Whitepaper

SUBSURFACE ENERGY STORAGE IS ESSENTIAL FOR THE FUTURE ENERGY SYSTEM

STORAGE GUARANTEES SECURITY OF SUPPLY AND FLEXIBILITY

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Beyond 2030, there will be a large demand for subsurface storage of energy to safeguard an uninterrupted energy supply. It can also ensure the security of supply and flexibility of our future energy system. The storage of hydrogen as a sustainable energy carrier will make an essential contribution.
The timely realisation in reality of subsurface storage represents a major challenge. Studies by TNO and EBN show that the period between now and 2030 will be crucial for the safe and fitting development of sustainable subsurface energy storage between 2030 and 2050.

SUMMARY

OUR ENERGY SYSTEM DEMANDS GREATER FLEXIBILITY

The subsurface storage of natural gas is an important cornerstone in today's national energy system. It helps ensure that we can supply sufficient natural gas to the country, throughout the year. At present, natural gas is used to produce both heat and electricity.
The transition to a climate-neutral energy system - with different energy carriers - will require new technologies and new solutions. The Netherlands will not only have to replace natural gas as a seasonal buffer with some other form of energy storage. The energy system itself will have to become far more flexible due to the greater reliance on weather-dependent energy sources such as solar and wind.

HUGE DEMAND FOR STORAGE FROM 2030 ONWARDS

Based on the need to maintain a balance between the heavily fluctuating supply of renewable energy in the future and the also variable demand, subsurface energy storage will become crucial, from 2030 onwards, as a means of safeguarding the security of supply of energy. Studies by TNO and EBN have concluded that in response to the expected start of the large-scale production of hydrogen in the period between 2030 and 2050, there will be substantial demand for the storage of hydrogen both in salt caverns and gas fields. Other technologies including high-temperature heat storage in aquifers could also make a major contribution to realising more sustainable and more efficient district heat networks.

PREPARING FOR THE RESPONSIBLE SCALING UP OF STORAGE

At present, the various technologies are at the development or demonstration stage. Over the coming years, the following actions will have to be taken, in order to scale up subsurface energy storage beyond 2030:

- It is vital to demonstrate the technical feasibility, the safety and economic viability of hydrogen storage and high-temperature heat storage, in suitable underground space.
- The Netherlands needs to develop robust policy and supervisory frameworks for responsible demonstration and scaling up. The policy framework includes a clear vision on the spatial distribution of storage locations within suitable subsurface storage space, in combination with the integration with national and regional energy strategies and on choices with regard to existing and future activities below and above surface.
- The government will have to work on a societal license to operate within society, whereby local communities and stakeholders are involved from the outset in the possible choice of locations, the evaluation of alternatives and the balancing of local and national interests.

CONTENTS

TOWARDS A RELIABLE AND RENEWABLE ENERGY SYSTEM

The Dutch energy system is recognised as one of the most reliable in the world. An important cornerstone of that system is the subsurface storage of natural gas. Even in exceptional situations, for example extremely cold winters, the current system can guarantee the production of heat and electricity. Large-scale power disruptions are extremely rare.

ENERGY TRANSITION: A SYSTEM SHIFT IN 30 YEARS

By 2050, the Netherlands must have reduced the emission of greenhouse gases by at least 95% as compared with the level in 1990. National and local government, network operators, energy supply companies and bulk consumers are faced with the huge challenge of transforming the entire energy system over the next three decades. This transformation will require a shift to cleaner and renewable energy sources and energy carriers, and the development of the infrastructure necessary to transport all that energy safely and reliably to the end users.
Energy storage is a key element of that infrastructure.

DIRECT CONSEQUENCES OF THE ENERGY TRANSITION

Four developments play a key role in the transition to a system based on renewable energy.

Supply depends on the weather
On a cloudy, windless day, the yield from solar and wind energy will be too low to satisfy the national energy demand. This is especially true in the winter, when demand for energy is far greater than in the rest of the year. As the share of wind and solar energy for the generation of electricity grows, the supply of and demand for energy will become further disconnected, thereby increasing the scale of the challenge.

Greater dependency on imports
Natural gas production in the Netherlands is declining rapidly and this production downturn cannot be fully compensated by domestic renewable energy production. The uncertainties surrounding the energy mix and the level of imports in the longer term (through to around 2050) are still considerable. What is clear is that the dependency on imports is set to grow significantly, over the coming years.

The energy infrastructure must undergo major changes

The patterns of demand for and production of energy are heading for a period of major change; geographically and in terms of timing, and in the form of energy supplied. In the future, heat and electricity will more commonly be generated locally, for example from geothermal sources, residual heat and solar panels. A major share of electricity will be produced at sea, in offshore wind farms. Electricity grids will be faced with larger and more irregular peaks in supply and demand.

The Dutch energy system is recognised as one of the most reliable in the world. Subsurface storage of natural gas plays an important role.

Hydrogen to become a vital energy carrier

Hydrogen is becoming increasingly recognised as a major energy carrier that offers possibilities for large-scale energy storage. Reinforcing the necessary electricity infrastructure and establishing a hydrogen infrastructure go hand in hand with a whole raft of questions, for example in what circumstances is it preferable to transport electricity direct via newly installed electricity cables and when is it in fact better to first convert the electricity into hydrogen, before transport.

Besides fulfilling this role in the electricity chain, we will probably see the development of a hydrogen economy, in which hydrogen also fulfils a series of other roles. Take for example hydrogen in mobility, the delivery of heat to the industrial sector and as a raw material for sustainable synthetic products. The storage of hydrogen could well be important for all of those applications, too. The construction of a central infrastructure for hydrogen can only be achieved if backed up by large-scale storage.

THE NEED FOR GREATER FLEXIBILITY

All these challenges demand greater flexibility in the energy system, so that energy can be delivered in the required form, anywhere, any time. It is also essential that the various subsystems are better integrated. The large-scale subsurface storage of energy could provide a large part of the solution.

TNO and EBN have investigated the potential contribution of subsurface energy storage to the future energy system, and have assessed the actions that need to be taken now, to put that contribution in place, on time. The publication by TNO and EBN in 2018 of the report *Ondergrondse opslag in Nederland: Technische verkenning* provided an overall picture of this potential. The potential for the storage of hydrogen and compressed air was further elaborated, in greater detail, in the TKI project 'Large Scale Energy Storage in Salt Caverns and Depleted Fields' (TNO, 2020). The WINDOW project (TNO, 2020) investigated the potential for storage of heat. The recent report *Ondergrondse energieopslag in Nederland 2030--2080* (TNO and EBN, 2021) presents the results of new work and a synthesis of the work undertaken by various parties.

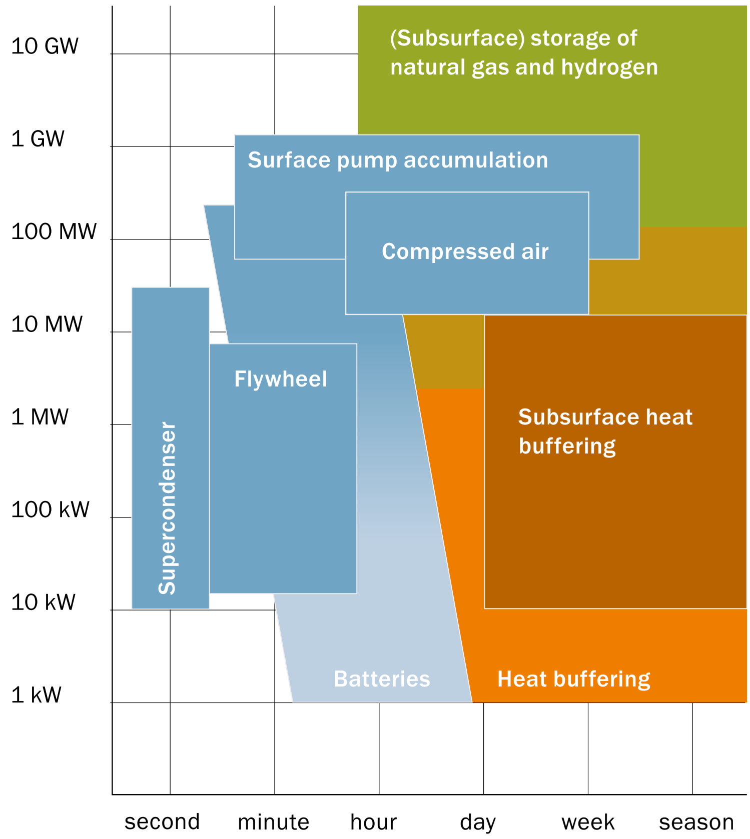

Figure 1: *Relative capacity and duration of techniques to provide for the buffering of energy.*

HUGE DEMAND FOR SUBSURFACE STORAGE OF ENERGY BEYOND 2030

Over the coming years, the Climate Agreement and the ambitions for 2050 will bring about rapid changes in the energy system. The precise nature of those changes is not yet known. Many of the choices will have to be made over the coming decades. Nevertheless, these changes will to an important extent determine the nature and size of the need for large-scale energy storage.

GROWTH OF VARIABLE ENERGY GENERATION HAS CONSEQUENCES

The massive growth of variable electricity generation from wind and solar sources will be a central theme during the energy transition. A number of key themes will emerge including upgrading the energy transport system and grids, the production of (blue and green) hydrogen and the establishment of renewable heat production within a growing number of district heat networks.

RATIONALE BEHIND SUBSURFACE STORAGE

The construction of subsurface storage facilities is important for a number of different reasons.

- Achieving a balance in supply and demand (security of supply) in central and regional energy grids and in the energy systems at district and municipal level, whereby subsurface storage offers a cheaper and more robust alternative than the other flexibility options.
- Avoiding high costs and negative social impact.
- Contributing to the more efficient use of renewable heat supply by using both constant (baseload) sources of heat (geothermal and residual heat) and seasonal heat sources (solar thermal energy).
- Developing revenue models that take energy price fluctuations into account, deliver specific energy system services and support the (international) trade in energy carriers.
- Saving costs and space by implementing large-scale solutions.

MULTIPLE SCENARIOS POSSIBLE

Using models of the energy system, various parties have calculated how the future energy supply can contribute to the climate ambitions that have been set. The input for these models is a range of scenarios. As it turns out, all roads lead to Rome, as explained in the various publications. Each scenario offers a different set of predictions (final views) for the way in which our country may produce, transport and use energy in 2050, all based on the assumption that the climate targets will be achieved.

The outcomes of these scenario studies provide an insight, among others, into the costs of energy supply, the resultant CO_2 emission levels, the dependency on imported energy and the means of flexibilisation (including storage) that must safeguard the reliability of supply in a whole range of circumstances.

ANALYSIS OF RECENT SCENARIOS BY TNO AND EBN

To gain an insight into the future demand for and the importance of (subsurface) storage, alongside a range of other flexibility options, TNO and EBN analysed a number of these studies. (see box 1). Each scenario in these studies is based on the National Climate Agreement, and subsequently specifies a range of options that result in a balanced and CO_2neutral energy supply, in 2050. The outcomes of the analysis by TNO and EBN were then translated into proposed development pathways for subsurface energy storage. Those pathways will be used to understand the bottlenecks, the boundary conditions the necessary policy contributions and the accompanying timelines.

BOX 1

Forms of energy carriers

Broadly speaking, three forms of energy can be stored in the subsurface:

- In chemical form: molecules such as methane and hydrogen
- In thermal form: hot water
- In mechanical form: compressed air and pump accumulation

These subsurface energy storage technologies offer far greater storage capacity and have a far greater achievable output per installation than their aboveground counterparts, such as batteries.

Storage locations

In general terms, the Dutch subsurface offers three types of spaces where energy can be stored:

- Subsurface cavities (generally created by human activity), such as salt caverns
- Depleted gas fields
- Aquifers (water-bearing geological formations)

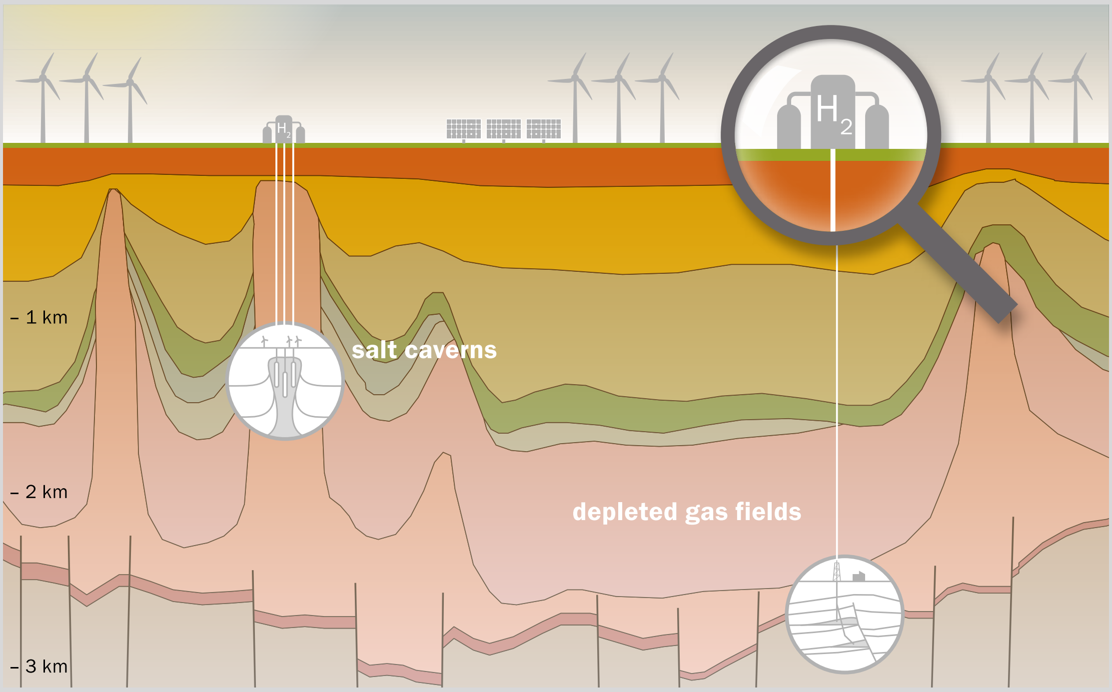

Figure 2: *Subsurface spaces for the storage of hydrogen; cavities in salt pillars and depleted gas fields.*

BOX 2

Scenarios for the future energy system
Three recent energy system studies have been investigated to assess the future demand for subsurface energy storage. The studies are: i) “Klimaat-neutrale energiescenario’s 2050” by Berenschot & Kalavasta (BK), ii) “The role of large-scale energy storage in the energy system of the Netherlands, 2030-2050” (report WP1) by the TKI Energy joint industry project “Large-Scale Energy Storage” (LSES) and iii) “Towards a sustainable energy system for the Netherlands in 2050” by TNO Energy Transition Studies (ETS). Together, these studies provide new insights into the demand for flexibility in the changing energy system between 2030 and 2050, including the potential necessary storage capacity in the form of subsurface energy storage. All of the scenarios meet the target of 95% emission reduction (in CO_2 equivalents) by 2050 as compared with the level in 1990.

The BK study presents four scenarios for 2050, based on different societal developments. BK used Quintel’s Energy Transition Model to calculate the outcomes. The scenario choices result in a need to establish subsurface storage capacity (in particular for hydrogen) for balancing the seasonal fluctuations in supply and demand, and the variable electricity production from solar and wind sources.

- **Regional management:** Focus on regional energy production and energy grids. High degree of self-sufficiency with the renewable production of electricity (solar and wind), heat (geothermal, residual and ambient heat) and circularity. A decline of energy-intensive industry.
- **National management:** Focus on large-scale national energy projects and distribution grids. High degree of national self-sufficiency with the renewable production of electricity (solar and wind), heat (geothermal, residual and ambient heat) and circularity. No change in the level of energy-intensive energy.
- **European CO_2 management:** Universal CO_2 tax with import charges and compensation at the borders of Europe. Natural gas retains an important share in the energy system alongside hydrogen and biomass, for which there are global markets. High dependency on imported energy. CCS (CO_2 capture and storage) will be given considerable freedom of application to achieve the climate targets. Expansion of energy-intensive industry.
- **International management:** Fossil-based energy will be restricted worldwide. Free trade will be encouraged with a global hydrogen and biomass market. High dependency on imported energy. CCS will be given considerable freedom of application to achieve the climate targets. Expansion of energy-intensive industry.

The LSES study adopts as its starting points both the Climate Agreement scenario for 2030 and a revised version of the ‘National management’ scenario presented by BK for 2050. The calculations in these scenarios make use of the OPERA and COMPETES models in which technologies are selected on the basis of lowest costs to society (cost optimisation), in a given situation. As a consequence, in many cases, alternative flexibility options (interconnectivity, curtailment and demand response) enjoy preference above the establishment of extensive subsurface storage capacity.

The study by TNO-ETS presents two scenarios for the period 2030-2050, based on two extremes in intrinsic motivation among citizens and businesses. The results are calculated using the OPERA model.

- **TRANSFORM:** The Netherlands is willing to demonstrate behavioural change and switch to a clean, energy-efficient economy with new innovative technologies. As a result, the Netherlands becomes less energy intensive and renewable production from solar, wind and geothermal sources acquires a greater share in the energy supply.
- **ADAPT:** The Netherlands builds on its current economic strengths and opts for certainty and retaining its current lifestyle. Biomass and natural gas occupy a large share in the energy supply and CCS plays an important role in achieving the targets for greenhouse gas reductions.

EXPECTED DEVELOPMENTS FOR STORAGE

With regard to the various forms of subsurface energy storage, generally speaking a number of different developments are expected.

Natural gas and biomethane: sufficient storage capacity
Globally, natural gas storage is the furthest developed form of large-scale energy storage with a broad range of technical options. At present, the Netherlands has five locations for gas storage in former gas fields and in salt caverns.
These locations are employed both for security of supply and for the (international) trade in natural gas. Based on the examined energy scenarios, no new locations will be needed for the storage of natural gas. The existing natural gas storage locations offer ample storage capacity for the future supply-demand balance, including the possible establishment of strategic reserves (needed in a system heavily dependent on imports). According to estimates, one or two of these locations will be sufficient to maintain the balance between the supply and demand for natural gas and biomethane[1] after 2030. Questions that as yet remain unanswered are:

- Which of the five locations should be retained for natural gas storage?
- Could the other locations possibly be employed for hydrogen storage and if yes, what are the legal and technical boundary conditions for bringing about this transformation?

[1] Methane equivalent gas, produced from biomethane.

Hydrogen storage necessary according to all scenarios
At present, no storage sites have been developed in the Netherlands for the subsurface storage of hydrogen. Deep caverns in thick rock salt formations already offer a technically proven concept for the storage of pure hydrogen.
Four such sites are already in operation in the United Kingdom and the United States. Preparations are underway for a test and a pilot project in the Netherlands, at the natural gas storage site in Zuidwending. The technical and economic feasibility of pure hydrogen storage in porous media (including gas fields) still needs to be proven.
A number of pilot and demonstration projects are currently being developed in Europe and beyond.

Subsurface storage of hydrogen will acquire an essential role over the next 20 to 30 years.

According to all the scenarios evaluated, the subsurface storage of hydrogen will be essential to ensure the security of supply of energy in the Netherlands. In addition to the storage necessary to balance supply and demand, a need may also emerge for establishing additional (strategic) reserves in storage locations, in order to safeguard our country against large-scale disruptions in supply, such as failure of the main infrastructure or geopolitical conflicts.
Estimates of the demand for hydrogen storage by 2050 vary widely from between 2 TWh with a very limited role for hydrogen in balancing the energy system, up to more than 50 TWh if hydrogen acquires a central role in the energy system, and is primarily produced from variable sources such as solar and wind. To place this number in perspective, at present, electricity consumption in the Netherlands amounts to around 110 TWh per year.

Over the coming years, salt caverns offer the most obvious possibility for developing the first locations for the subsurface storage of hydrogen in the Netherlands. The technical and operational achievability of these locations are already fairly well known. However, the majority of the scenarios examined require greater storage capacity than can be achieved in salt caverns alone. In that case, the development of additional storage capacity in gas fields will be necessary.

Heat storage: making better use of baseload and cheap sources
The storage of high-temperature heat is above all attractive for utilising heat from constant production (baseload) sources more efficiently, such as geothermal sources and residual heat from industry. High-temperature heat is also ideal for use in combination with seasonal sources of heat such as solar thermal heat and large heat pumps capable of delivering cheap heat in the summer. By establishing high-temperature heat storage, overproduction in the summer can be deployed in the winter months thereby restricting the need for flexible heat sources, that primarily deliver heat with natural gas, electricity and biomass.

The growth of high-temperature heat storage will depend on the increase in district heat networks (which at present are only available on a limited scale) based on geothermal heat, residual and solar thermal heat. The large-scale storage of high-temperature heat is possible in groundwater present in aquifers located several hundred metres below ground. In the Netherlands, this technology is still in an early stage of development. To date, only a small number of recent pilot projects have been developed or realised. Comparable technologies for thermal energy storage (heat and cold) and low-temperature heat storage in the shallow subsurface are widely developed, in the Netherlands.

Large-scale development of high-temperature heat storage can make a major contribution to the more efficient use of renewable heat sources in district heat networks.

Compressed air and subsurface pump accumulation for regional needs
Compressed air energy storage and pump accumulation are well-known technologies for the storage of electrical energy. As yet, the Netherlands has no installations in place, but there are plans for their development. Internationally, two operational subsurface compressed air storage sites in salt caverns are known. The major technical challenges are to achieve the full sustainability of this technology, which at present still depends on natural gas, and increasing the efficiency, which is currently around 50%. Pump accumulation is in widespread use in combination with water reservoirs in mountainous areas. In flat areas, in theory, reservoirs could be built deep below ground (in tunnels). This form of technology has not yet been employed in practice.

According to the scenarios and models examined, compressed air storage and pump accumulation are not critical technologies for safeguarding the national security of supply. There appear to be sufficient (aboveground) alternatives for balancing the supply and demand of electricity. The establishment of these storage techniques could nonetheless be attractive for private initiatives with revenue models focused on the support services for the electricity grid, with timescales ranging between fifteen minutes and a maximum of one to two days.

The installation of compressed air storage will have to compete with the space required for the installation of caverns for the storage of hydrogen. There are ideas for developing subsurface pump accumulation in tunnels in limestone formations in Zuid-Limburg, at a depth of 1400 metres. These ideas are not yet at an advanced stage.

CURRENT SUBSURFACE STORAGE POTENTIAL IS LIMITED

Subsurface energy storage encompasses a wide range of technologies that relate to various different forms of energy and energy carriers. Although in theory the subsurface offers vast amounts of space, the practical potential is far smaller.

POSSIBILITIES FOR STORAGE PER ENERGY CARRIER

Not all types of subsurface space are suitable for the storage of all three forms of energy. Table 1 provides an overview of the possibilities.

	Natural gas	Hydrogen	CAES*	Heat	OPAC*
Cavities – salt caverns	Developed (NL)	Development planned (NL)	Development planned (NL); Developed demo (abroad)	Possibilities investigated (NL)	Unsuitable
– abandoned mines	Unsuitable	Unsuitable	Unsuitable	Developed (NL)	Conceptual
– tunnels	Developed demo (abroad)	Possibilities investigated (abroad)	Developed demo (abroad)	Conceptual	Possibilities investigated (NL)
Porous media – (depleted) gas fields	Developed (NL)	Possibilities investigated (NL)	Conceptual	Conceptual	Unsuitable
– aquifers	Developed demo (abroad)	Possibilities investigated (abroad)	Conceptual	Developed (NL)	Unsuitable

- Developed (NL)
- Developed demo (abroad)
- Development planned (NL)
- Possibilities investigated (NL)
- Possibilities investigated (abroad)
- Conceptual
- Unsuitable

Table 1*: Overview of forms of subsurface energy storage and the theoretical suitability of subsurface space. * = compressed air;*

*** = subsurface pump accumulation*

PRACTICAL POTENTIAL FOR SUBSURFACE STORAGE

The Dutch subsurface offers a huge technical potential for subsurface storage of energy (Figure 3), but the realisable potential is far smaller, in practice.

Salt caverns offer part of the volume

On a global scale, for a number of decades, salt caverns have been used for the storage of natural gas. It may be possible in the future to equip caverns to store hydrogen and compressed air. With this in mind, TNO and EBN initially evaluated the rock salt formations in the northern and eastern Netherlands (see Figure 4). In a more detailed survey, the suitability of these locations still has to be demonstrated.
This will be achieved with exploration surveys and drillings.

In theory, salt formations below the sea could also be used, but the overall practical and economic feasibility of that option requires further research. Whatever the case, offshore projects will always involve considerably higher costs than onshore projects.

The maximum space available for the creation of new caverns in the investigated salt structures that were presumed to be suitable represents the theoretical storage capacity. The study by TNO and EBN reveals that on land - in a technical sense - there is space for the creation of several hundred new salt caverns, but between 2030 and 2050, it is expected that no more than 60 caverns could be created because of practical constraints.

For a number of reasons, there is a limit to the number of caverns that can be practically realised. For example the speed with which caverns are leached: the creation of a single large cavern takes around three years. In addition, there is a limit to the number of locations that can be operated simultaneously.
Other relevant aspects are the capacity for disposal of the extracted rock salt; the spatial restrictions when it comes to creating cavern clusters, and the subsidence as a result of the creation of multiple caverns.
All these aspects together mean that a maximum hydrogen storage capacity of 15 TWh can be achieved in salt caverns in the northern and eastern Netherlands, including the conversion of salt caverns near Zuidwending and Winschoten, that are currently in use for natural gas storage (see Table 2).

	Theoretical/Technical		Practically achievable	
Gas fields (land/coast)	**Number**	**TWh**	**Number**	**TWh**
Existing natural gas storages	4	33	2-3*	16-24
Other gas fields	90	296	4	32

(Number of gas storage locations available for hydrogen depending on the demand for natural gas/green gas storage in 2050.)*

	Theoretical/Technical		Practically achievable	
Salt caverns (land)	**Number**	**TWh**	**Number**	**TWh**
Existing storage caverns	5	1	5	1
New salt caverns	160-315*	42	60	15

Table 2: *Overview of theoretically and practically achievable storage capacity for hydrogen in gas fields and salt caverns.*
(The theoretical number depends on the chosen size of the caverns.)*

Most capacity available in gas fields, but there are challenges

Between now and 2030, a large proportion of the onshore and offshore gas fields will cease production. These fields offer space for the storage of carbon dioxide and hydrogen.
The storage of hydrogen in gas fields is not yet a proven and viable technology. Against that background, a number of (international) parties are working together to remove outstanding technical issues. On land and in near-coastal sea areas, there are around 90 developed gas fields that satisfy the basic technical suitability criteria. In total this represents a theoretical estimated capacity of 296 TWh for hydrogen.

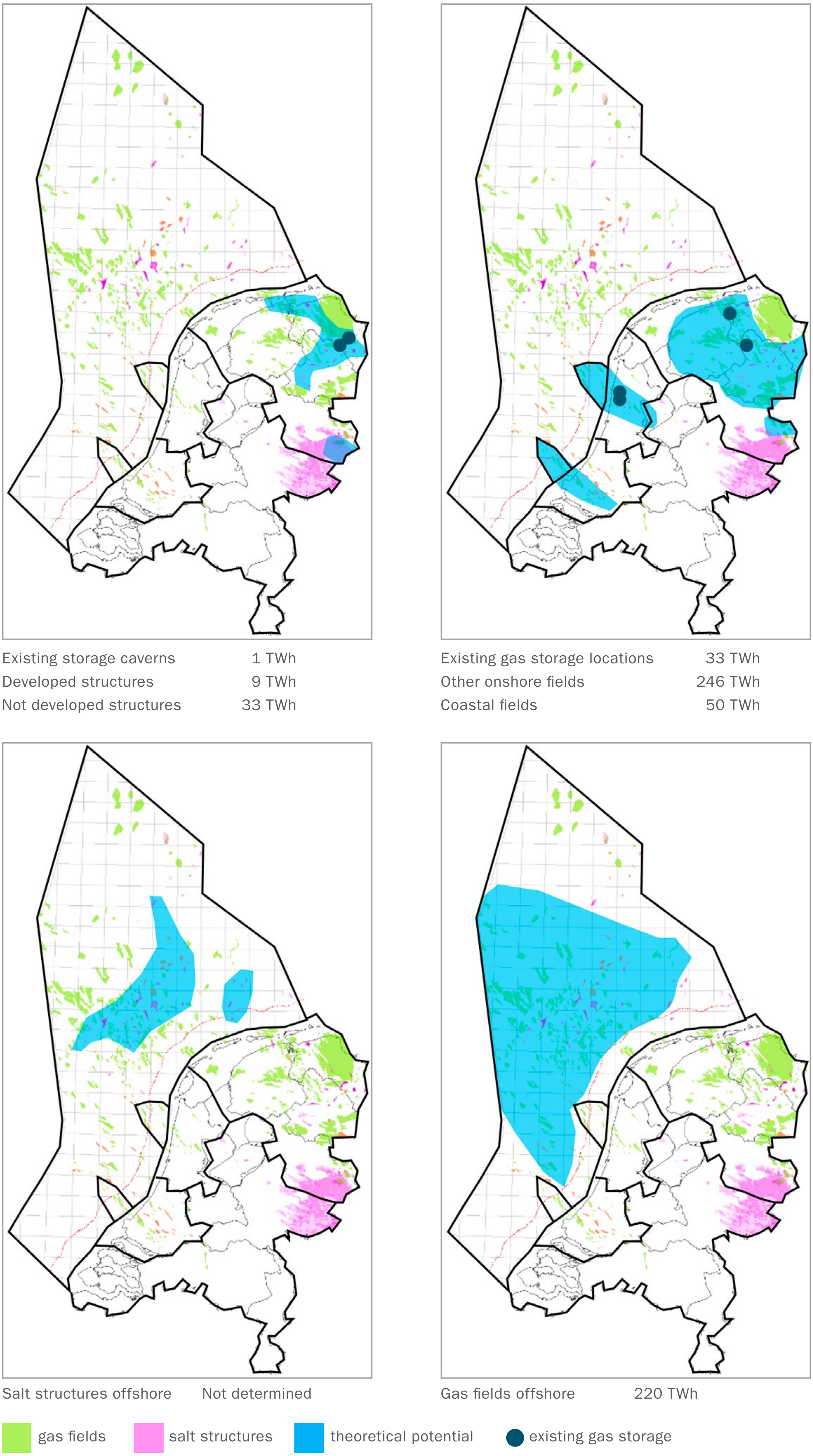

Figure 3: *Overview of areas with sites of gas fields and salt structures in which storage sites could be created. The numbers show the theoretical storage capacity of hydrogen.*

When it comes to storing hydrogen in gas fields, depending on the location there are a range of operational challenges. There is a risk of chemical and microbiological conversion (and therefore loss) of hydrogen. Reaction products or other substances could pollute the hydrogen; the flow in the reservoir could become blocked; it may prove impossible to fully retrieve all the hydrogen; or the integrity of sealing formations or the production well could be compromised. Together with international partners, TNO and EBN are involved in research work to minimise the consequences of these impacts.

In a recent study, for the period between 2030 and 2050, it is assumed that a maximum of between six and seven gas fields could be developed as hydrogen storage locations. Two or three of those fields could be existing natural gas storage sites that are converted for hydrogen. This operating principle would represent a practically achievable storage capacity of approx. 56 TWh. The actual capacity will depend on the specific gas field characteristics and applied operational criteria. It will not be possible to store hydrogen in gas fields until all the technical, policy-based and social obstacles have been overcome.

Aquifers for heat storage

At a depth between 100 and 1500 metres, the Dutch subsurface contains a series of water-bearing geological formations known as aquifers. In theory, these aquifers are suitable for the storage of high-temperature heat on the condition that they are located close to an area of 'concentrated heat demand', in this case a residential area of sufficient size.

The technology has already been demonstrated at several locations. Many of the regional aquifers have been mapped out in the framework of national geological and geohydrological mapping procedures. Local suitability will depend on subsurface factors such as the thickness of the sand layer, permeability and the presence of a top sealing layer. There are also aboveground factors: the proximity of district heat networks with renewable heat sources is essential. In addition, there must be no interfere with nature conservation areas and surface water.

The results of the WINDOW research project present the likelihood of success of the storage of high-temperature heat in a number of areas. Large parts of the western Netherlands are favourably located for the storage of hot water, with the urban areas in the Province of Zuid-Holland, such as the Rotterdam-The Hague region, standing out as particularly promising.

The development of subsurface heat storage still faces a series of barriers that will have to be removed through further study. Examples are the less favourable depth of the aquifers, the absence of a sealing rock layer, uncertainties about flow rates, faults in the rock formations and the proximity of protected groundwater areas.

Further research will have to be carried out for much of the rest of the Netherlands to obtain a clear picture of the suitability of these locations for heat storage. A small proportion of the Netherlands, in particular the area against the eastern border, appears to be unsuitable for this form of heat storage.

NEXT 10 YEARS ESSENTIAL FOR SUBSURFACE ENERGY STORAGE BEYOND 2030

In today's energy system in the Netherlands, there is as yet no urgent necessity to implement sustainable forms of subsurface energy storage: for the time being, the supply of natural gas currently available and the natural gas storage locations offer sufficient flexibility, while renewable energy carriers of the future do not yet occupy a major share of the energy system. At present we are still in the comfortable position that the balance between supply and demand can be achieved relatively simply; but that is set to change, quickly.

THE PATHWAYS EXAMINED BY TNO AND EBN PREDICT SHARP GROWTH IN HYDROGEN STORAGE

The pathways prepared by TNO and EBN predict a sharp growth in the need for storage of hydrogen beyond 2030. In addition to the volume required for balancing supply and demand, the storage capacity must also provide additional reserves to counter the risk of serious and long-term disruption to the production and import of energy. By 2050, the total additional reserves for hydrogen could amount to more than 50 TWh. In that case, in addition to a maximum of 60 new salt caverns, 5 or 6 gas fields will also be needed.

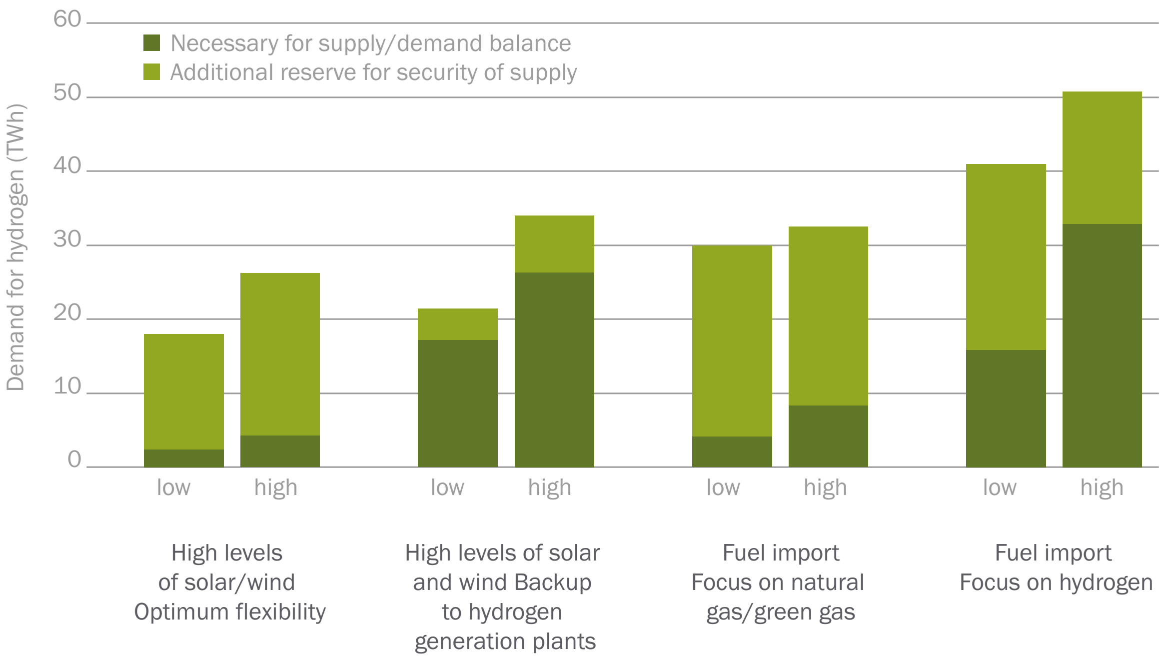

Figure 4: *Potential demand for hydrogen storage in 2050 in relation to various developments in the energy system.*

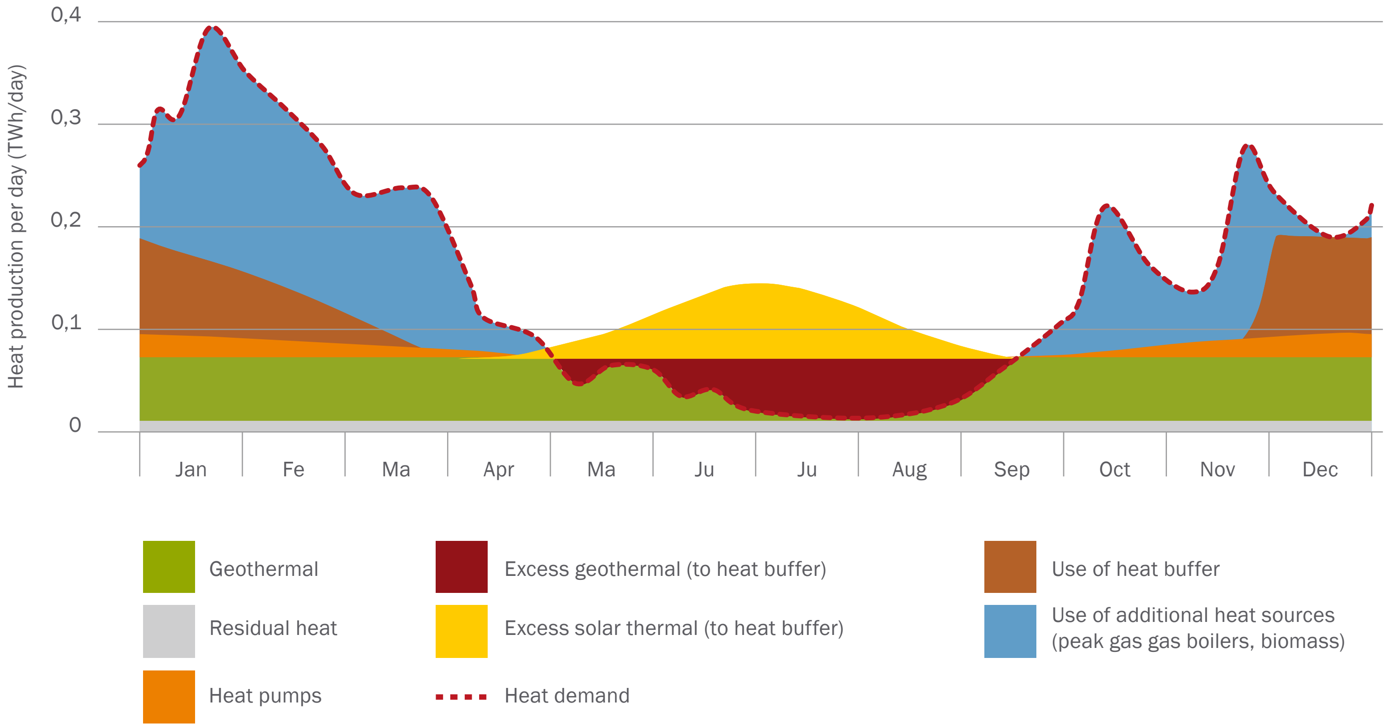

Figure 5: *Schematic showing the effect of the use of subsurface heat buffering in 2050 with renewable heat sources.*

USING RENEWABLE SOURCES MORE EFFICIENTLY WITH HEAT STORAGE

The large-scale development of high-temperature heat storage could make a major contribution to the more efficient use of renewable heat sources, thereby helping to prevent the use of other (fossil) sources. The development pathways from TNO and EBN predict 100 to 200 storage systems in aquifers within the top few hundred metres of the subsurface. This number will depend heavily on the development of district heat networks within the areas where the development of high-temperature storage is feasible.

The Dutch subsurface offers large potential for subsurface storage for hydrogen and heat.

As a general rule, much work is required before high-temperature heat storage can be seriously scaled up. Although already technically demonstrated, the technology is still very much at the start of its development curve. Given the development of district heat networks and baseload heat sources, the efficient deployment of the technology in district heat networks will need to be tested before 2030, in the form of a series of pilot projects.
In addition, the government will have to remove crucial uncertainties about the potential of the subsurface and look into how the licencing procedures can be matched with the developments. Key relevant questions include the relationship between the Mining Act and the Environment and Planning Act, spatial integration and interaction, and how to deal with projects taking place at the outer limits of application of the Mining Act.

LIMITED ROLE FOR COMPRESSED AIR ENERGY STORAGE IN SAFEGUARDING ENERGY SUPPLY

According to the latest scenarios and models, compressed air will not play a significant role in maintaining the balance in the national energy system. This technology could nevertheless be attractive for private commercial services, for example as part of regional energy strategies.

URGENT ACTION REQUIRED NOW

There are still significant technical and economic barriers to be overcome before large-scale implementation of subsurface storage of hydrogen and high-temperature heat is feasible. In addition, the development of technologies of this kind generally takes several years, up to as much as decade. For these reasons, urgent action is needed in order to successfully scale up beyond 2030, in a socially responsible and efficient manner. We therefore emphasise the importance of making the necessary preparations and tackling the challenges, before 2030.

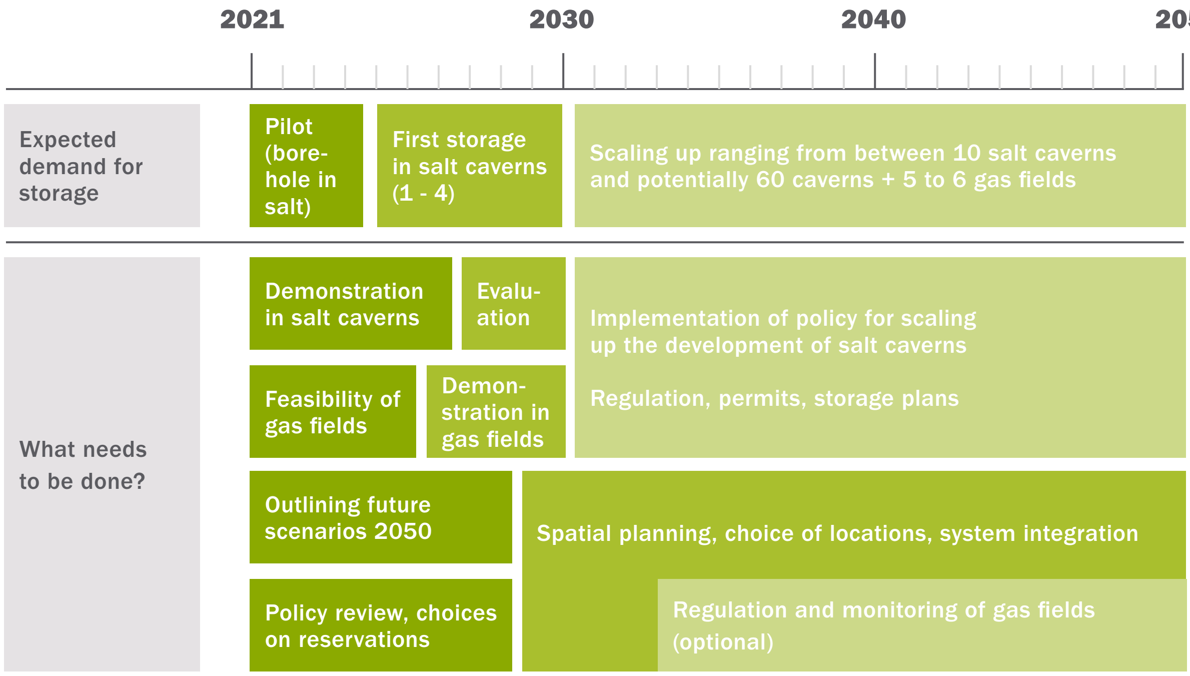

Figure 6: *Graphic representation of the timeline showing the barriers to subsurface hydrogen storage that need to be overcome.*

DEMONSTRATE THE SAFETY AND FEASIBILITY OF DEPLOYING STORAGE TECHNOLOGIES

Hydrogen

In principle, the storage of hydrogen in salt caverns is a proven technology. Further research will be needed to assess the consequences of the creation of large numbers of caverns - including the effect of long-term subsidence - and how fast-cyclic production and injection could influence the integrity of wells and the storage installation.

The technical feasibility of hydrogen storage in gas fields still has to be demonstrated. The key areas for further study are the impact of converting hydrogen, the mixing with other substances in the subsurface, the flow behaviour and the geomechanical effects on safety and the overall storage yield.

New insights from national and international research should help in drawing up improved selection criteria for technically suitable gas fields, in drafting design schedules for the creation of caverns and for formulating guidelines for efficient and safe operation, including the monitoring and mitigation of any risks.

Heat
The successful scaling up of high-temperature heat storage will depend on obtaining a sound picture of the subsurface possibilities and an estimate of the uncertainties. Both are essential for a careful assessment of the investment risks.
R&D programmes should be focused on monitoring and performance; they should also result in demonstration projects, as well as investigating the lifecycle and integrity of wells, and examining strategies for decommissioning.

DEFINE POLICY FRAMEWORKS AND THE RELATED VISION ON SUSTAINABLE ENERGY STORAGE

Hydrogen
Over the coming years, growing numbers of gas fields will become eligible for decommissioning. Our recommendation in deciding on gas field decommissioning is to also consider the possibilities of hydrogen storage. In particular this applies to existing natural gas storage locations that could help accelerate the development of hydrogen storage, for example proven solid performance and the presence of aboveground facilities, including connections to the gas grid. In selecting new locations for salt extraction, the design could be geared to potential future storage. Strategic choices of this kind require additional policy in order to reserve space so that it remains available for the development of storage facilities.

In addition to the possibilities for storage on land, we must also consider the feasibility of offshore storage. This could offer further solutions for the storage challenge.

The preparation and development of storage locations is a complex and long-term process, involving numerous licencing procedures and interaction with local communities and stakeholders. The Netherlands needs to acquire experience in order to establish an effective decision making process. This in turn requires a shared knowledge base for all parties and clarity on the various roles and elements in licencing procedures and decision making processes.

Heat

At present, high-temperature heat storage still enjoys only ‘pilot status’. Regulations will have to be introduced to provide continuity (investment security) and to allow scaling up. It is also important to harmonise licencing requirements according to the Water Act and the Mining Act. Experts will have to define design standards and safety standards for the construction and operation of high-temperature heat storage.

The use of high-temperature heat storage offers excellent possibilities if a number of conditions are met.

- Presence of district heat networks with the appropriate heat sources.
- Seasonal demand for heating, for example in urban areas.
- Favourable subsurface conditions.
- There must be no interference with other uses of the subsurface (for example groundwater extraction).
- Balancing of social interests (participation by local government and citizens).

EXAMINE VIABLE BUSINESS CASES

Hydrogen

Alternative income will be needed in order to make the investments in flexible hydrogen production with subsurface storage in a salt cavern economically viable. Results from this and previous studies show that large-scale energy storage can offer essential services to society: strategic energy reserves and security of supply. At present, the system value - in other words the increased flexibility for security of supply - is not sufficiently accounted for in the market value of a hydrogen storage system. As a consequence, businesses are simply not able to generate sufficient income to operate a system of this kind. Value stacking of different sources of income in order to arrive at a viable business case will be essential to the implementation of large-scale hydrogen storage without major financial interventions by government. The parties responsible for implementing energy storage projects can create value by still being able to deliver energy in the event of large-scale disruptions to imports or in extreme weather conditions.

Heat

Any party with plans to implement high-temperature heat storage will be partly dependent for its financial needs on the success of previous projects.

Policy instruments can also make a contribution, for example extending the RNES guarantee scheme for heat storage, or making it possible to apply for grants via the SDE++ fund for sustainable initiatives. Finally, it is important for developers, service providers and knowledge carriers to develop a full (value) chain to ensure that projects are well received and integrated.

CHOOSE AN ENERGY SCENARIO

In the period after 2030, the various energy scenarios diverge widely. This fact has a huge influence on the scale and nature of energy storage in general, and hydrogen storage in particular. In order to be able to develop the necessary storage capacity on time, by 2030, the direction in which the energy system is set to develop will have to be made far clearer. Although the year 2030 seems a long way away, right now we must achieve greater clarity for future energy scenarios or we will be too late. As a result, we will either not meet the emission targets or we will be faced with an unreliable energy system. The worst-case scenario would be a cold winter with no heating.

Against that background, it is essential that we urgently establish a clear picture of the potential (forms of) supply and demand for hydrogen. It is also important to clarify the extent to which our country needs to establish additional hydrogen reserves for those years in which the output from wind and solar energy is disappointing, or if imports become disrupted.

GATHERING SUPPORT

When making choices and decisions on possible locations it is advisable to involve the public and local authorities as early as possible. Investigating perceptions, utilising local knowledge and creating awareness and understanding of the possibilities and impossibilities can make a major contribution to the balancing of national, regional and local interests.

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