

In the Netherlands thermal storage is supported by two financial instruments, the ISDE and SDE++ subsidies. The SDE++ subsidy is an operational subsidy for industrial and district heating applications, allocated based on CO_2 reduction. This implies that only storage with significant emissions reductions (e.g., by replacing natural gas heating) can qualify. Benefits for greater flexibility in the energy system are not awarded. In 2024 the scheme included €1 bln each for high temperature heat, low temperature heat and molecules (green gas, hydrogen). The ISDE subsidy targets households and small businesses by subsidizing sustainable energy investments, possibly integrating TES solutions such as phase-change materials or buffer tanks.

Next to this, a national guarantee scheme (RNES Aardwarmte) was put in place to cover the risks of failed drillings. Geothermal and aquifer-related projects receive separate funding through EU or research-driven programs, but not from core Dutch subsidy schemes. EU subsidies take long to obtain however, and national subsidies may be blocked by European state support rules. Therefore, it is desirable to elaborate a broad policy framework for promoting all forms thermal storage, in which all benefits (CO_2 reduction, but also system flexibility and grid congestion) are awarded.

In spite of its vast potential deep aquifer storage in The Netherlands has not received the same attention as the production and storage of green hydrogen. A study by leading Dutch institutes concluded that until 2030 estimated storage capacity for hydrogen until ranges from 0.042 to 0.475 TWh in 1 to 4 new salt caverns. Estimates for heat storage capacity deep aquifers alone amounted 0.16 to 0.48 TWh across 10 to 30 locations [3]. Yet, policy recommendations tend to focus on advancing green hydrogen.

Assuming sufficient heating networks will become operational, several key milestones must be achieved by 2030 to boost HT-ATES. By 2030, the Netherlands must map subsurface storage potential and create a storage atlas. A knowledge-sharing program will be established to monitor HT-ATES projects, including lifetime assessment and decommissioning strategies. Regulatory barriers must be removed, with new rules ensuring investment security and scalability. A financeable business case is needed, requiring proven technology from at least ten successful projects and potential public support. Spatial planning must consider stakeholders and competing land use. After 2030, further steps will ensure HT-ATES becomes a mature, financeable technology. Design standards and safety norms must be established, with ongoing public support monitoring. A full value chain of developers and service providers should support at least ten projects annually, integrating HT-ATES into the broader energy system.

Importantly, the number and average size of future HT-ATES projects will depend critically on the number of district heating networks operated and the organization of heat supply through these networks.

Conclusions

The Netherlands will realize a fraction of its objective for green hydrogen production in 2032. The previous government aimed for 8 GW of electrolysis capacity by 2032 – at least doubling the target from the Climate Agreement. However, domestic production is getting off the ground very slowly. Difficult supply chain coordination hampers the realization of domestic production capacity. The unprofitable top component for electrolysis, i.e. the difference between cost and product market value, has increased in recent years due to increased costs for interest and raw materials. In addition, high grid tariffs in The Netherlands increase the cost for domestic electrolysis compared to foreign production. A European auction for hydrogen subsidies in April 2024 confirmed that Dutch green hydrogen production is relatively expensive. In addition, Meanwhile, direct electrification has become more attractive, as a result of rapidly falling production costs. The costs for renewable generation have fallen drastically and the price of lithium batteries is a fraction of what it was fifteen years ago. Grid reinforcement to address grid congestion is a major challenge, but at the same time it is clear and plannable. Moreover, direct use of electricity prevents half of the energy being lost as conversion during the production and use of green hydrogen.

Blue hydrogen is an indispensable and cost-efficient element in the Dutch hydrogen strategy. With production costs on the order of 2 to 3 euro/t until 2030 and beyond, blue hydrogen is a cost-efficient way to supply Dutch industry with low carbon hydrogen. Around 100 depleted gas fields under the North Sea with a total capacity of around 1000 Mt CO_2 should suffice to store the CO_2 that would be produced when all industrial hydrogen needs (1.5 Mt annually) would be fulfilled with blue hydrogen. The Porthos project near Rotterdam, which required a 1.3 bln euro investment, will store 2.5 Mt CO_2 annually over the next 15 years, while the Aramis project will eventually transport and store 22 Mt CO_2 under the North Sea every year.

Short term storage of sustainable heat offers much needed system flexibility. Short-term heat storage can utilize phase change materials (PCM), thermochemical materials (TCM), or tank thermal storage (TTES), where sensible heat is retained in water or solids such as sand, stone, or salts. Additionally, redox heat storage, such as in iron, is an option. These methods enable the storage of excess electricity and support a flexible heat supply while providing balancing services or helping to alleviate grid congestion, provided a grid connection is available.

Long term storage of sustainable heat is critical to overcome cold spells. In the Netherlands, geothermal, solar thermal, aqua thermal, aerothermal and residual heat sources together may offer hundreds of petajoules and cover a 250 PJ heat demand in the built environment and horticulture in 2050. Long duration thermal storage may help to make efficient use of these resources and overcome colder periods of weeks to entire seasons. Such storage can be done either in aquifers or through closed boreholes, in a great variety of shallow individual or deep collective systems, depending on local options and needs. Also, storage in pits, mines or tanks can play a role.

High temperature thermal storage in deep aquifers is particularly promising. For large systems costs less than €15 per GJ have been reported. HT-ATES would allow for central thermal storage for both the built environment and industry. It would support the efficient use of geothermal heat, which eventually may contribute over 100 PJ to total heat supply. Required surface area is relatively small, which is helpful in populated areas, and storage potentials are large. Geographical conditions are favorable and can help put The Netherlands in a leading position on this technology, and enable export of this expertise. The ongoing pilot at Delft University campus is a very relevant experiment in this regard that possibly should be expanded or followed up elsewhere.

The 8 GW ambition for green hydrogen in 2032 may easily be split into separate targets for green hydrogen, and for sustainable heat supply and storage. This implies a return to the 3-4 GW target for green hydrogen from the Climate Agreement, which is sufficiently challenging. More subsidies and at the same time more risk appetite is needed to actually reach this level. Then meaningful experiments can be conducted with revenue models for hydrogen electrolysis with fluctuating, domestically produced green power. Next to this, equally ambitious objectives can be formulated for sustainable heat and thermal energy storage.

A coherent policy framework to advance sustainable heat supply and storage is lacking. Operational subsidies are available to close business cases for sustainable energy projects, but only if these result in tangible CO_2 reductions. Investment subsidies are available to support sustainable heat projects by individual home owners and businesses. Large scale sustainable heat projects mostly rely on subsidies for demonstrations. A comprehensive policy framework for long duration energy storage, including thermal storage, should account for all societal benefits, including CO_2 reduction, but also system flexibility and grid congestion. In addition, it must enable large-scale sustainable heat projects, including new heat networks and centralized storage systems [23].

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