hystories
Hydrogen Storage in European Subsurface

Opportunities in Europe for geological storage of hydrogen in depleted hydrocarbon fields and saline aquifers

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Clean Hydrogen Partnership

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Revision History

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0	06 September 2023	Initial published version – Final v19 internal working version

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Name	Institute	Date
Helen TAYLOR	CO_2GeoNet-BGS	11 August 2023

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1. Introduction

The Hydrogen Storage in European Subsurface (Hystories) project addresses the main technical feasibility questions for underground storage of pure hydrogen in aquifers or depleted hydrocarbon fields, and will provide market, societal and environmental insights on the deployment of underground storage of hydrogen in Europe.

Work Package (WP) 1 generated a comprehensive, cross-border, database of potential opportunities for geological storage of hydrogen in porous media reservoirs (depleted oil and gas fields, aquifers, and existing natural gas storage sites). The purpose of the database is to highlight locations that may be suitable for development for the geological storage of hydrogen from a geological perspective across Europe (Figure 1).

The extensive data, on potential stores for hydrogen, which has been collated and stored in the Hystories relational database represents significant new knowledge and this database will enable more accurate assessments of the potential future for green hydrogen storage in Europe.

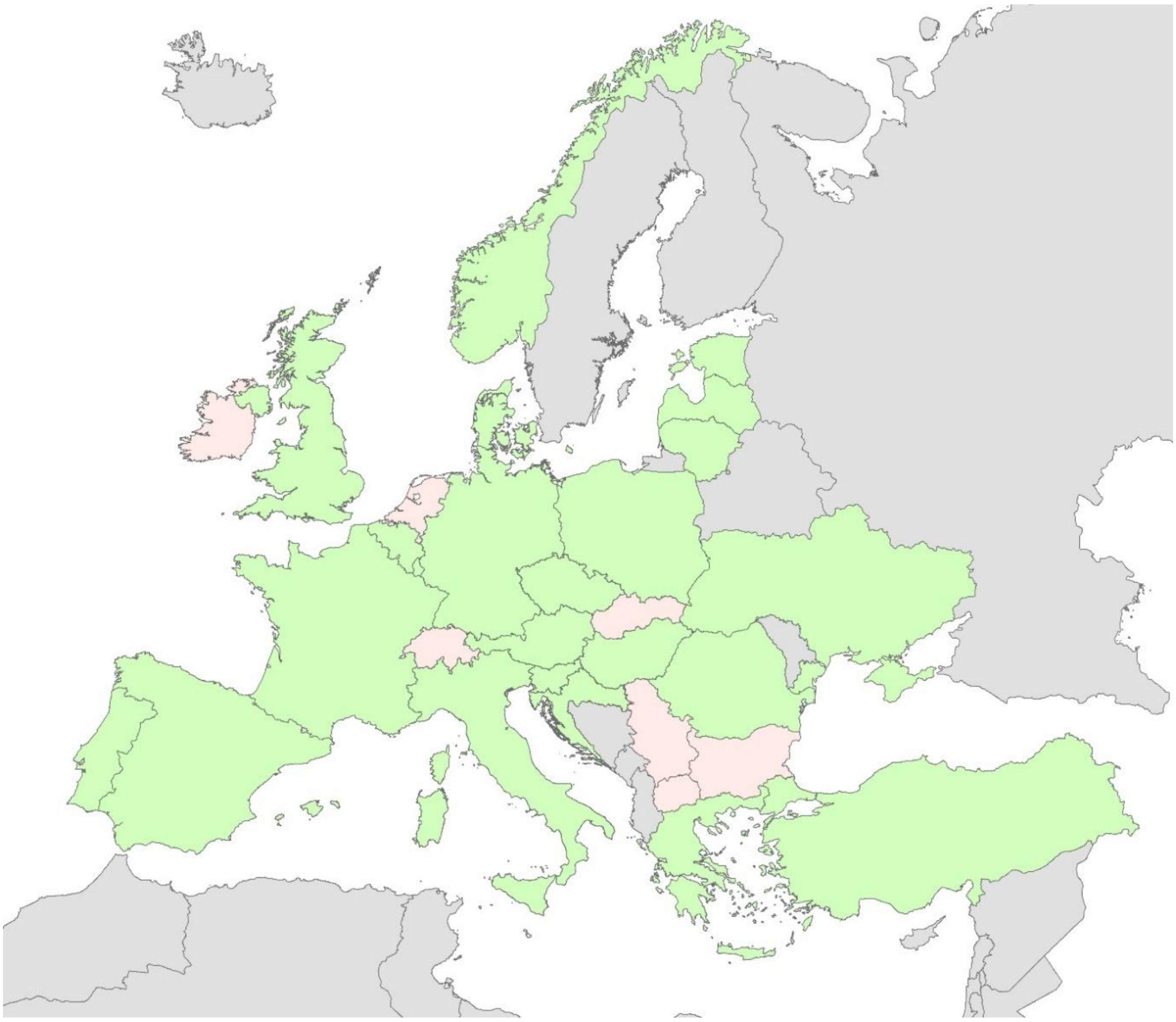


Figure 1: Hystories country coverage. Green indicates countries covered by Hystories, pink represents countries where data were included from the previous CO_2Stop project, grey represents countries not included in the project.

Table 1: Hystories partners and Third Parties collating data. Countries in blue are covered by in-country experts, countries in orange are covered by experts from adjacent countries

Country	Hystories partner/Third Party
Austria	GeoSphere Austria (Austrian Geological Survey)
Belgium	Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium (RBINS-GSB)
Croatia	University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (UNIZG-RGNF)
Czech Republic	Czech Geological Survey (CGS)
Denmark	Geological Survey of Denmark and Greenland (GEUS)
Estonia	Tallinn University of Technology, Department of Geology (TalTech-DG)
France	Bureau de Recherches Géologiques et Minières (BRGM)
Germany	Deutsches GeoForschungsZentrum (GFZ)
Greece	Centre for Research and Technology Hellas (CERTH)
Hungary	GeoSphere Austria
Italy	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS)
Latvia	TalTech-DG
Lithuania	TalTech-DG
Luxembourg	RBINS-GSB
Norway	Norway – Norwegian Research Center AS (NORCE)
Poland	Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS) Central Mining Institute (Główny Instytut Górnictwa GIG)
Portugal	Institute of Earth Sciences (ICT) as represented by University of Evora (Evora)
Romania	Institutul National de Cercetare – Dezvoltare pentru Geologie si Geoecologie Marina (GeoEcoMar)
Slovenia	Geološke raziskave in drugo svetovanje supporting UNIZG-RGNF
Spain	Instituto Geológico y Minero de España (IGME)
Turkey	Middle East Technical University – Petroleum Research Center (METU-PAL)
Ukraine	Geothermal Ukraine
United Kingdom	UK Research and Innovation as represented by British Geological Survey (BGS)

2. The Hystories database and Geographical Information System (GIS)

Data that is linked to geographical location, also known as geodata, is a key component in enhancing stakeholder ability to make informed decisions across a wide variety of scientific and social disciplines. Having access to data and the knowledge on how to process, manage and manipulate this geodata will have a wide-ranging impact on the capacity for strategic decision making. Collecting, processing, and storing this data in a consistent and managed way is critical to ensuring the data can add value to existing data sets, thereby enabling its use in providing solutions to everyday problems, as well as inputting into policy making.

The power of Geographical Information Systems (GIS) is in enabling users to analyse and interpret data, to study relationships and patterns. This is of fundamental benefit when interrogating data for use across a variety of remits. Geographical Information Systems can be used to compile, process, manipulate and deliver data. To enable the power of GIS to be fully realised, it is essential to have accessible data stored in a well-structured, machine-readable database that can be input to the GIS.

The database fed into Hystories WP2 (reservoir engineering, including geochemistry) and WP3 (microbial reactions) as well as modelling of the European energy system (WP5) and ranking and assessment of the techno-economic feasibility of storing hydrogen (WP7). Outside of Hystories, this database could be used to help inform strategic decisions at European/national scale for decarbonisation using the subsurface.

2.1. Database attribute selection

The Hystories database advances the level of knowledge for hydrogen storage in Europe by collating geodata on potential storage sites. Particular attention was focused on supporting the assessment of the geochemical and microbiological impacts of hydrogen storage. These criteria were defined in Hystories Deliverable D1.1, which considers the current state of storage assessment for the geological storage of natural gas in porous media.

The database builds on previous projects such as the Energy Storage Mapping and Planning (ESTMAP, 2015) and CO_2 Storage Potential in Europe (CO_2StoP[1], 2013). The data from these projects were reviewed and revised, as needed, to provide the base data for the Hystories project, additional. newly available data from reports, scientific papers and other reputable sources has also been captured to offer the latest information on potential stores in Europe.

Through a series of meetings and workshops it was agreed that the database would consider current best practice for geological natural gas storage with the addition of parameters considered most relevant to hydrogen storage, based on the expected geochemical or biological response of the subsurface. These attributes were highlighted in Hystories D1.1

[1] The CO_2StoP database is available through the EGDI platform http://www.europe-geology.eu/map-viewer/

'Definition of Selection Criteria for a Hydrogen Storage Site in Depleted Fields or Aquifers'. A workshop was also held during January 2021 to consider which data would be needed to support capacity estimation, ranking of storage sites, and techno-economic modelling for the Hystories sites in other WP's. Hystories D1.1 summarises screening criteria based on experience from natural gas storage worldwide.

During the database design phase, discussions were held with all Hystories Work Package teams to establish user requirements in relation to database structure, data attribution and the database front-end (data entry forms), therefore ensuring the potential for inclusion of all relevant, publicly available, storage site data.

The database contains a broad range of data including basic geological characteristics relevant when considering other uses of the subsurface such as natural gas storage, CO_2 storage, and deep geothermal potential. This will maximise the usefulness of the database.

Collated data for potential porous media hydrogen stores includes basic storage formation and petrophysical data (e.g., depth, thickness, porosity, permeability, lithology and net-to-gross, reservoir pressure, temperature, salinity of pore water) as well as publicly available geochemical data. Data on possible leakage pathways, that could make a site unsuitable or less attractive for storage or mean it requires remedial action, were included i.e., geological faults, wells, and other possible pathways for vertical or lateral migration. It is important to note that since only publicly available data were used, there are regions where storage potential could not be identified owing to a lack of data, so an absence of identified storage potential does not always mean an absence of potential.

It was also decided that the database should include stores that may be excluded by parameters in D1.1 (e.g., depth to top structure), if national geological experts deem these stores to have the potential to securely store hydrogen (WP1 workshop, January 2021). Thus, the database will provide a more complete picture and enable other Hystories work packages to analyse additional data and consider, through experimentation and techno-economic modelling, whether these stores may be needed to meet demands for hydrogen storage in Europe. The main criteria discussed at the January 2021 workshop are shown in Table 2.

Depleted hydrocarbon fields were considered for this study as they have a caprock that is proven to trap buoyant fluids over geological timescales. However, it should be noted that there is some uncertainty over the reactions of hydrogen with the native pore fluids. The containment ability of these stores, over geological timescales, was proven for the specific fossil fuel types at pre-development (initial) pressure conditions and the caprock must be re-evaluated in terms of its ability to trap hydrogen which has different properties to oil and gas. Legacy wells must also be evaluated and potentially recompleted, prior to hydrogen storage at any given site, to ensure secure storage.

Saline aquifers offer a large potential storage resource. However, there are generally fewer data to assess their potential for storage as most have not been assessed for their ability to store buoyant fluids. The ability of the caprock to trap buoyant fluids over geological timescales has to be assumed based on available data, laboratory experiments and/or the adjacent areas where the same caprock traps hydrocarbons. The lack of legacy wells offers the opportunity to drill new wells specifically designed and completed for storage.

During the WP1 workshop in January 2021, it was proposed to focus on the sites which were considered to have the fewer barriers to develop as a storage site. Discussions also took place in relation to how to prioritise research i.e., whether to focus on depleted or depleting gas fields and then aquifer closures. The final decision on prioritising data to add to the Hystories database, and on deciding if a store could be suitable for storage based on geological/geographical aspects, lay with the in-country partner.

Data collected by WP1 was used in WP2 of the Hystories project to estimate storage potential for each trap. The outcomes of experiments assessing the geomicrobiological implications of native fluids and minerals which could impact on storage efficiency, combined with data from WP1, were used to screen potential storage sites in WP7.

Table 2: Additional criteria to D1.1, included following discussion at the dedicated database workshop, January 2021

Potential Screening Criteria	Limit	Comment
Depth	250 – 5000 m to be reported if the national geological experts feel these are acceptable (superseding 500 – 3000 m limits indicated in D1.1)	1000 m storage is best practice but in the UK there are natural gas stores at ~350 m Below 2000 m porosity/permeability is expected to be unfavourable, but have stored at ~5km **Decided to use 250 m as minimum depth following discussions (D1.1 proposes 500 m as minimum depth)**
Location	**Not used as screening criteria**	Germany has gas stores under cities and in the UK there is gas storage under a wetland nature reserve, France under a regional nature park. So this may not be a constant in terms of screening. distance from potential users was also discarded as a screening criterion to avoid discarding opportunities too early – for example offshore hydrogen hubs could be part of a hydrogen future.
Composition of rocks/fluid	Very limited practical experience so **not using as screening criteria**	Risk of losing hydrogen - thickness of regional seal is important. Want to avoid unfavourable rock/fluids - but Hystories will investigate the impacts of rock/fluid composition and very limited practical experience at this point, so can't really use as screening criteria
Size	No common criteria	As a starting point - for Traps database, interested in traps/closures of similar size to gas storage in that country.

2.2. Data model for the database

The Hystories database was developed to allow for the input of geological data and its display in a Geographical Information Systems (GIS). The data model for the database was designed such that it can accommodate data at three levels of granularity: formation, storage units (within those formations) and traps (hydrocarbon or aquifer traps). The tables containing the data for each of these levels of detail are linked together through database relationships enabling a one-to-many relational database structure (Figure 2). A unique identifier for each entry (row) in the database is automatically created as data is entered. The identifier is then passed down to the next level of the data structure as a foreign key, enabling the relationship between the data in the tables to be maintained. The relational nature of the database means that to populate the traps table, the formation and unit tables must also be populated. When attribute data that are common to all three data tables are included, the user only enters the data once and it is automatically entered into all three tables.

The database contains the high-level geological formations, identified within each country, that may have the potential for hydrogen storage. Within those formations lie one or more storage units (areas within the formation) where hydrogen could be stored. Within these storage units lie one or more traps, which represent geological closures, that could be considered for storage of hydrogen. If insufficient data are available to identify traps, data entry can stop at formation or storage unit level. Figure 2 shows this relational database structure. The database allows the addition of information for each formation, storage unit and trap to build as complete a picture as possible of the potential for hydrogen storage within each of the Hystories countries. Note that an absence of identified stores does not necessarily mean an absence of storage potential but reflects an absence of data to enable confident identification of potential stores. The database structure (data model) allows further geological detail to be added as the user progresses through data entry, with the ability to include far more detailed geological information for the traps than for the formations, which only include high-level geological and geographical data.

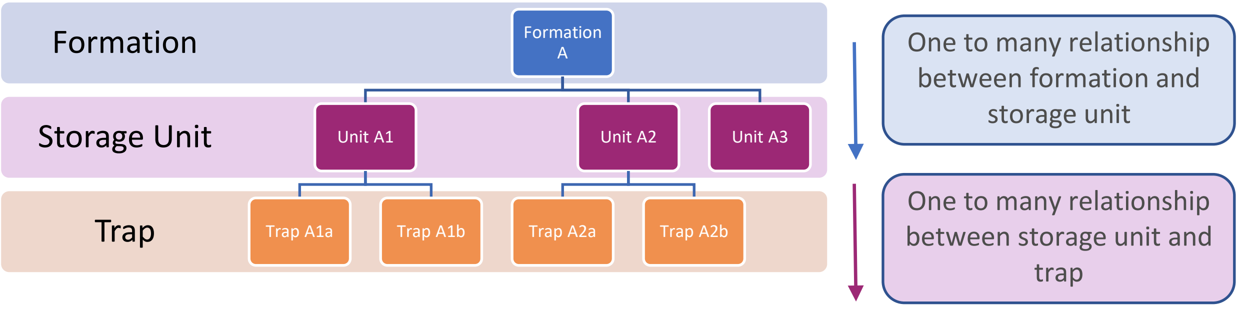


Figure 2: Relational database

To allow the data in the database to be comparable across all sites and countries, and to facilitate searching, analysis and interpretation of the data, data entry into some of the data fields was constrained by dictionaries, enabling users to choose from a drop-down list of pre-defined options. Whilst this is a key benefit for the useability of the final data, removing the risk of incompatible entries or typographical errors, this did not always allow researchers populating the database to fully detail all characteristics of a potential storage site. To address this a free-text field was included to allow researchers to add additional detail and to ensure extra data/complexities were also recorded in the database. The value of being able to compare and search the database to obtain a European overview was considered high and therefore some loss of granularity, in the specific data fields, was an acceptable compromise.

The database was designed following discussions with all Hystories work packages that will rely on the database to ensure inclusion of relevant storage site data, where such data are available in the public domain. Collated data for potential porous media hydrogen stores include basic reservoir and petrophysical data (e.g. depth, area, thickness, porosity, permeability, lithology and net-to-gross, reservoir pressure, temperature, salinity of pore water) as well as geochemical data where available in the public domain.

In relation to data for depth to reservoir, it was decided to record two separate depths; median/average depth of the reservoir across its extent and the depth to the top of the reservoir. The median/average depth was recorded for CO_2StoP and is adopted as it enables modelling of reservoir behaviour. The decision to include the depth to top of the reservoir in addition to the median depth was based on its value in risk assessments and the depth to the crest of a hydrocarbon field is often published in the public domain.

2.3. Data Entry

The data entry system consists of a series of custom-built forms designed to guide the user through the entry of complex data, required by the project, into the database. The database was developed in Microsoft Access 2019 to facilitate delivery of standalone databases to all the partners across the project. Additionally, standard Microsoft Access tools enabled the export of data to alternative data formats (e.g., Microsoft Excel). The design of the data entry forms built on previous experience from the CO_2StoP project.

Once the entire system (database and data entry system) was developed it was populated with data from the CO_2StoP project, since this was the baseline data the Hystories project would build on. Each country partner was then provided with a standalone database containing the existing data specific to their country. Partners were responsible for checking and amending/updating existing data and adding new data that has become available since the CO_2StoP project was completed, or for adding storage sites that became relevant for hydrogen storage. Databases were then returned, quality checked and merged centrally to create the final database covering the entire geographical area of the Hystories project.

2.3.1. Overview of data entry form

To facilitate data entry into the relational structure of the database, the forms guide the user through the formation-storage unit-trap hierarchy. Data entry begins by selecting an existing, or creating a new, geological formation in the database. Once the geological formation data was entered, users can then select or add storage units falling within it, and then once storage units have been entered data for traps in the storage unit could be entered. To check / amend existing data, users could use these same data entry forms to navigate through the data in the database, with the user selecting a geological formation to check and the forms populating all relevant storage and trap data associated to that formation (Figure 3).

To help with data entry and maintain the integrity of the data, some attributes were auto-populated including the unique (primary) identifiers (which were then used through all levels of the database) and the country (based on the selection made by the user on opening the database). Automatic counts of aquifer and hydrocarbon traps were also put in place to assist users in checking their data. To further ensure useability of the data entry forms, data entry for attributes that were constrained by dictionaries (described earlier) happens through selection from a drop-down list.

The *storage unit* and *storage trap* sections of the database have multiple tabs to allow entry of more detailed data.

The data fields included in the *storage formation*, *unit* and *trap* tables are shown in Appendix 1.

2.3.2. Database formations

The interface for adding data on *geological formations* is shown in Figure 3. This collects high-level data on geological formations present within national boundaries that have favourable reservoir properties and could offer potential storage sites.

2.3.3. Database storage units

The interface for adding *storage unit* data is shown in Figure 3. Storage units indicate regions of interest, where there is identified potential for storage, e.g., a hydrocarbon province. This may also capture areas where there are insufficient or restricted data, but it is deemed reasonable to anticipate the presence of storage potential. Data on storage units include name, location coordinates, areal extent, issues with use of the subsurface, basic reservoir parameters such as lithology and porosity, seal data such as lithology and thickness, information on potential leakage pathways such as wells and faults, and whether data for more detailed assessments, such as well and seismic data, are present.

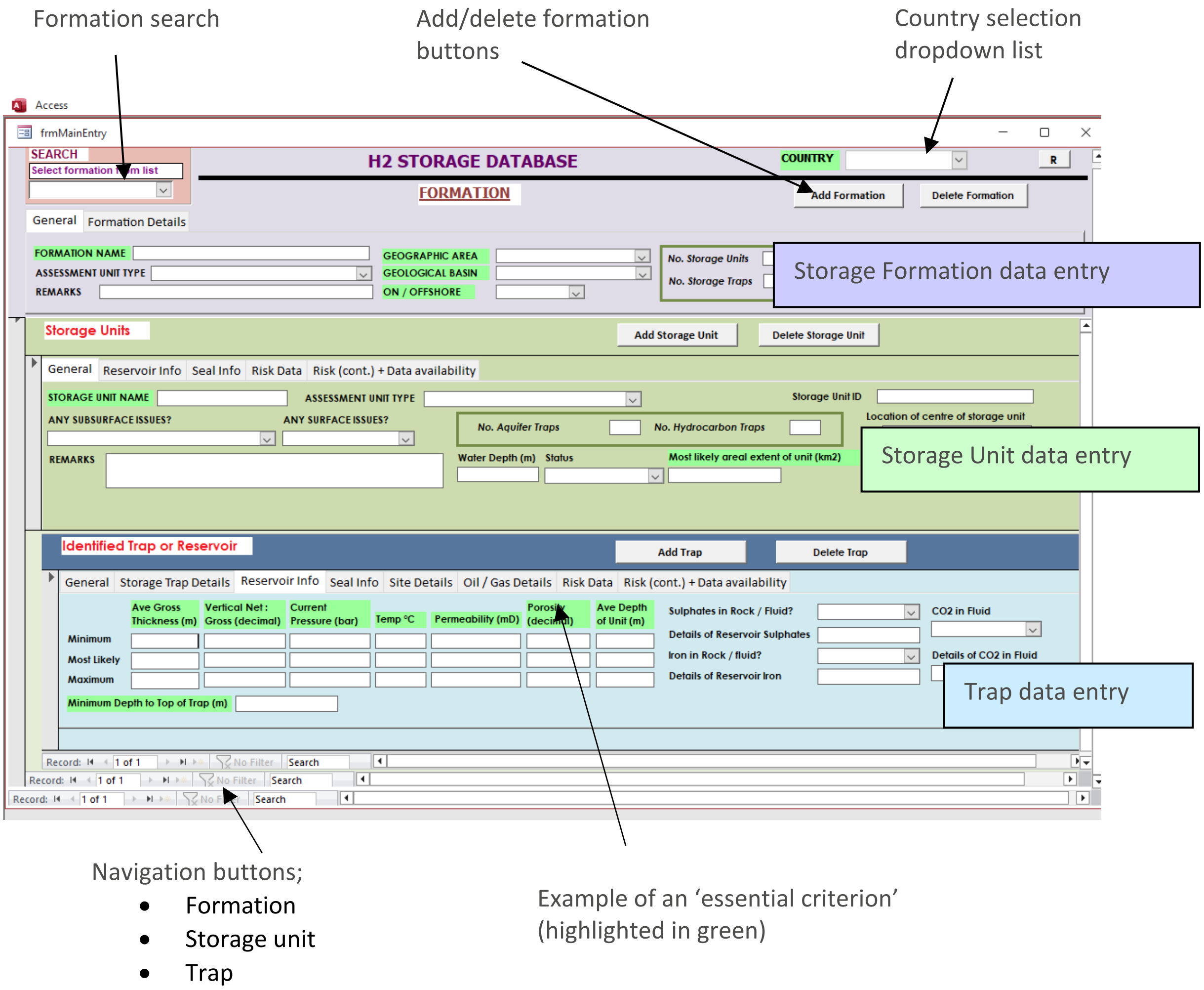


Figure 3: Data entry interface for project partners to populate the Hystories WP1 database

2.3.4. Database storage traps

The *trap* section of the database allows more detailed information to be entered on the aquifer or hydrocarbon field trap that is within the storage unit. There are many tabs on the *traps* form to input general information on the individual trap including its type (saline aquifer/hydrocarbon field), reservoir information, seal information, details about the site, risk of unwanted migration out of the trap, and the availability of advanced data (e.g., seismic, core) for the trap.

The *General* tab (Figure 4) allows the entry of overview information about the storage trap including the name of the trap, type (hydrocarbon field or aquifer), conflicts of interest with planned or existing surface or subsurface use (e.g., for natural gas storage, or in a national park). The *trap ID* field is a unique identifier generated and populated automatically by the database.

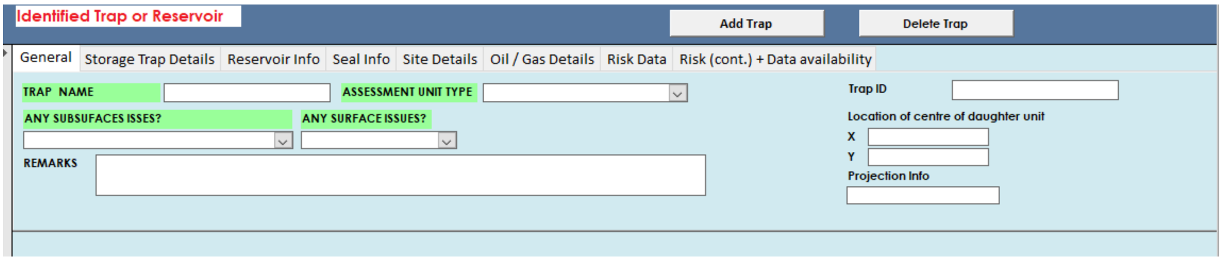


Figure 4: Trap section of the database; general information tab.

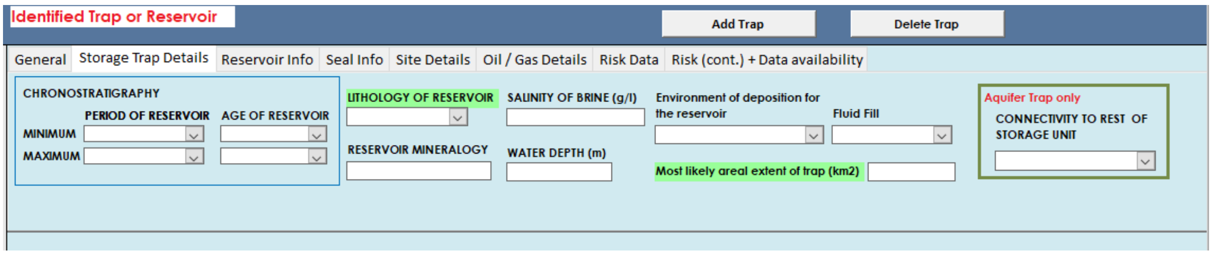


Figure 5: Trap section of the database; additional site details tab

The *Storage Trap Details* tab (Figure 5) collects basic information on the chronostratigraphy and lithology of the storage reservoir, areal extent, water depth (e.g. sea or lake depth), and fluid fill (saline water, oil, gas etc). Lithology is a drop-down list, to ensure consistency of data entry, across all the partner countries, for this data field.

The *Identified Trap or Reservoir* tab (Figure 6) contains basic reservoir parameters such as average gross thickness of the trap, pressure, temperature, porosity and permeability. Many of these data are classed as essential (green highlight). Criteria were classed essential where they were identified in WP2 as being needed to undertake capacity calculations, or where these parameters would strongly influence decisions on developing a potential storage site. Parameters relevant to hydrogen storage such as details on sulphates, iron or CO_2 already present in the trap can be added here.

Under the *Seal info* tab (Figure 7) more information such as lithology and chronostratigraphy and minimum thickness of the geological seal rocks can be added. Information on the current use of the site (e.g., hydrocarbon production) or planned use of the site (e.g., natural gas storage) can be added in the *Site info* tab (Figure 8). For sites which are hydrocarbon traps, data on production and properties of the in-situ fluids can also be added on the *Oil/Gas Details* tab (Figure 9).

Information on geological risks to the site seal (faulting), possibility for lateral migration of fluids and wells can be added into the *Risk* and *Risk(cont.) + data availability* tabs (Figure 10).

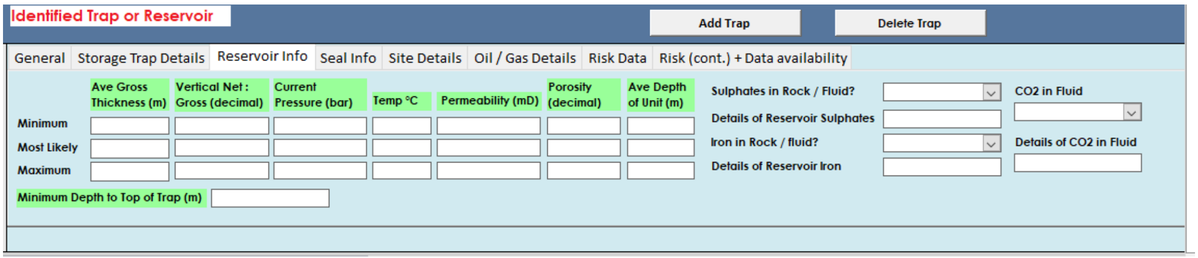


Figure 6: Trap section of the database; reservoir information tab.

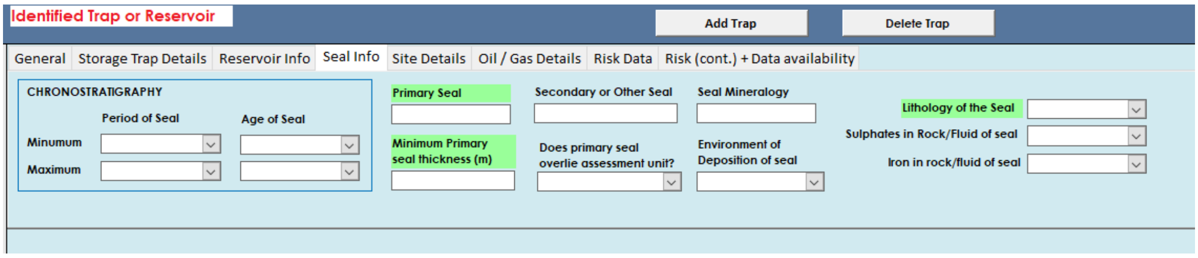


Figure 7: Trap section of the database; seal information tab.

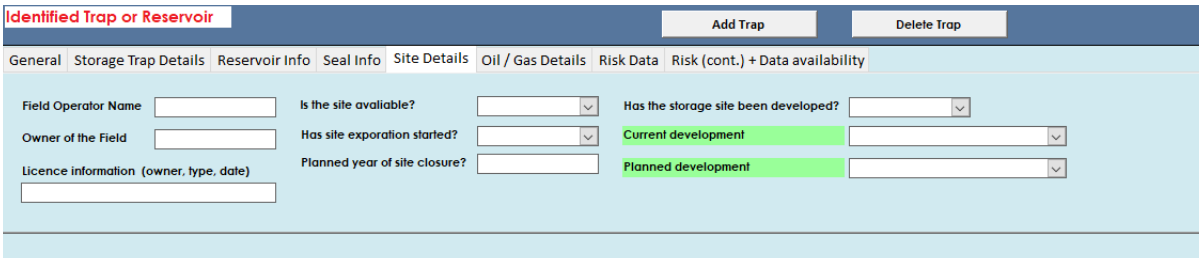


Figure 8: Trap section of the database; site information tab.

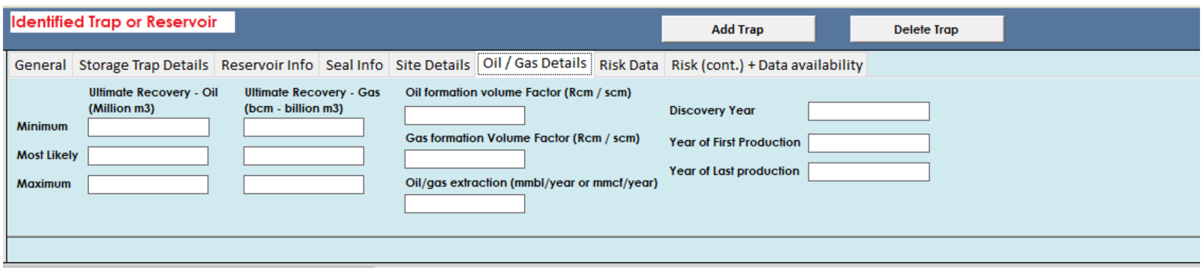


Figure 9: Trap section of the database; oil/gas details tab.

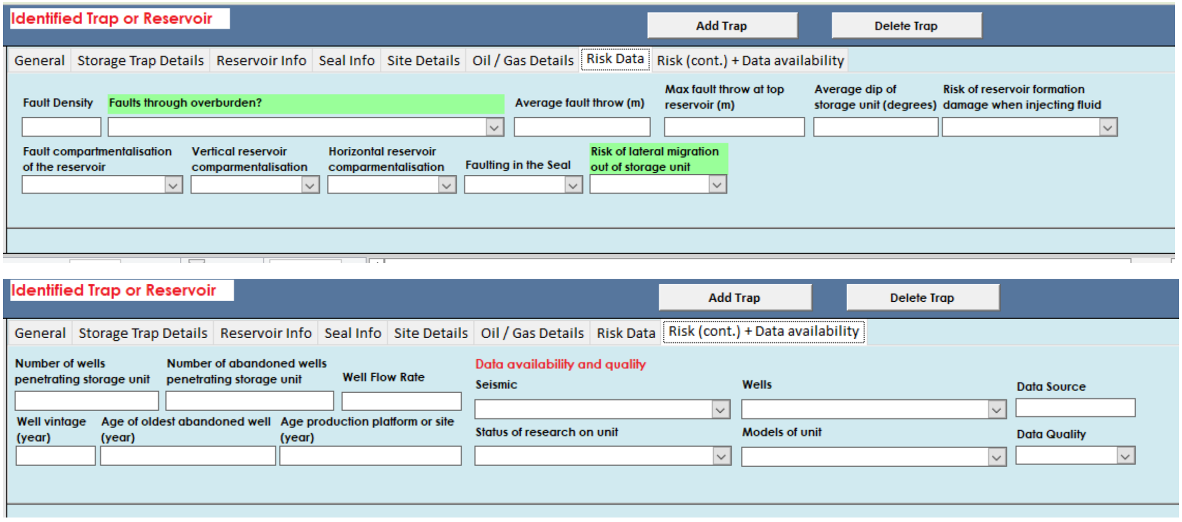


Figure 10: Trap section of the database; risk and data availability tabs.

2.3.5. Evolution of ideas during data collection

Natural gas storage sites: In some countries, natural gas storage sites are present. In discussion with WP2 (online workshop, January 2022) it was agreed that where the deliverable gas quantity was present in the Underground Gas Storage (UGS) database for Europe[2] or otherwise in the public domain, this would be used for WP2 storage capacity assessments in preference to the public domain reservoir data being collected in WP1.

This also raised an additional interesting point on how to classify saline aquifers being used for natural gas storage since there are only two categories in the database dropdown list: hydrocarbon trap and aquifer trap. It was decided these would be categorised as saline aquifer stores in the database with 'gas storage' indicated in both the comments and reservoir fluid attribute fields.

Depleted gas fields used for UGS were indicated as 'gas fields' in the database, with gas indicated as the reservoir fluid.

Structures that were drilled for hydrocarbon exploration and deemed 'dry' are indicated as 'saline aquifers' in the database, with saline water indicated as the fluid fill.

Essential criteria for modelling the storage capacity: During database population, WP1 remained in consultation with WP2 to ensure data to support capacity calculations were provided wherever possible. The essential criteria identified were:

- Area
- Thickness
- Porosity
- Depth

[2] https://www.gie.eu/transparency/databases/storage-database/ [accessed 30/06/23]

During this ongoing collaboration with WP2, the following criteria were identified as useful for the capacity calculation. It was decided that where these data were not available, assumptions would be made on their value, along with an assumed uncertainty in the capacity estimate (see parentheses in list below):

- Permeability (assume 100 mD if not provided)
- Salinity (assume 100 g/L if not provided)
- Pressure (assume hydrostatic gradient 0.1 bar/m, uncertainty +/-10% if not provided)
- Temperature (assume 0.03°C/m, uncertainty +/- 10% if not provided)
- Net to gross (assume 80%, uncertainty +/- 10% if not provided)

These assumptions are not included in the database and solely used in the capacity calculation in WP.

2.3.6. Database quality check and merge

During population of the database, there were two rounds of data checking to confirm the integrity of the data and ensure that as much data had been entered as possible. This data check was carried out against the formation, unit and trap data submitted by each WP1 party with the aim being to confirm that the 'essential criteria' in the database had been populated and that auto generated information had been correctly assigned (e.g. Unique ID's). This was not a quality check of the data itself, but instead a confirmation that the database fields had been populated. Gaps remain in the database where access to data is restricted or where data are not available.

As an example of the process, the data check report for traps contained the following information:

- Blank entries: *yes/no*
- All traps have unique identifier: *yes/no*
- Trap Names assigned: *yes/no*
- X & Y coordinates present: *yes/no*
- Projection details for X & Ys provided: *yes/no*
- Location check: Does data plot in correct country: *yes/no*
- Does number of traps match the sum total number of traps for each storage unit: *yes/no*
- Mandatory data populated?: *yes/no for each parameter* (Trap name; Assessment unit type; Subsurface issues?; Surface issues?; Lithology of reservoir; Most likely areal extent of unit (km^2); Ave Gross Thickness (m); Vertical Net/Gross (decimal); Current Pressure (bar); Temp °C; Permeability (mD); Porosity (decimal); Ave Depth of Unit (m); Minimum Depth to Top of Trap (m); Primary Seal; Minimum Primary seal thickness (m); Lithology of Seal; Current development; Planned development; Faults through overburden?; Risk of lateral migration out of storage unit.)

The data check report was sent back to each partner to highlight any issues that were identified and to see if additional data could be retrieved, and the database updated.

Once the data checks were complete, the Microsoft Access databases from the Hystories WP1 partners were merged into a unified Hystories database containing all identified storage formations, units and traps.

Since not all European countries are represented in Hystories, it was decided to incorporate data from the CO_2StoP database where data attributes directly overlap. An additional attribute was added to the database to indicate if the data were from Hystories or CO_2StoP, to keep track of when data were last reviewed.

2.3.7. Database limitations

A few key limitations are presented here.

The database only contains publicly available data: The database represents the latest information available in the public domain. Data collection agents and requirements for release vary between countries. Some data are held as commercial in confidence and were therefore not included in the Hystories database. The database indicates where data exist but are not available to allow database users to distinguish regions where no data have been collected but storage potential might be available.

Variable presentation of data and data collection bias: In some cases, data varied in available quality, quantity, and presentation. As an example, in some potential stores, a range for average porosity was given rather than minimum and maximum values. In addition, since much of the data are collected during exploration for hydrocarbons, porosity data are often biased towards the most promising sections of the reservoir.

Geological interpretation: There will always be some variability in geological interpretation, depending on expert opinion and the available data. For example, where data are not available, one researcher might feel more confident in predicting the expected conditions for a store, where another might leave these data fields blank.

2.4. Data visualisation using a Geographical Information System

To enhance the useability of data collected during the project it was proposed that it be visualised in a map format (geographical information system, GIS) since this offers a visual and easy to navigate option to access the data. The objective of the Hystories GIS is to incorporate the Hystories polygon data for the formations, storage units and traps alongside the Hystories project data stored in the database. This will provide meaningful access to the Hystories project data in a spatial format and to enable query and analysis of the data. Two versions of the GIS were produced during the Hystories project: a webGIS (publicly accessible) and desktop GIS (held by the partners). Both versions offer access to the same data, but the ability to query, analyse and manipulate the data is only possible in the desktop version of the system.

Calculated storage capacities were contributed by Hystories WP2 for all traps where sufficient data were available. This is included in the database as a separate table on the basis that the geological parameters are considered raw data, and the estimated capacity is an interpretation/derivation of these data.

The Hystories webGIS and desktop GIS contains 311 formations, 581 units and 917 traps collated by the Hystories team. The inclusion of data from the CO_2StoP project (for countries not assessed by Hystories) resulted in the final webGIS contains 381 formations, 665 storage units and 1088 traps. There are some data in the Hystories database that cannot be displayed in the GIS because the location or polygons for the traps are confidential. The calculated capacities provided by WP2 are included in the webGIS for each identified trap where sufficient data were available to calculate this value.

2.4.1. GIS-specific data and data collation

The primary data included in the GIS are the three-level hierarchy of geological formations, storage units and traps. These data are held in the GIS as polygons that define their location and area. The GIS polygons represent:

- Reservoir formations (geological formations with reservoir properties)
- Storage units (parts of reservoir formations suitable for hydrogen storage)
- Traps (hydrocarbon fields and mapped traps in aquifers)

Only polygons which are in the public domain are included.

The GIS polygons are relationally linked to the Hystories database. This means that as a user clicks on a formation polygon, they will also be able to view the related data for the storage unit and the traps within that formation. The same method has been applied to the storage units where data for the associated traps are accessible when analysing the storage unit. The GIS also contains base-map data (country base-map, cities and major towns, median lines) to allow the user to locate themselves geographically. Thus, in addition to populating the database, partners were asked to provide polygons that show the areal extent and location of the geological formations, units and traps within the database. These polygons are linked to the formations, units and traps in the database via the formation, storage unit and trap IDs.

Data associated with each polygon is as follows:

- Name: name of the formation/storage unit/trap – this should match the name entered in the database for the corresponding database entry
- Remarks: this can be used to enter any additional information about the polygon.
- Country: the name of the country that the polygon belongs to, e.g. Austria
- Country Code: the country code for the country the polygon belongs to e.g. AT
- ID: the identifier from the database of the formation or storage unit or trap that the polygon represents.

When populating the database, understanding the relationship between the data and the polygons is important. For example, two polygons can link to a single database entry since the same formation/unit/trap ID can be given to multiple polygons. However, one polygon cannot link to two entries in the database; only one formation/unit/trap ID can be given to the polygon, so it can't be linked to two formations/units/traps. Additional polygons could be added, or traps could be split as appropriate. This means that if there are multiple horizons that are producing within one hydrocarbon field, then data can only be entered for one of these horizons, and the database populators will have to decide which is the main horizon with potential for hydrogen storage. Alternatively, two polygons which overlap could be used, depending on the approach deemed most appropriate by the Hystories geological experts.

A data check was carried out to confirm that the polygons contained the essential data listed above. The data check also confirmed that the polygons appeared within the country boundaries.

In addition to the database polygons, other information added to the GIS to help the user locate and screen storage potential includes:

- Salt deposits – Hystories has obtained agreement from SMRI to use the salt shapefile from SMRI research report Horvath et al. (2018)
- Location of towns/cities
- Topographic data (Publicly available base datasets can be used)

2.4.2. GIS development

The Hystories desktop GIS (Figure 11) has been developed using ESRI® ArcGIS 10.8 software. Data has been stored in ESRI file geodatabases and Access databases and linked into ArcGIS. To facilitate the use of the data in other GIS software the data has also be stored in a GeoPackage format for delivery to Hystories Partners. This will enable partners who have other GIS software to create their own version of the Hystories GIS. The WebGIS also allows partners who do not have access to GIS software to view the data.

The webGIS (Figure 12) has been developed using the ESRI® ArcGIS Dashboard and is compatible with most web browsers such as Chrome, Firefox and Edge. This dashboard is available on the Hystories website. The purpose behind developing the online webGIS as well as the desktop GIS was to ensure that the data could easily be shared on the Hystories website to enable better external (to the project) accessibility to the data and results and facilitate knowledge exchange with external stakeholders.

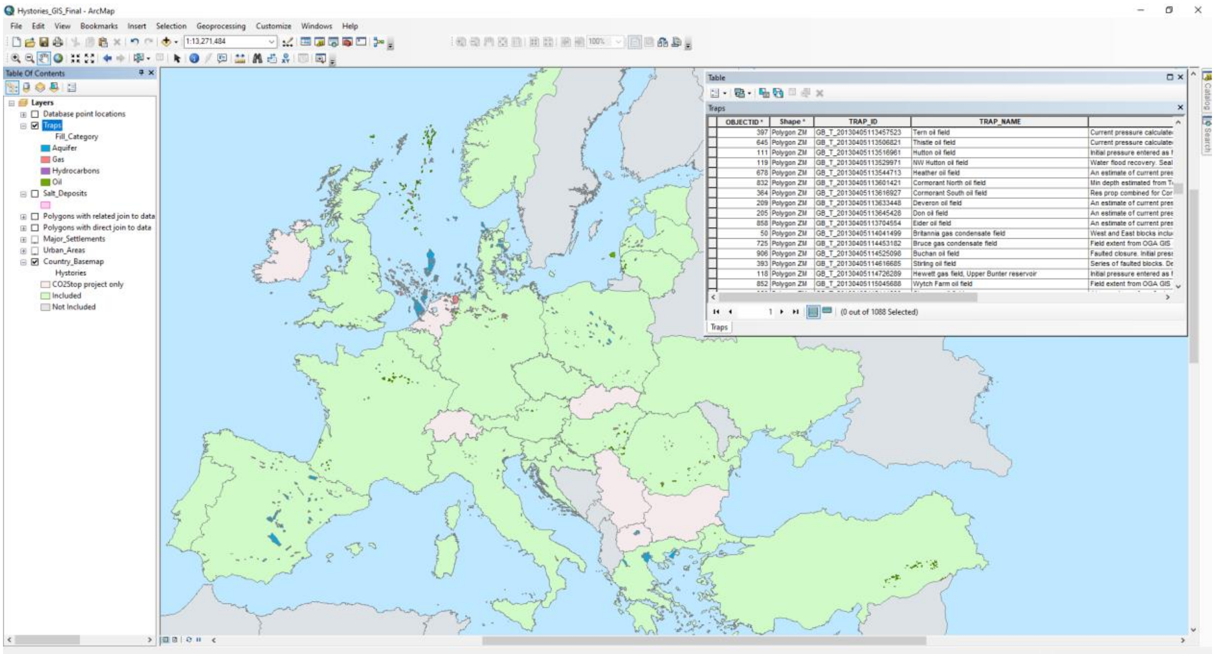


Figure 11: Screenshot of the Hystories desktop GIS showing the traps table

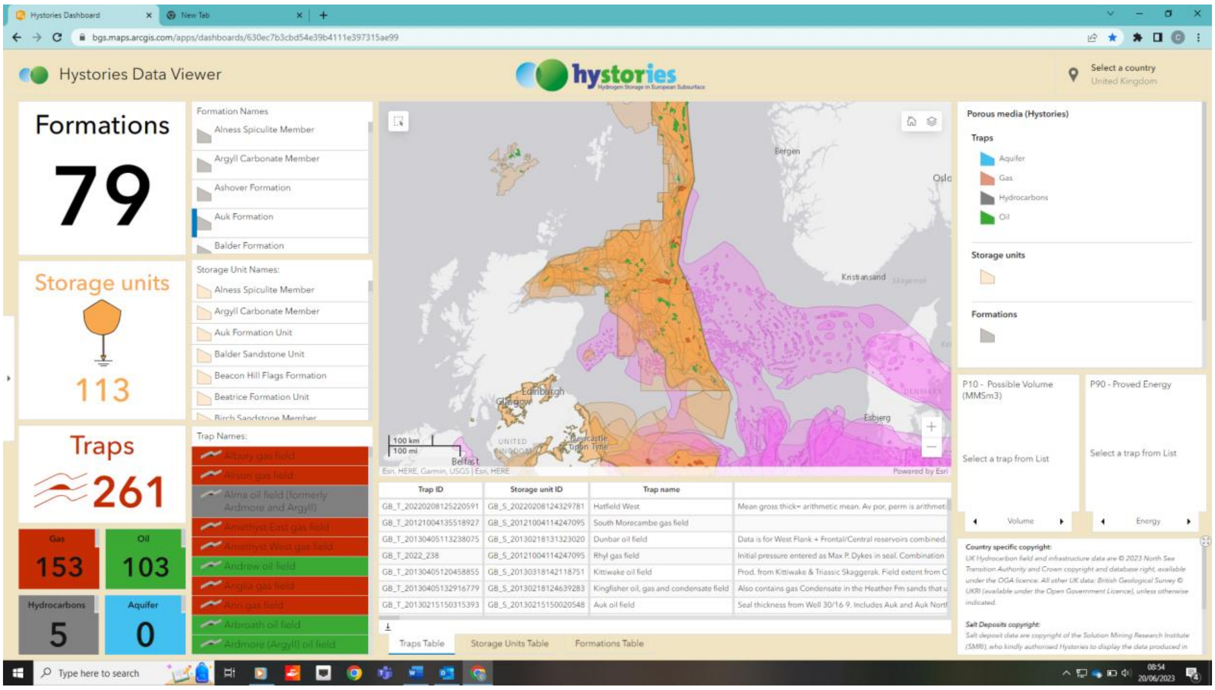


Figure 12: Screenshot of the Hystories webGIS.

2.4.3. Data display, search, accessibility and re-use

Geographical Information Systems offer a visually attractive portal to access Hystories data in a meaningful and effective way. The database has been linked to the online webGIS and desktop GIS. This allows the user to visualise the data, carry out geographical searches on the database and understand the data in a more spatial context. The desktop GIS can also facilitate additional analysis of the data using standard GIS tools.

The webGIS allows the user to select the country of interest. Potential storage formations, units and traps for that country are then displayed. It is possible to select all countries to display all polygons/locatable traps. The traps have been coloured by fluid fill, including ‘hydrocarbons’ where the trap contains a mix of oil or gas, or for CO_2StoP traps where fluid fill was not confirmed. Storage capacity for traps calculated by WP2 has been added (Figure 13). The aim is that the data should be finable, accessible, interoperable and reusable. There are some traps in the database that could not be displayed because the location data are confidential or not available.

The webGIS contains a statement about the Hystories project, and a brief explanation of how the data were collected (Figure 14). This statement also highlights that the database contains only publicly available data, and that the absence of identified storage potential does not necessarily indicate an absence of opportunity, since sometimes data do not exist or are restricted. The webGIS also indicates that data can be re-used, but that the data owner and Hystories project must be acknowledged. The data copyright statements were agreed by all Hystories partners. As each country is selected, the copyright statement for that country is displayed. Partners from CO_2StoP were contacted and asked to confirm the copyright statement was correct, or to provide an updated version. A copy of the data copyright statements is given in Appendix 2.

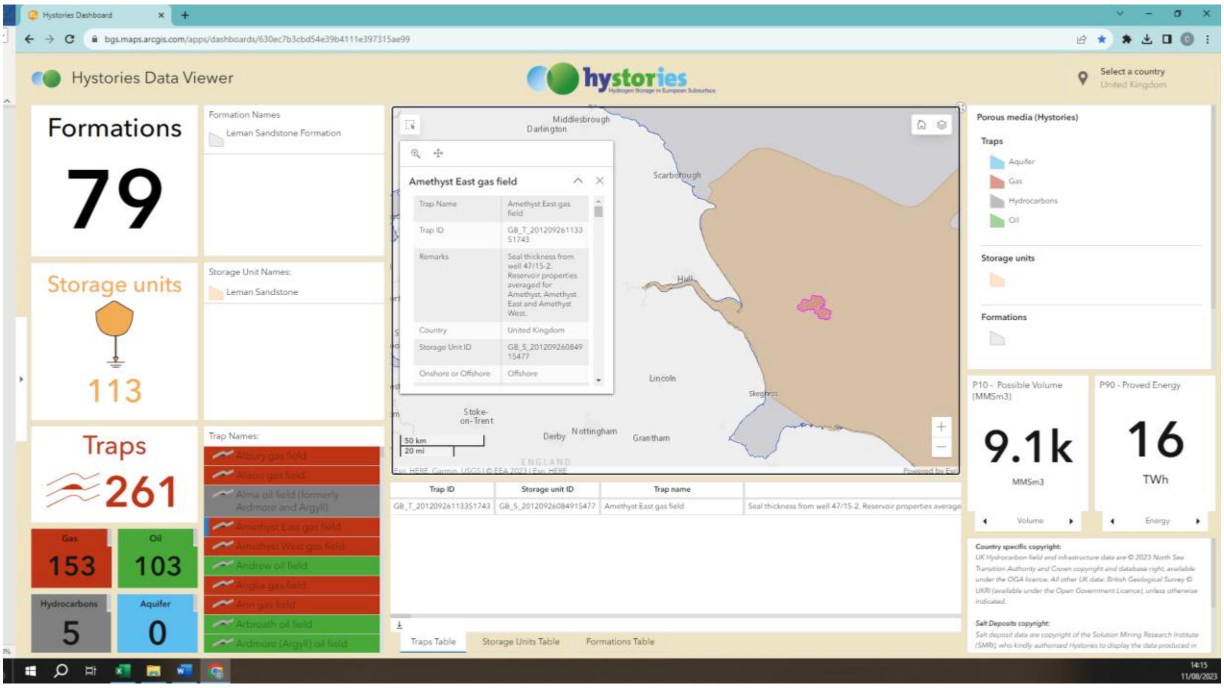


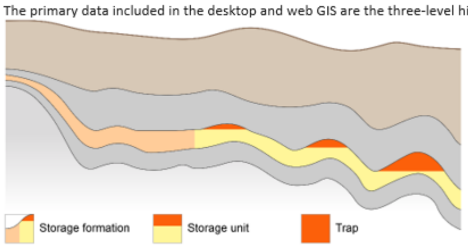
Figure 13: WebGIS showing data for one trap, including estimated hydrogen storage capacity. Salt shapefile layer has been hidden to make searching for porous media traps easier.

About Hystories

The Hydrogen Storage in European Subsurface (Hystories) project addresses the main technical feasibility questions for subsurface storage of green hydrogen as an enabler to help meet climate targets. The main deliverable from workpackage 1 was a unified database collating available geological data on reservoir and seal characteristics for depleted hydrocarbon fields and saline aquifers to support strategic decision making. The database is accessed via this GIS to highlight regions and sites that may be suitable for development into storage sites for hydrogen, from a geological perspective. This GIS only displays data available in the public domain and therefore the absence of identified storage potential does not necessarily indicate an absence of opportunity.

The Hystories database

The primary data included in the desktop and web GIS are the three-level hierarchy of storage used by the Hystories database:



- Storage formations (rock bodies which may have suitable reservoir properties)
- Storage units (parts of the storage formations which have promising reservoir properties)
- Storage traps (parts of storage units that should locally contain hydrogen; hydrocarbon fields or mapped geological closures)

Data is added in the following order to the database; first a storage formation is added, then the storage units that fall within that formation. Storage traps, which fall within each storage unit are then added, where data are available.

Reference and copyright: Reuse of Hystories data is authorised, provided that the "Hystories" project is acknowledged, and the copyright of data are acknowledged as per the statements for each country.

External data: SMRI has kindly allowed display of their salt deposits layer. These data remain the property of SMRI and cannot be reused under the Hystories data reuse statement. Coastline data © EEA 2021

Capacity estimation data: Porous media trap capacity estimates are based on GIE Storage database published on 14/07/2021 for existing natural gas storages or are Hystories' own estimation derived from collated geological data for other porous traps. Computation details are given in Hystories report D2.2-1_3D multi-realisation simulations for fluid flow and mixing issues, please refer to this report for methodological details.

Acknowledgements: This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007176. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

co-funded by the European Union

Clean Hydrogen Partnership

Figure 14: Hystories introductory statement and brief explanation of the database displayed in the left sidebar of the webGIS.

2.4.4. Evolution of ideas during GIS population

As data are not uniformly available, discussions were held within the Hystories team on how best to present data where polygons could not be provided. It was decided that, where no coordinates could be provided, a list of formations, units and traps would be presented when a country was selected, but no point would be indicated on the map to avoid misconceptions on storage locations. Where a polygon could not be provided, but a centre point was given for a unit or trap, a small circle was added to the map.

Another issue was the large number of attributes in the Hystories database, particularly in the *Traps* table. There were concerns that the data presentation would be slow for online access. However, in practice, since there are many instances where data were not available, the data could be hosted successfully via ArcGIS Online.

It was agreed that the traps would be coloured by fluid fill type to make it easier for webGIS users to understand the balance of storage availability in each country.

2.5. Benefits of the Hystories database and GIS

The Hystories database and GIS allow users to access geological data and data on identified sites that could be further investigated with a view to developing hydrogen storage projects.

The database contains geological data, but also data on plans for site development, operators and the availability of data to undertake more detailed studies. The list of the identified traps is by no means exhaustive as data access is restricted and only publicly available data was used for the Hystories project. Nevertheless, this database offers useful insights into the most promising storage structures for hydrogen, based on data which is currently publicly available.

Visualising the data in a GIS allows decision makers to identify areas where there are multiple possible stores, to support strategic decision making. The GIS will also allow project developers to identify possible sites for further investigation.

The webGIS and the availability of the shapefiles share results of the Hystories project with external stakeholders. This will assist in assessing where there is potential for geological storage of hydrogen and where infrastructure, including transport corridors, may develop. This information, alongside the outcomes of the Hystories techno-economic modelling and screening exercise, can help inform strategic decisions on the availability of green hydrogen to support efforts to meet climate targets.

The desktop GIS allows more extensive interrogation of the data. Hystories participants who have access to ESRI® GIS software can open the Hystories GIS. Users with other GIS software brands can load in the shapefiles which can be downloaded from the webGIS. The shapefiles have been made available via the Hystories website so external partners can also use the data within the terms of the Hystories copyright statement.

3. Overview of data collated during Hystories

Geological and geochemical data were collected from publicly available sources and collated by participating geological experts into the Hystories database from many sources including published papers, national databases, and data repositories.

The CO_2StoP and ESTMAP databases offered a starting point for many countries. Hydrocarbon exploration also usually offered a wealth of data. Basic data such as field location or depth were often available. National atlases of CO_2 storage opportunities were available in some countries and provided additional information (e.g. UK, Norway, Spain).

Data availability was variable across Europe and for different storage types. Overall, the Hystories database contains 311 formations, 581 storage units and 965 traps (Table 3). With the addition of the CO_2StoP data to infill countries not covered by Hystories participants, the database then contained 386 formations, 665 storage units, and 1136 traps. The CO_2StoP data from countries not assessed during the Hystories project were given a quality check but have not been verified or updated by the Hystories project.

All countries assessed by the Hystories project, except for Estonia, were able to identify formations and storage units for potential hydrogen storage. In some instances, it was not possible to identify structural closures (traps) that could store hydrogen, but the identification of potential storage areas (formations and units) identifies that there are regions for further investigation. Data is sometimes confidential or has not yet been collected and an absence of identified traps in Hystories does not always indicate an absence of storage potential.

Data availability is variable across the countries involved in the Hystories project. Different countries have differing data availability in the public domain, and this has restricted the population of the database in some areas. A review is included in Table 4. Summary maps which show data availability for each country are shown in Figure 15 and Figure 16.

Basic reservoir data were usually available. More detailed storage formation data were less likely to be available (Table 4). Publications often don't provide as much information on the seal as on the reservoir. The database allowed entry of minimum, average and maximum values for parameters to try to capture geological heterogeneity within each potential storage opportunity. Data on the seal was included where available, and potential traps where the seal seemed unlikely to contain buoyant fluids were excluded from the database. Geological faults and wells were indicated in the database where data were available since these could offer potential migration pathways if not sufficiently managed. It is worth noting that there are often fewer data on the seal since hydrocarbon exploration tends to focus data collection on the reservoir.

The database provides the ability to input a very wide range of available data to build a complete picture of the potential storage location. However, given that not all data will be available, some key attributes were highlighted for the partners to focus their data capture efforts. The database was completed using publicly available data and gaps exist since some data remain confidential. In addition, some of the required data have not been collected in areas where seismic data has not been collected and wells have not been drilled.

Table 3: Identified geological formations, units and traps in the Hystories database (please note that aquifer traps used for gas storage are included in the 'aquifer trap' column) and depleted gas fields used for gas storage are listed in the 'hydrocarbon field traps' column. Not all data in the database can be displayed in the webGIS since locations are not always public domain, the numbers in this table represent the database

Country	Formations	Units	Traps (All)	Aquifer Traps	Hydrocarbon Field Traps
Austria	4	8	30	0	30
Belgium	9	7	3	3	0
Croatia	8	20	26	5	21
Czech Republic	3	25	6	1	5
Denmark	5	6	14	14	0
Estonia	0	0	0	0	0
France	5	5	48	10	38
Germany	25	25	75	24	51
Greece	6	5	10	7	3
Hungary	4	20	27	0	27
Italy	49	66	26	0	26
Latvia	1	1	18	18	0
Lithuania	1	1	15	3	12
Luxembourg	2	1	0	0	0
Norway	9	9	11	3	8
Poland	14	16	102	38	64
Portugal	2	5	0	0	0
Romania	12	13	41	4	37
Slovenia	8	17	21	17	4
Spain	43	99	89	89	0
Turkey	14	94	94	0	94
Ukraine	8	25	48	3	45
UK	79	113	261	0	261
Hystories TOTALS	**311**	**581**	**965**	**239**	**726**
Bulgaria	8	11	1	0	1
Ireland	3	9	2	1	1
Republic of North Macedonia	3	3	17	17	0
The Netherlands	18	18	147	5	142
Serbia and Montenegro	2	2	0	0	0
Slovakia	37	37	4	0	4
Switzerland	4	4	0	0	0
Hystories + CO_2StoP TOTALS	**386**	**665**	**1136**	**262**	**874**

There are a few additional points to note in terms of national data availability and the number of storage opportunities shown in Table 3: Estonia could not define any formations that would be suitable for hydrogen storage. The UK has a database of potential 'traps' for CO_2 storage including both aquifer structural closures and hydrocarbon fields. The raw data were not available to include in the Hystories database for commercial reasons. However, basic reservoir data can be downloaded from the CO_2Stored website for research purposes, to consider aquifer storage potential in the UK sector of the North Sea. For Ukraine, owing to the ongoing national situation, locations of the traps were considered confidential and could not be shared with the Hystories project at this time.

Table 4: Data availability as a percentage, for the Hystories 'traps' (null replies such as 'unknown' have been ignored for the purpose of the calculation. Traps from CO_2StoP have been excluded on the basis that several of the Hystories data fields were not included in the CO_2StoP database.

Data availability	Database fields considered	Hydrocarbon 'traps'	Aquifer 'traps'
Basic site data	Operator, owner, license, current development surface/subsurface interference, status, water depth	71	46
Additional site data	Planned development, availability, exploration for storage started, storage developed	48	54
Basic reservoir data	Geological period & age, lithology, thickness, porosity, permeability, average depth, minimum depth, areal extent, fluid fill	67	79
Additional reservoir data	Environment of deposition, pressure & temperature, net-to-gross, average dip of formations, brine salinity, susceptibility of damage during injection, lateral connectivity, risk of lateral migration, compartmentalisation	37	51
Reservoir geochemical data	Mineralogy, presence and details of CO_2, sulphides/sulphates and iron	27	18
Oil and gas data, well data	Ultimately recoverable reserves, oil formation volume factor/gas expansion factor, discovery year, start/end of production, number and age of wells, abandoned wells, age of platform, well flow rate, annual production	30	21
Basic seal data	Geological period & age, lithology, thickness, seal overlies whole formation	53	77
Additional seal data	Environment of deposition, additional seals	29	48
Seal geochemical data	Mineralogy, presence of sulphides/ sulphates and iron	19	32
Geological fault data	Fault density, faults in seal, displacement vs seal thickness, fault throw	21	17
Detailed geological/ geophysical data and models	Have seismic and well data been collected? Rock cores? Geophysical logs? Geological models done? Data quality	29	70

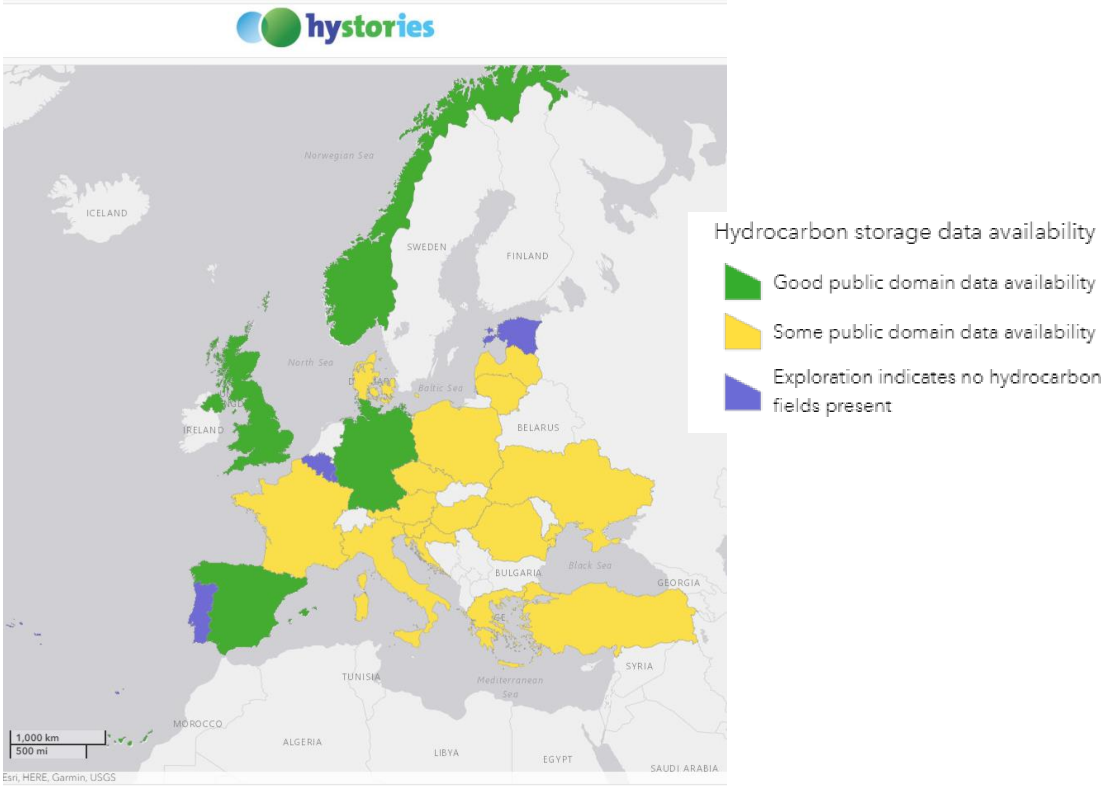


Figure 15: [Online map](#) of data availability for identifying hydrocarbon storage sites.

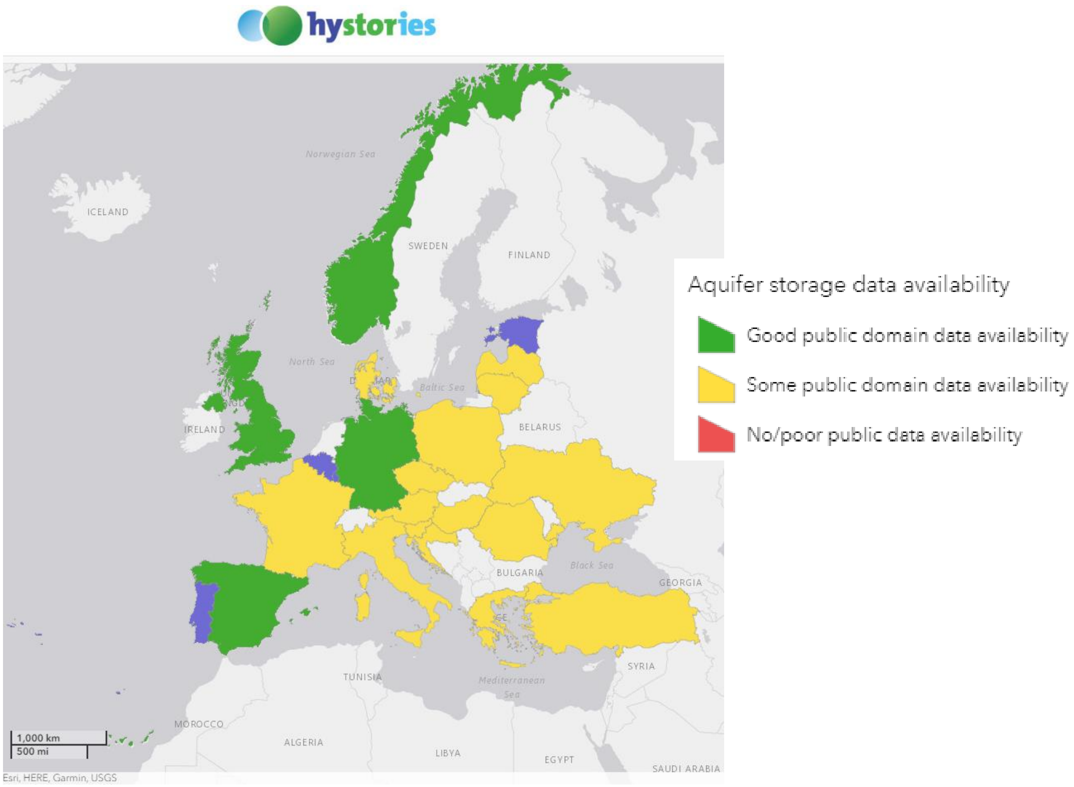


Figure 16: [Online map](#) of data availability for identifying aquifer storage sites

Seismic and well data are made available in most countries but, commonly, access was restricted to some degree. A summary of data used by the Hystories project, and of availability of detailed data for future site studies, is given in Table 5.

Table 5: Summary of data used for Hystories project and availability of detailed data

Country	Hydrocarbons exploited	Basic data - main data sources	Detailed data – main source
Austria	Yes	Basic geological data from national geological survey but usually only made available after field has been abandoned. CO_2StoP, ESTMAP, published literature	Detailed seismic and borehole data are not automatically made publicly available. Data belongs to the storage or field operators.
Belgium	No	CO_2StoP, national CO_2 storage projects	Absence of seismic data largely prevented the identification of potential trap structures
Croatia	Yes	CO_2StoP, ESTMAP, published literature	2D seismic data has been acquired in hydrocarbon-rich areas and is available for purchase. The Croatian Hydrocarbon Agency (CHA) makes data available for research under a confidentiality agreement. 2D seismic data in the Adriatic offshore and the SW corner of the Pannonian basin are available through CHA. All exploration wells are available from CHA and can be used for research. Only 3D data that are in the most hydrocarbon-rich areas with a number of active exploitation fields are still restricted.
Czech Republic	Yes	Publications. Published data on this topic are often generalised and simplified. National geological survey holds data. CO_2StoP and ESTMAP.	More recently acquired data, seismic data and well data, are often confidential and thus not available in the archives.
Denmark	Yes, offshore only	National assessment of the Danish CO_2 storage potential and the geothermal GIS-portal.	Detailed data about oil and gas fields are owned by the operators and their partners.
Estonia	No	storage sites are not available as aquifers are too shallow	Detailed data about oil and gas fields are owned by the operators and their partners
France	Yes	Information was collected from the French ministry in charge of mines, published literature. CO_2StoP and ESTMAP	All oil exploration data older than 10 years can be requested from the French Ministry in charge of mines http://www.minergies.fr/en). Raw seismic data, drilling logs and drilling reports are available but have a cost.
Germany	Yes	3D model published by the Federal Institute for Geosciences and Natural Resources (BGR). GFZ physical property database	Legacy seismic and well data has to be obtained through the individual state land offices. Current provision of data is therefore highly limited and subject to change.

Greece	Yes	CO_2StoP, ESTMAP and scientific publications	Onshore seismic data and borehole are not yet publicly available.
Hungary	Yes	CO_2StoP and published literature	Most seismic and borehole data can be requested from the Mining and Geological Survey of Hungary. Seismic or well data is only available in published literature for a few storage sites. Detailed seismic and borehole data is not automatically made publicly available
Italy	Yes	CO_2StoP, national project to assess CO_2 storage capacity	Well and seismic data available through national web portal. Information concerning depleted oil and gas fields are rarely available, except for some fields which are currently used/being evaluated for UGS
Latvia	No	GeoCapacity, CO_2StoP and ESTMAP projects, and data collected for other research projects (sometimes paper only, and sometimes in Russian). Geological database available in the University of Latvia (not public).	Well and seismic data could be purchased from the national authority.
Lithuania	Yes	INSPIRE geological dataset. Public reports and databases of EU projects: EU GeoCapacity, CO_2StoP and ESTMAP. Journal publications and in research institute databases	More detailed data available from national geological survey (for purchase)
Luxembourg	No	No pre-existing studies on storage potential. Published geological maps and profiles were used to identify possible geological formations and areas of interest	Geological maps are publicly available.
Norway	Yes, offshore	CO_2 storage assessment available as national storage atlas. National authority holds and makes available all seismic and well data	Access to some datasets requires membership, which is free for research institutions
Poland	Yes	CO_2StoP, Publications and reports on CCS and UHS. National database on deep well logs. National geological database such as MIDAS.	National geological survey holds and makes available well data and seismic data for a fee. Privately drilled wells require contracts with the operator to access data. Gas storage data available by contract with the national operator.
Portugal	Not economic	ESTMAP, CO_2StoP /COMET, STRATEGY CCUS, PilotSTRATEGY, national repository of petroleum exploration data. National data holdings including maps, boreholes etc	Most deep geological data is available from the national authority and is available via their webGIS. National energy and geology research institute makes available data from subsurface activities.

Romania	Yes	CO_2StoP and ESTMAP. National databases on oil licences. European UGS database. Published literature.	few data are available in the public domain on hydrocarbon fields. Researchers can request access to the data via the national authority, but cannot publish the data.
Slovenia	Mostly depleted	CO_2StoP, ESTMAP, published literature. Most seismic and well data collected for hydrocarbon exploration are old (collected pre-1960s)	A few 2D seismic lines have been acquired but are not generally available. The Survey is in the process of transferring all vintage well data in GIS. A database of wells is available from the national geological survey.
Spain	All depleted, one operational field onshore	ESTMAP and CO_2StoP. National CO_2 storage project, ALGECO$_2$. National database on hydrocarbon permits, geophysical data, and oil/gas production.	National geological survey holds and makes available most subsurface data, including seismic and well data
Turkey	yes	National research project on CO_2 storage. National publications on UGS.	National petroleum company holds the data and it is not publicly available
Ukraine	yes	ESTMAP, published literature.	National database (Geoinform) makes available geological reports and seismic data. National geological survey holds data on oil and gas wells, in the relevant Register, the administrator of which is Geoinform. Currently data access is restricted owing to the ongoing situation.
United Kingdom	Yes	CO_2StoP, ESTMAP. Published literature. National databases on offshore wells.	Older well data are available from the national authority. Seismic data are made available by a company that manages the data on behalf of the government. Newer data are confidential. Storage atlas for offshore is freely available.

4. Austria; geological assessment of storage opportunities

In Austria, the potential underground hydrogen stores identified are situated in the two major oil and gas provinces, the Vienna Basin and the Molasse Basin. Twelve Underground Gas Storage (UGS) sites and several depleted or near-depleted oil and gas fields have been identified as the most promising hydrogen storage candidates through the Hystories project. Most of the reservoir rocks comprise sandstones, though some are carbonates. Saline aquifers are not included in the database for Austria, as hardly any data are available that would inform assessment of potential for storage. Although some salt structures are present in Austria, owing to tectonic deformation, they are unlikely to be suitable for hydrogen storage.

4.1.Data collation and collection

4.1.1. Data availability and collation

Basic geological data are available from the Geological Survey of Austria. Detailed data on hydrocarbon fields belong to the respective company involved. Geological and geophysical data such as reservoir depth, reservoir thickness, geological profiles from boreholes, structural maps of traps, well logging data, or results from chemical analyses, are archived at the Geological Survey. However, these data are only made available after a hydrocarbon field or well has been abandoned and are usually not made available for public access. Seismic or well data are only published for a few hydrocarbon fields.

Data used for the Hystories project were collected using existing databases such as ESTMAP and CO_2StoP as well as published literature (Table 6). A detailed overview of existing oil and gas fields in Austria can be found in Brix and Schultz (1993). This book served as a basis for previous storage evaluations and data from this publication was supplemented with results from newer published work. It is especially difficult to find data on the seal as published research projects usually concentrate on reservoir rock properties.

4.1.2. Availability of detailed data for further site characterisation

For Austria, detailed seismic and borehole data are not automatically made publicly available. Data belongs to the storage or field operators. Additionally, there is no dataset showing all seismic data acquired in country. The BergIS information system[3] gives an overview of current claims and licenses. Most of these fields were covered by seismic data acquisitions in the past.

Data on saline aquifers are almost completely lacking as they were not in the focus of the oil and gas industry until recently. Nevertheless, oil and gas operators will almost certainly have

[3] https://bergis.rmdatacloud.com/Compact?defaultmap=bundeseigene%20min.Rohstoffe

come across these structures as exploration for hydrocarbons in the past century has been extensive.

Table 6: List of key data sources for the Austrian Hystories database

Source name / URL	Description	Version / Date
Brix and Schultz, 1993. Erdöl und Erdgas in Österreich https://www.isbn.de/buch/9783850282369_erdoel-und-erdgas-in-oesterreich.htm	Overview of oil and gas fields in Austria	Second edition, 1993
CO_2 Sequestration Potential in Austrian Oil and Gas Fields: https://www.researchgate.net/publication/254541489_CO2Sequestration_Potential_in_Austrian_Oil_and_Gas_Fields	Assessment of CO_2 storage potential	2006
Final Report: Underground Sun Storage Project, 2017 https://www.underground-sun-storage.at/fileadmin/bilder/SUNSTORAGE/Publikationen/UndergroundSunStorage_Publizierbarer_Endbericht_3.1_web.pdf	Reporting on Hydrogen Storage in a depleted reservoir is Austria	2013
E-Control: UGS in Austria https://www.e-control.at/marktteilnehmer/gas/gasmarkt/speicher	Overview of current UGS in Austria	2022
Montan-Handbuch https://info.bml.gv.at/service/publikationen/bergbau/oesterreichisches-montan-handbuch-2021.html	Status report on mineral resources and oil & gas reservoirs in Austria	2021

4.1.3. Identified gaps in data availability

The current database could be complemented by collaboration with storage or field operators. In particular, well and field data from new exploration campaigns are missing from the archives of the Geological Survey of Austria. As energy storage becomes an important topic of the future, it is still unclear how interested companies are in collaboration and publicly sharing subsurface data.

For the identified traps in the Hystories database, it was especially challenging to find data on seal properties as well as risk information (e.g., location and characteristics of geological faults, vintage and number of wells in hydrocarbon fields). Published literature usually refers only to the reservoir rocks and the presence of faults, and data on their characteristics would require detailed seismic information that is not available in most cases.

There is no compelling overview on data for saline aquifers. The lateral extension of these structures is particularly poorly constrained by currently available data.

4.2. Geological opportunities for hydrogen storage

4.2.1. Geological summary

As previously mentioned, the most promising storage structures in Austria are depleted/near-depleted oil and gas reservoirs located in the Vienna Basin and the Molasse Basin. Oil and gas production in Austria started during the 1930s and is still ongoing with an ultimate recovery of more than 110 million tonnes of oil and 70 billion m^3 of gas. The identified traps belong to several structural units and are bound within various trap types.

The Molasse Basin is a typical asymmetric retroarc foreland basin. On top of the crystalline basement of the Bohemian Massif, some Carboniferous-Permian sandstone remnants can be found along the "Zentrale Schwellenzone". The lateral extension of these sandstones is unknown, but they have been mentioned in literature as possible stores. These sandstones are overlain by Middle Jurassic age sandstones and Upper Jurassic age carbonates that are used for geothermal energy production. One of the most important oil-bearing layers in this basin are the glauconitic sandstones of the Cenomanian Stage and sandstones of the Upper Eocene Era that sometimes form combined traps together with Middle Jurassic age sandstones. Hydrocarbons trapped within these layers are typically a result of thermogenic heating of fine-grained rocks of Lower Oligocene – Lower Miocene age. The most important gas reservoirs in the Molasse Basin (biogenic origin) are sandstones and conglomerates of the Lower Oligocene – Lower Miocene age Puchkirchen Group and the Miocene age basal Haller Formation. These reservoir formations have intraformational mudstone seals. These reservoir-seal formations formed in a deep-water environment and have thickness of several thousand metres. RAG Austria is operating several underground gas storages in the Puchkirchen Formation.

The Vienna Basin is divided into three main sedimentary packages, all of which contain hydrocarbons. The youngest package is the Miocene basin fill that usually comprises siliciclastic sediments such as sandstones, claystones and conglomerates. As a result of the presence of oil and gas, drilling of wells has been extensive (more than 7000 wells), and several 3D seismic acquisition programmes have been undertaken. OMV AG is operating several UGS sites within the Miocene-age basin fill. Sedimentary thickness is typically up to 2000 – 3000 metres and can reach more than 8000 metres in structural lows. These siliciclastic sediments are underlain by thrust sheets from the Flysch Zone and Northern Calcareous Alps which comprises folded shallow water deposits. Several oil and gas fields have been found within this package. Important reservoirs can be found in dolomitic anticlines and have typically lower permeabilities compared to the Miocene sediments. The autochthonous Mesozoic age strata that rests on top of the crystalline basement represents the oldest sedimentary package.

4.2.2. Storage assessments

During Hystories, efforts focused on the evaluation of storage data solely at trap level. All identified traps are hydrocarbon fields, as the lateral extent of saline aquifers is currently unknown. All UGS sites in Austria were also added to the Hystories database. Hydrocarbon traps where a structural map and porosity or permeability data is publicly available are also included. Altogether, 30 traps were identified and added to the database, see Table 7, Figure 17 and Figure 18. Five traps lie within carbonate rocks, the remaining potential storage reservoirs comprise siliciclastic rocks.

Detailed reservoir data are usually not published, which results in overall poor data availability. Nevertheless, for reservoirs where simulations (e.g., CO_2 storage evaluations) have been performed and published in literature, additional reservoir data are available. Where reservoir parameters are given in the database, they should be reliable. The exact number of wells penetrating each trap is uncertain, however. Owing to the sparsity of available data, the overall storage potential is unknown, but the “low hanging fruit” have most likely been identified.

Table 7: Summary of storage capacity options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	0	No aquifer stores identified. Important data such as lateral extension and the presence of seal rocks is missing.	Regional geological mapping and assessment of aquifers may reveal further potential for energy storage
Gas fields (active, depleted or abandoned)	10	Exploited from 1930s onwards. Most of them are depleted or close to depletion.	Site specific studies required
Oil fields (active or depleted)	7	Exploited from 1930s onwards. Most of them are depleted or close to depletion.	Site specific studies required
UGS	12	All current UGS sites in Austria have been added to the database	Site specific studies required
Condensate field (active)	1		Site specific studies require

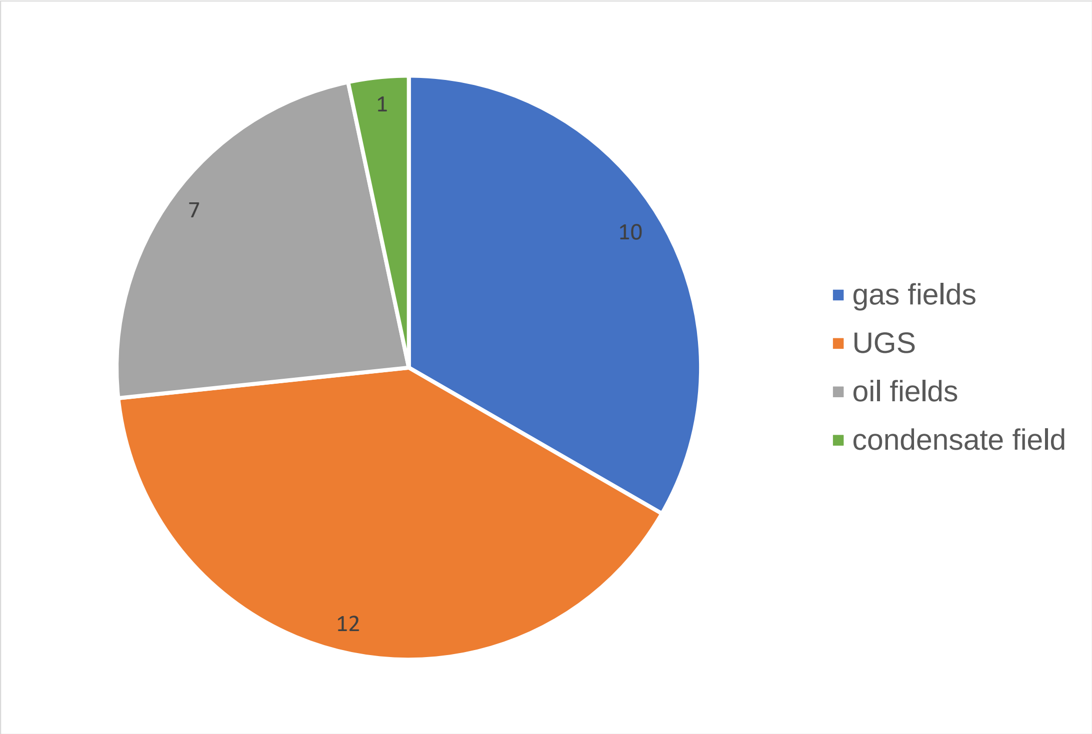


Figure 17: Frequency pie chart showing categories of identified potential storage traps in Austria (pie chart shows number of traps)

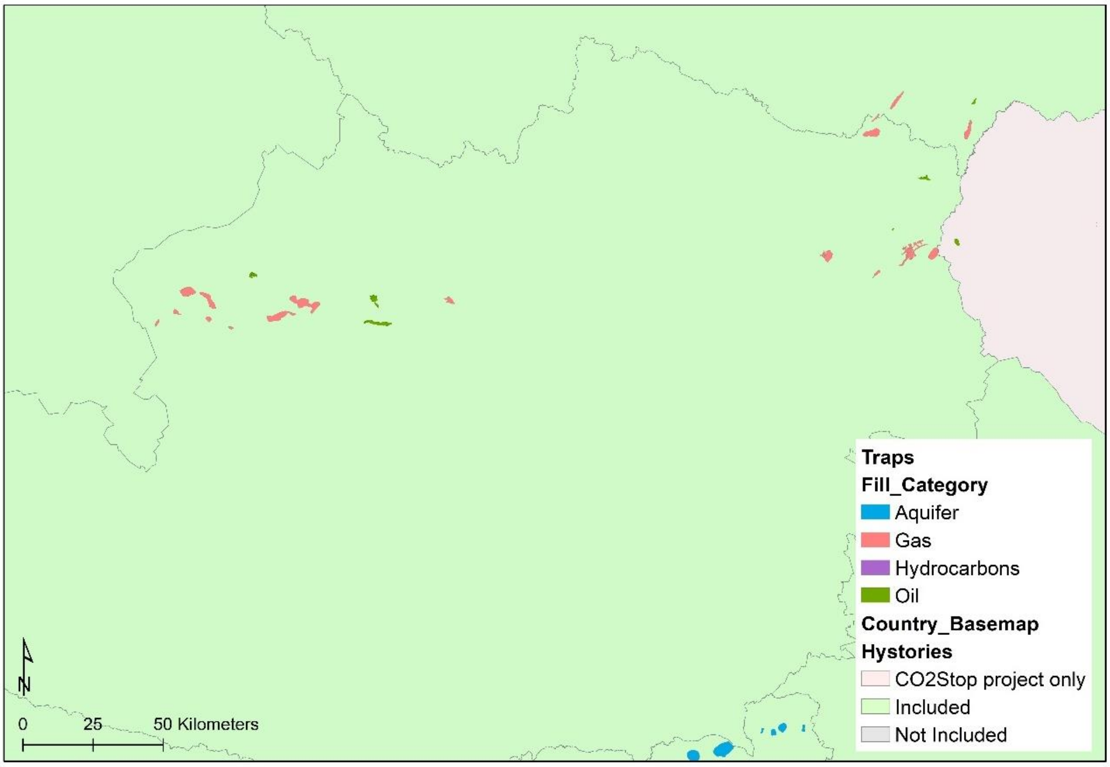


Figure 18: Overview of identified potential traps in the Hystories database within Austria.

4.2.3. Existing storage sites

Austria has several UGS sights that all have been added to the Hystories database. Currently around 8.2 Bn m^3 of gas can be stored in Austrian storage fields. The storage operators are OMV in the Vienna Basin and RAG Austria AG in the Molasse Basin. All UGS sites are former gas fields.

4.2.4. Potential future development opportunities

The low hanging fruits for Hydrogen storage in Austria are probably depleted sandstone gas reservoirs of the 1st sedimentary package of the Vienna Basin, as well as the sandstones of the basal Hall Formation and the Puch kirchen Group in the Molasse Basin. Those storage structures are already well understood from gas production or UGS operation. Site-specific surveys should be performed for these stores to assess storage potential in detail.

4.3. Discussion and conclusions

Only hydrocarbon traps could be identified for this project, as studies on the storage potential of saline aquifers in Austria have not yet been conducted. Although not included in the database, saline aquifers are certainly present in Austria. Intensive drilling by the oil and gas industry as well as drilling from geothermal wells revealed several saline aquifers. The most promising aquifers are located in the Vienna Basin, the Molasse Basin and the Styrian Basin. One of the few that is better known is the Aderklaa Conglomerate Formation in the youngest sedimentary package of the Vienna Basin. Nevertheless, owing to the absence of a caprock, it was not included in the database.

The database comprises all UGS sites and all hydrocarbon traps where the important reservoir properties (extent, porosity & permeability) have been published. However, several of the oil reservoirs within the database are probably less suitable for hydrogen storage compared to the gas reservoirs. Many oil fields have a large number of wells and therefore may not be suitable for development as storage sites. For example, the Matzen oil field (the largest producing oil field in Austria) that targets the 16th Badenien horizon, was not included as it has been perforated more than 1000 times by wells and hence its development for storage might be unlikely.

Austria has several existing natural gas storage sites in porous rocks. These structures are well known and might become hydrogen stores in the future. Regarding the seal rocks and risks to security of storage, further site-specific investigations are required to evaluate these traps. It is important to emphasise that the database is by no means exhaustive as the list of the potential sites is based on published literature only.

5. Belgium and Luxembourg; geological assessment of storage opportunities

No traditional oil or gas reservoirs are known to occur in Belgium or in Luxembourg. Salt deposits thick enough to be considered for cavern storage are also absent. Both countries do have potential storage complexes comprising reservoir and cap rocks, opening the possibility for aquifer storage sites. In Belgium, one dome structure was prospected at the end of the 1970's and has been operational since 1985 as a natural gas storage site. Other traps have not been confirmed, but some candidates can be inferred from 2D seismic sections.

5.1. Data availability and gaps

5.1.1. Data availability and collation

For Belgium, storage sites for CO_2 have been summarized in the CO_2Stop database, which partly inherits data from earlier national and European projects. Luxembourg is not known to possess potential storage sites, because the depth of the top seal is too shallow for efficient storage of CO_2. The CO_2StoP database was used as a starting point for the investigation into potential storage options for the Hystories project since both uses of the subsurface have similar requirements in terms of a good quality reservoir and seal.

Investigations into CO_2 storage possibilities in Belgium started in 2000 with the FP5 GESTCO project. Between 2005 and 2012 a suite of national projects assessed the feasibility of CO_2 capture and storage as a mitigation option for Belgium, and various aquifer storage sites were inventoried based on available data. This resulted in 13 identified or inferred potential storage complexes (Welkenhuysen et al., 2013). The absence of seismic data largely prevented the identification of potential trap structures. Only few additional studies further identified storage options for CO_2 (Piessens et al., 2007), and the estimates were never updated.

5.1.2. Availability of detailed data for further site characterisation

For Luxembourg, there are no pre-existing studies on storage potential, but because the minimal depth constraints for hydrogen are less strict than for CO_2, reservoir-seal pairs could be present for storage. During the Hystories project, information from published geological maps and profiles was used to identify possible geological formations and areas of interest. There is increased interest in exploration of these reservoirs for geothermal projects, from which data on porosity and permeability can be obtained.

While for Belgium relatively little additional data has become available since the CO_2StoP database was compiled, the original inventory was based on geographical location of the potential reservoirs, and was therefore lacking in the correct geological identification of the reservoir and sealing formations. Improving this involved restructuring all available information and updating it with current lithostratigraphic nomenclature. For some important reservoirs that were also of interest for geothermal application, more detailed contour maps or 3D models were available. These new data were used during Hystories to create reservoir depth contour maps.

5.1.3. Identified gaps in data availability

The amount of data in the public domain is relatively restricted, especially regarding the sealing formations. The data in the Hystories database comprises both actual measurements, and where necessary, parameters generated using extrapolation by experts.

5.2.Geological opportunities for hydrogen storage

5.2.1. Geological summary

The nine potential storage strata that were identified for Belgium, and the two for Luxembourg, span a significant geological time, and represent different reservoir types and geological settings. No hydrocarbon accumulations (with the exception of coal and shale gas) have been identified, thus the focus is exclusively on aquifers. All reservoirs are onshore, with offshore geology not being suitable for geological storage of buoyant fluids (Piessens, 2011).

The oldest formations in Belgium that can be found in-situ are of Cambrian to Silurian age (Lower Paleozoic) and typically have been deformed during either the Brabantian or Ardennian events (Legrand, 1968; De Vos et al., 1993; Piessens et al., 2005). The Brabantian deformation belt continues into England. The Ardennian belt is only identified in Belgium and Luxemburg; its regional extent is unknown owing to a lack of outcrops in France and Germany. Although some strata of this age have reasonable reservoir properties, they are not known to occur in association with sealing formations at a suitable depth and are therefore unlikely to offer storage potential.

The Upper Palaeozoic strata, specifically the Devonian and Carboniferous deposits (and for Luxemburg also the Rotliegend Group), provide several storage options and have undergone varying degrees of exploration.

The Variscan deformation took place at the end of the Carboniferous Period and affected Luxembourg and the south-east part of Belgium (Sintubin et al., 2009). South of this deformation front, in the Dinant synclinorium, the numerous anticlines that are observed at the surface are hypothesised to have given rise to elongated domelike traps at depth. These strata could offer storage potential provided that the Givetian- and Frasnian-age limestones are sufficiently permeable, and the Famennian-age shales offer a suitable caprock. This option remains completely unexplored. The Campine Basin in the north of Belgium remained largely unaffected by the Variscan deformation.

In the Campine Basin, where the lithostratigraphy is different but still comparable to that found in the Dinant synclinorium, three drilling campaigns, of which two lie at relevant locations, have reached these formations at depth. The Frasnian-age Aisemont Formation was recognised as a promising target and has been drilled for geothermal exploration. The lower beds of this formation comprise argillaceous limestones, while the upper beds are dominated by dolostones (van Tongeren, 2001). Drilling for geothermal energy exploitation was eventually abandoned because the Aisemont Formation proved less productive than the overlying Dinantian (Lower Carboniferous) reservoirs.

The Dinantian Supergroup (Lower Carboniferous) occur in three main areas in Belgium. These carbonate strata are being used for the storage of natural gas and are the primary target of deeper geothermal projects. Namurian stage deposits are dominated by shaly deposits and offer the main seal for potential reservoirs of Lower Carboniferous age. The base of the Namurian stage strata comprise black shales of the Chokier Formation. These black shales may be absent, in which case the Namurian stage Andenne Formation offers the primary seal.

In the Campine Basin, Dinantian limestones occur only in subcrop and are known from 2D and a small 3D seismic campaign, as well as from a few drill cores (Dreesen et al., 1987). The principal strata of interest is the Loenhout Formation, named after the community where the formation has been best explored and subsequently utilised for natural gas storage. Only a small amount of data has been released into the public domain. Porosity and permeability seem largely determined by the degree of karstification (paleokarst), making projections about formation properties prior to drilling, a major challenge. One other, smaller dome structure is also known: the Poederlee structure.

In the Mons Basin the Dinantian Supergroup strata of Lower Carboniferous age typically comprises evaporitic beds, which positively influence permeability (Delmer, 1977). In this region Lower Carboniferous strata have been deformed into a monoclinal structure, and traps are yet to be identified. This unit has a history of geothermal exploitation, with current development plans to increase production. New seismic campaigns accompanied the recent exploration for geothermal sites have been undertaken, but results have not been made public.

A third area where the Dinantian Supergroup (Lower Carboniferous age) may offer opportunities lies along and around the Variscan front zone (more or less between the cities of Mons and Liège). Here, interest in this unit for geothermal projects, has recently emerged. A 3D model based mainly on extrapolations and structural modelling has been newly developed. Early results from this work were used to outline this reservoir. A seismic campaign is planned for the end of 2022, but results are not expected to become available within the Hystories timeframe. Core data are not available, so reservoir properties are not verified.

The last formation of interest from this geological time interval is the Neeroeteren Formation of Upper Carboniferous age (Westphalian stage; Bertier et al., 2008). Contrary to the older carbonate reservoir rocks, the Neeroeteren Formation comprises fluviatile and relatively coarse sandstones (Paproth et al., 1983). The Neeroeteren Formation outside of the Roer Valley Graben occurs at sufficient depth and has good reservoir properties. However, it is only partly covered by a sealing formation (Pharaoh et al., 2010). It is assumed that the northern part of the reservoir is appropriately sealed, and it is this part that is identified as having potential for hydrogen storage. Further verification of the seal and identification of trapping structures is required.

The situation is different in the Roer Valley Graben. The Neeroeteren Formation is expected to be present but has not been confirmed by drilling. The potential caprocks will be different than those outside of the graben owing to different sedimentation and erosional conditions. Structural traps may be present. Present-day seismic activity needs to be considered.

The Permian Rotliegend Group occurs in Luxemburg at sufficient depth for hydrogen storage, however, it is not considered further because no directly overlying sealing formation could be identified.

The oldest Mesozoic age strata that may be suitable for storage comprise the Triassic Buntsandstein Formation. These strata are coarse-grained siliciclastic deposits and well-known for possessing good porosity and permeability. In Luxembourg, the Vogesensandstein Formation occurs relatively close to the top of the Buntsandstein Formation and is overlain by marls that may offer a sufficient seal. The Vogesensandstein Formation is an aquifer that is heavily explored for geothermal purposes. Depending on the authors, depth changes in profiles are explained by undulations or fault displacement. Either could result in local trapping structures. Closer to the Upper Rhine Graben, fault-bounded traps become more likely.

In Belgium, the Buntsandstein Formation occurs in the Campine Basin and the adjacent Roer Valley Graben, potential stores with adequate seals occur below depths of 500 m only in the Roer Valley Graben. The primary seal is the Muschelkalk Formation, in a succession equivalent to that found in Luxembourg.

The youngest reservoir formations that occur at sufficient depth with a suitable seal are of Cretaceous to early Palaeocene age. The Formations of Maastricht and Houthem form one continuous chalk reservoir and are overlain by marls with sealing potential (Robaszinski et al., 2001; Langenaeker, 1999). Dome-like structures have been identified in previous studies, and included in the current geological model that is believed to be more accurate than older geological assessments. Nevertheless, considering the resolution and available data, as-yet unidentified shallow dome structures may be present.

5.2.2. Storage assessments

This report is the first overview of the potential to store hydrogen in Belgium and Luxembourg. Potential storage options exist only onshore, and exploration is in an immature stage for most reservoir-seal combinations. Several interesting regional targets warrant further investigation, but without further exploration efforts the number of identified storage structures is limited to three: one dome structure that is currently in use for the seasonal storage of natural gas (Loenhout), one similar but smaller dome structure (Poederlee), and one potential dome structure that has only been identified on a single 2D seismic line and therefore lacks a confirmed geometry (Verloren Kamp).

A summary of the onshore units and traps in the Belgium and Luxembourg Hystories database are presented in Table 8, Figure 19 and Figure 20. No ‘traps’ were identified in Luxembourg owing to the sparsity of data.

Table 8: Main storage types included in the Hystories database.

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifer traps (Belgium)	3	Aquifer traps/dome structures, of which one developed as natural gas storage site.	Site-specific studies including seismic survey
Aquifer units (Belgium)	7	Deep aquifers with varying but low exploration level	General exploration, seismic campaigns
Aquifer units (Luxembourg)	1	Deep aquifers with low exploration level	General exploration, seismic campaigns

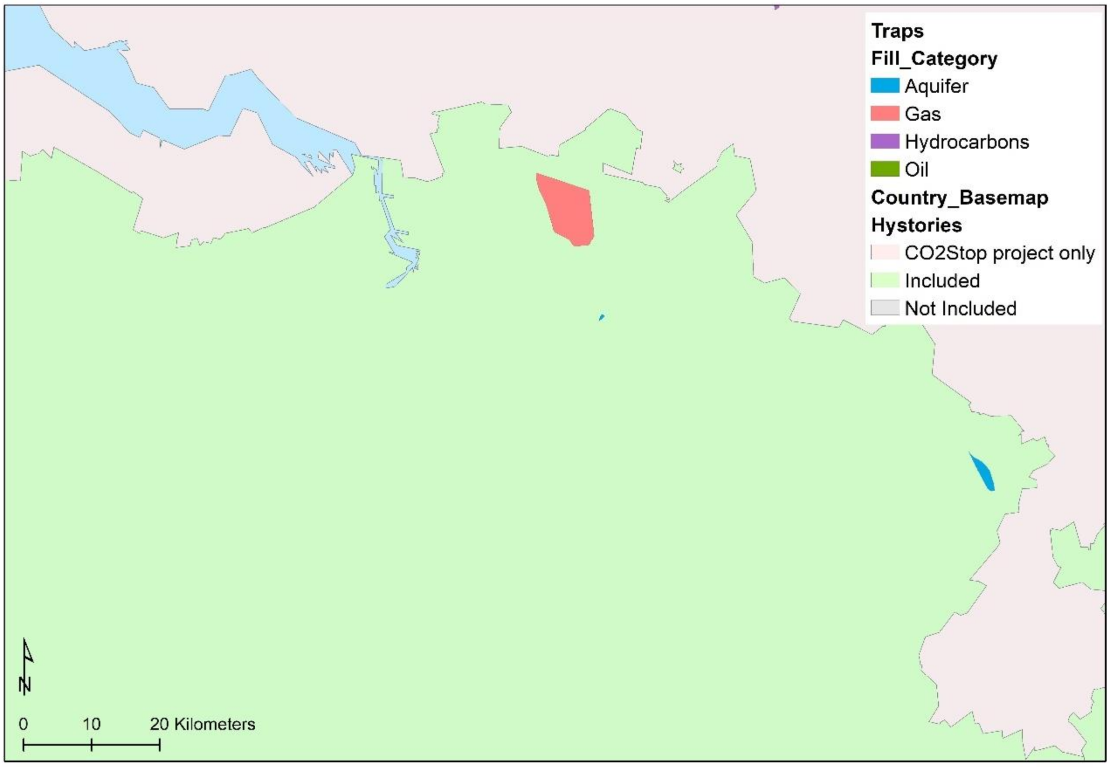


Figure 19: Overview of identified potential traps in the Hystories database within Belgium (all in the north).

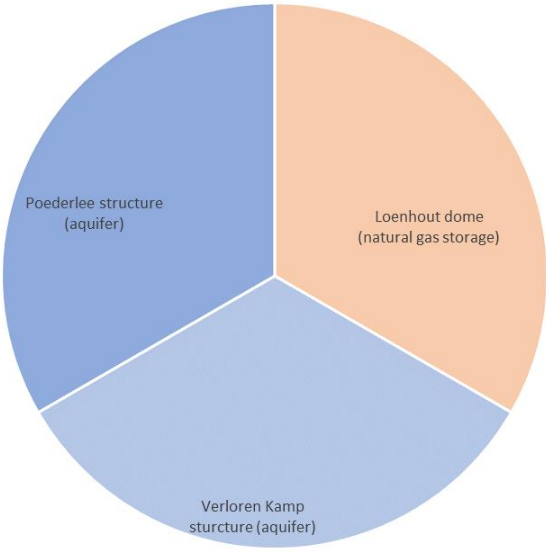


Figure 20: Frequency pie chart showing categories of identified potential storage traps in Belgium. No traps were identified in Luxembourg.

5.2.3. Existing storage sites

Belgium has one natural gas storage site, which is aquifer-based and operates for seasonal buffering. This is located in Loenhout (Campine Basin). Historically, two abandoned coal mines were used as additional natural gas storage sites, but these were closed owing to high operational costs. Luxembourg does not have any geological natural gas storage sites.

5.2.4. Potential future development opportunities

The current operator of the natural gas storage site has tentatively shown interest in full or partial conversion to hydrogen storage, but no official public statement has been made to date.

5.3. Discussion and conclusions

Given the absence of salt formations and oil and gas fields, aquifer storage seems the only option available for large-scale storage of hydrogen in Belgium and Luxembourg. Previous studies (Piessens, 2011.) indicate, with considerable certainty, that offshore storage is not feasible. The most feasible and near-term options currently lie in the conversion of geological trap structures that are either already in use, or that have been only partly explored and therefore have a high uncertainty in terms of suitability for hydrogen storage. An absence of exploration data across much of Belgium and Luxembourg has resulted in a focus on the few known dome structures. Since interest for hydrogen storage and geothermal exploitation overlap in terms of targets to explore, the current and planned deep geothermal exploration efforts may benefit the development of both activities. In any case, the capacity of the currently identified potential traps will likely prove to be too small.

6. Croatia; geological assessment of storage opportunities

Croatian territory can be subdivided into three large units; Pannonian Basin (north-east onshore Croatia), Dinarides (western onshore Croatia) and the Adriatic offshore area. The Pannonian Basin and Adriatic areas offer significant thicknesses of sandstones, particularly in the Upper Miocene age sandstone-marl sequence, and there is also a younger Pliocene to Pleistocene sequence of clastic sediments, but its potential is restricted to the Adriatic area. Because of the very complex geological structure and prevailingly carbonate rocks that are karstified, it is expected that developing projects in the Dinarides area could be challenging and therefore this region is considered less favourable for storage.

The onshore Pannonian Basin has many oil and gas fields that have been exploited over the last 180 years. Many of the gas fields are still producing, but as they eventually deplete, these fields could be considered for Underground hydrogen storage (UHS). There is one Underground natural gas storage (UGS) site which lies in the Sava sub-basin in the south of the Pannonian basin. This UGS site is a depleted gas field. Miocene sandstones are the most common reservoir rocks in the Pannonian Basin and these strata could also offer potential for storage in saline aquifers. However, there are insufficient data available to delineate and quantify saline aquifer storage capacity. New hydrocarbon resources are still being identified in the Pannonian Basin as oil and gas exploration is ongoing, as well as a (still small) number of deep geothermal projects.

Intensive exploration for natural gas in the Croatian part of the North Adriatic Sea started in the early 1990s. This is still an area of active hydrocarbon exploration and development. Gas is trapped in the Pliocene poorly consolidated sandstones and Upper Cretaceous limestones. In the central and southern Adriatic basin, these could potentially offer saline aquifer storage opportunities. However, there are insufficient data available to delineate and quantify saline aquifer storage capacity.

The Ministry of Economy and Sustainable Development recently (2022) published a hydrogen strategy for Croatia which includes hydrogen to support increased renewable energy, and electrification of transport so there could be an appetite to develop hydrogen storage to help reach climate objectives.

6.1. Data availability and gaps

6.1.1. Data availability and collation

Data were sourced from published literature including information on oil and gas fields, UGS development and regional geological maps. The main data sources are given in Table 9. Based on these data sources, information from the earlier CO_2StoP and ESTMAP projects assessing potential for geological storage of CO_2 and underground energy storage, respectively, were updated.

Data in the public domain are sparse, particularly for the offshore regions. It was not possible to provide formation outlines owing to a lack of available data. For many of the traps, both saline and hydrocarbon, there were insufficient data to confirm the extent of the storage unit in which they sit, and an arbitrary polygon was provided for the Hystories GIS. A summary of the traps and units included in the database is given in Figure 23.

Table 9: Summary of data sources used for Hystories

Source name / URL	Description	Version / Date
INA Group https://www.ina.hr/	National oil and gas company	Various
Examples: The Miocene petroleum system of the Sava Depression, Croatia: https://doi.org/10.1144/petgeo.6.2.165 CCS actions and options in Croatia: http://epa.niif.hu/02900/02941/00101/pdf/EPA02941_geofizikai_kozlemenyek_2011_45_4_193-206.pdf Development of CCUS clusters in Croatia: https://doi.org/10.1016/j.ijggc.2023.103857	Published literature on CO_2 storage and oil and gas fields in Croatia	Various
EU GeoCapacity: Assessing European Capacity for geological storage of carbon dioxide. D16 WP2 report. Storage capacity http://www.geology.cz/geocapacity/publications	Geological description of Croatia and assessment of CO_2 storage capacity	2009
PSP d.o.o. official web site ; Strategija gospodarenja mineralnim sirovinama: https://www.psp.hr/	National strategy for exploitation of mineral resources	2022 (website is regularly updated)
Gas Infrastructure Europe 2015: Gas storage map and database for Europe https://www.gie.eu/transparency/databases/storage-database/	Overview of planned and operated underground gas storage	April 2015
Croatian Hydrocarbon Agency – data use is controlled by a confidentiality agreement but the source is included here for completeness since these data can be used for research https://azu.hr/en-us	Public body that supports the competent authorities in the field of exploration and production of hydrocarbons, geothermal water for energy purposes, underground gas storage and carbon capture and storage. Also responsible for managing stocks of oil and oil derivatives	2022 (website is regularly updated)

Oil and gas fields

More than 60 economic and uneconomic hydrocarbon accumulations have been discovered in Croatia over the last 70 years. The largest fields have been added to the Hystories database. The oil fields are generally more depleted than the gas fields and are therefore would be expected to be available sooner. However, the use of depleted oil fields for hydrogen storage is not a simple topic given the lack of maturity in modelling fluid flow and mixing and geochemistry in this situation. The exact outline of the hydrocarbon traps was modified owing to data confidentiality.

Saline aquifers

There are insufficient data on saline aquifers to fully assess their potential. The aquifer trap and unit outlines are assessed from regional geological maps. Basic storage formation data (e.g. thickness, porosity) have been extrapolated from the averages of data acquired in oil and gas fields in that area.

6.1.2. Availability of detailed data for further site characterisation

There is extensive coverage of 2D seismic data in the petroliferous onshore and offshore areas of Croatia (e.g. TGS[4]). However, these data are only available for purchase.

In November 2020, the Croatian Hydrocarbon Agency (CHA) opened a physical and virtual 'data room' to enable access to subsurface data. Initially, the data room included access to data on approximately 200 wells, but this offering has been expanded over time. To access the data room, a confidentiality agreement must be signed. The data room makes available for viewing three projects using Kingdom Software; the Adriatic Sea, the Pannonian Basin and the Dinarides. All seismic (2D and 3D) and basic well data are loaded into these projects. Well data including well reports, well logs and velocity measurements, are available via the online data room (in .pdf or .tif format). All exploration wells are available from the CHA and can be used for research. Data contained in the data room are the property of the Republic of Croatia and may not be used without permission. Owing to timing of availability of these data and the available resources within Hystories, not all the well data from CHA could be reviewed.

In the public domain, a few well logs are available via publications.

6.1.3. Identified gaps in data availability

Additional 2D and 3D seismic data could be purchased/acquired from the CHA data room and interpreted. Available 2D and 3D seismic covers the offshore and continental Croatia where there are oil and gas fields. Access to 3D data in areas where hydrocarbons are actively being exploited is currently restricted, but these data will likely be released when the hydrocarbon fields are exhausted.

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[4] https://www.tgs.com/products-services/offshore/africa-mediterranean-middle-east/mediterranean-middle-east

There are few seismic data for the Dinarides area, however this mountainous region is not expected to be prospective for storage. Part of the geological Dinarides includes the complete chains of islands parallel to the Dinaric Alps (the "Dinaric type of coastline" is a type, as an antonym to the Nordic type). So, instead of fjords, there are the many so-called "channels" between the islands. These narrow strips of sea have been covered with 2D seismic, but its grid is irregular and in the given situation of structural complexity offers slim chances for definition of hydrogen storage objects, unless it is strongly upgraded by additional targeted surveys.

There are more well data available which could also be interpreted, again this would require considerable additional resources. Around 800 vintage wells are present. To date, only wells in the most promising areas have been assessed. If additional resource were available to extent the assessment, more potential storage sites would likely be identified.

6.2.Geological opportunities for hydrogen storage

6.2.1. Geological summary

Pannonian Basin

The Pannonian Basin covers Hungary and parts of Austria, Bosnia and Herzegovina, Croatia, Romania, Serbia, Slovakia, and Slovenia. Exploration of oil and gas in Croatia started here in 1844 (EFG, 2018). More than 700 exploration wells have been drilled in the Pannonian Basin in Croatia.

The structure in Croatia is complex with elongated basement highs and narrow depressions that developed during mid-Miocene rifting and were affected by several phases of basin inversion. The Croatian part of the Pannonian Basin is divided into four sub-basins; Drava, Mura, Sava and Slavonija-Srijem. The basement is represented by igneous and metamorphic rocks of mostly Paleozoic age. These are mainly granites, gabbros, gneisses, amphibolites and green schists. In some locations, carbonate rocks of Mesozoic age can be found, which are called "Base Tertiary". These comprise mostly dolomites and limestones that can be weathered or/and extensively fractured, forming breccias and conglomerates. Most the sedimentary fill in these sub-basins comprises strata of Neogene and Quaternary age. Sediments are of lacustrine-marine to lacustrine-fluvial origin, with some volcaniclastics (Pavelić, 2000; Saftić et al., 2003). Lower and Middle Miocene sediments show larger variety of lithological composition, reflecting the changes in the depositional environment during the syn-rift and post-rift stage of the basin development. The greatest thicknesses can be assigned to Upper Miocene sandstone-marl succession resulting from the balance between sediment supply and opening of the accommodation space, as a consequence of a post-rift thermal subsidence. The Mura sub-basin extends into neighbouring Slovenia.

The south-western Pannonian Basin is considered most promising for storage and more detail on the stratigraphic succession is given in Figure 21.

The oil and gas reservoirs are found in fractured crystalline rocks underlying Neogene deposits down to the Upper Miocene (Pannonian) sediments. CO_2-EOR operations are conducted in two fields in Sava sub-basin; Ivanić and Žutica, with plans for similar projects in other oil fields in the near future (Novosel et al., 2020). The Croatian part of Pannonian Basin is still being explored and new hydrocarbon discoveries could be expected (EFG 2018).

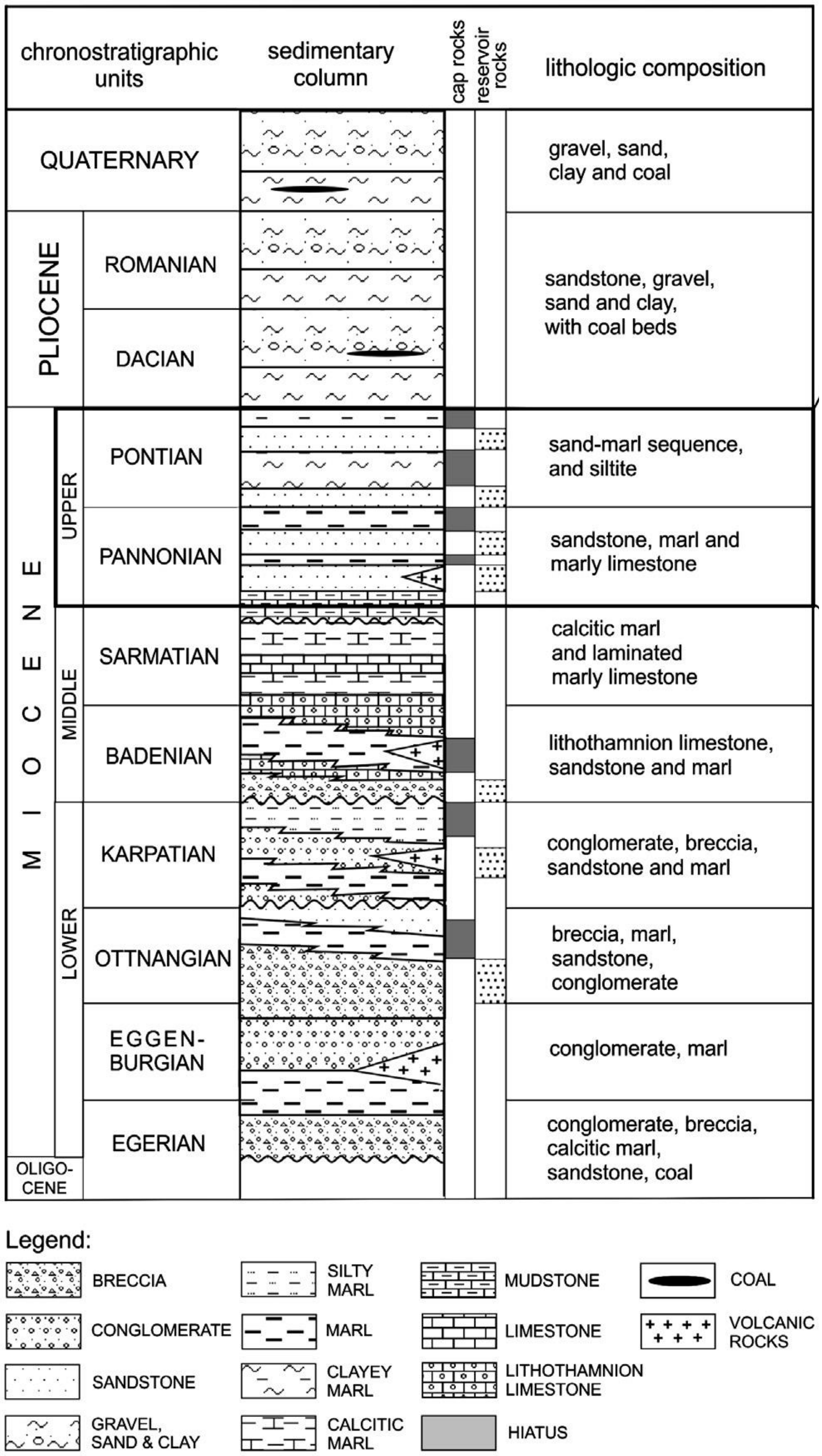

Figure 21: Geological succession in the stratigraphic column of the Neogene basin fill of the southern part of the Pannonian basin (reprinted from International Journal of Greenhouse Gas Control, 16, Kolenković, I., Saftić, B and Perešin D., Regional capacity estimates for CO_2 geological storage in deep saline aquifers – Upper Miocene sandstones in the SW part of the Pannonian Basin, 180 – 186, Copyright 2013, with permission from Elsevier)

The Sava sub-basin, located on the south-western margin of the Pannonian Basin, contains a number of small oil and gas fields (Baric et al., 2000). The first oil wells in Croatia were drilled in the Mura sub-basin, the first oil field was Gojlo (Velic et al., 2012). Limited oil and gas have been produced from the Mura subbasin since 1942 (EFG, 2018). The western part of Drava sub-basin in north-east Croatia contains large gas and gas-condensate fields (Baric et al. 1991, 1998), while both the oil and gas reservoirs can be found in the eastern part of the subbasin. The Slavonija – Srijem Depression is an area of active hydrocarbon exploration (Vuic, 2015).

The Dinarides

The Dinarides are a mountain chain, stretching from Italy, through Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro and Albania. The Dinarides are still underexplored, although 30 wells have been drilled in this region so far. However, the area is considered challenging for seismic exploration; although seismic refraction techniques can provide information on the near-surface heterogeneities, the increase of seismic velocity needed for investigating deeper parts of the subsurface often lead to unwanted effect of near-surface fast layer hiding deeper underground structures (Chalikakis et al., 2011). Recently, magnetotelluric survey has been conducted on block Dinaridi-14 by MOL Group. However, there are no published data on results of this survey, it is assumed that it is still in interpretation phase. Gas was discovered at the Island of Brač in 1979 and occurrences of extra heavy oil were reported in wells in Ravni Kotari, western from Zadar and in Olib-1 well located on the island of Olib where the oil was found in carbonate – anhydrite succession of Upper Jurassic to Lower Cretaceous age. Another occurrence of natural gas as well as heavy oil was registered in carbonates and anhydrites in Dugi Otok-1 well located on the island of Dugi Otok (Velić, 2007). The Dinarides are not expected to offer the easiest storage development since they mainly comprise Mesozoic carbonates that are karstified to depths exceeding 1 km, contain important groundwater resources, and are prone to seismicity.

This area has not been explored in detail for oil and gas. The probability of finding commercial quantities of oil and gas is considered low (EFG, 2018).

Adriatic Sea

The Adriatic is the north basin of the Mediterranean, located between the Italian and Balkan Peninsula. The Miocene age subbasins are Dugi otok, South Adriatic - Albania and Molise. Pliocene subsidence formed the Venetto, Po, Marche-Abruzzi, Middle Adriatic, Bradano and Adriatic-Ionian subbasins (Prelogović and Kranjec, 1983; Velić and Malvić, 2011). The largest subbasins are Po and South Adriatic-Albania. The Croatian area of the Adriatic Sea includes the entire Dugi otok sub-basin, northeastern parts of Po and Middle Adriatic sub-basins and the northern part of Southern Adriatic-Albania sub-basin. These subbasins are predominantly asymmetric, with displacements of the sedimentation base and rotational displacements present. They are characterised by unequal filling of the accommodation space and unconformable contacts between individual units. The gas in the fields of the Po Plain-Adriatic Foredeep is of biogenic origin; source rocks are organic-rich Pliocene shales and gas accumulations occur mostly in unconsolidated Pleistocene sands at depths of 600 - 1250 m (Velić et al., 2015).

The oldest geological formations reached by wells are Permian in age, and comprise mainly sandstones and shales, with some carbonates and evaporites (Tišljar, 1992; Spaić, 2012). The mixed carbonate and clastic sedimentation continued through the Lower Triassic. The Middle Triassic unit is characterised by shallow-water carbonates, but also with intensive volcanic activity which is manifested through the widespread occurrences of andesite and pyroclastics.

The basal deposits of the Upper Triassic are dominated by evaporites in the central Adriatic, and by dolomites in the northern Adriatic. Shallow water carbonate platform deposition began in Late Triassic and continued into the Middle Jurassic (mainly dolomites), Late Jurassic and Cretaceous (limestones) until the Palaeogene-Middle Eocene (Vlahović et al., 2005).

During the Middle Eocene, Late Eocene and Lower Oligocene, intensive tectonic movements gradually led to the formation of a foreland basin system characterised by deposition of syntectonic flysch sediments mainly of Middle–Upper Eocene age, with occurrences Lower Oligocene and up to Lower Miocene age (Vlahović et al., 2005). Tectonic movements were accompanied by the deposition of marl, sandstone and occasional limestones. Miocene strata were deposited in multiple basins with marl in the basin centres and turbidites on the basin margins. Miocene comprise marl, calcareous and marly siltites interbedded with sandy limestones and sandstones.

Pliocene strata comprise clays, marls and sands deposited during the subsequent transgression, which continued into the Quaternary, when sands, silts, clays with lignite interbeds were deposited.

Intensive exploration for natural gas offshore Croatia (in the North Adriatic) started in the early 1990s, while oil exploration began in 1998. Production comes from the fields in North Adriatic field group and the Marica field group. Production is mostly from the Pliocene-Quaternary sandstones of the Po Depression, with exception of Ika gas field which contains one reservoir in Upper Cretaceous limestones (Malvić et al., 2011).

6.2.2. Storage assessments

A summary of the storage opportunities is presented in Figure 22**,** Figure 23 and Table 10.

Pannonian Basin

Sedimentary basin fill is kilometres thick, e.g. 5000 m in the Sava sub-basin and over 6000 m in the Drava sub-basin.

The Lower and Middle Miocene saline aquifers (fluvial sandstones and conglomerates, talus breccia, reefs, shallow marine sandstones) could offer some potential for storage. However, data are sparse; many wells don't reach this deep and only regional geological maps are available to assess extent of the sandstones.

Oil and gas are reservoirs are dominantly found in Miocene strata, particularly Upper Miocene sandstones. Most reservoirs lie at depths between 1000 – 2500 m. Base Miocene breccia-conglomerate reservoirs could also offer storage opportunities, particularly where they are hydraulically connected with underlying Mesozoic or Palaeozoic basement rocks.

Pliocene and Quaternary strata deposited in Lake Pannon and subsequent fluvial systems comprise sands and sandy gravels with some clay and silt. These reservoir rocks could offer are not regarded as promising for fluid storage, because they represent potable aquifers and the presence of a caprock is not confirmed.

Adriatic

Upper Cretaceous limestones sealed by impermeable Miocene or Pliocene strata could offer saline aquifer storage options, especially in deep depressions like the Dugi Otok Basin.

Pliocene/Quaternary sandstones are documented to be gas-tight and lie at depths of 750 – 850 m. However, insufficient data are available to delineate the extent of potential saline aquifer storage sites.

There are three gas fields in the northern Adriatic included in the Hystories database. Reservoirs for two of these are in Pliocene-Quaternary sandstones, the third is in Upper Cretaceous limestone. These gas fields are around 60 km offshore from the nearest Croatian island shoreline.

Table 10: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore gas/condensate fields	7	Some of these traps are different geological horizons in the same field.	Additional studies required
Onshore oil fields	1	Tests of CO_2 injection to enhance oil recovery was carried out in Ivanic oil field (2003 – 2005)	Additional studies required
Onshore hydrocarbon fields	10	Some of these traps are different geological horizons in the same field. CO_2 present in some fields.	Additional studies required
Offshore gas fields	3		Additional studies required
Offshore saline aquifers	5	Identified during CO_2StoP project	Additional data collection required (seismic/wells)

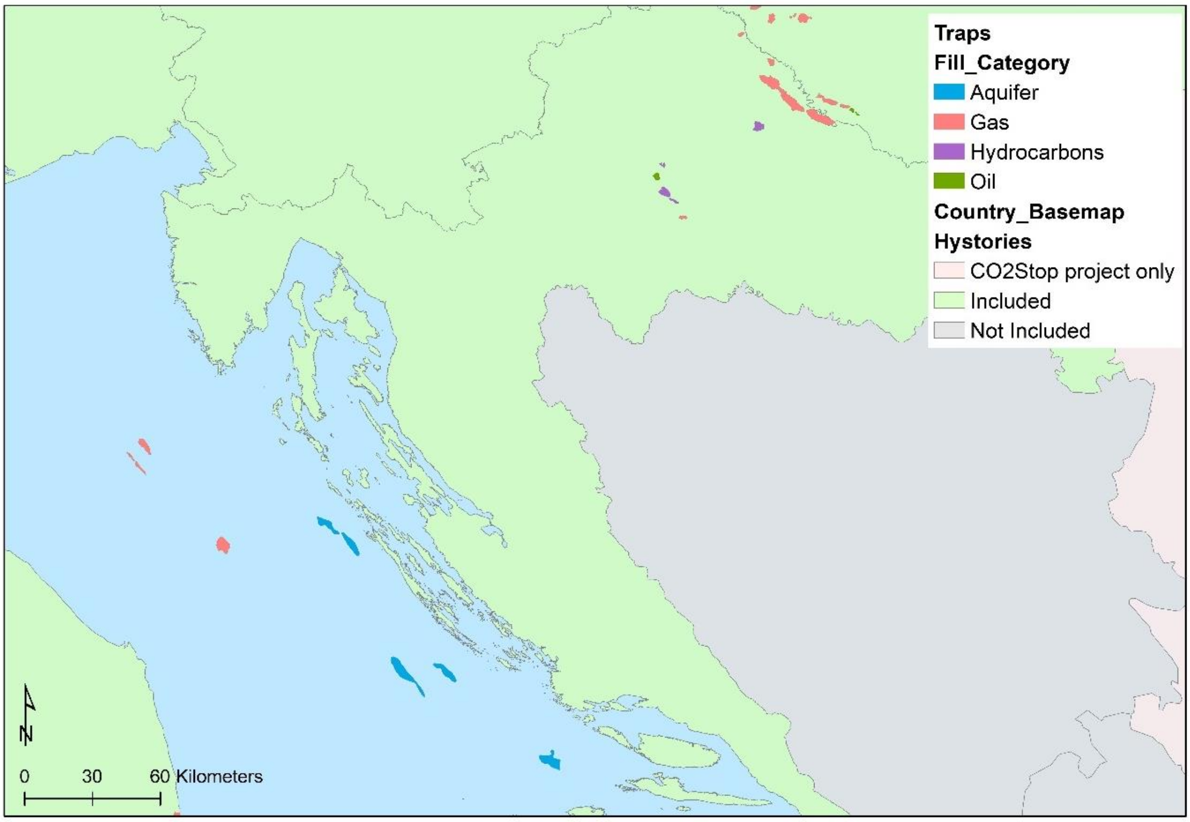

Figure 22: Overview of identified potential traps in the Hystories database within Croatia (and surrounding areas).

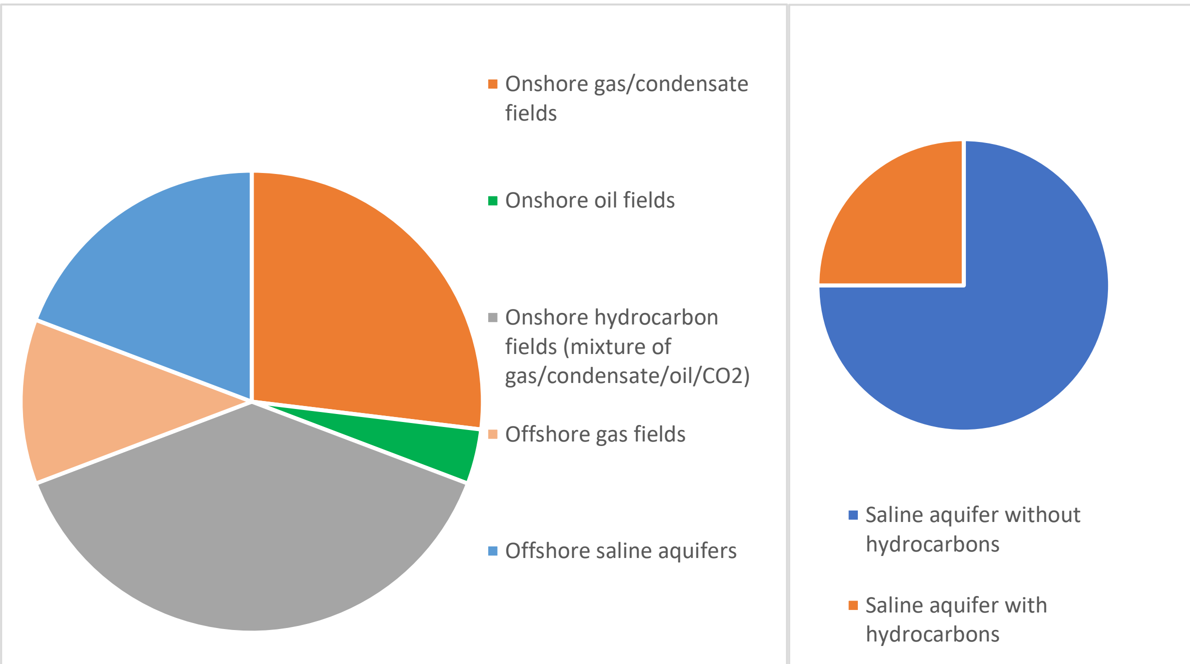

Figure 23: Frequency pie chart showing categories of identified potential storage opportunities in Croatia; storage traps (left) and units (right). Please note that some of the traps are different geological horizons in the same field. The 'fluid fill' attribute in the database has been completed with the fluid that represents the largest quantity

6.2.3. Existing storage sites

In 1987, the depleted gas field, Okoli was established as a UGS site with storage in the lower Pontian sandstone reservoir rocks within the Kloštar Ivanić Formation. Maximum storage capacity of the Underground Gas Storage Okoli is 553×10^6 Sm^3 (ECOINA 2017). Underground gas storage in Okoli is led by the Plinacro Group[5], the national gas distribution company.

6.2.4. Potential future development opportunities

The Ministry of Economy and Sustainable Development recently published a hydrogen strategy for Croatia until 2050 (Ministry of Economy and Sustainable Development, 2022[6]). This strategy highlights the need for the development of new power infrastructure that can accommodate more energy from renewables, and measures to stimulate electrification of transport (using electricity and renewable hydrogen). 'The Strategy therefore sets out indicative possibilities for the development of production, storage, transport and general use of hydrogen with the aim of reducing CO_2 emissions, as well as the possibility of including the economy in the equipment production sector (such as electrolyser layers and bundles of fuel cells, measuring and control equipment, sensors, etc.), thus ensuring technological adaptation and participation in the European and global market of hydrogen technologies' (Ministry of Economy and Sustainable Development, 2022).

The data included in the Hystories database should be considered as an initial estimate of the opportunities for underground hydrogen storage. A more thorough assessment of the individual characteristics of each site is required, including detailed lithology, mineralogy, geochemistry, microbiology if any of the identified traps were to be developed. In addition, the identified aquifer units will require further data collection or access to understand the properties of both the reservoir and sealing rocks to establish their effective storage potential.

6.3. Discussion and conclusions

The onshore Pannonian and offshore Adriatic basins have potentially large but currently poorly quantified storage potential. Access and resource to interpret seismic data is needed, along with access to well data. The onshore Pannonian basin has depleted oil fields and depleting gas fields which could be considered for UHS. The gas fields in the Adriatic Basin are still producing and are unlikely to be depleted and available for UHS anytime soon. The offshore gas fields are also quite distant from shore (around 60 km from the closest island shoreline) which will add to the logistical challenges of project development.

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[5] https://www.plinacro.hr/default.aspx?id=663

[6] https://mingor.gov.hr/UserDocsImages/UPRAVA%20ZA%20ENERGETIKU/Croatian%20Hydrogen%20Strategy%20ENG%20FIN%2022%208.pdf

7. The Czech Republic; geological assessment of storage opportunities

In the Czech Republic, the most promising geological structures suitable for hydrogen storage are in the eastern part of the country within the geological formations of the Carpathian Foredeep and the Vienna Basin. The geological settings provide potential opportunities for hydrogen storage in a variety of trap types and reservoir lithologies. Many hydrocarbon traps have been proven during nearly 100 years of oil and gas exploration in this region. Many of the known hydrocarbon fields have already been depleted or are in the final stages of production, some of them are already being used as for underground natural gas storage. These structures represent the most promising candidates for hydrogen storage. In addition, the presence and suitability of aquifer structures for underground gas storage is also verified by one practical example in the region, and the presence of more traps in aquifers is assumed. Additional storage potential, even though without any identified traps so far, is assumed in aquifers of the Bohemian Permo-Carboniferous succession in Central-North Bohemia.

7.1.Data availability and gaps

7.1.1. Data availability and collation

One source of data for the Hystories project was published literature including publications summarising geological information on oil and gas fields, publications describing geology and structures within individual subareas or geological and reservoir parameters of individual structures. A list of the main publications related to the geology of hydrocarbon-bearing structures in the Czech Republic is provided in Table 11. Published data on this topic are often generalised and simplified and provide only approximate parameters of structures and reservoirs.

Further, and often more specific and precise information was obtained from manuscripts held in the archives of the Czech Geological Survey. These sources include reports related to geological and geophysical exploration, reports on well results, well stratigraphy and lithology, structure and thickness maps. These archival data do not cover all known structures, but in some cases have provided relatively accurate parameters. More recently acquired data are often confidential and thus not available in the archives.

Based on the above sources, data from the earlier CO_2StoP and ESTMAP projects assessing potential for geological storage of CO_2 and underground energy storage, respectively, have been added and updated. The additional data concern mainly traps and units in the Hystories database, for which some parameters have been specified. For some parameters it was not possible to find plausible minimum/maximum values, so average values are given in the database (e.g., porosity, reservoir / seal thickness, pressures). In the case of limited or lacking data, estimations of the required parameters were necessary.

Archived and published maps were georeferenced and digitised into Shape files to generate contours of geological formations, which were in turn used to outline units and traps for the

Hystories database. The contours of the other objects in Shape format are from the existing CO_2StoP and ESTMAP databases.

Table 11: List of key data sources for the Czech Republic Hystories database

Source name / URL	Description	Version / Date
Durica, D., Suk, M. and Ciprys, V.: Energy resources – yesterday, today and tomorrow (in Czech). Moravske zemske muzeum, Brno.	A brief overview of hydrocarbon fields in the Czech Republic (in Czech).	2017
Golonka, J. and Picha, F.J. (eds.): The Carpathians and their foreland: Geology and hydrocarbon resources. AAPG Memoir 84.	Publication describing geology of the Carpathians and hydrocarbon fields in the area, incl. the Czech Republic	2006
Minarikova, D. and Lobitzer, H. (eds.): Thirty years of geological cooperation between Austria and Czechoslovakia. Fed. Geol. Survey Vienna, Geol. Survey Prague.	Publication related to geology and hydrocarbon fields in the Czech Republic, Slovakia and Austria.	1990
Bednarikova, J. and Thon, A. (eds): Oil industry in Czechoslovakia (in Czech). Knihovnicka zemniho plynu a nafty. Hodonin.	Publication related to geology of hydrocarbon fields in the Czech Republic and Slovakia.	1984
Pesek, J., Oplustil, S., Kumpera, O., Holub, V. and Skocek, V. (eds.): Paleogeographic Atlas of Late Palaeozoic and Triassic Formations, Czech Republic. Czech Geological Survey, Prague.	Publication describing geology of Palaeozoic sediments of the Bohemian Permo-Carboniferous basins	1998

7.1.2. Availability of detailed data for further site characterisation

The eastern part of the Czech Republic, where the most promising structures for underground hydrogen storage are located, is a well-explored area with generally well-known geological settings. Large parts of the area are covered by 3D seismic data, but these data are owned by private companies, and are not publicly available. For the same reason, not all well data are available in the Czech Geological Survey databases; especially data from more recent exploration and production wells targeting hydrocarbon fields. Detailed data for further site characterisation of hydrocarbon fields and UGS sites, including production data, are mostly held confidential by the operators of individual sites and are therefore not available in the public domain. Cooperation with Czech Geological Survey is usually based on case-by-case negotiations.

In general, data coverage of hydrocarbon fields is much better that that of aquifers. In particular, data are largely lacking for the aquifers of the Bohemian Permo-Carboniferous.

The location of wells and seismic lines are available in the Czech Geological Survey databases and can be viewed online and downloaded via CGS map apps[7], CGS WMS services[8], CGS Esri® ArcGIS server services[9] or via the CGS website[10].

7.1.3. Identified gaps in data availability

The aforementioned lack of access to 3D seismic, borehole and other geological and production data from hydrocarbon fields and UGS sites is reflected in the lack of some parameters and the necessity to use only results of earlier interpretations, for the Hystories database. However, published literature and reports provide data that is largely sufficient (even though often quite general) on known oil and gas fields in the Czech Republic for the purposes of the Hystories project.

The situation is different in the case of aquifers, for which there are – in most cases – very limited data available. This stems from the fact that these structures have been (so far) not of interest to exploration and production companies and therefore insufficiently or almost not at all explored by wells or seismic acquisition. Therefore, most aquifers in the Hystories database can only be considered as units within the Hystories database hierarchy, with a relatively high degree of uncertainty regarding the presence of structures / traps suitable for underground hydrogen storage. Verification of potential storage sites will require further geological and geophysical exploration, including drilling additional exploration and appraisal wells.

7.2. Geological opportunities for hydrogen storage

7.2.1. Geological summary

The most promising traps potentially suitable for hydrogen storage lie within the hydrocarbon production area in the east of the Czech Republic, at the contact zone between the Bohemian Massif and the Carpathian Mountains. Strata complexes in this region belong to several structural packages.

The units of the Bohemian Massif are represented by Precambrian crystalline rocks and, overlying clastic and carbonate sedimentary successions deposited during the Palaeozoic era to Paleogene epoch. Towards the southeast, the slopes of the Bohemian Massif dip below the Neogene fill of the Carpathian Foredeep. The units of the Bohemian Massif and partly also of

[7] http://www.geology.cz/extranet-eng/maps/online/map-applications

[8] http://www.geology.cz/extranet-eng/maps/online/wms

[9] http://www.geology.cz/extranet-eng/maps/online/esri

[10] http://www.geology.cz/extranet/mapy/mapy-online/stahovaci-sluzby

the Carpathian Foredeep are covered by the Late Cretaceous to Paleogene flysch complexes of Western Carpathians. On the units of Alpine-Carpathian nappes, the Vienna Basin is superimposed in the very south-east of the country, as a tectonic depression filled by Miocene deposits.

From the regional geology point of view, this area includes the Vienna Basin, Alpine-Carpathian Foredeep and Carpathian Flysch Belt overlying eastern / south-eastern slopes of the Bohemian Massif.

As a result of the complex tectono-sedimentary evolution of the area at the junction of the European foreland plate, the Alpine and the Carpathian orogeny, the local geological settings provide a varied range of lithological reservoir types in different types of hydrocarbon-bearing structures. Known hydrocarbon reservoirs in the area include tectonic, stratigraphic, lithologic, and combination trap types.

Hydrocarbon-bearing structures on the slopes of the Bohemian Massif are found in the upper parts of fractured and weathered crystalline basement, in siliciclastic and fractured carbonate formations deposited during the Devonian and Jurassic periods. Reservoirs with hydrocarbon accumulations in the Vienna Basin are predominantly clastic-only with locally developed carbonates. Hydrocarbon traps are present in all Miocene strata, the most important are found in deposits from the Badenian Stage. The Carpathian Foredeep traps are also developed in clastic formations.

Systematic hydrocarbon exploration of the area has been going on for almost 100 years. Many of the known hydrocarbon fields have already been depleted or are in the final stages of production. Some of the depleted fields have been converted for use as underground gas storage sites. All underground gas storage sites in this area are located in porous formations, one of them in an aquifer trap and the others in depleted hydrocarbon fields.

The area also contains a number of aquifer units with both CO_2 and hydrogen storage potential. In the eastern part of the Czech Republic, they are mostly situated in the clastic Miocene fill of the Carpathian Foredeep. Paleogene clastics and fractured Palaeozoic rocks may also be considered as suitable reservoirs. The presence of structures potentially capable of being used as underground hydrogen storages is assumed here, particularly based on the presence of geological formations with suitable lithology of reservoir and seal rocks, however no traps have yet been verified within these aquifer units.

The Bohemian Permo-Carboniferous basins represent another geological unit with interesting geo-energy potential. They are situated in the central-northern part of the country. The basins are filled with Upper Carboniferous to Lower Permian (Pennsylvanian – Cisuralian) continental clastic sediments, which represent potential for geological storage of CO_2 and/or hydrogen in saline aquifers located close to the basin floor and forming two stratigraphic levels in the basin centre. The aquifer units comprise sandstones and conglomerates most likely of braided fluvial to alluvial fan origin, pertaining to the Kladno and Tynec formations.

7.2.2. Storage assessments

For the purposes of the Hystories database, three areas (formations in the database hierarchy) have been defined within the territory of the Czech Republic where reservoirs with good lithological development and – in two cases – also hydrocarbon traps are proven. Two formations are found in the eastern part of the Czech Republic in the Carpathian Foredeep and the Vienna Basin. The geological structures in these formations, predominantly clastic reservoirs (sandstones, gravels), are considered the most promising in terms of the proven occurrence of traps potentially suitable for hydrogen storage.

In the Hystories database, 19 potential saline aquifer storage 'units' are identified within the Carpathian Foredeep. Within four of these units, underground natural gas storage sites have been developed. Three UGS sites have been developed in depleted hydrocarbon fields (Tranovice, Stramberk, Dolni Dunajovice) and one in an aquifer (Lobodice). These existing gas stores are included in the Hystories database as traps. For all these database units, the reservoirs formations are Neogene sandstones. Neogene claystones or the impermeable claystone parts of Flysch units would be expected to seal these potential stores.

In the Vienna Basin, two (tectonic) units have been selected for the Hystories database, which contain underground gas storage sites (Poddvorov – West field and Tvrdonice) in depleted hydrocarbon traps. Again, these structures are included as traps in the database. Reservoir rocks in both structures are Neogene sandstones, the seal is provided by Neogene pelitic deposits.

A summary of identified storage opportunities in the Czech Republic is shown in Table 12, Figure 24 and Figure 25.

Table 12: Summary of identified storage capacity options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	1	Natural gas storage	Site specific studies required.
Aquifers (units)	23	-	More geo data and detailed interpretation required.
Hydrocarbon reservoirs	5	Natural gas storages	Site specific studies required.

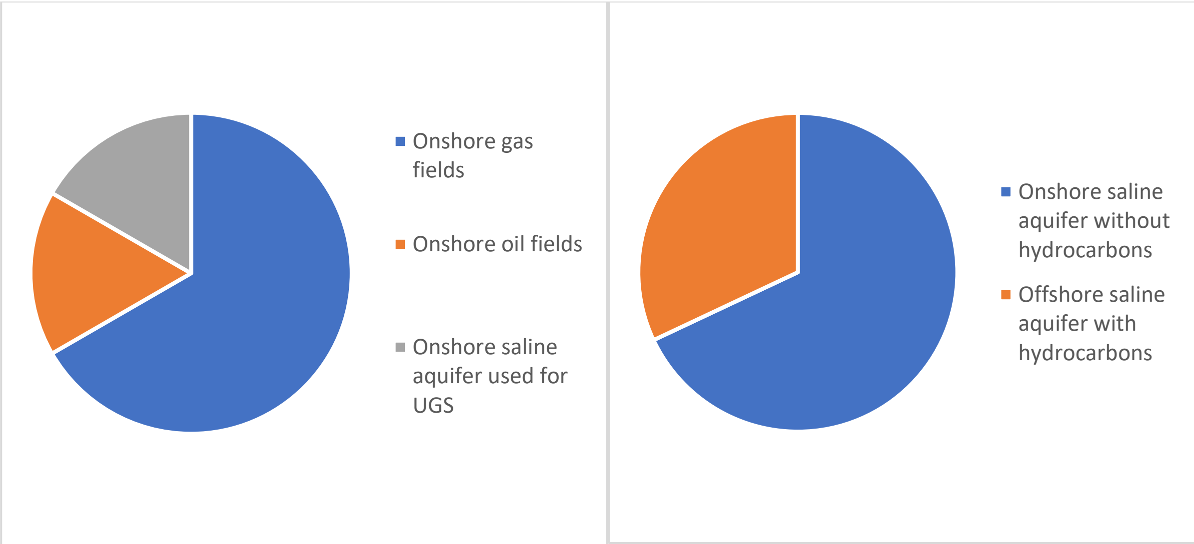

Figure 24: Frequency pie chart showing categories of identified potential storage opportunities in the Czech Republic; traps (left) and units (right). Please note that in the traps pie chart that the oil field indicated here is an oil field with a gas cap. This field is depleted. The onshore saline aquifer indicated here is used as a natural gas storage site.

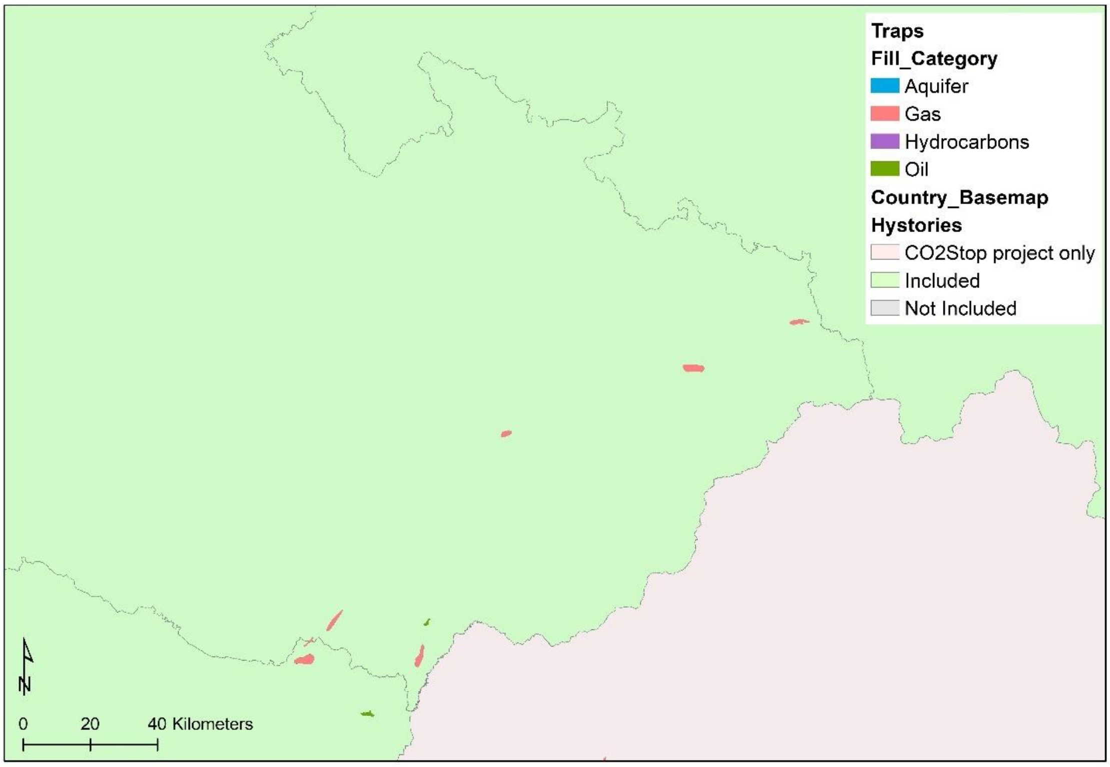

Figure 25: Overview of identified potential traps in the Hystories database within the Czech Republic (all in the east).

Other opportunities for underground hydrogen storage in these two tectonic units of the Vienna Basin are mainly in hydrocarbon traps that are depleted or are in the final phases of production. There are number of such structures in the Vienna Basin, the Carpathian Foredeep, and the formations on the slopes of the Bohemian Massif.

Clastic reservoirs in rocks of Jurassic and Devonian age have been verified on the buried slopes of the Bohemian Massif. In the Jurassic and Devonian formations, good reservoir rocks also occur in fractured carbonates (limestones, dolomites). Rocks in the upper zones of the crystalline basement in areas where they are fractured and weathered also have relatively good reservoir properties. However, not enough public data are available to fully assess all these structures in terms of which provide opportunities for large-scale capacity underground storage. Where sufficient data are available in the public domain are summarised in the project database.

The third of the main formations is the Bohemian Permo-Carboniferous in Central-North Bohemia. However, the occurrence of promising traps is less likely. In this formation, four units have been defined that are expected to offer suitable reservoir conditions for storage. No traps have yet been verified in this area.

7.2.3. Existing storage sites

There are nine underground gas storage sites in the Czech Republic. One gas storage site (Haje) is in caverns in crystalline rocks. All the others are in porous formations of the slopes of the Bohemian Massif (Damborice, Uhrice), Neogene of the Carpathian Foredeep (Dolni Dunajovice, Lobodice, Tranovice, Stramberk) and of the Vienna Basin (Tvrdonice, Dolni Bojanovice). Only one of the UGS sites in porous media is in an aquifer (Lobodice), the others are in depleted hydrocarbon fields.

In the context of geological storage of hydrogen, the Lobodice underground storage requires some attention. It is the only aquifer gas storage and the first underground gas storage in the Czech Republic, operated since 1965. Town gas with high hydrogen content (more than 50%) was originally stored here. During 1990, the structure was converted to natural gas storage. Hydrogen losses are documented from the town gas storage period, the cause of which could be microbial methanation, chemical reactions in the reservoir or hydrogen leakage through the caprock, or (most probably) a combination of these. More detailed information on this issue can be found in Smigan et al. (1989), Onderka and Buzek (1991 – in Czech), Buzek et al. (1994).

7.2.4. Potential future development opportunities

The Czech Republic data included in the Hystories database should be considered as an initial estimate of the opportunities for underground hydrogen storage. For possible conversion of any of the structures to a hydrogen storage site, a more thorough assessment of the individual characteristics of each site is required, including detailed lithology, mineralogy, geochemistry, microbiology. In addition, the identified aquifer units will require further exploration and more precise definition of the geological settings and properties of both the reservoir and sealing rocks to specify their effective storage potential.

7.3. Discussion and conclusions

There is abundant experience in the Czech Republic with the operation of underground gas storage in both crystalline rock caverns and porous rocks, including from UGS in depleted hydrocarbon traps and one aquifer structure. There is also more than 20-years' experience of aquifer town gas storage operations with high hydrogen content. This UGS site encountered significant losses of hydrogen caused by several reasons, possibly including microbiological activity or leakage through the caprock, and was converted to a conventional UGS over 20 years ago.

There are depleted and nearly depleted hydrocarbon fields in traps of various types and lithologies that could possibly be used for hydrogen storage. Other storage opportunities may be in aquifers but, so far, these lack sufficient geological data to specify or confirm their potential. Existing underground gas storage sites and known hydrocarbon traps are considered the best opportunities at present.

8. Denmark; geological assessment of storage opportunities

The geology of Denmark is characterized by a thick cover of sedimentary rocks of Late Palaeozoic – Cenozoic age. In the Norwegian-Danish Basin, the sedimentary succession above the top Pre-Zechstein is up to 10 km thick.

Five sandstone rich formations are mapped and within these formations, 14 geological structures have been identified. Based on available data, the Gassum and Haldager Sand Formations appears to offer the best storage options. Significant storage potential appears to be present. Owing to limitations in the existing data, the geophysical and geological interpretations of the structures are not expected to be accurate and new seismic data acquisition and assessment wells are required to improve the current evaluation. Maturing these potential opportunities for hydrogen storage will demand detailed geological characterisation of the structures.

All Danish hydrocarbon fields are situated offshore in the Central Graben and detailed data are not publicly available. Most of the Danish hydrocarbon field reservoirs lie in chalk, a few in sandstones.

Many salt domes and diapirs are mapped throughout the Danish area and storage in salt caverns will probably be the most economic option for storage of hydrogen in Denmark.

8.1. Data availability and gaps

8.1.1. Data availability and collation

During 2020, the Geological Survey of Denmark and Greenland (GEUS) assessed the national CO_2 storage potential (Hjelm *et al.* 2020). Four potential storage formations and 14 geological structures (traps in the Hystories hierarchy) from this assessment are included in the Hystories database and GIS. Additionally, one more potential store has been included in the Hystories database, because the reservoir depth recommendation from Hystories is 500 metres whereas the minimum reservoir depth recommended for CO_2 storage is 800 metres. The outlines of storage units and formations in the Hystories GIS are based on the latest regional geological mapping exercise of the Danish onshore and inland waters published via the geothermal WebGIS-portal[11]. Salt structures are also included in the Geothermal WebGIS-portal but not in the Hystories database.

All oil and gas activities in Denmark are located offshore in the Danish North Sea sector. Data about the oil and gas fields are owned by the operators and their partners, but production data from the oil and gas fields are available from the Danish Energy Agency[12].

[11] https://data.geus.dk/geoterm/ (updated 2015)

[12] https://ens.dk/en/our-services/oil-and-gas-related-data

In general, the data availability and quality are unevenly distributed throughout Denmark and detailed data are not always available, either because data are sparse, older (low quality) or owned by licence holders, present or past (Figure 26). Models have been built for some of the structures included in the Hystories database and a summary of data availability and existing models is given in Table 13.

Table 13: List of key data sources for the Danish Hystories database

Source name / URL	Description	Version / Date
Danish Energy Agency: Oil and Gas Production in Denmark and Subsoil Use 2013. oil_and_gas_in_denmark_2013.pdf (ens.dk)	Reporting of oil and gas reserves Denmark	2013
The Nordic CO_2 Storage Atlas: Nordic CCS Competence Centre (geus.dk)	Assessment of CO_2 storage potential	2015
Danish Energy Agency: oil_and_gas_in_denmark_2013.pdf (ens.dk)	Reporting of subsurface storage uses	2013
Geotermi WebGIS-portal: Geotermi WebGIS-portalen (geus.dk)	Geothermal reservoir maps incl. salt structures	2015
Carbon, Capture, Usages and Storage (CCUS) 2020 project: CCUS-projekt 2020 (geus.dk)	National assessment of CO_2 storage sites	2020
Danish Energy Agency: Oil and Gas Related Data | Energistyrelsen (ens.dk)	Public data about the Danish oil and gas fields	2022, continuously updated

The formation, storage unit and geological trap structures included in the Hystories database combine data from several research projects. In particular, the latest national assessment of the Danish CO_2 storage potential (Hjelm *et al.* 2020) and the geothermal GIS-portal[13], proved useful for confirming sources of detailed data (Table 14 and Figure 26). The geothermal GIS-portal includes the latest regional seismic interpretation of Denmark.

More geological data (including structural maps and seismic sections) for 14 potential aquifer traps (geological structures) included in the Hystories project GIS database are available in Appendix B of Hjelm *et al*., 2020. A summary of available data for the identified traps is shown in Table 14.

8.1.2. Availability of detailed data for further site characterisation

An overview of Danish subsurface data is available from the Danish Deep Subsurface Data[14]. In general, GEUS is the primary contact for further information and data related to Danish onshore or nearshore storage options.

[13] https://data.geus.dk/geoterm/

[14] https://data.geus.dk/geusmap/?mapname=oil_and_gas&lang=en#baslay=&optlay=&extent=-411207.20151359634,5787725.2756015835,1282126.131819737,6596468.3311571395&layers=samba_

Detailed data about oil and gas fields are owned by the operators and their partners. Information on current oil and gas field licence holders are available from the Danish Energy Agency website [About oil and gas](https://ens.dk/en/our-responsibilities/oil-gas/about-oil-and-gas) [15].

8.1.3. Identified gaps in data availability

As the geological data in general (wells, seismic surveys, and models) are sparse, older, or owned by licence holders, the geological heterogeneity of the storage formations, storage units and structures is not always well documented. Likewise, reservoir fluid composition data are rarely available and generally only sampled in relation to geothermal exploration.

Detailed data about caprocks are difficult to find, very few data are available on porosity, permeability, heterogeneity or geomechanical rock properties.

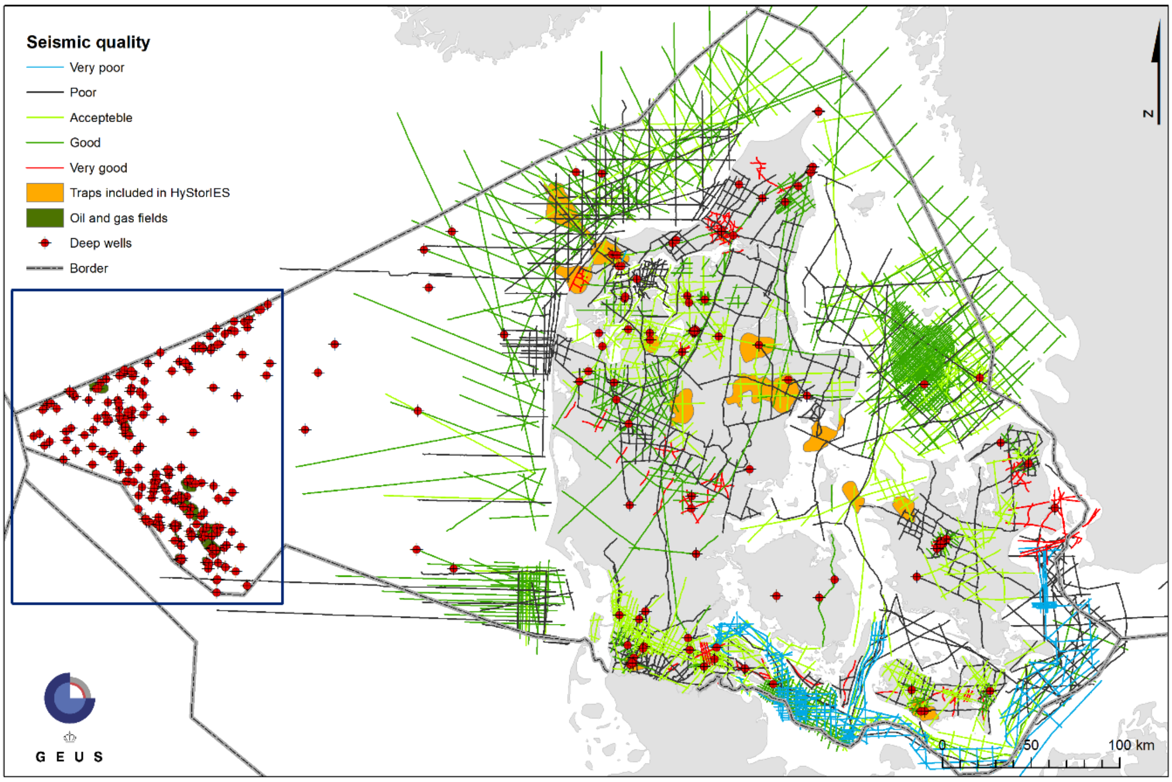

Figure 26: Seismic data quality and density (Danish onshore and near shore) and all deep wells. The blue square highlights the hydrocarbon production area. No seismic lines are shown for this area and detailed geological data are not publicly available.

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wellbores,seismic_lines,dkterritorialgraense,oil_and_gas_basemap&filter_0=txt_search.part%3D&filter_1=line_name.part%3D%26survey_name.part%3D%26survey_type.part%3D%26completion_date.min%3D%26start_date.max%3D

[15] https://ens.dk/en/our-responsibilities/oil-gas/about-oil-and-gas

Table 14: Summary of data availability for the 14 structures included in the GIS database.

Name	Wells	Seismic surveys quality*	Models
Hanstholm Reservoir for both Skagerrak and Gassum Fms	Felicia-1, located at the flank of the structure	Poor to good	Model is published in Frykman (2020a) and CO_2 injection simulation in Nielsen (2020).
Thisted	Thisted-1, -2, -3 and -4 Thisted-5 (not released)	Poor to good	none
Legind	none	Poor to very good	none
Vedsted	Vedsted-1	Very good	The structure has been surveyed for CO_2 storage in 2009. Model is published in Frykman *et al*. 2011; Nielsen *et al*. 2013; Nielsen *et al*. 2015.
Skive	Skive-1 and -2	Acceptable	none
Gassum	Gassum-1	Poor to good Sparse data	Model is published in Nielsen & Frykman (2012).
Thorning	none	Acceptable Sparse data	none
Voldum	none	Acceptable to good	none
Helgenæs	none	Poor Sparse data	none
Røsnæs	none	Poor to acceptable Sparse data	none
Havnsø	none	Poor to acceptable New seismic data are assembled in 2022 The structure is surveyed for CO_2 storage	Model is published in Frykman (2020b) and CO_2 injection simulation in Nielsen (2020).
Rødby	Rødby-1 and -2	Acceptable to good	none
Tønder	Tønder-1, -2, -3, -4 and -5	Poor to acceptable	Geothermal model owned by Tønder Fjernvarme and not publicly available. Gas storage model owned by DONG/ Ørsted and not publicly available.

**Definitions of the seismic survey quality. Before 1970: Very poor or poor; 1971-1980: Acceptable; 1981-1990: Good; 1991 and later: Very good.*

8.2. Geological opportunities for hydrogen storage

8.2.1. Geological summary

The geology of Denmark is characterised by thick sedimentary cover of Late Palaeozoic – Cenozoic age. In the Norwegian-Danish Basin, the sedimentary succession above the top Pre-Zechstein is up to 10 km thick (Figure 27). The basin is bounded to the north and northeast by the Sorgenfrie-Tornquist Zone and Skagerrak-Kattegat Platform (the Fennoscandian Border Zone) and to northwest–southeast by the Ringkøbing–Fyn basement high. The sedimentary cover on this structural high is relatively thin (1 – 2 km). The North German Basin is situated south of the Ringkøbing–Fyn High with sediment thickness comparable to the Norwegian-Danish Basin, but only the northern rim of the basin is located within the Danish area.

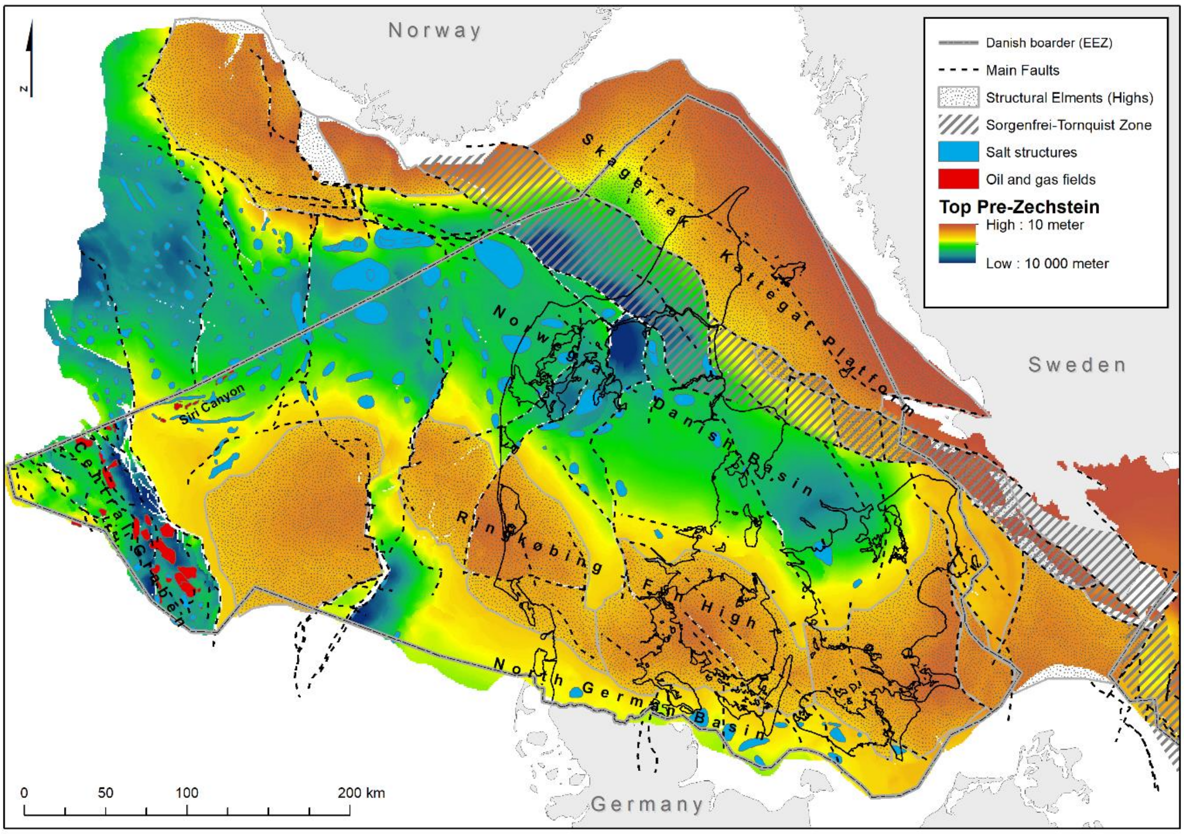

Figure 27: Map showing major structural elements and depth to top Pre-Zechstein in Denmark. Modified from Vejbæk & Britze (1984).

The sediments are affected by mainly northwest–southeast striking normal faults. In the Norwegian-Danish Basin and the North German Basin, post-depositional flow of Permian salt formed large domal structures which strongly influenced later deposition. Locally, the overlying sedimentary succession is strongly truncated over the top of rising salt domes and diapirs, and minor faults often accompany the salt structures.

The Central Graben area, in the westernmost part of the Danish offshore area, is the main hydrocarbon exploration and production area in Denmark. Hydrocarbon reserves are present in chalk of Late Cretaceous and Danian age. The Chalk Group continues and thickens eastwards into the onshore area of Denmark where it reaches a thickness between 1 and 2 km in the Danish Basin (eastern part of the Norwegian-Danish Basin).

During the Cenozoic, the North Sea constituted a large epicontinental sea with a north-south axis. Sediments are dominated by offshore mudstones reaching a total thickness of more than 3 km in the western part of the Danish Exclusive Economic Zone (Michelsen 1994). Locally, sandstones are present in the succession, representing a target for hydrocarbon exploration and CO_2 storage, e.g., the Siri Canyon system (Project Greensand) (Figure 27).

The primary aquifer storage option in Denmark is sandstone layers. As shown in Figure 28, based on their relatively high content of sandstone layers the most prospective formations for storage in Denmark are:

- Bunter Sandstone (Triassic)
- Skagerrak Formations (Triassic)
- Gassum Formation (Upper Triassic–Lower Jurassic)
- Haldager Sand Formation (Middle Jurassic)
- Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)
-

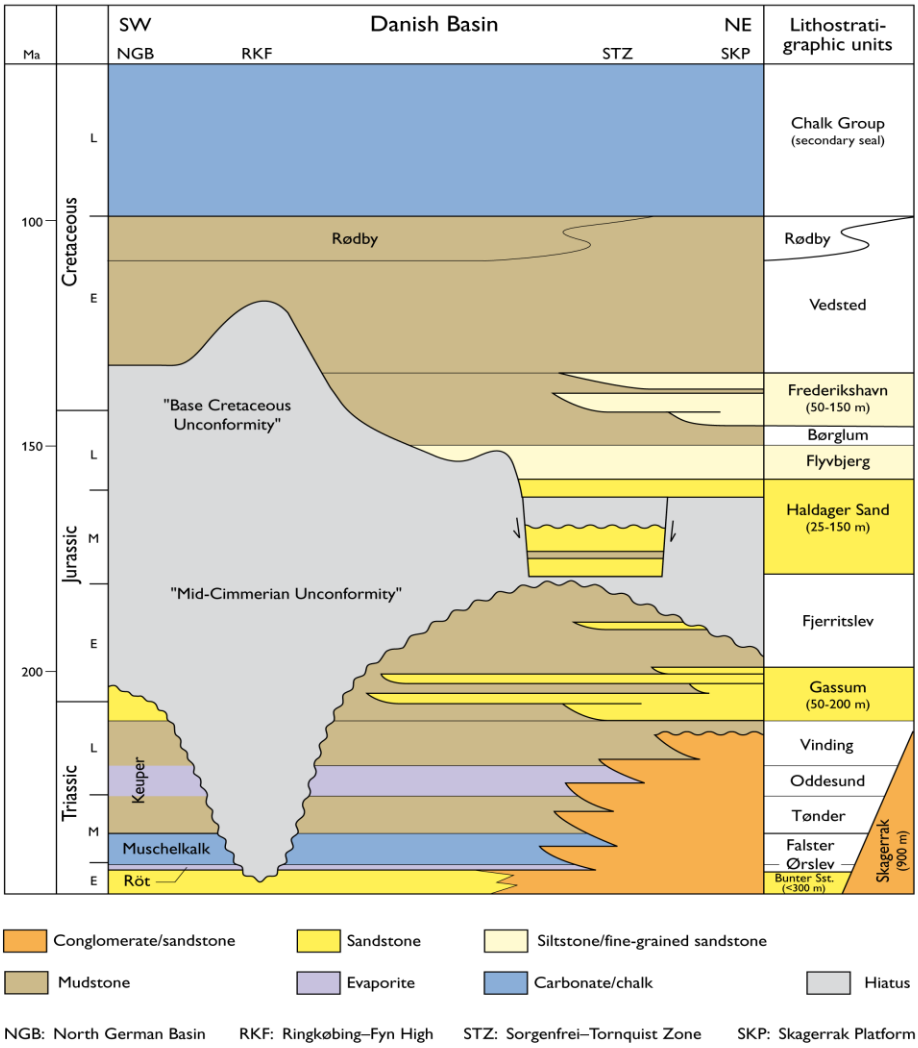

Figure 28: Simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish part of the Norwegian-Danish Basin. Based on Bertelsen 1980; Michelsen & Clausen 2002; Michelsen et al. 2003.

Geological formations in Denmark with good caprock properties are lacustrine and marine mudrocks, evaporites and carbonates. The most important caprock type is marine mudstones, which are present at several stratigraphic levels (Figure 28). Leakage could potentially take place through the caprock due to slow capillary migration, through micro-fractures or along faults unless the seal is suitably impermeable. Detailed site surveys will be required to test the integrity of the seal at future storage sites.

Bunter Sandstone Formation and Skagerrak Formation (Triassic) reservoirs

The Bunter Sandstone and Skagerrak Formations are present throughout the Danish area. Lower Triassic sandstones of the Bunter Sandstone Formation are dominant in the southern, western, and central part of the Danish Exclusive Economic Zone and are gradually replaced by the Skagerrak Formation encompassing most of the Triassic sediments towards the north-eastern basin margin (Figure 29).

The sandstone dominated succession of the Bunter Sandstone Formation forms a widespread unit with thickness around 300 m, although it may reach 900 m in the central part of the Danish Basin. The thickness of the individual sandstone intervals may be up to 30 – 50 m (Weibel *et al*. 2020). It is anticipated that no strong primary hydraulic barriers exist within the sheet sandstone (Sørensen et al. 1998). The succession is thin and locally absent across the Ringkøbing–Fyn High.

Core analyses show that several sandstones layers in the Bunter Sandstone Formation have porosity of 15 – 35% and a corresponding permeability of 10 – 3000 mD (Weibel *et al*. 2020).

The Skagerrak Formation is present in the Norwegian–Danish Basin where it locally occurs with thicknesses up to 5 km (Bertelsen 1980; Liboriussen *et al.* 1987). Onshore wells penetrating the Skagerrak Formation are limited but indicate that individual sandstone-dominated intervals may exceed 200 m. The sandstone-dominated intervals consist primarily of clayey sandstones and the reservoir permeability is generally quite low (Weibel *et al*. 2020). The conclusion that permeability is low is primarily based on analysis of well test data.

Caprocks for the Bunter Sandstone and Skagerrak Formations

Ørslev/Röt Formation (Lower Triassic)

This formation is time-equivalent and transitional to parts of the coarse-grained deposits of the Skagerrak Formation. The Ørslev/Röt Formation is found on the northern edge of the depositional system. The fine-grained formation reaches 100 – 400 m in thickness in the North German basin, south of the Ringkøbing-Fyn High.

Muschelkalk /Falster Formation (Middle Triassic)

This formation is characterised by intercalated limestones, claystones and halites (Bertelsen 1980). Fine-grained sandstones are locally present in the upper part of the formation. The formation reaches 100 – 200 m in thickness and forms a secondary seal for the Bunter Sandstone Formation in the Rødby and Tønder structures. It was deposited contemporaneously with parts of the Skagerrak Formation.

Keuper /Oddesund Formation (Upper Triassic)

This formation is described as a unit characterised by calcareous, anhydritic claystones and siltstones intercalated with thin beds of dolomitic limestone (Bertelsen 1980). In the central part of the Danish Basin two prominent units of halite are present dividing the formation into three informally recognised members. The formation varies in thickness due to local uplift of the underlying Zechstein salt and reaches a maximum thickness of 1500 m. It was deposited contemporaneously with parts of the Skagerrak Formation.

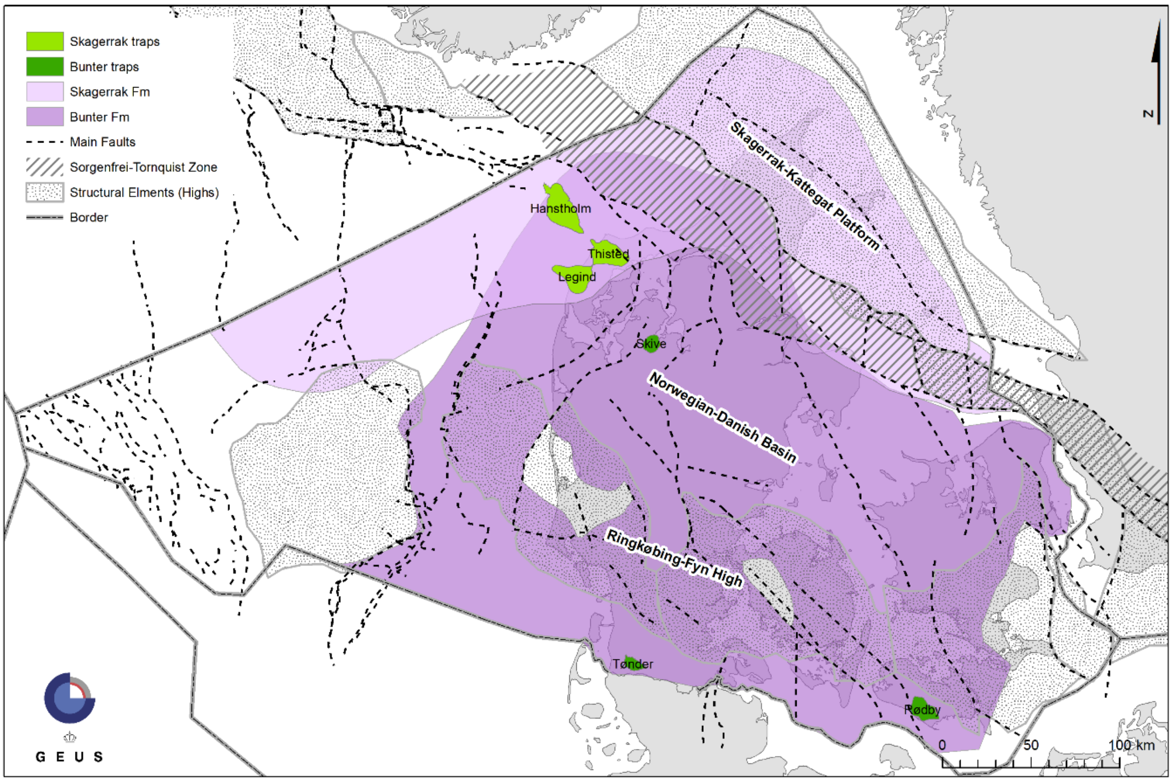

Figure 29: The distribution of the Bunter and Skagerrak Formations and identified trap structures within these two formations.

Gassum Formation (Upper Triassic–Lower Jurassic) reservoirs

The formation is widely distributed in the Norwegian–Danish Basin and shows a remarkable continuity with thickness between 50 and 150 m throughout most of Denmark, reaching a maximum thickness of 300 m in the Sorgenfrei-Tornquist Zone. Locally it may be missing due to uplift and erosion related to vertical salt movements and it is generally lacking over the Ringkøbing–Fyn High, though it is patchily preserved south of the high (Nielsen & Japsen 1991; Nielsen 2003). It further occurs with reduced thicknesses on the Skagerrak–Kattegat Platform Figure 30).

The Gassum Formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with heteroliths, claystones and locally thin coal beds (Michelsen *et al*. 2003; Nielsen 2003). In general, the reservoir properties are excellent with porosities ranging from 10 – 35% (maximum 36%) and permeability up to 10,000 mD.

In the eastern onshore and nearshore parts of the Norwegian–Danish Basin, the formation may reach up to 150 m in thickness and contain 5 to 20 sandstone layers. The thickness of the individual sandstone-dominated intervals varies between 5 and 60 m, and about half of the sand gross thickness offers reservoir-quality sandstone, having high porosity and permeability (Weibel *et al*. 2020).

Caprock for the Gassum Formation

Fjerritslev Formation (Lower Jurassic)

The formation is characterised by a relatively uniform succession of marine, slightly calcareous claystones, with varying content of silt and siltstone laminae. Siltstones and fine-grained sandstones are locally present being most common in the north-eastern and eastern, marginal areas of the Norwegian-Danish Basin (Michelsen 1975, 1978; Michelsen *et al*. 2003; Nielsen 2003). The formation is present over most of the Danish Basin with a thickness of up to 1000 m although this varies significantly due to mid-Jurassic erosion.

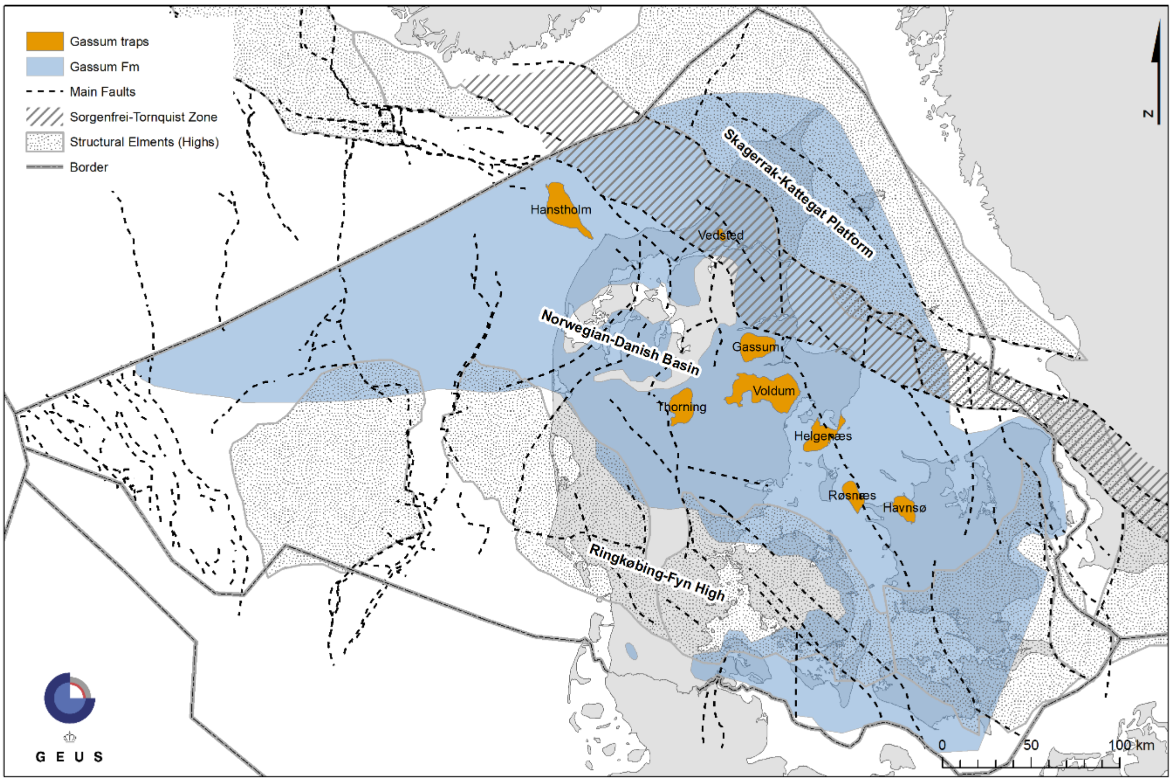

Figure 30: The distribution of the Gassum Formation and the identified trap structures.

Haldager Sand Formation (Middle Jurassic) reservoirs

The formation is present in the eastern onshore and nearshore parts of the Norwegian–Danish Basin, in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform (Figure 31). It is absent on and along the Ringkøbing-Fyn High and is thin and patchy in large parts of the basin except for in rim-synclines to salt structures. The formation reaches its greatest thickness of approximately 150 m in wells in the Sorgenfrei-Tornquist Zone and generally thins towards the North on the Skagerrak-Kattegat Platform and towards the South in the central part of the basin. According to the results of the core analysis, the porosity of the sandstones is typically 10 – 35% with varying permeability of 1 – 2000 mD (Weibel *et al*. 2020).

The Haldager Sand Formation comprises thick beds of fine- to coarse-grained, locally pebbly sandstones intercalated with thin siltstone, claystone and coal beds. Deposition was locally affected by movement of underlying salt structures.

Caprocks for the Haldager Sand Formation

Flyvbjerg and Børglum Formations

The Flyvbjerg Formation comprises primarily siltstones and fine-grained sandstones with poor reservoir quality. It is regarded neither as a prime reservoir formation nor as a seal. However, it directly overlies the Haldager Sand Formation and thus may act as a transitional formation into the sealing claystones of the overlying Børglum Formation.

The Upper Jurassic Børglum Formation comprises a uniform succession of slightly calcareous claystones (Michelsen *et al*. 2003). The Børglum Formation is present in most of the Danish Basin and reaches a maximum thickness of 300 m towards the Fjerritslev Fault (rim of the Sorgenfrei-Tornquist Zone). It thins rapidly towards the northeast, south and southwest.

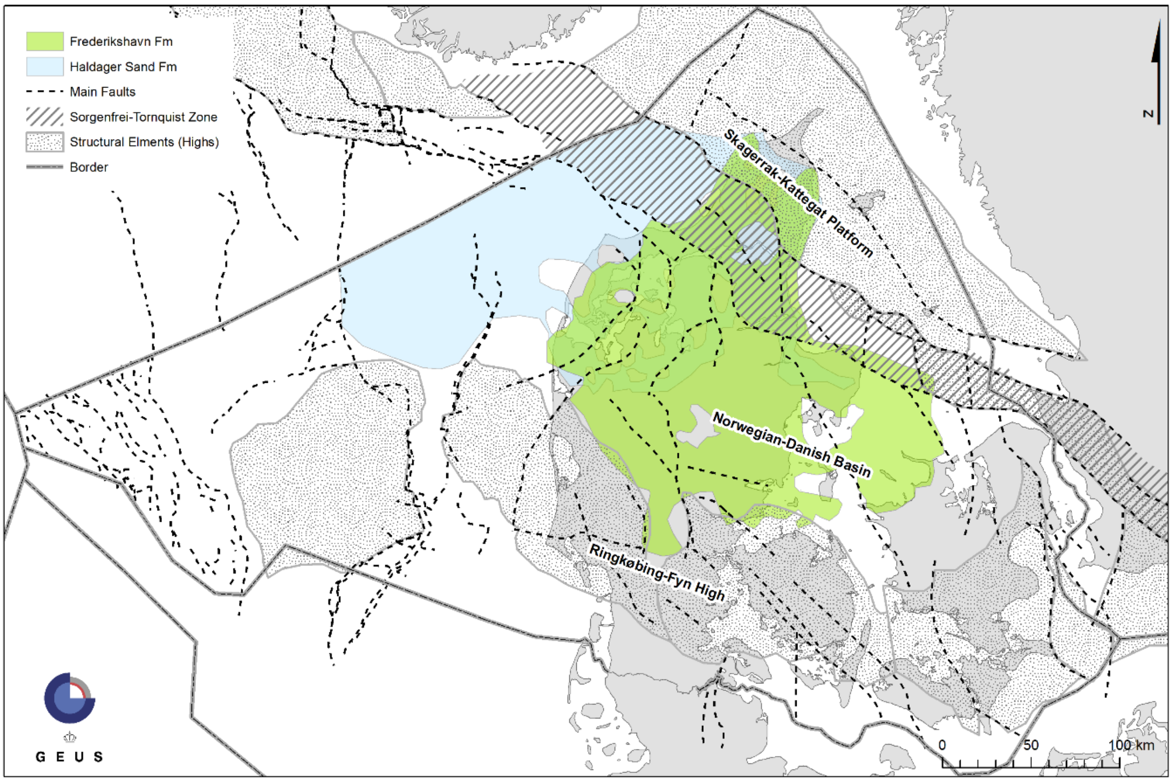

Figure 31: The distribution of the Haldager Sand and Frederikshavn Formations. No trap structures have been identified within these two formations as they are too shallow for CO_2 storage and therefore seismic interpretation was not undertaken in the previous large-scale studies that formed the basis for the Hystories assessment.

Frederikshavn Formation (Upper Jurassic–Lower Cretaceous) reservoirs

The formation is present in the northern part of the Norwegian–Danish Basin and reaches a maximum thickness of more than 230 m in the Sorgenfrei-Tornquist fault zone (Figure 31). Local faults and salt tectonics are the primary control on thickness variations. The formation comprises siltstones and fine-grained sandstones forming two to three coarsening-upwards units separated by claystones (Michelsen *et al*. 2003). The reservoir zones of the Frederikshavn Formation mainly comprise fine-grained and rather clay-rich sandstones, which negatively affect reservoir properties. For a given porosity, the permeability is commonly only half the permeability of the Haldager Sand and Gassum Formation sandstones (cf. data from well-specific core analysis reports available from the GEUS subsurface archive[16]https://eng.geus.dk/products-services-facilities/archives/the-subsurface-archive).

Caprocks for the Frederikshavn Formation

Vedsted and Rødby Formations (Lower Cretaceous)

Marine mudstones of the Vedsted and Rødby Formations form the primary sealing formation for the Frederikshavn Formation.

Chalk Group (Upper Cretaceous – Lower Palaeocene)

In most of the Danish Basin, a succession of carbonate rocks several kilometres thick forms a possible secondary seal. The sealing effect is dependent on chemical reactions between the dissolved gas and the generally low permeable carbonate rock.

8.2.2. Storage assessment

An accurate delineation of potential storage structures in the Danish subsurface continues to be challenged by a limited amount of data and varying data quality. Limitations imposed on the existing database by sparse seismic coverage, low seismic resolution, mismatch between intersecting seismic lines, low number of deep boreholes, insufficient borehole information (e.g., wireline logs, core data) mean that there is considerable inaccuracy associated with the geophysical and geological interpretations of the structures in the Danish subsurface (Hjelm *et al.* 2020).

A summary of identified closures is provided in Table 15 (for locations see Figure 29, Figure 30). The current assessment has considered the structures shown in Figure 32. It is assumed that the potential is larger than has currently been identified and that new data would indicate more storage opportunities.

[16] https://eng.geus.dk/products-services-facilities/archives/the-subsurface-archive

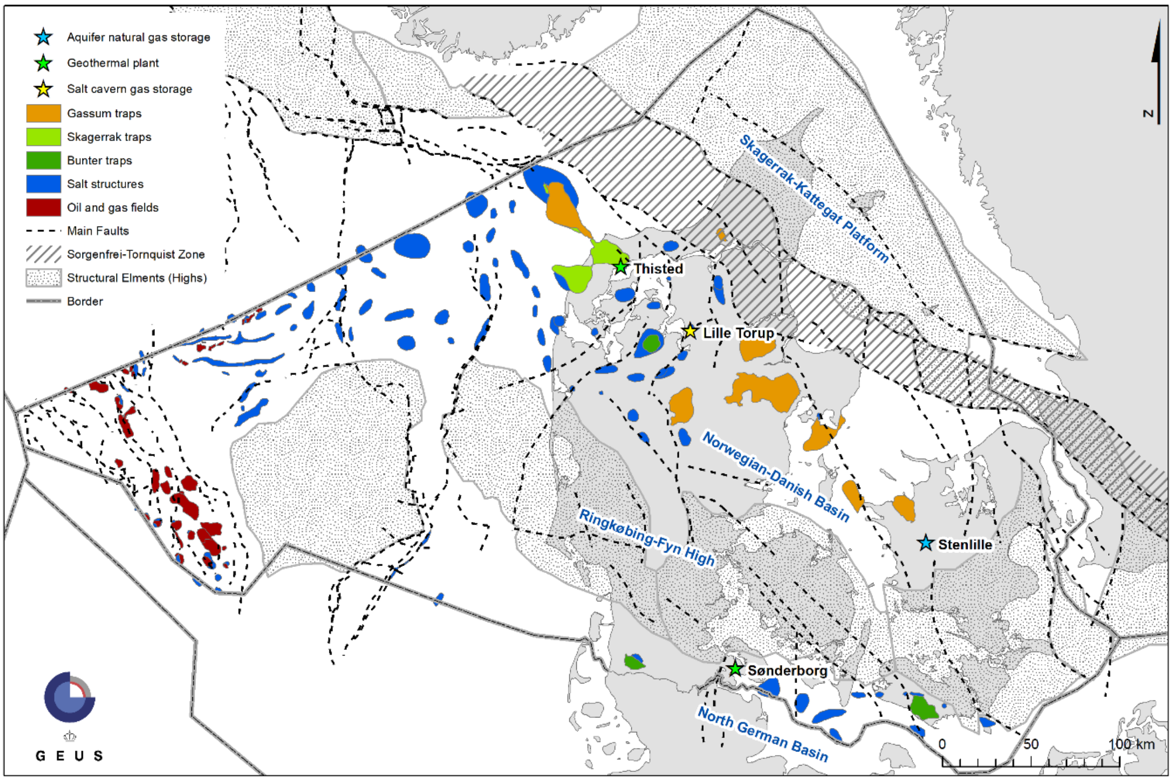

Figure 32: Overview of identified potential traps in the Hystories database Denmark; hydrocarbon fields, salt domes, the 14 potential aquifer traps included in Hystories, and the existing energy production and storage facilities. Hydrogen storage is planned in the salt cavern storage at Lille Torup from 2025.

Table 15: Structures/traps and storage formations included in the Hystories database

Structure/trap	Storage Formation
Gassum	Gassum Formation and Skagerrak Formation
Havnsø	Gassum Formation
Hanstholm	Gassum Formation
Rødby	Bunter Formation
Thisted	Skagerrak Formation
Voldum	Gassum Formation
Tønder	Bunter Formation
Vedsted	Gassum Formation
Thorning	Gassum Formation
Røsnæs	Gassum Formation
Hanstholm	Skagerrak Formation
Legind	Skagerrak Formation
Skive	Skagerrak Formation
Helgenæs	Gassum Formation

8.2.3. Existing storage sites

Demark has two underground natural gas storages, one in Stenlille where the gas is stored in sandstone aquifers, and a salt cavern storage project in Lille Torup, both operated by Gas Storage Denmark A/S (for more information see website[17] and Figure 32). The salt caverns in Lille Torup may be transitioned to hydrogen storage after 2025, evaluation of this possibility is currently underway. Gas Storage Denmark is involved in storage projects related to both CO_2 and hydrogen. The salt gas storage caverns at Lille Torup typically lie in the depth range of 1000 – 1700 m. Each cavern is 200 – 300 m of high with a diameter of 40 – 60 m (Hjelm *et al.* 2020).

Production of biogas is increasing in Denmark but thus far, no biogas is stored in the subsurface.

Denmark has an extensive natural gas grid, both transmission from the North Sea gas fields to national processing facilities and for distribution to the households in the larger cities.

8.2.4. Potential future development opportunities

Aquifers in Denmark have significant potential for gas storage. Sandstone-rich formations are present both on- and offshore, and within these formations several geological structures have been mapped based on regional data. Some of these structures have been surveyed for CO_2 storage but could potentially be used for hydrogen storage (Table 16).

All Danish hydrocarbon fields are in the North Sea, approximately 200 km from the Danish coast (Figure 32). A few fields are producing from sandstone reservoirs, but most of the reservoirs are in chalk. Whether these offshore oil and gas fields are attractive for hydrogen storage is not clear as detailed data are not available in the public domain. In addition, their distance from shore may affect the economic feasibility of hydrogen storage.

Table 16: Summary of storage options and recommended development actions (for locations see Figure 32)

Reservoir Type	No. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	5 Storage formations 6 Storage units 14 geological structures	Only the Thisted structure is partly developed for geothermal production. Several structures are at present being further characterised by GEUS for potential future CO_2 storage.	Regional geological mapping and assessment of aquifers may reveal further potential for storage.
Hydrocarbon reservoirs	36 hydrocarbon reservoirs	Data are owned by the operators and their partners. Only production data are available from the Danish Energy Agency (Oil and Gas Related Data Energistyrelsen (ens.dk). The Nini field is planning a CO_2 test injection (operated by INEOS).	Mapping of structures offshore Denmark is ongoing work by GEUS. These works primarily focus on the North Sea and Baltic Sea.
Salt	Not included		

[17] https://gasstorage.dk/Our-storage

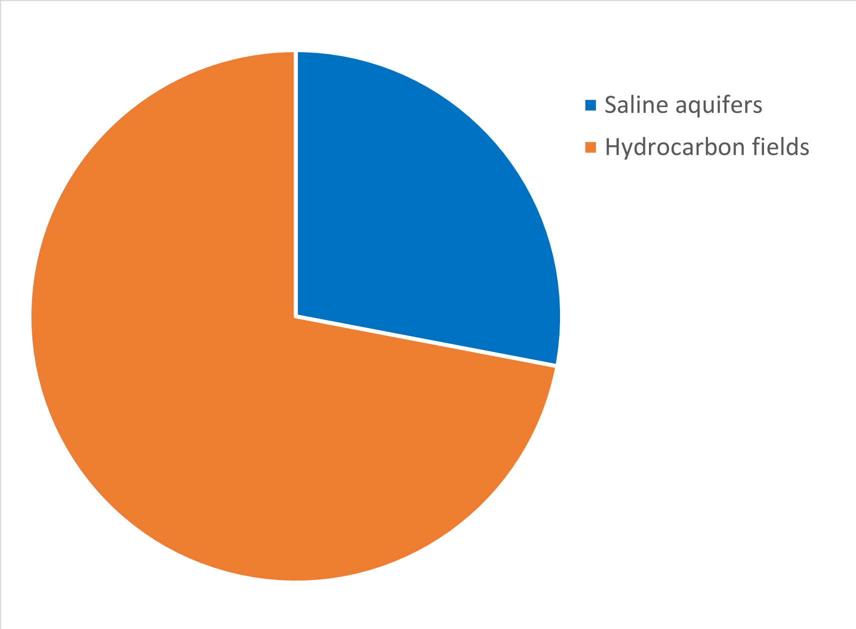

Figure 33: Frequency pie chart showing categories of identified potential storage traps in Denmark. Please note that only saline aquifers are included in the Hystories database since the data on hydrocarbon fields is not available in the public domain

Since salt caverns are a relatively inexpensive gas storage option and Denmark has several large salt structures, these would probably be the most obvious storage option for hydrogen storage in Denmark (Figure 32).

In Denmark, one hydrogen storage project is presently under consideration; the possibility to store hydrogen in the existing salt caverns in Lille Torup (North Jutland) from 2025 is being evaluated (Green Hydrogen Hub Denmark[18]). The remaining projects listed on the Hydrogen Denmark (Brintbrancen)[19] website are assessing hydrogen and Power-to-X, but not subsurface storage of hydrogen (Figure 34).

[18] https://greenhydrogenhub.dk/about/

[19] https://brintbranchen.dk/en/

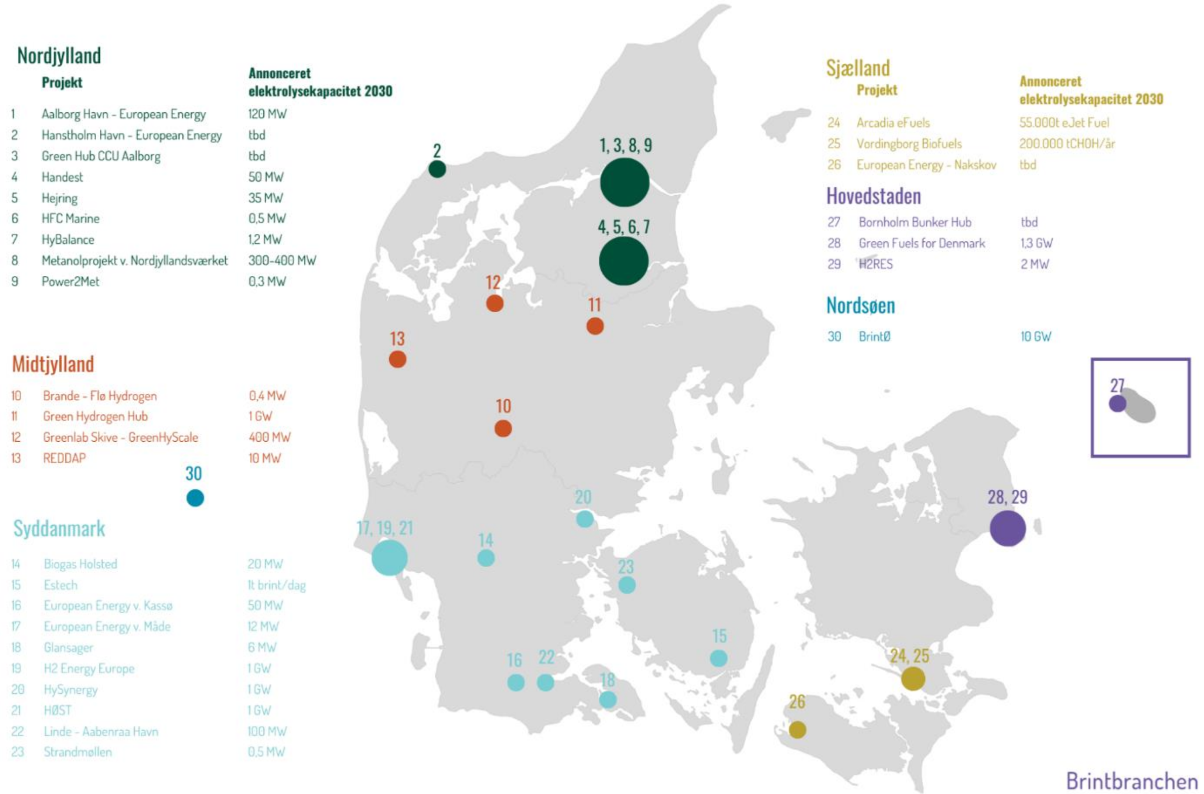

Figure 34: A geographical overview of Danish hydrogen projects. The map is updated every month and an alphabetical list of all active Danish hydrogen projects is available at: [Danish hydrogen and Power-to-X-projects – Brintbranchen](https://brintbranchen.dk/brintprojekter-i-danmark/)[20] [map downloaded 05/09/22]

8.3. Discussion and conclusions

Aquifers

Denmark appears to have significant potential for hydrogen storage in aquifers. Several sandstone-rich formations are widely distributed throughout the country. The Gassum and Haldager Sand formations seem to offer the most promising storage options. Reservoir porosity and permeability seem favourable, based on available data. The caprock for the Gassum Formation is the Fjerritslev Formation, a marine claystone which has a considerable thickness in the Danish Basin (up to 1000 m). Likewise, the caprocks above the Haldager Sand Formation seem very likely to seal the reservoir. Directly above the Haldager Sand Formation is the silty Flyvbjerg Formation, which is neither at reservoir nor a caprock, but this is overlain by the clay-rich Børglum Formation which is expected to offer a good seal.

The 14 mapped potential storage structures are all four-way closures originated by movement of the Zechstein salt below. Eight structures have been identified in the Gassum Formation

[20] https://brintbranchen.dk/brintprojekter-i-danmark/

and the remaining six structures lie within either within the Bunter or the Skagerrak Formation (Figure 32). No structures have been mapped for the Haldager Sand Formation since it is considered too shallow for CO_2 storage and was therefore not assessed in previous large-scale storage assessments, but the formation could be attractive for hydrogen storage.

Limitations imposed on the existing database by sparse and lower quality seismic data, and insufficient borehole information mean that there is considerable inaccuracy associated with the geophysical and geological interpretations of the structures in the Danish subsurface. Maturation of identified structures for hydrogen storage will demand detailed geological characterisation and acquisition of new data.

Hydrocarbon fields

All Danish hydrocarbon fields are situated offshore in the North Sea, and except for production data, all detailed data are owned by the licence holders and their partners and are not publicly available. Most of the Danish hydrocarbon fields reservoirs lie in chalk, a few in sandstones.

Salt domes and diapirs

Many salt domes and diapirs are mapped throughout the Danish area and these are all situated within either the Norwegian-Danish Basin, the North German Basin or in the Central Graben (Figure 32). Onshore salt structures will probably offer the most economic option for geological storage of hydrogen in Denmark.

9. Estonia; geological assessment of storage opportunities

Assessment of the available data indicates that storage sites are not available as aquifers are too shallow and therefore do not meet the storage site requirements defined by the Hystories project. There are no identified oil or gas fields.

10. France; geological assessment of storage opportunities

Extensive oil exploration took place in the Paris Basin during the 1980s. In the Paris Basin, the main reservoirs are in the Triassic (Keuper) sandstones and upper Jurassic (Dogger) carbonates. The southern part of the Aquitaine Basin is well known for gas discoveries that took place during the 1950s. In the Aquitaine Basin, both onshore and offshore, carbonates of Jurassic to Cretaceous age are the main reservoir rock for the large gas deposits. These depleted reservoirs could offer geological storage opportunities for hydrogen.

The Alpine Foreland Basin in southeast France has not been extensively investigated for oil and gas therefore its storage potential in terms of porous media is unknown. Three salt cavern UGS sites exist in this region. These salt caverns could potentially be converted to hydrogen storage.

Knowledge on deep aquifers is incomplete as they were not considered strategic targets for potable water (too deep and water is too salty) and they do not contain hydrocarbons. A limited number of potential saline aquifer stores have been identified from seismic and well data. It is likely that additional potential saline aquifer stores could be identified if more seismic and well data were released.

10.1. Data collation and collection

10.1.1. Data availability and collation

Data for the CO_2StoP and ESTMAP databases comprised hydrocarbon fields and saline aquifers formations that could be considered for geological storage of CO_2 and possibly for hydrogen. These databases were completed at local scale (traps) by a review of the legacy hydrocarbon permit information available on the Ministry of Energy website[21].

The CO_2StoP database contained 20 traps: 10 underground gas storage sites in porous media (mainly aquifers) and 10 depleted gas fields in the Aquitaine Basin (southwest France) and depleted oil fields were included in the CO_2StoP database.

Research was conducted on hydrocarbon reservoirs in France, where data are available in the public domain, to complete the Hystories database. Information was collected from the French ministry of Petroleum, published literature, and operator websites (but very few data are available from the latter source) (Table 17).

Regional syntheses give some information on storage units but data on potential traps is extremely limited.

In addition to information from petroleum exploration, some reservoir data may be provided by geothermal exploration activities. There are a few ongoing evaluations for potential

[21] http://www.minergies.fr/

geothermal projects in France. However, these studies focus on the reservoir formations and provide little information on the impermeable formations (caprock). Operators have rarely cored the potential caprocks and have not tested their overpressure resistance.

All CO_2 storage capacity assessments in France have been on deep saline aquifers. No detailed study (with seismic reinterpretation and injection modelling) has been carried out on depleted fields (studies are in progress during 2022).

Table 17: List of key data sources for the French Hystories database

Source name / URL	Description	Version / Date
https://www.storengy.com/countries/france/fr/nos-sites	Map and short descriptions of natural gas storage sites in France	2021
http://www.minergies.fr/en	Oil and gas mining acreage. Extent of exploration permits and production concessions (active licences only)	2021
Synthèse Géologique du Bassin de Paris. Mémoires B.R.G.M., Nos. 101 (Stratigraphie et Paléogéographie), 102 (Atlas) and 103 (Lexique des Noms de Formation). Cl. Mégnien, F. Mégnien and S. Debrand-Passard. B.R.G.M., Paris, 1980, 101: 466 pp., 102: 55 maps, 103: 466 pp.	Geological information on storage units in the Paris basin (facies, thickness, depth)	1980
Le Bassin d'Aquitaine : valorisation des données sismiques, cartographie structurale et potentiel pétrolier – Serrano, O., Delmas, J.,Hanot, F., Vially, R., Herbin, J.P., Houel P., Tourlière, B (2006), Ed. BRGM, 245 p., 142 figures, 17 tableaux, 17 annexes	Geological information on storage units and traps in the Aquitaine basin (facies, thickness, depth)	2006

10.1.2. Availability of detailed data for further site characterisation

All oil exploration data older than 10 years can be requested from the French Ministry of Industry via the Ministry of Energy website. Raw seismic data, drilling logs and drilling reports are available but have a cost. Therefore, these data were not available for the Hystories project.

Figure 35 shows available exploration data. Knowledge of the subsurface in France is very heterogeneous. Information on traps is only available for reservoirs depleted of oil or gas and natural gas storage in aquifers. Existing 2D seismic assessments can be used to identify traps to store energy, CO_2 and Hydrogen in aquifers.

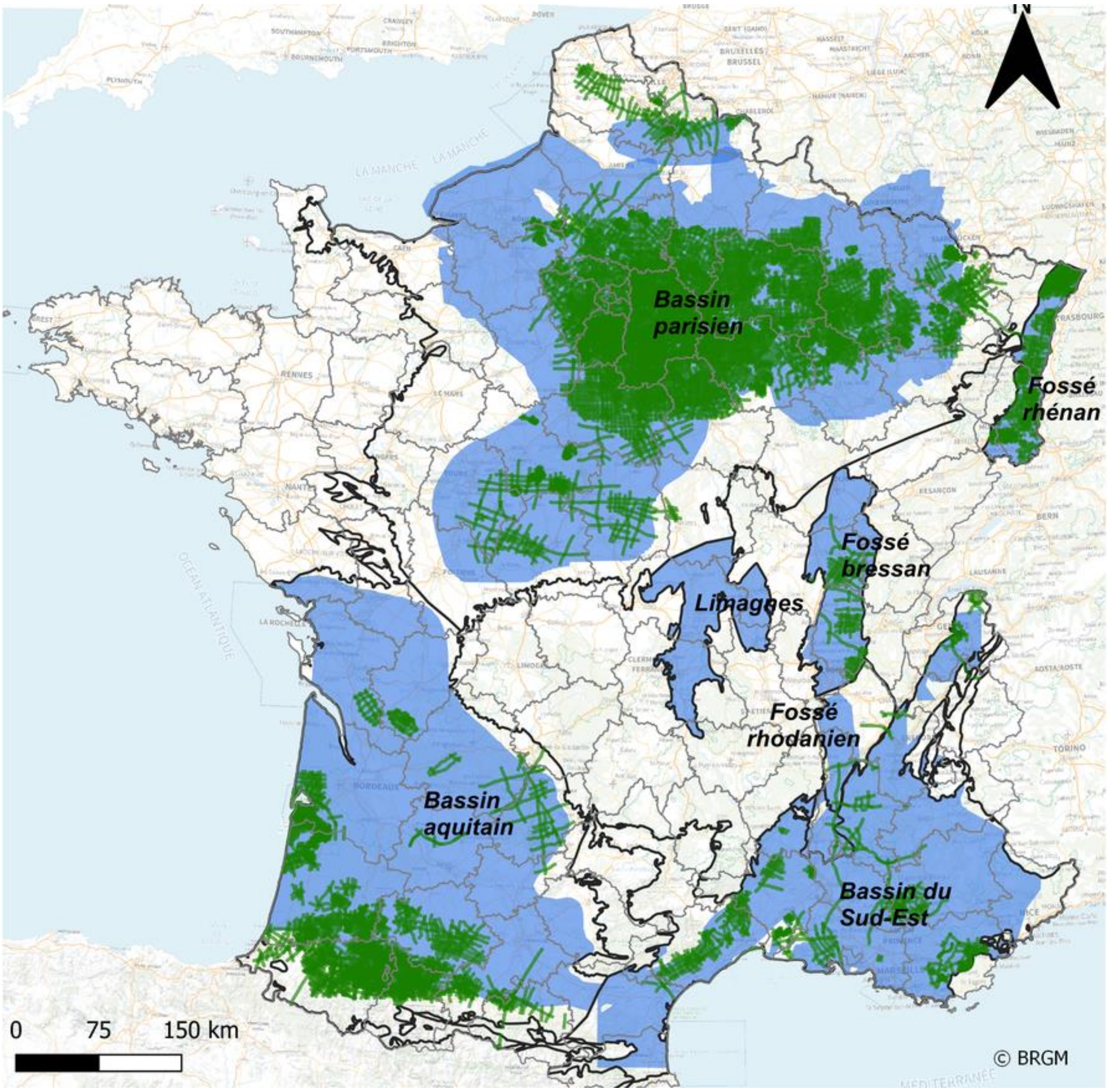

Figure 35: Deep sedimentary basins (blue) and location of seismic survey for further investigations (e.g. traps identification)

10.1.3. Identified gaps in data availability

Production data such as the initial oil or gas in place, initial and depleted pressure, are not considered public data under French regulations. These data are the property of operators, and not available in the public domain. Processed seismic data also belongs to the field operators and there is no legal obligation to make these data available.

In the petroleum provinces, seismic coverage is dense. However, many regions (including sedimentary basins) have not been explored (north of the Bassin Aquitaine or Bassin du Sud-Est for example). In these areas, the exploration for structures that could constitute a trap requires new seismic acquisitions as well as drilling of wells.

10.2.Geological opportunities for hydrogen storage

10.2.1. Geological summary

There are two major sedimentary basins in France; the Paris Basin and the Aquitaine Basin.

Paris Basin

The Paris basin is an intracratonic basin. Mesozoic and Cenozoic sediments lie on Hercynian basement (Figure 36).

During the Permian, an extension regime begins, leading to the collapse of the Hercynian chain initiated in the Upper Carboniferous: the Paris and Aquitaine basins are formed.

During the Mesozoic, a thickness of 3000 m of sediments were deposited owing to subsidence. The sedimentary series found within the Paris Basin comprises rocks of marine, lacustrine, lagoonal and fluvial origin.

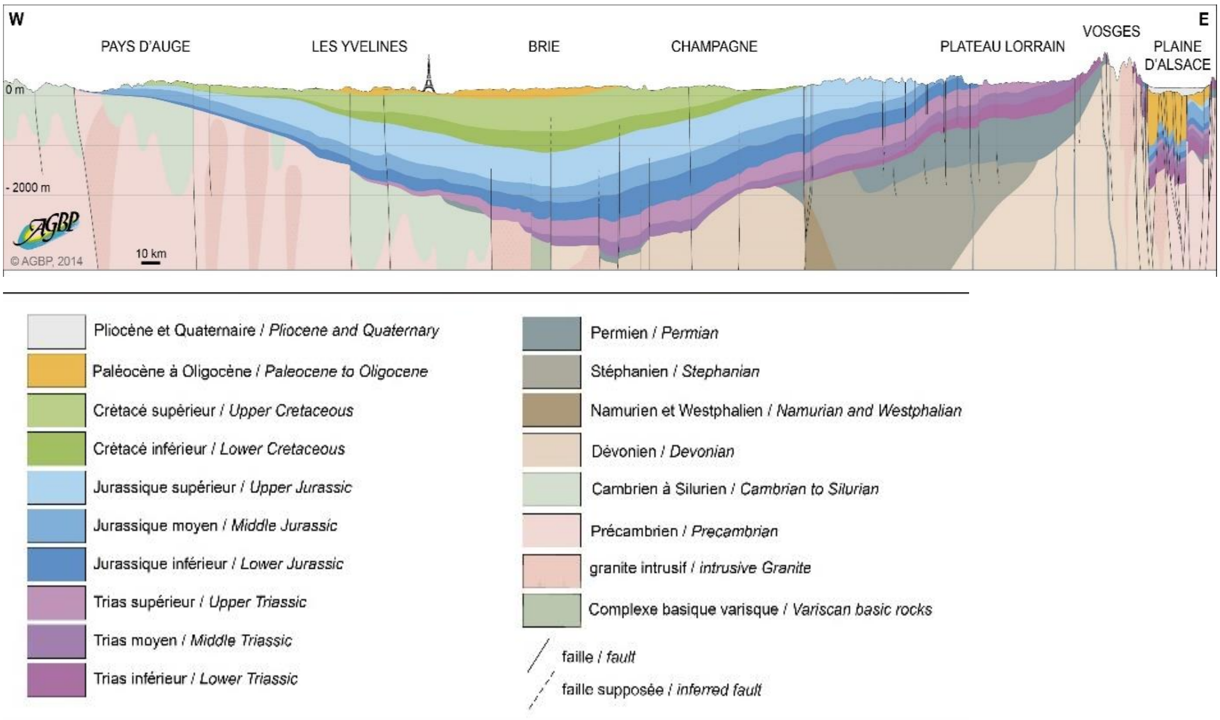

Figure 36 : Geological cross section of the Paris Basin and Rhine graben (AGBP, 2015)

The Mesozoic-Cenozoic evolution of the Paris Basin can be subdivided into five main steps (Robin et al., 2003):

- During the Triassic – Lower Jurassic (Scythian to Toarcian), arcuate subsidence took place along northeast-southwest and east-west to east-northeast and south-southwest orientations. The intra-Norian unconformity (Upper Triassic) records the beginning of subsidence in the central part of the present-day Paris Basin. Rhaetian (Triassic) sandstones contain hydrocarbon deposits capped by Lower Jurassic Lias deposits.

- Mid to Upper Jurassic (Aalenian to Tithonian) times were characterised by northwest-southeast flexural controls. The kinematics of the Dogger deformation are poorly known. The development of progradational (Callovian-Oxfordian) and aggregational (Kimmeridgian-Tithonian) carbonate platforms occurred this time. Creation of significant accommodation space took place during latest Jurassic (Kimmeridgian to Tithonian times). Hydrocarbons are trapped in the Upper Jurassic (Dogger) carbonates, capped by marly caprocks of Callovian-Oxfordian age.
- Lower Cretaceous (Berriasian to late Aptian) was characterised by a northwest-southeast flexural control bounded by two major unconformities (late-Cimmerian: Jurassic/Cretaceous boundary, Lower/Upper Berriasian boundary) and a change in the sedimentary system with the development of siliciclastic deltas.
- The Late Aptian to Turonian (Cretaceous) is characterized by a northwest-southeast flexural control with an increase of the subsidence rate and a change from a siliciclastic system (tidal-dominated Greensands) to carbonate platforms (Cenomano- Turonian chalks).
- The Turonian (Upper Cretaceous) to Recent is characterized by a decrease of the subsidence rate, sediment by-pass and finally uplift and erosion, in a generally compressional setting.

Extensive oil exploration took place in the Paris Basin during the 1980s. In the Paris Basin, the main reservoirs are located in the Triassic (Keuper) sandstones and upper Jurassic (Dogger) carbonates.

Aquitaine Basin

The Aquitaine Basin is located in the southwest of France, between the Gironde Arch in the north and the Pyrenean Mountain Chain in the south. Only the Parentis sub-basin, the foreland of the Pyrenean Chain and a minor part of the fold-and-thrust belt itself are proven hydrocarbon provinces (Biteau et al., 2006).

The Mesozoic-Cenozoic evolution of the basin was strongly influenced by the Hercynian framework of the basement (Villien & Matheron 1989). The inherited fault zones played a major role during the Mesozoic extensional regime, as well as during the Cenozoic compressive phases (Biteau et al., 2006).

The northeast-southwest extensional phase started during the Triassic and the Early Liassic. This phase was characterised by the deposition of a thick evaporitic section. After this evaporitic cycle, development a carbonate platform extending over most of the area developed (Canerot 1989). These marine sediments provide the major petroleum plays. Reservoirs were developed in the Lias/Dogger Mezos Formation, the Kimmeridgian Meillon Dolomite and the Portlandian Mano Dolomite (Biteau et al., 2006).

The main source rocks are represented by the Lower Jurassic (Lias Marls) and Upper Jurassic (Upper Kimmeridgian Lons Limestones in the southern sub-basins and the Upper Kimmeridgian Lituolidae Limestones in the Parentis sub-basin). These source rocks were deposited during major trans transgressive cycles. A regional unconformity (the Base Cretaceous Unconformity) characterizes the transition between the Jurassic and the

Cretaceous. The Upper Jurassic shows a regression, while the Cretaceous begins with the Neocomian transgression (Biteau et al,. 2006).

During the Early Cretaceous, the differentiation of the Parentis sub-basin and the South Aquitaine sub-basins (Arzacq–Tarbes) resulted from extension of the continental crust in conjunction with the separation of Iberia and Europe. The Cretaceous displacement between the Iberian plate and the European plate occurred in four main phases (Biteau et al., 2006):

- Barremian deposition was guided by northeast-southwest extensional stress-induced normal faulting. The Parentis and Arzacq–Tarbes areas became individualised depocentres.
- The Aptian–Mid-Albian was dominated by a major northwest-southeast extensional phase. The Arzacq and Parentis sub-basins were created. As a result of Aptian–Albian sediment overload, Triassic evaporites migrated towards the edges of the newly formed basins, where salt ridges formed and where the overlying sediments were breached.
- During Mid-Late Albian–Early Senonian times, sinistral transtension displaced Iberia
- During Coniacian–Campanian times, rotation of Iberia generated a transpressive sinistral system in the eastern Pyrenees and a strike-slip motion to the west.

Halokinetic movements started during the Early Cretaceous and resulted in erosion of pre-Cretaceous sediments along the edges of the main sub-basins. These movements continued during the Cretaceous. The first compressive movements related to the subduction of the Iberian plate beneath the European plate occurred during the Campanian (Biteau et al., 2006).

In the South Arzacq, Tarbes and Comminges sub-basins, a northward-migrating foredeep trough offsets the wide and stable carbonate platforms of Cenomanian to Maastrichtian age. Thick flysch sediments deposited in the foredeep do not have hydrocarbon potential owing to a lack of reservoirs and mature source rocks. In contrast, the northern platforms, developed from Lacq to the north of Meillon, contain a secondary play as observed in the Upper Lacq and Lagrave oil fields (Biteau et al., 2006).

The Eocene Pyrenean and Miocene Alpine orogenies resulted in compressional stresses in the Aquitaine Basin. After a period of tectonic quiescence during the Danian, minor reactivations along the northern salt ridges (northern oil province) and by the deposition of syn-tectonic 'Molasse' sediments indicate renewed movement during the Oligocene-Miocene (Biteau et al., 2006).

The southern part of the Aquitaine Basin is well known for gas discoveries that took place during the 1950s. In the Aquitaine Basin, both onshore and offshore (including the offshore Parentis Trough) reservoirs of Jurassic to Cretaceous age have potential for storage. The main carbonate reservoir formations of the Aquitaine Basin are the Lias Marls (Pliensbachian-Toarcian) and the Lons Limestones Formation and Lituolidae Limestones Formation (Kimmeridge) (Bastianini et al., 2017, Hardenbol *et al.*, 1998; Biteau *et al.*, 2006).

Alpine Foreland Basin

The Alpine Foreland Basin in southeast France has not been extensively investigated for oil and gas therefore its storage potential in terms of porous media is unknown. Three salt cavern

UGS sites exist in the Rhone Trough in this region. These salt caverns could potentially be converted to hydrogen storage.

10.2.2. Storage assessments

A summary of the storage opportunities assessed for the Hystories project is presented in Table 18 and Figure 37.

Hydrocarbon fields

In the Paris Basin, eight hydrocarbon traps and four UGS traps in Dogger carbonate platform deposits were identified. These are sealed by thick Callovo-Oxfordian marls. A further 21 hydrocarbon traps have been identified in the Triassic (Rhaetian) sandstones of the Paris Basin. The Trois Fontaines l'Abbaye depleted gas field (Triassic Sandstone) is now used for UGS. Three Triassic sandstone aquifer 'traps' are used for natural gas storage (Chemery, Soing-en-Sologne, Céré-la-Ronde).

In the Aquitaine Basin, reservoirs of Jurassic to Cretaceous age have potential for storage. These traps comprise mainly carbonate strata (limestone or dolomite) and are known as gas-bearing reservoirs sealed by Cretaceous marls (Sainte-Suzanne Marls Formation). Nine gas fields are included in the Hystories database. Two Paleogene sandstone aquifers currently used for natural gas storage are also included the Hystories database. Offshore, no hydrocarbon fields have been found, but some potential traps have been identified from exploration data (seismic and well data).

Table 18: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore aquifers	10	10 traps used for UGS Possible locations identified in regional (large-scale) CO_2 storage project. Very few data. High uncertainties.	Need further assessment with geophysical exploration in order to identify more traps and characterise caprock. Regional geological mapping and assessment of aquifers may reveal further potential.
Onshore gas fields	3	Gas exploitation in Aquitaine Basin since the 50s. Most of gas fields are depleted and closed. Only one site actually converted for UGS	Good knowledge of the sites. Additional studies required for storage conversion.
Onshore oil fields	35	Oil exploitation in Paris Basin from 1970s. Most of gas fields are depleted and closed.	Good knowledge of the sites. Additional studies required for storage conversion.
Offshore hydrocarbon fields	0	Offshore Aquitaine has been explored for hydrocarbons. Data exists, traps were identified and drilled. No traps used for UGS	Need further assessment and modern data to characterise the traps and caprock. Further assessment possible if sufficient storage in onshore gas and oil fields is not available.
Offshore aquifers	0	Offshore Aquitaine has been explored for hydrocarbons. Data exists	

Saline aquifers

In France, studies for CO_2 storage focused on deep saline aquifers since depleted fields are not numerous and are often located at depths less than 800 m (the usual minimum target depth for CO_2 storage).

Knowledge on deep aquifers is incomplete as they were not considered strategic targets for potable water (too deep and water is too salty) and they do not contain hydrocarbons. Saline aquifers have been studied in terms of potential for deep geothermal projects. However, for the latter purpose, assessments focus on the reservoir properties and identification of storage traps is not required.

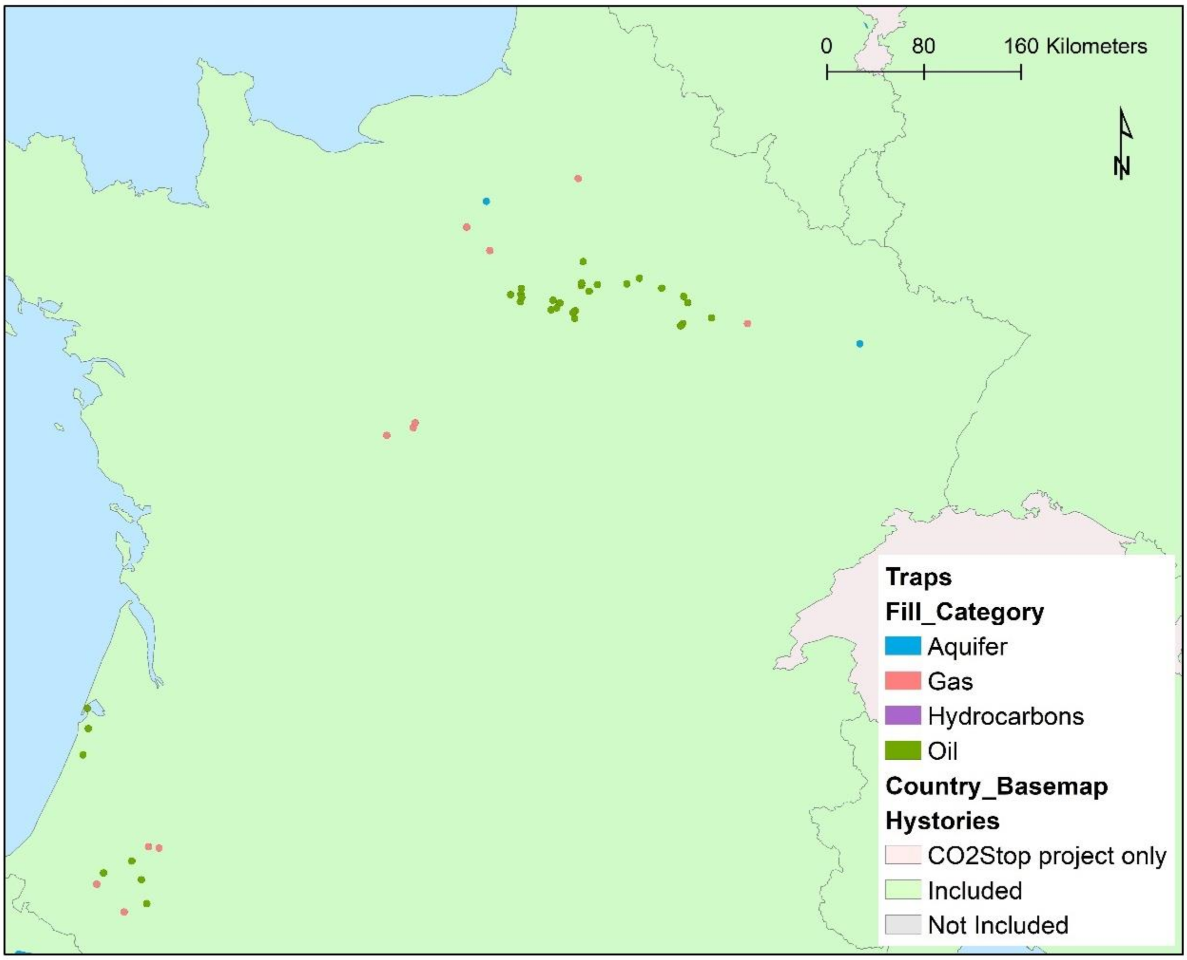

Figure 37: Overview of identified potential traps in the Hystories database within France; point locations for aquifers, oil and gas fields, and UGS sites.

10.2.3. Existing storage sites

In France, there are 10 natural gas storage sites. Ten of these in aquifers, four in salt caverns (plus one closed site), and UGS site is a converted gas field (Table 19).

One aquifer site (Beynes) started with storage of manufactured gas in the 1950's. This gas contained more than 50% hydrogen and no incidents were reported at the time.

Feasibility studies are ongoing for the conversion to hydrogen storage of one salt cavern in Etrez, and one salt cavern in the closed Caresse-Cassabert site.

Table 19: Summary of UGS sites in France

Basin	Reservoir Type	N.o. in Hystories database	Status description, remarks
Paris Basin	Aquifer	8	Beynes, Céré-la-Ronde, Cerville, Chemery / Soings en sologne, Germigny Sous Coulombs, Gournay Sur Aronde, Saint Clair Sur Epte and Saint Illiers La Ville
Aquitaine Basin	Aquifer	2	Lussagnet and Izaute
Rhone Trough	Salt caverns	4	Etrez, Tersanne-Hauterive, Manosque (plus 1 closed site; Caresse-Cassabert)
Paris Basin	Gas field	1	Trois-Fontaines-l'Abbaye

10.2.4. Potential future development opportunities

Only one depleted gas field in France so far has been converted for storage of natural gas (Trois Fontaine). All the other gas fields can be considered as good candidates for a hydrogen storage conversion if appropriate studies are undertaken. Several saline aquifer structures are used for UGS which could be converted to hydrogen storage. The presence of UGS sites in saline aquifers structures also indicates that good geological seals are present, and these structures could be assessed for storage of hydrogen.

10.3. Discussion and conclusions

In France, natural gas stores are located in both porous media (aquifers and one depleted gas field) and salt caverns. There are onshore depleted gas and oil fields and salt resources that could be utilised for hydrogen storage.

There may also be onshore opportunities for hydrogen storage in deep saline aquifers but potential traps have not yet been identified on a national basis. There are some projects that have looked at various regions to examine potential for natural gas or CO_2 storage that could be used to support further assessment of hydrogen storage potential.

11. Germany; geological assessment of storage opportunities

Germany has numerous proven traps, both in depleted fields, and in fields that are nearing the end of production. Trapped hydrocarbons indicate the presence of seals that can trap buoyant fluids for geological timescales, including saline aquifers by extension. Most of the German hydrocarbon resources lie in the Schleswig-Holstein and Lower Saxony regions.

8.1. Data availability and gaps

11.1.1. Data availability and collation

The German CO_2StoP database comprised a long list of hydrocarbon fields that could be considered for geological storage of CO_2. During the Hystories project, the GFZ team checked, and updated data collated during the CO_2StoP and ESTMAP projects.

Updates to key parameters (i.e. porosities, depths, areal extents) were made, based on existing shapefiles and the information sources presented in Table 20. Other fields in the database were populated with averages using available data from that area.

The main input to the closures and depths were obtained from a 3D model published by the Federal Institute for Geosciences and Natural Resources (BGR). Shapefiles are also available from this same project. The data made available from this report were cross-referenced against traps identified in the CO_2Stop and ESTMAP databases. Where feasible, input data from CO_2Stop and ESTMAP were updated with data provided by the Landesamt für Bergbau und Energie (LBEG) on hydrocarbon fields. The main petrophysical properties of these 'traps' were obtained from published information, particularly the Southern Permian Basin Atlas and the BGR Speicherkataster final report (Table 20).

Table 20: List of key data sources for the German Hystories database

Source name / URL	Description	Version / Date
BGR TUNB Model https://gst.bgr.de/	3D model of the North German Basin	2018
HC Field LBEG https://memas02.lbeg.de/cardomap3/	HC Field in Lower Saxony	NA
P3 Database https://dataservices.gfz-potsdam.de/panmetaworks/showshort.php?id=escidoc:2263895	PetroPhysical Property Database	2019
South Permian Basin Atlas https://www.nlog.nl/southern-permian-basin-atlas	PETROLEUM GEOLOGICAL ATLAS OF THE SOUTHERN PERMIAN BASIN	2010
BGR Speicherkataster https://www.bgr.bund.de/DE/Themen/Nutzung_tieferer_Untergrund_CO_2Speicherung/Projekte/CO_2-Speicherung+Nutzungspotenziale/Abgeschlossen/speicherkataster.html	Information system on reservoir rocks for Germany – a basis for climate-friendly geotechnical and energy use of the deep subsurface	2011

11.1.2. Availability of detailed data for further site characterisation

Due to its federalistic nature, legacy seismic and well data has to be obtained through the individual state land offices (Landesämter). Such data are compiled by, and should be made available through, the corresponding agency. The current provision of data is therefore highly limited and subject to change.

11.1.3. Identified gaps in data availability

As most publications are focused on hydrocarbon resources, data on the reservoir is more readily available than data on overlying seals.

The CO_2StoP database for Germany contained potential storage sites (saline aquifers and hydrocarbon fields). This database was populated using seismic data and well interpretation.

A wealth of data is available for the offshore and onshore hydrocarbon fields in Germany. These data are not easily accessible however, as the provision of these data still lies within the responsibility of the federal states. Further work would be needed to undertake site-specific investigation to develop potential hydrogen storage sites including obtaining new relevant data from the relevant state land office, and then obtaining new physical data as required.

8.2.Geological opportunities for hydrogen storage

11.1.4. Geological summary

Germany offshore comprises large sedimentary basins with hundreds of metres of potential storage formations. A 2019 report from The global 'Extractive Industries Transparency Initiative' (EITI) reports the following: 'Crude oil has been industrially extracted in Germany for more than 150 years. The successful oil well in Wietze near Celle in 1858/59 is generally recognised as being one of the first production wells in the world. Crude oil production in Germany peaked during 1968 with an annual production of around 8 million tonnes. Proven and potential crude oil reserves in Germany were estimated to be around 28 million tonnes as of 1 January 2020. Most of the crude oil reserves are in the North German Basin, primarily in Schleswig-Holstein and Lower Saxony. At the end of 2019, there were 51 oil fields. Around 94% of produced German natural gas was extracted in Lower Saxony during 2019. Other federal states (Saxony-Anhalt, Schleswig-Holstein, Thuringia and Bavaria) contributed only marginally to the total production. A reported 419 production wells extracted natural gas from 72 gas fields. The A6/B4 gas field in the 'Entenschnabel' (duckbill) area is the only German offshore gas field'.

Following the BGR Speicherkataster report, the following key reservoir sequences have been identified:

Permo-Carboniferous deposits

Lower Permian (Rotliegend) comprise clastic deposits; aeolian sandstones, fluvial fans and shallow-lake deposits.

In northern Germany, Upper Rotliegend sediments were deposited in a roughly east-west striking basin structure, today's North German Basin. initiation of the Northern German Basin took place in the Late Carboniferous in association with the Variscan Orogeny.

To the south, several intramontane basins developed, in which great thicknesses of Upper Rotliegend sediments accumulated. Deposition of sediments in the basin started in the late Carboniferous and Early Permian as part of the Variscan orogeny. Underlain by the Central German Crystalline Zone, these basins formed southwest-northeast striking subsidence zones found from southwestern Germany (e.g., Saar-Nahe basin) to central Germany (e.g. Saale basin; e.g., Rappsilber, 2003). Further south, the Schramberg Basin and Kraichgau Basin developed in the Late Carboniferous and Early Permian (Nitsch & Zedler, 2009).

In contrast to the sedimentary basins mentioned above, the basins with Upper Carboniferous to Lower Permian (Rotliegend) deposits found in the subsurface of the Alpine Molasse Basin, are relatively small (e.g., Bachmann & Müller, 1996).

Rotliegend reservoirs are usually sealed by Lower Zechstein shales.

Permian Zechstein Group

The Zechstein sequences comprise carbonates and evaporites deposited as a result of repeated marine transgression during the Upper Permian. Hydrocarbons are found in carbonate reservoirs sealed by anhydrites within the Zechstein cyclical deposits.

Triassic Bunter Sandstone Group (Buntsandstein)

At the time of deposition of the Middle Bunter Sandstone Group, in the northern part of the North German Basin, thick sandy sediments were deposited in the regions of Schleswig-Holstein, north-eastern Mecklenburg, and Western Pomerania. These sediments were primarily derived from the north-eastern Fennoscandian shield.

In Lower Saxony, sedimentary fill was mainly derived from the Rhenish Massif to the south. To the northwest-southeast striking basin centre, which extended from the North Sea to north-west Mecklenburg, the sandstone portions of the bedding sequence rapidly decrease in thickness and the basal sandstones of the individual formations become increasingly clay- and carbonate-rich (Feist-Burkhardt et al. 2008). The formation of potential reservoir rocks was particularly concentrated at the basin margins. The southern depositional area of the Middle Bunter Sandstone Group was bounded by the Vindelician-Bohemian Massif (Beutler & Szulc, 1999). The sands transported from this area form primary reservoir rocks in southern Brandenburg, the Thuringian Basin and the Upper Rhine Graben.

The Upper Bunter Sandstone Group becomes increasingly shaly upwards and acts as a reservoir seal.

Upper Triassic Mercia Mudstone (Keuper) Group

During Triassic to Early Jurassic times, a large rift system developed in the North Sea area and resulted in large and relatively wide graben structures filled with predominantly non-marine sediments. The Keuper group mainly comprises continental facies. The stratigraphic succession is dominated by lacustrine claystones, mudstones and marls with intercalations of evaporite and carbonate beds. Fluvial sandstones interfinger with these basinal facies near the basin margins (Beutler et al., 2005). Channel sandstones of the Middle Keuper (Schilfsandstein beds) offer good reservoir properties and are distributed basin-wide. The storage properties of these sandstones are very good in the north-eastern and eastern parts of the basin (Feldrappe et al., 2007). These sandstones offer potential geothermal resources and potential for hydrogen and CO_2 storage. The Keuper sandstones are sealed by fine-grained Keuper seals or Lias mudrocks.

Rhaetian-Liassic aquifer complex (Upper Triassic – Lower Jurassic sandstones)

The global Mesozoic sea level rise resulted in stepwise flooding across this region, transitioning from a late Triassic continental conditions to an early Jurassic semi-enclosed inland sea (Barth et al., 2018). Rhaetian and lower Liassic sandstones were deposited. The lower Liassic succession (Hettangian to Pliensbachian) comprises claystones, siltstones and sandstones. Massive sandstone beds appear in the Hettangian sequence (Barth et al., 2018). Fine grained sandstones deposited during the Sinemurian are widespread in the Northern German Basin (Petzka 1999, Göthel 2006). Upper Rhaetian and Liassic deposits are widely distributed across the Northern German Basin. The sandstones of the Rhaetian and Liassic are mostly very good aquifers. The Dogger-ß sandstone (Upper Aalenian, formally known as the Altmark sandstone (Deutsche Stratigraphische Kommission 2002) hosts many oil fields in the western part of the basin (Barth et al., 2018).

Lower Cretaceous aquifers

Following regional uplift during the Middle Jurassic, intense rifting took place during the Middle Jurassic-Early Cretaceous. Siliciclastic sediments dominate. Depositional environments vary over relatively short distances. Lower Cretaceous sediments in north-east Germany comprise clayey and marly sediments in the central parts of the North German Basin. Sandstones with intercalated thin mudstones and marls occur at the marginal parts of the basin (Feldrappe et al., 2007, Verreussel et al., 2018).

11.1.5. Storage assessments

Traps identified in the CO_2StoP project were used for the Hystories storage evaluation. Onshore hydrocarbon fields are usually quite small but infrastructure/access costs would be lower compared with offshore sites. Data for some onshore fields was not available for the Hystories project since field exploration started some decades ago and the data for active fields is more easily accessible than for depleted fields.

A summary of onshore and offshore traps in the German Hystories database are presented in Table 21, Figure 38 and Figure 39. One hydrocarbon trap did not have any information on its status, and it was not possible to confirm if it is being abandoned or still producing.

Structural information was extracted from existing shapefiles and the BGR TUNB Model (see Table 20). Figure porosities were compiled from literature (Reinhold and Müller, 2011; Doornenbal and Stevenson, 2010). Averages and variation in trap thickness and porosity is shown in Figure 40.

Table 21: Summary of storage capacity options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore HC fields	44	Exploited from 1930s onwards. Mostly small. Many already depleted.	Site specific studies required and additional well data. Additional data could be added to database with further resources
On-Offshore HC traps	7	Exploited from 1960s onwards. Mostly small. Many already depleted.	Site specific studies required and additional well data. Additional data could be added to database with further resources
On-Offshore aquifer traps	9	A few possible locations identified	Further assessment required if sufficient storage in onshore gas fields is not available. Regional geological mapping and assessment may reveal further potential
Offshore Aquifer traps	15	A few possible locations identified	Further assessment required if sufficient storage in onshore gas fields is not available. Regional geological mapping and assessment may reveal further potential

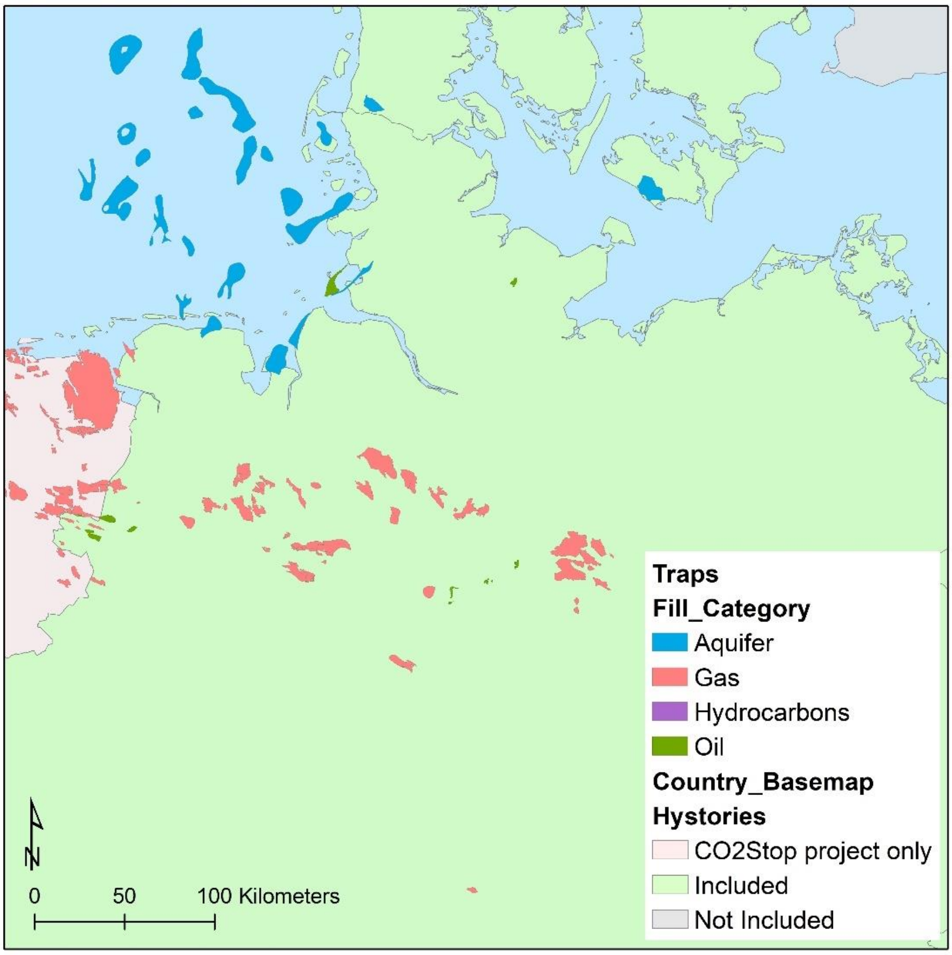

Figure 38: Overview of identified potential traps in the Hystories database in Germany (all in the north), plus surrounding areas.

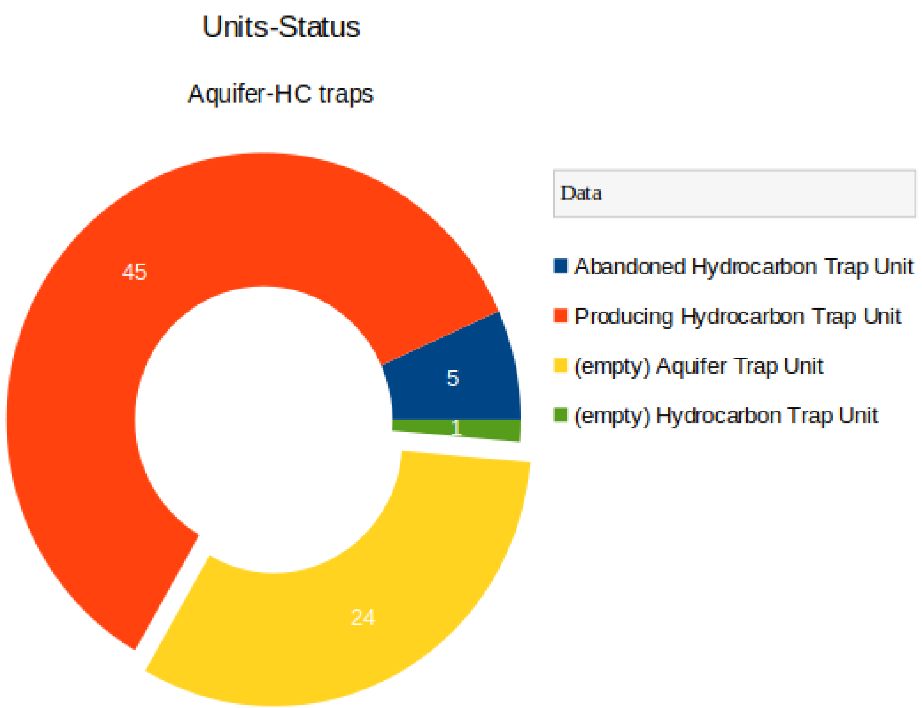

Figure 39: Frequency pie chart showing categories of identified potential storage traps in Germany.

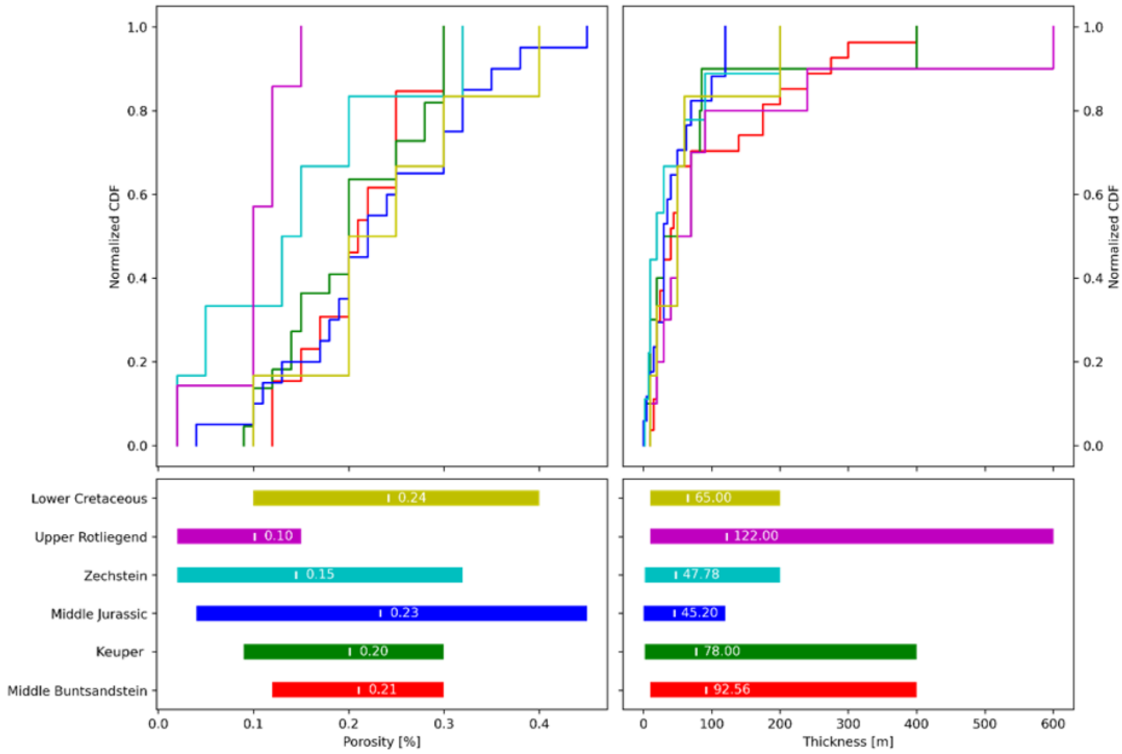

Figure 40: Distribution of porosities and thicknesses for the identified potential traps.

11.1.6. Existing storage sites

There are multiple natural gas storage sites in saline aquifers and salt caverns. Some of these have been operated with a high hydrogen content (up to 60% hydrogen in stored town gas). Depending on the field development infrastructure could be reused or would require significant changes.

11.1.7. Potential future development opportunities

Legacy data are available to enable identification of potential stores. Further site-specific work would be required to advance the potential storage sites identified during Hystories towards active storage of hydrogen.

11.2. Discussion and conclusions

Germany has existing natural gas stores in both salt caverns and porous media. There are onshore near-depleted and depleted gas fields and salt reserves that could be utilised for onshore storage of hydrogen. There may also be onshore opportunities for storage in saline aquifers, but these have not been identified on a national basis. There are some projects that have looked at specific regions to examine potential for natural gas or CO_2 storage. These project findings could be used to identify potential hydrogen stores.

12. Greece, Western Macedonia; geological assessment of storage opportunities

In Greece, during the last decade, potential oil and gas resources have been identified onshore in West Greece and offshore in the Ionian Sea, together with the existing depleted fields of Prinos in the North Aegean Sea. Furthermore, past and present geological field surveys coupled with geophysical investigation, indicate the existence of saline aquifers in the Mesohellenic Trough and West Macedonia that offer the potential for large-scale geological hydrogen storage at comparatively low cost (Jafari Raad et al., 2022). The current report presents research conducted by CERTH for the Hystories project focuses on these saline aquifers.

12.1.Data availability and gaps

12.1.1. Data availability and collation

During the Hystories project, data collated during the CO_2StoP and ESTMAP projects and publicly available scientific literature were used. As these previous projects focused on deep aquifers, during the Hystories project, onshore aquifers which lie at depths above 800 m were assessed in terms of potential for hydrogen storage.

Some interpretation and interpolation of results were required where limited data were available. For example, data on seal thickness were often not fully available and assessments had to be made based on limited data. The ‘comment’ field in the database was used in the Hystories database to highlight such uncertainties. Table 22 lists the primary sources of data and information.

12.1.2. Availability of detailed data for further site characterisation

For Greece, onshore seismic data together with borehole logs exists, but is not publicly available as yet.

12.1.3. Identified gaps in data availability

Most publications focus on hydrocarbon resources, with the most recent literature (post-2015) dealing with CO_2 storage; data on the reservoir is more easily available than for overlying seals.

Further work would be needed to undertake site-specific investigations to develop potential hydrogen storage sites. These include geological survey mapping, intrusive and geophysical investigation, and petrophysical laboratory research. Understanding the geological characteristics will provide information on the suitability, storage capacity, and trapping capability of the saline aquifers in West Macedonia.

Table 22: List of key data sources for the Greek Hystories database

Source name / URL	Description	Version / Date
Koukouzas, N. *et al.* Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece). *Energies* **14**, 3321 (2021). https://doi.org:10.3390/en14113321	Scientific publication	2021
Tasianas, A. & Koukouzas, N. CO_2 Storage Capacity Estimate in the Lithology of the Mesohellenic Trough, Greece. *Energy Procedia* **86**, 334-341 (2016). https://doi.org:10.1016/j.egypro.2016.01.034	Scientific publication	2016
Ferriere, J. *et al.* Evolution of the Mesohellenic Basin (Greece) : a synthesis. *Journal of the Virtual Explorer* **45**, 1-51 (2013).	Scientific publication	2013
Gardin, S. *et al.* Geologic evolution and geodynamic controls of the Tertiary intramontane piggyback Meso-Hellenic basin, Greece. *Bulletin de la Société Géologique de France* **175**, 361-381 (2004). https://doi.org:10.2113/175.4.361	Scientific publication	2004
Vamvaka, A., Kilias, A., Mountrakis, D. & Papaoikonomou, J. Geometry and structural evolution of the Mesohellenic Trough (Greece): a new approach. *Geological Society, London, Special Publications* **260**, 521-538 (2006). https://doi.org:10.1144/gsl.Sp.2006.260.01.22	Scientific publication	2006
Rassios, A. H. E. & Moores, E. M. Heterogeneous mantle complex, crustal processes, and obduction kinematics in a unified Pindos-Vourinos ophiolitic slab (northern Greece). *Geological Society, London, Special Publications* **260**, 237-266 (2006). https://doi.org:10.1144/gsl.Sp.2006.260.01.11	Scientific publication	2006
Kontopoulos, N., Fokianou, T., Zelilidis, A., Alexiadis, C. & Rigakis, N. Hydrocarbon potential of the middle Eocene-middle Miocene Mesohellenic piggy-back basin (central Greece): A case study. *Marine and Petroleum Geology* **16**, 811-824 (1999). https://doi.org:10.1016/s0264-8172(99)00031-8	Scientific publication	1999
Doutsos, T., Koukouvelas, J., Zelilidas, A. & Kontopoulos, N. Intracontinental wedging and post-orogenic collapse in the mesohellenic trough. *Geologische Rundschau* **83**, 257-275 (1994). https://doi.org:10.1007/BF00210544	Scientific publication	1994
Kilias Ad. *et al.* The Mesohellenic trough and the thrace basin. two tertiary molassic basins in hellenides: do they really correlate? . *Bulletin of the Geological Society of Greece* **XLVII No 2** (2013).	Scientific publication	2013
Mountrakis, D. *et al.* Neotectonic and seismological data concerning major active faults, and the stress regimes of Northern Greece. *Geological Society, London, Special Publications* **260**, 649-670 (2006). https://doi.org:10.1144/gsl.Sp.2006.260.01.28	Scientific publication	2006
A. Zelilidis, D., nbsp, J, nbsp & W, P. Sedimentation and basin evolution of the Oligocene-Miocene Mesohellenic basin, Greece. *AAPG Bulletin* **86**, 161-182 (2002). https://doi.org:10.1306/61eeda6c-173e-11d7-8645000102c1865d	Scientific publication	2002
Robertson, A. H. F. & Mountrakis, D. Tectonic development of the Eastern Mediterranean region: an introduction. *Geological Society, London, Special Publications* **260**, 1-9 (2006). https://doi.org:10.1144/gsl.Sp.2006.260.01.01	Scientific publication	2006
Sharp, I. R. & Robertson, A. H. F. Tectonic-sedimentary evolution of the western margin of the Mesozoic Vardar Ocean: evidence from the Pelagonian and Almopias zones, northern Greece. Geological Society, London, Special Publications 260, 373-412 (2006). https://doi.org:10.1144/gsl.Sp.2006.260.01.16	Scientific publication	2006
Vamvaka, Agni. Geometry of deformation and kinematic analysis in mesohellenic trough (2009). PhD thesis. https://doi.org:10.12681/eadd/19733, http://hdl.handle.net/10442/hedi/19733	Thesis	2009
Koukouzas, N. *et al.* Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece). *Energies* **14**, 3321 (2021). https://doi.org:10.3390/en14113321	Scientific publication	2021
Arvanitis, A. *et al.* Potential Sites for Underground Energy and CO_2 Storage in Greece: A Geological and Petrological Approach. *Energies* **13**, 2707 (2020). https://doi.org:10.3390/en13112707	Scientific publication	2021

12.2. Geological opportunities for hydrogen storage

12.2.1. Geological summary

The Mesohellenic basin is approximately 150 km by 30 km. It is partly located in Northern Greece and partly in Albania and developed from Middle Eocene to Upper Miocene times.

Grevena sub-basin

The Grevena sub-basin area is suitable for hydrogen storage and comprises five molassic-type geological formations in a gently dipping syncline setting (Figure 41). From oldest to youngest these are as follows:

The Krania Formation (Middle-Upper Eocene epoch) is characterised by various facies, including coarse breccias, olistolithic blocks, turbiditic siltstones, and fine-grained sandstones. The formation has an estimated thickness of 1500 m.

The Eptachori Formation (Uppermost Eocene—Lower Oligocene epoch) comprises conglomerates and sandstones overlain by marine turbiditic shales. Structurally, the Eptachori Formation has a thickness of about 1100 m, dipping 60–70◦ to the east.

The Pentalofos Formation (Upper Oligocene-Lower Miocene epoch) comprises conglomerates, followed by turbiditic sandstones and shales. The formation has an average thickness of 2500 m. The local maximum thickness of 4000 m is observed in the centre of the Grevena sub-basin.

The Tsotyli Formation (Lower-Middle Miocene epoch) has a thickness of approximately 1500 m to 2000 m. The Tsotyli Formation comprises ophiolite-derived conglomerates and has been characterised as an effective cap rock for trapping buoyant fluids (Tasianas and Koukouzas 1994). In the southern part of the sub-basin, the Tsotyli Formation unconformably overlies the Pentalofos Formation.

Ondria Formation (Early-Middle Miocene epoch), comprises sandstones and marls with a maximum estimated thickness of about 350 m. This upmost formation is partly eroded in the basin.

Storage opportunities

Two formations provide the storage capacity in the Grevena sub-basin: (i) the Pentalofos Formation, with Tsarnos and Kalloni daughter units of similar lithological composition, comprising conglomerates, turbiditic sandstones (occasionally coarse-grained) and shales, with porosity ranging from 7% to 25% and; (ii) the Eptachori Formation (undivided) comprising conglomerates and sandstones that are overlain by marine turbiditic shales. Porosity is typically around 12%.

Onshore hydrocarbon exploration in this region began in 1962. Seismic acquisition campaigns have been carried out and some of the information published in literature (Table 22). There are at least two investigative drilling campaigns performed in the area, but the data have not been made publicly available. Natural gas needs in this area are served by the Trans Adriatic Pipeline.

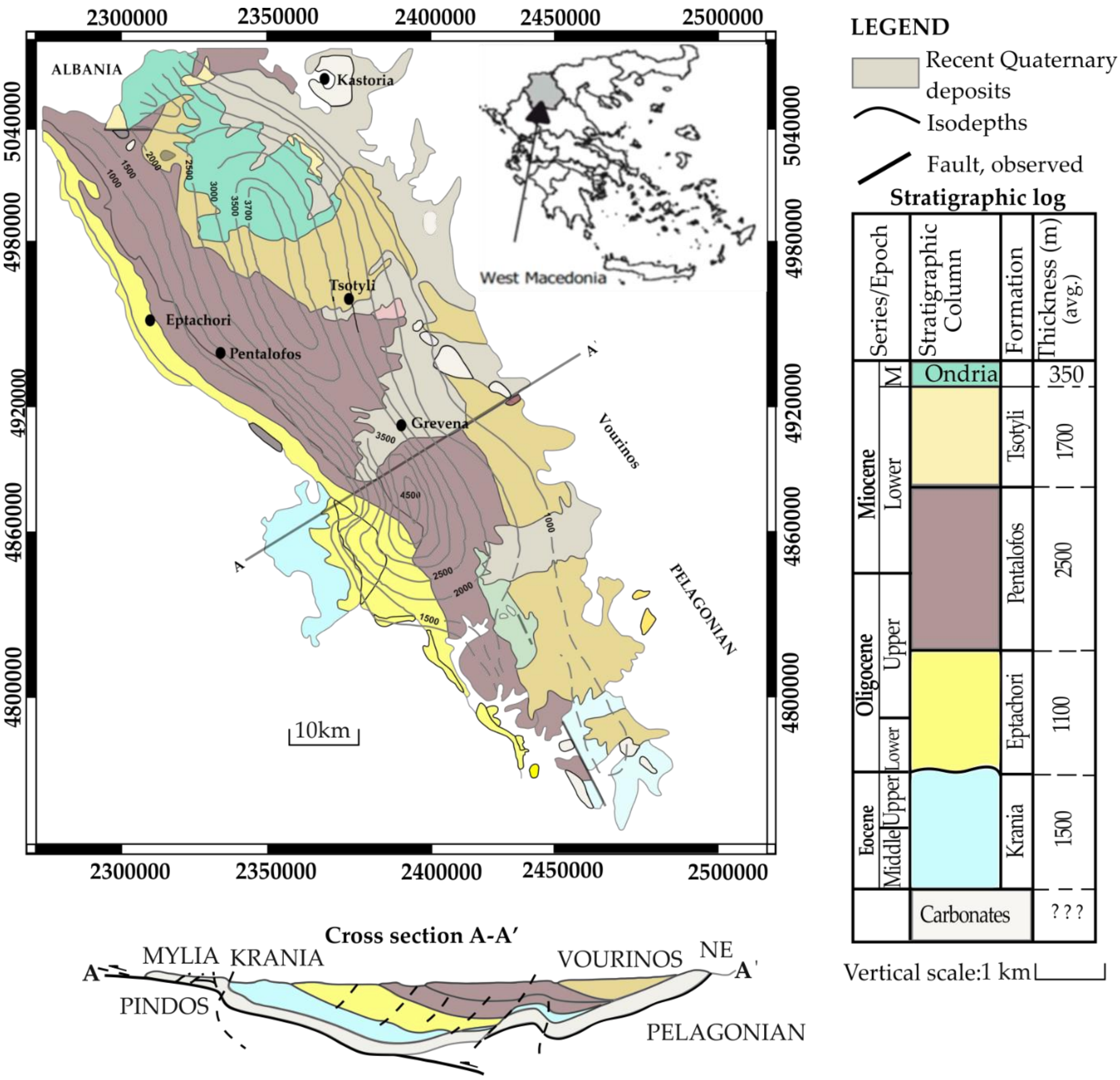

Figure 41: Geological Map and stratigraphic column adapted from Ferriere et al., 2004, of the proposed hydrogen Storage basins in Grevena area depicting Pentalofos and Eptachori formations, scale 1:1,000,000. Cross-sections of the Mesohellenic Trough. Lithological formations: Krania Turbidites, Eptachori, Taliaros, Pentalofos, Tsotyli. M stands for Middle Miocene, scale 1:500,000, Ordnance Survey Greek Grid reference system: EGSA 87, licensed under CC- BY-4.

Greece has hydrocarbon production from the offshore Epsilon, Prinos and Prinos North oil fields in the Northern Aegean Sea. Gas is periodically produced from the South Kavala gas field in the same region, and there are plans to convert this depleted field into a natural gas storage site. The small on-to-offshore Katakolon oil field in Western Greece started production within the last couple of years.

Owing to increased demands for European oil and gas, the Greek government has invited bids for exploration for gas in six areas in the Ionian Sea, the Gulf of Kyparissia, west and southwest of Crete, and around Ioannina (Greek City Times, 2022).

12.2.2. Storage assessments

Onshore, storage potential in the saline aquifers of the Mesohellenic Troughs has been identified through the Hystories project. To fully characterise the storage potential and minimise the risks associated with development of these storage targets, further investigation is required to identify adequate capacity (porosity and thickness), injectivity (permeability), a satisfactory impermeable caprock, and to confirm hydrostatic and threshold pressures to ensure confinement of the injected hydrogen.

A summary of onshore traps in the Hystories database are presented in Table 23, Figure 42 and Figure 43.

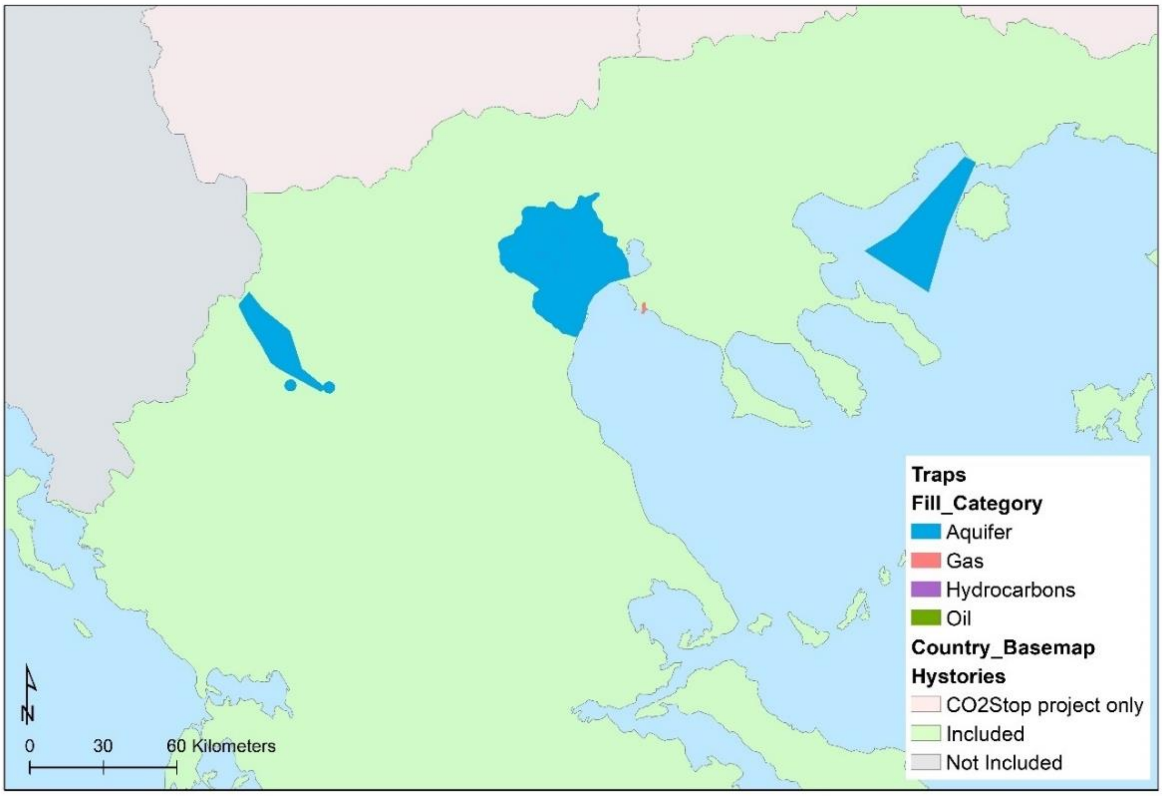

Figure 42: Overview of identified potential traps in the Hystories database within Greece (including some trap point locations).

Table 23: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore aquifers	7	A few possible locations were identified in the regional project assessing CO_2 storage opportunities. Uncertainty is noted in the report owing to a lack of data	Further assessment is required if sufficient storage in onshore gas fields is not available. Regional geological mapping and assessment may reveal further potential
Offshore hydrocarbon fields	3	Fields included in the Hystories database are the producing Prinos oil field and the abandoned South Kavala gas field and the abandoned on-to-offshore Epanomi gas field.	There are a few offshore oil and gas fields, however, very few data are available in the public domain Further assessment to characterise the storage reservoirs and caprocks is required. Data will most likely have to be obtained on a case-by-case basis from the hydrocarbon field operators.

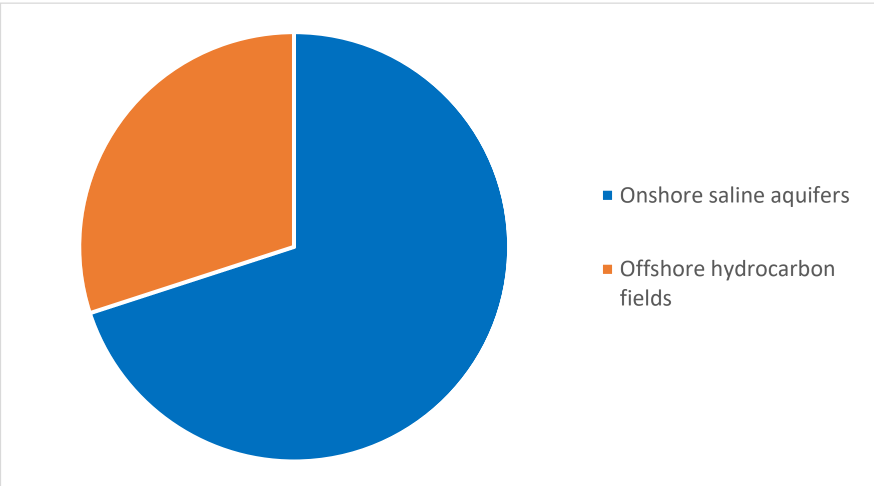

Figure 43: Frequency pie chart showing categories of identified potential storage traps in Greece, Western Macedonia.

12.2.3. Existing storage sites

The offshore Prinos oil field in the Aegean Sea will soon become a natural gas storage site. As yet, there are no onshore porous media natural gas storage sites in Greece.

12.3. Discussion and conclusions

Geological hydrogen storage provides a unique opportunity for Greece to move forward in renewable energy while avoiding the expected seasonal fluctuations in supply and maintaining electricity grid stability and low energy costs.

In the past, hydrocarbon exploration and oil field development were minimal, hence the scarcity of data available for proper reservoir characterisation. The Hystories project provided the opportunity to identify the gaps in data and understanding, as to identify aspects for future investigation.

A desktop study for the whole country is needed to identify potential sites for underground hydrogen storage related to salt caverns, unlined and lined rock caverns, and porous media.

Further characterisation with geological mapping surveys, geophysical and intrusive investigations and laboratory research will provide data for reservoir modelling of the saline aquifers of the Mesohellenic Trough.

West Macedonia has always been associated with the Greek energy industry. As such, the region has available infrastructure, a workforce with relevant experience, and would be expected to offer a higher level of social acceptance for geological storage projects. Development of hydrogen storage in this region could also help offer a smooth transition from coal to renewable energy.

13. Hungary; geological assessment of storage opportunities

In Hungary, 27 hydrocarbon 'traps' have been identified that might be of interest when it comes to subsurface hydrogen storage in the future. The identified traps are situated in formations that occur across several geographic areas and sub-basins. Most of the documented hydrocarbon fields are producing and can only be considered as potential subsurface hydrogen storage sites after depletion. The list of the identified traps is by no means exhaustive as only publicly available data were used.

13.1. Data collation and collection

13.1.1. Data availability and collation

Basic geological data can be requested from the Mining and Geological Survey of Hungary. As the Geological Survey of Austria does not have access to the database of the Mining and Geological Survey of Hungary, data could only be collected from published literature as well as from existing databases such as CO_2StoP (Table 24). Seismic or well data is only available in published literature for a few storage sites. A detailed overview of existing oil and gas fields in Hungary can be found in the 2018 published book "Szénhidrogének Magyarországon". This book supplemented by various site-specific publications served as a basis for populating the Hystories database. It is especially difficult to find data on the seal rock as published research projects usually concentrate on reservoir rock properties.

Table 24: List of key data sources for the Hungarian Hystories database

Source name / URL	Description	Version / Date
Szénhidrogének Magyarországon (Kovács et al., 2018) http://www.mekh.hu/download/3/20/60000/szenhidrogenek_magyarorszagon.pdf	Overview of oil and gas fields in Hungary	2018
A hazai földtani szerkezetek felmérése a szén-dioxid-visszasajtolás szempontjából (Falus et al., 2011) http://epa.niif.hu/00600/00691/00088/pdf/mtud_2011_04_0450-0458.pdf	Assessment of CO_2 storage potential of geological structures in Hungary	2011
Magyarország ásványinyersanyag katasztere https://map.mbfsz.gov.hu/asvanyvagyon_kataszter/	Mineral resources map of Hungary	2020
The potential options of storing CO_2 in saline reservoirs in Hungary (Szamosfalvi et al., 2011) http://epa.niif.hu/03400/03436/00206/pdf/EPA03436_magyar_geofizika_2011_02_095-105.pdf	Assessment of CO_2 storage potential of saline aquifers in Hungary	2011

13.1.2. Availability of detailed data for further site characterisation

For Hungary, detailed seismic and borehole data is not automatically made publicly available. In the information system of the Mining and Geological Survey of Hungary there is a dataset showing the location of boreholes and one showing the lines of the 2D seismic cross sections and the polygons of the interpreted 3D blocks (MBFSZ[22]). Most of the seismic and borehole data can be requested from the Mining and Geological Survey of Hungary. However, some of these data are not publicly available as they are considered a trade secret.

13.1.3. Identified gaps in data availability

Missing data could be complemented by collaboration with the Mining and Geological Survey of Hungary, and storage or field operators. Nevertheless, as hydrogen storage might become an important topic in the future, it is unclear how interested these companies are in publicly sharing subsurface data.

For the identified traps, it was especially challenging to find data on seal properties as well as the 'risk' information (e.g. faults and the number of boreholes) and oil/gas details (e.g., salinity, production quantities). Published literature usually refers only to the reservoir rocks and the presence of faults and confirming characteristics of these geological components would require detailed seismic information that is not available in most cases.

13.2. Geological opportunities for hydrogen storage

13.2.1. Geological summary

The most extensive potential storage targets are saline aquifers, which here are represented by hydrodynamically-closed geological formations with significant thickness. Among the saline aquifers, the Upper Miocene Szolnok Formation is the most promising option for storage. The Szolnok Formation represents a range of depositional environments and comprises deep water fine-grained pelitic deposits to turbidite fans, fine grained channel sandstones, and deltaic siltstones and claystones from basins (El Sayed and El Sayed 2017). In the case of this reservoir formation, the overlying seal could even provide a regional hydrodynamic closure. The clayey Algyő Formation over the foot-slope turbidites of the Szolnok Formation was deposited on the slope of the continental shelf. The top of the usually 200 – 900 m thick Szolnok Formation lies at a depth of 900 m. The formation occurs across several sub-basins and the spatial extent of the turbidite sandstones can be traced easily (Szamosfalvi et al., 2011).

Seventeen of the 27 identified hydrocarbon fields/traps are in the sandy Szolnok Formation. Three additional traps lie in Pannonian sandstones and seven hydrocarbon traps were

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[22] https://map.mbfsz.gov.hu/

identified in the basal conglomerate. Seals comprise claystones and claymarls. More precise information on the seals is not available as the publications focus on the properties of the reservoir.

Exploration for hydrocarbons started in Hungary in the 1850s, focusing on oil and asphalt. The discovery of gas due to a potash exploratory drilling near Kissármás (today: Sărmăşel, Romania) triggered significant drilling activity and led to a state monopoly on hydrocarbon exploration and production. As a result, the basic principles of the oil and gas law were developed (Kovács et al., 2018).

13.2.2. Storage assessments

Based on published literature the saline reservoirs of the Szolnok Formation offer the greatest CO_2 storage capacity (Szamosfalvi et al., 2011).

The CO_2StoP database includes five saline aquifer traps, but based on their spatial extent these objects were treated as storage units in the Hystories database. Owing to lack of detailed information, only saline aquifer storage 'units' were added to the Hystories database and no aquifer traps. To identify aquifer traps, geological mapping and interpretation of seismic data would be required. The location of identified potential aquifer storage units are shown in Figure 44.

Depleted hydrocarbon reservoirs also look promising for hydrogen storage, but they represent limited capacity. In Hungary, onshore hydrocarbon traps were considered as these are expected to offer a more cost-effective option than storage in offshore fields. Predominantly gas fields were added to the database as hydrogen storage in depleted gas fields is expected to be more straightforward than in oil fields for a number of factors (e.g. geochemical reactions, multi-phase flow). Mainly, producing hydrocarbon fields were identified, as data for active fields is more easily accessible than data for depleted fields. There might be some more promising sites for hydrogen storage but there was not enough available data in the published literature to include these traps in the database. Based on the collected data, onshore hydrogen storage is an option in Hungary, as there is a storage potential. However, further investigation is required to advance the identified storage sites, and to identify additional traps. The location of the identified hydrocarbon traps is shown in Figure 45 Overview of identified potential traps in the Hystories database within Hungary.

A summary of traps and storage units in the Hungarian Hystories database are presented in Table 25 and Figure 46.

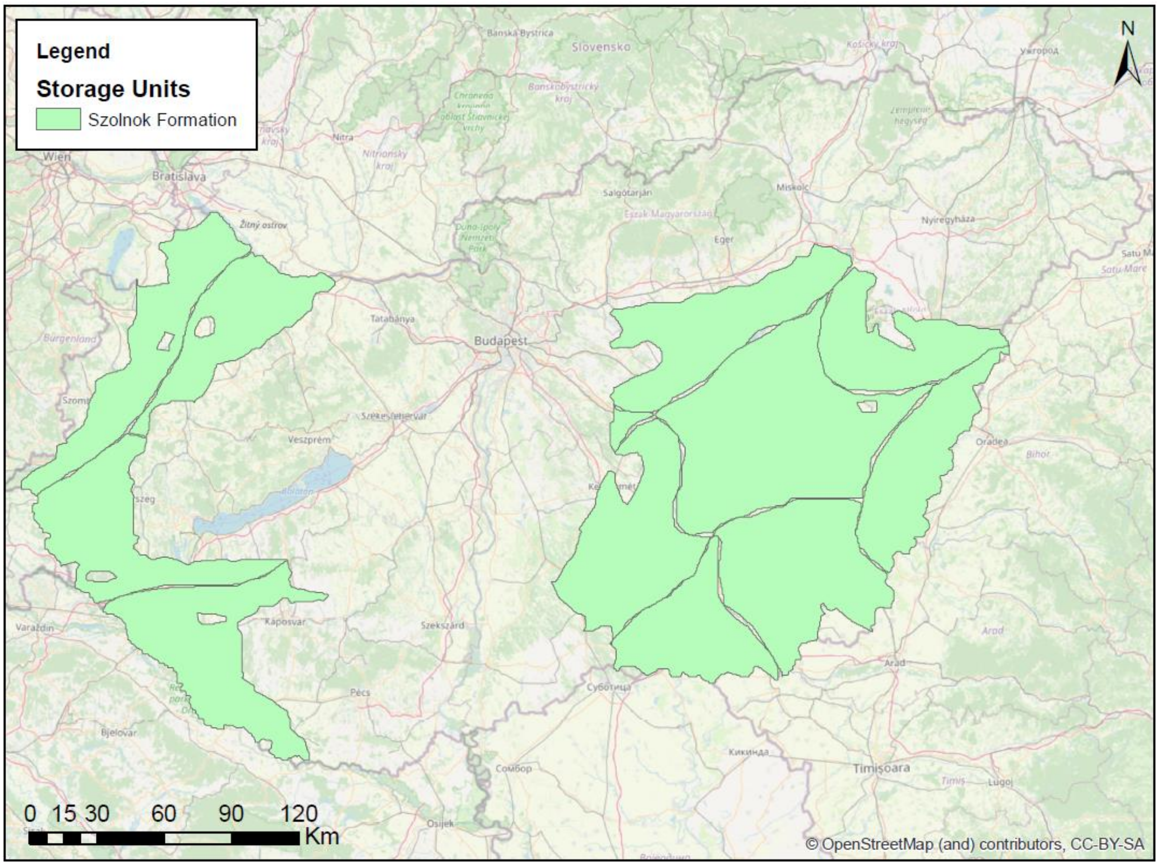

Figure 44: Storage units of the Szolnok Formation

Table 25: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore aquifers	-	Saline aquifers are characterised by large extent and high potential storage capacity. However, no traps could be identified as research has not yet provided sufficient data	Mapping and assessment of closure structures is required to identify traps
Onshore gas fields	9	Main reservoir type. Most of the fields are still producing. Many potential sites but with limited storage capacity.	Additional data and site-specific studies are required to advance the identified traps and to complete the database with further promising traps.
Onshore oil fields	1	Producing, not depleted fields with limited storage capacity.	Additional data and site - specific studies required
Onshore oil and gas fields	17	Many traps have oil and gas pools trapped in different stratigraphical horizons	
Offshore aquifers	-	Not relevant	
Offshore gas fields	-	Not relevant	
Offshore oil fields	-	Not relevant	

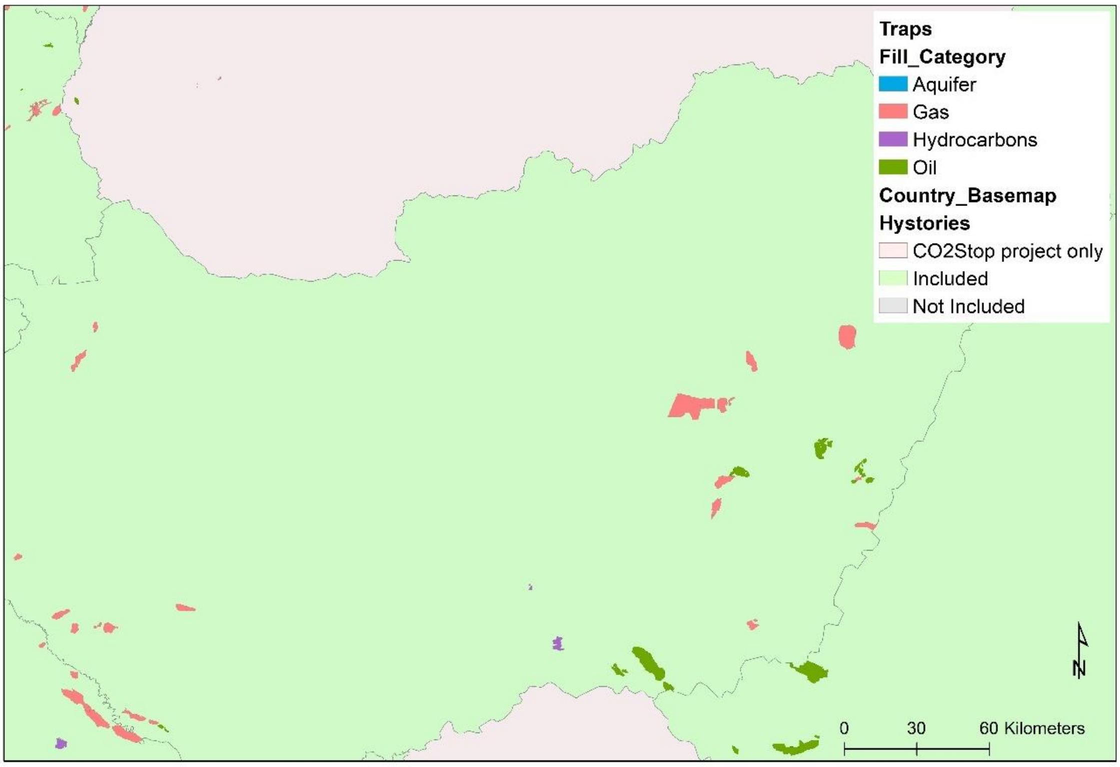

Figure 45 Overview of identified potential traps in the Hystories database within Hungary.

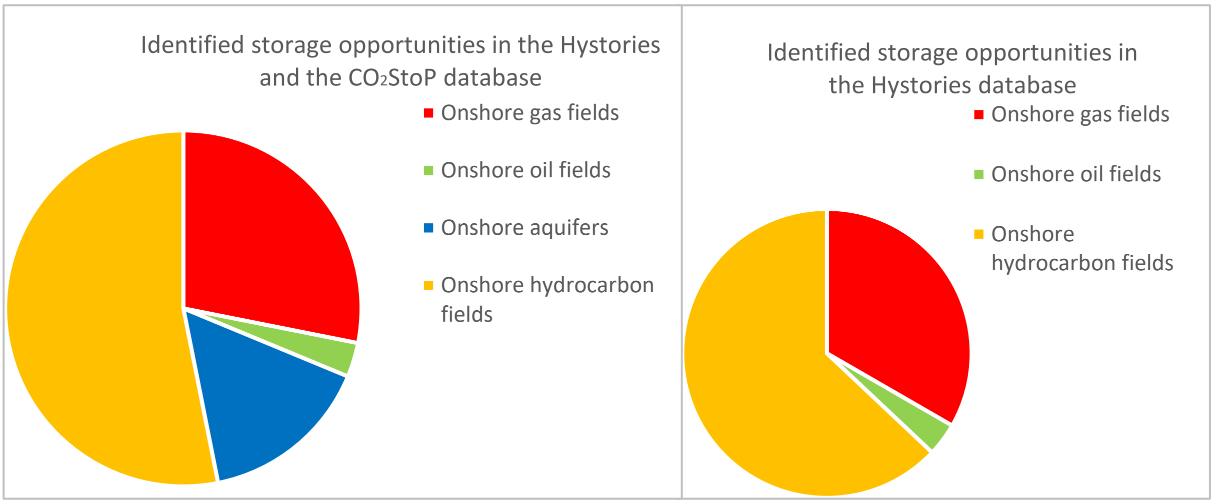

Figure 46: Frequency pie chart showing categories of identified potential storage opportunities in Hungary; lefthand figure includes CO_2 storage saline aquifers in the CO_2StoP database which were not included in Hystories database as no traps have yet been identified owing to sparse data availability. Righthand figure shows traps included in the Hystories database for onshore hydrocarbon fields.

13.2.3. Existing storage sites

Magyar Földgáztároló Zrt. operates four natural gas storage sites in porous media with a total storage capacity of 4.43 billion m^3 mobile gas. Three UGS sites are located in sandstone (Hajdúszoboszló, Kardoskút and Pusztaederics) and one in limestone (Zsana) (MFGT[23]).

There is an additional underground gas storage site (Szöreg-I) in a Pannonian gas-cap oil reservoir, which belongs to Hexum Földgáz Zrt (Hexum[24]).

13.2.4. Potential future development opportunities

Publicly available data enabled the identification of some potential sites in Hungary. Further site-specific studies are required to advance the potential storage sites of the Hystories database towards active storage of hydrogen. A collaboration with the Mining and Geological Survey of Hungary may result in a more complete database, possibly including some even more promising potential sites for which the data availability was insufficient in the published literature.

13.3. Discussion and conclusions

Hungary has existing natural gas storage sites in porous media. Several hydrocarbon traps were identified during the Hystories project, which could be considered for hydrogen storage after depletion. Regarding the seal rocks and risks, further investigation is required to evaluate these traps as available publications focus on the properties of the reservoir. It is important to emphasise that the database is by no means exhaustive as the list of the potential sites is based solely on published literature.

Saline aquifers represent the most abundant potential storage sites. Saline aquifers comprise hydrodynamically closed formations with a considerable thickness and further investigation would be expected to identify traps/closures which would be suitable for geological storage of hydrogen. To utilise the saline reservoirs, mapping of traps and delimitation of specific hydrodynamic units suitable for storage, are necessary.

[23] https://mfgt.hu/hu-HU/Tevekenysegunk/Gaztarolok

[24] https://www.gaztarolo.hu/szoreg-1-foldalatti-gaztarolo/

14. Italy; geological assessment of hydrogen storage opportunities

Italy is one of the most hydrocarbon-endowed countries in Europe, thus hosting several traps potentially suitable for Underground Hydrogen Storage (UHS), both on- and offshore. Hydrocarbon occurrences derive from a variety of petroleum systems, that are the result of a complex geological history. Hydrocarbon occurrences are found in both carbonate and terrigenous formations, Mesozoic to Pleistocene in age. Oil occurs mainly in complex carbonate structures along the Apennines thrust-and-fold belt and in the foreland, whereas thermogenic and biogenic gas has been found in the foredeep terrigenous units of the highly tectonised Oligo-Miocene foredeep wedges and within the Pliocene-Pleistocene foredeeps, respectively. In the same geological provinces, deep saline aquifers, both in terrigenous and carbonate formations, would be expected to offer suitable conditions for UHS. Currently, there are 15 operating onshore natural gas storage sites in porous media in Italy, which could potentially be converted for hydrogen storage.

The Hystories analysis indicated that both deep saline terrigenous and carbonate aquifers and depleted gas fields have geological and stratigraphic conditions potentially suitable for UHS, both on- and offshore.

As part of the Hystories project, a site-specific study was undertaken in a promising onshore area. A petrophysical characterisation of two depleted gas fields and related aquifers was performed, together with a first evaluation of the UHS capacity.

14.1. Data availability and gaps

14.1.1. Data availability and collation

A comprehensive review of sites potentially suitable for CO_2 storage already identified in the CO_2StoP project and further characterised as discussed in two related scientific publications (Donda et al., 2011 and Civile et al., 2013) has been performed during the Hystories project. The OGS team checked, and updated data collated during the CO_2StoP project.

New data was also added during the Hystories project. Added data mainly comprised new hydrocarbon fields where data had been made public since the CO_2StoP project, and fields that had been excluded from the CO_2StoP database because they had been considered too shallow for commercial CO_2 storage (i.e., shallower than 800 m) but these potential stores could be considered for hydrogen.

Concerning deep saline aquifers, the evaluation carried out under the Hystories project started from the review of the sites potentially suitable for CO_2 identified in both terrigenous and carbonate formations published by Donda et al. (2011) and Civile et al. (2013), respectively. In the areas identified by these studies, borehole data, including at depths shallower than 800 m, was analysed during Hystories. This dataset consists of about 2,300 well data acquired by several oil companies both on- and offshore since 1957 and made available by the Italian Ministry of Environment and Energy Security in the framework of the project "Visibility of Petroleum Exploration Data in Italy (ViDEPI)" (Table 26).

Current regulations establish that operating oil companies shall provide the Ministry with progressive technical reports on the activities carried out on their permits and concessions; the reports must include several types of documents, such as geological maps, structural maps, final well logs, and seismic lines. Required well data consists of composite logs that contain the following information: (1) lithology derived from cuttings; (2) geological formation name; (3) formation age; (4) depth; (5) litho-stratigraphy; (6) fluid occurrence; (7) formation depositional environment; (8) bio-stratigraphy; (9) geophysical logs (commonly resistivity, spontaneous potential, sonic, gamma ray). Pressure and temperature values are also sometimes reported. This information is usually available for dry wells; few data are made publicly accessible for hydrocarbon-bearing wells.

Information concerning depleted oil and gas fields are rarely available, except for some fields which are currently used as gas storage sites or are being evaluated for this purpose. As of 31st December 2021, 15 storage concessions (land areas allocated by the government to companies) are in force. There are 499 wells in connection with these storage concessions, 376 of which are used for the storage of natural gas. Some of the information provided in the Hystories database is derived from the websites of the companies who own and manage the natural gas storage sites (Table 26).

Table 26: List of key data sources for the Italian Hystories database

Source name / URL	Description	Version / Date
Videpi https://www.videpi.com/videpi/videpi.asp	"Visibility of Petroleum Exploration Data in Italy"	2020 (website is regularly updated)
Ministero dell'ambiente e della sicurezza energetica-Direzione generale infrastrutture e sicurezza/Ministry of Environment and Energy Security unmig.mite.gov.it	Data concerning gas storage sites and hydrocarbon production	2021 (website is regularly updated)
Edison Stoccaggio https://www.edisonstoccaggio.it/it/attivita-e-impianti/i-nostri-impianti/	Information concerning gas storage sites managed by Edison	2021
SNAM https://www.snam.it/it/chi-siamo/infrastrutture-snam/stoccaggio/	Information concerning gas storage sites managed by SNAM	2021
Ital Gas Storage https://www.igs.eu/	Information concerning gas storage sites managed by Ital Gas	2021

14.1.2. Availability of detailed data for further site characterisation

The ViDEPI (Visibility of Petroleum Exploration Data in Italy) database also contains about 55,000 km of multichannel seismic lines collected on-and offshore within the hydrocarbon exploitation concessions. These old data have been recovered from the raster files available in the ViDEPI database by OGS, which has made these data available with internationally recognised standards on the SNAP web portal[25]. SNAP also contains other seismic datasets collected in the frame of other research projects. SNAP is fully interoperable with major data sharing initiatives at national and international level (e.g., SeaDataNet, EMODnet, NADC and similar).

14.1.3. Identified gaps in data availability

Detailed information that would enable evaluation of potential reservoir and caprock formations is often not available in the public domain or at all, and thus was not available for the Hystories database. The reason these data are not available is twofold: 1) There are very few publications concerning hydrocarbon resources, and most the publications provide assessments only at basin scale. This means that data on individual oil and gas reservoirs are rare and data which are available are often insufficient for site-specific investigations; 2) Most available borehole data are related to dry fields, i.e. sites devoid of commercial interest for oil and gas companies. In these cases, only some of the information is made available for these wells.

14.2. Geological opportunities for hydrogen storage

14.2.1. Geological summary

The whole Italian peninsula is one of the richest hydrocarbon-producing regions in southern Europe. Three of the most important source rocks were deposited during Mesozoic crustal extension and are mainly oil-prone. Hydrocarbon occurrences associated with these sources are usually found in complex carbonate structures along the Apennines thrust-and-fold belt and in the Alpine foreland. Villafortuna–Trecate (Po Plain), Val D'Agri/Tempa Rossa (southern Apennines) and Gela (Sicily) fields represent the largest oil accumulations pertaining to these systems (Bertello et al., 2010). Two other important sources rocks were deposited in the foredeep terrigenous units of the foreland basins which formed during the Cenozoic orogenesis. The older source is thermogenic gas-prone and is found in the highly tectonised Oligo-Miocene foredeep wedges: gas occurrences associated with this source are mainly concentrated along the northern Apennines margin (e.g. Cortemaggiore field), in Calabria (e.g. Luna field) and Sicily (e.g. Gagliano field). The younger source is biogenic gas-prone and is situated in the outer Pliocene-Pleistocene foredeeps. The most important gas fields of Italy have originated from this source. Basins lie parallel to the regional structural trends, and structural traps occur throughout the thrust belt, in the adjacent foredeep basin, and in the

[25] https://snap.ogs.trieste.it/cache/index.jsp

Adriatic foreland. Hydrocarbon fields are concentrated in the Po Plain and in the northern and central Adriatic Basin. Hydrocarbon exploration in Italy is mature overall, particularly for gas (Bertello et al., 2010).

14.2.2. Storage assessments

The analysis performed in the framework of the Hystories project confirms that Italian stratigraphy has potential for UHS, in terrigenous and carbonate, on-and offshore saline formations, and in depleted gas fields (Figure 47, Figure 48 and Table 27).

Natural seismicity

As several areas which have promise for UHS are tectonically active, the analysis performed under Hystories collated information on the location of potential sources for earthquakes with magnitude greater than 5.5, as provided by the Database of Individual Seismogenic Sources (DISS) of the Istituto Nazionale di Geofisica e Vulcanologia (INGV[26]). Two studies considered the correlation between depleted gas fields and large seismogenic faults in Italy (Mucciarelli et al., 2015 and Valensise et al., 2022) and observed that large earthquakes are a result of large slips within large active thrust systems and that these zones appear to be surrounded by dry wells even when the strata is similar to adjacent regions where hydrocarbons are trapped. These studies suggested a causal link, i.e., that gas escape over geological timescales can be correlated with these large seismogenic sources within large active thrust systems. Whereas smaller events are associated with slip that is too small to affect the integrity of the reservoir and therefore reservoirs hosted in smaller anticlines are more likely to be intact. Areas located above these large seismogenic sources were thus considered unsuitable for UHS, and not included in the Hystories database.

Saline aquifers

Concerning saline aquifers, both in terrigenous and carbonate formations, sites already identified during the CO_2StoP project confirm the potential suitability of the deep reservoir-caprock systems for geological storage of CO_2. Data for these sites was checked and updared during the Hystories project. Work during the Hystories project identified potential shallower storage systems, with reservoir tops between 500 and 800 m depth, in both onshore and offshore geological formations (Table 27). In the Hystories database, saline aquifers were included in the 'formation' and 'storage units' tables as the available geological and geophysical information does not allow definition of regional scale basins or traps.

The Apennine foredeep was identified as the most important depositional basin on the country scale. Some areas, e.g. the western Po plain and the north-eastern Italy, reveal multiple potential reservoir-caprock systems, e.g. deep and shallow saline aquifers, deep saline aquifers overlain by depleted gas fields. These areas require further site-specific work, to enable more realistic evaluation of the UHS potential here.

[26] https://diss.ingv.it/

Hydrocarbon fields

Concerning hydrocarbon fields, although Italy is one of the richest hydrocarbon-producing regions in southern Europe, for the Hystories database, only those fields that could be considered for UHS purposes in the near future were included in the Hystories database. Therefore, the 'traps' that were included in the Hystories database comprise depleted gas fields that are currently being used or considered for Underground natural gas storage (Table 27). For several of these fields, the publicly available information was sufficient to define 'traps' for the Hystories database.

Table 27: Summary of the Italian storage options and development actions

Reservoir Type	N.o. traps/ units in Hystories database	Status description, remarks	Recommended actions for maturing and extending future potential
Onshore depleted gas and oil fields - traps	24	Depleted fields for which some data are available	Site specific studies required and additional well and geophysical data needed. Additional geological and geophysical data are thus required
Onshore oil and gas fields	2	One producing, one depleted	
Offshore depleted gas fields - traps	0	No publicly available information	
Onshore aquifers – storage units	29	They consist of both carbonate and terrigenous saline aquifers. Some areas reveal overlapping aquifers, which we called "deep" (reservoir top < 800 m) and "shallow" (top reservoir between 500 and 800 m).	Geophysical analyses are strongly recommended to provide a comprehensive characterisation. However, a few seismic data are publicly available onshore Italy. Additional geological and geophysical data are thus required.
Offshore aquifers – storage units	9	They consist of both carbonate and terrigenous saline aquifers. Some areas reveal overlapping aquifers, which we called "deep" (reservoir top < 800 m) and "shallow" (top reservoir between 500 and 800 m).	Geophysical analyses are strongly recommended to provide a comprehensive characterisation. Although, several seismic datasets are publicly available, additional geological and geophysical data are required in the most promising sites.
Both onshore and offshore aquifers – storage units	2	They consist of both carbonate and terrigenous saline aquifers. Some areas reveal overlapping aquifers, which we called "deep" (reservoir top < 800 m) and "shallow" (top reservoir between 500 and 800 m).	Geophysical analyses are strongly recommended to provide a comprehensive characterisation. However, a few seismic data are publicly available onshore Italy. Additional geological and geophysical data are thus required.
Onshore storage units with hydrocarbons	26	Depleted fields for which some data are available, among them: 4 gas storage requested licence; 15 currently working storage sites; 7 derived from the CO_2Stop database.	Site specific studies required and additional well and geophysical data needed. Additional geological and geophysical data are thus required
Offshore storage units with hydrocarbons	0	No publicly available information	

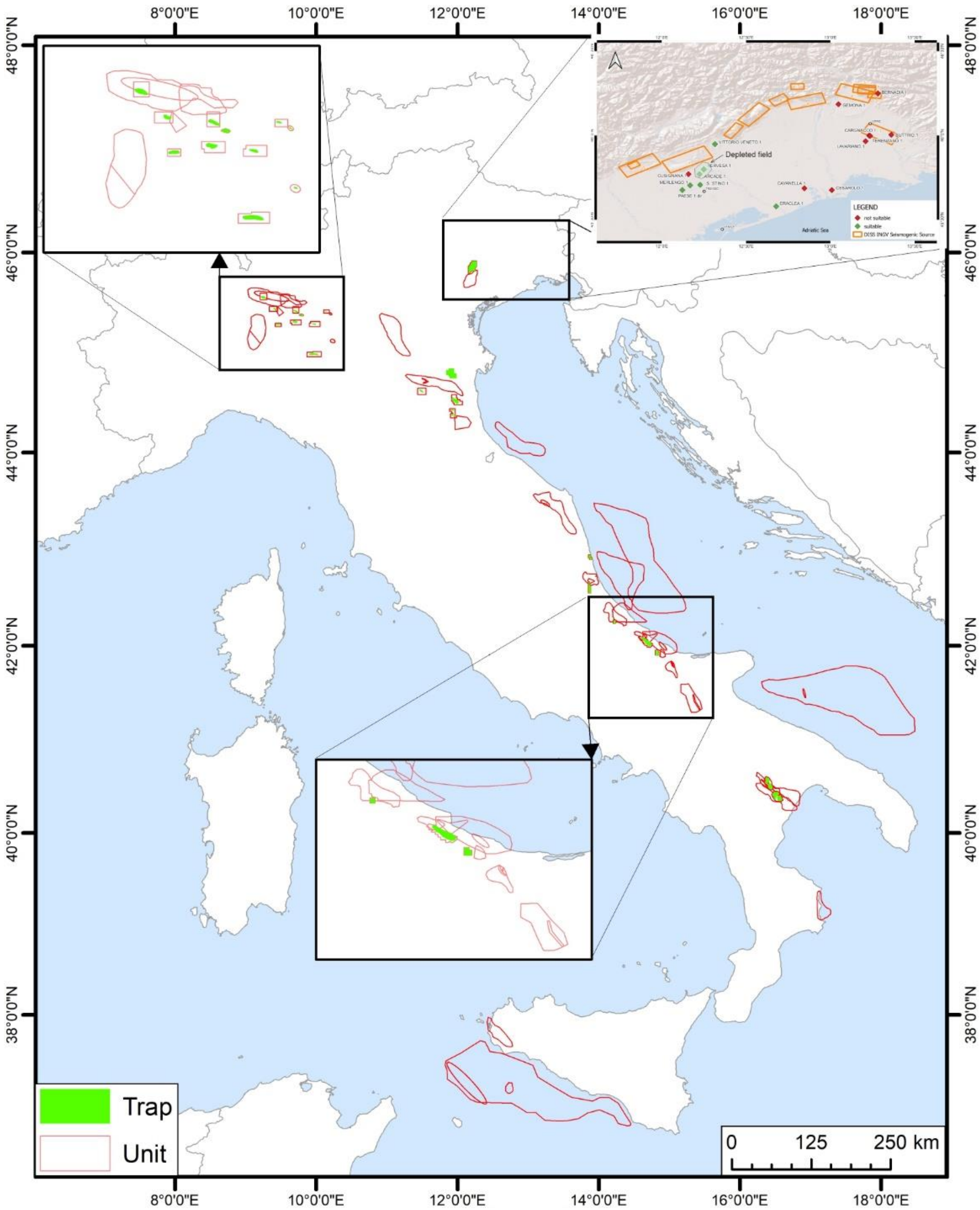

Figure 47: Overview of identified potential traps and units in the Hystories database within Italy. The enlargement in the top right corner shows the location of the area where a site-specific study has been conducted; red and green dots: boreholes; orange rectangles: seismogenic faults (from Mattera et al., 2023)

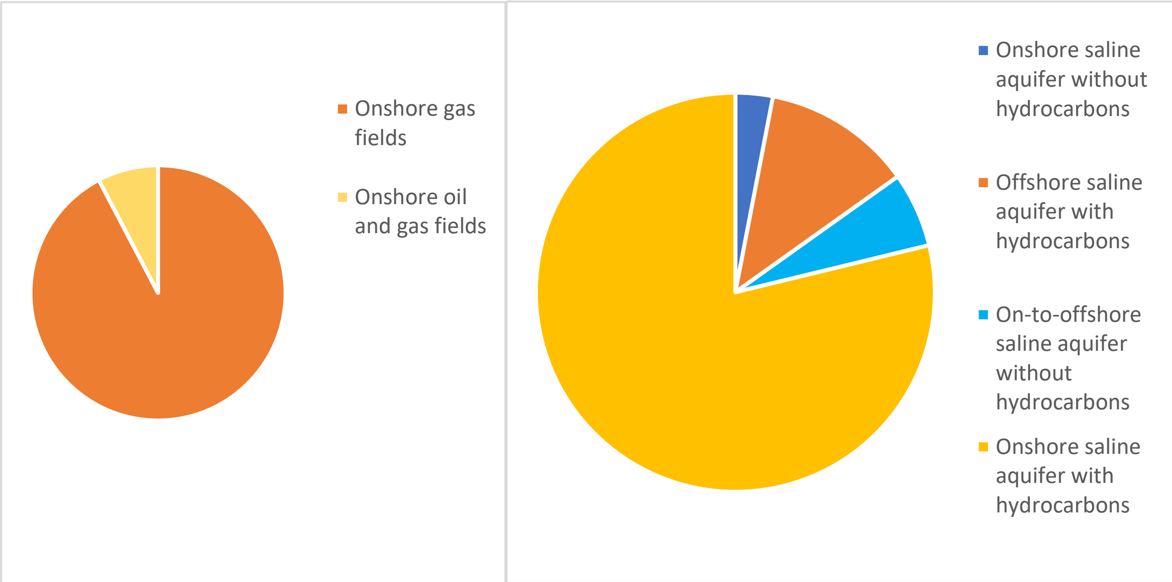

Figure 48: Frequency pie chart showing categories of identified potential storage opportunities in Italy; traps (left) and units (right). All identified traps are onshore gas or oil and gas fields.

Site specific study in a hydrocarbon bearing region

A site-specific study has been performed for an onshore area in north-east Italy. This site was chosen from several promising areas identified during the Hystories project because of its strategic location with respect to ongoing international hydrogen initiatives in Italy (please see Section 14.3). This site-specific study highlights saline aquifers and depleted gas fields in the area that could be considered eligible for UHS. The petrophysical characterisation that was performed on the potentially suitable 'Treviso area', included evaluation of porosity throughout each of the eligible wells, and enabled identification of the most promising stratigraphic levels for UHS. Moreover, estimates of the hydrogen storage capacity of the two depleted gas fields indicated a good working gas capacity for hydrogen would be expected. Results have been presented and discussed in a paper currently under review (Mattera et al., *in press*).

14.2.3. Existing storage sites

Currently, there are 15 operating onshore natural gas storage sites in Italy. These sites were included in the Hystories database, together with sites for which there is a pending storage licence concession, because they could potentially be utilised for hydrogen storage. If demand for hydrogen increases significantly and/or hydrogen-related technologies are more widely implemented, UHS could become more commercially attractive than UGS which could lead to these sites being converted.

14.2.4. Potential future development opportunities

The review of areas previously identified as suitable for CO_2 storage has been made on borehole data only. Some areas, e.g., the western Po plain and the north-eastern Italy reveal multiple, superimposed potential reservoir-caprock systems, e.g. deep and shallow saline aquifers, deep saline aquifers overlain by depleted gas fields. These areas merit additional, site-specific investigations, e.g., a seismic-borehole correlation, a comprehensive petrophysical characterisation, possibly accompanied by further data, in order to understand their actual hydrogen storage potential.

It is worth noting that uncertainty remains following the analysis of UHS potential as a result of the unavailability of specific data, such as the occurrence of local heterogeneities that can affect the behaviour of the injected hydrogen within the reservoir formations.

14.3. Discussion and conclusions

It is suggested that any UHS project in Italy must take into consideration the seismic hazard, which is high in some of the investigated areas. In fact, a recent study (Valensise et al., 2022), recommended that facilities for fluid (CH4, CO_2, hydrogen) storage in tectonically active areas should avoid large seismogenic faults and preferably opt for exploited gas reservoirs, which are more likely to be intact, i.e. unaffected by shallow active faults. This would also greatly reduce the hazard of fluid injection causing induced seismicity (Mucciarelli et al., 2015). However, it is noteworthy that saline aquifers are widespread both on and offshore in Italy, and host potential reservoir and caprock formations dozen-to-hundred metres thick, which merit further investigation. The faults of concern are sufficiently large to be identified on seismic sections and therefore areas without such faults are still worthy of investigation.

Among several promising areas identified during the Hystories project, the onshore area of north-east Italy, merits particular attention, because of its practical outcome. Some key initiatives have been undertaken in the northern Adriatic region concerning hydrogen-related technologies. During April 2022, the ‘North Adriatic Hydrogen Valley’ initiative was officially launched with the aim of building the first cross-border hydrogen valley. This initiative brings together the Friuli Venezia Giulia district, Slovenia and Croatia through a cooperation agreement that has been finalised to pursue the Hydrogen Strategy for a climate-neutral Europe[27], which was launched in 2020 by the European Commission. Further data and analyses in the whole northern Adriatic region could unveil the actual potential for UHS purposed of this strategic area.

[27] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

15. Latvia; geological assessment of storage opportunities

The most promising geological conditions for underground storage of gases in Latvia are in the Cambrian Series 3 Deimena Formation sandstones. Data were collected for the available Inčukalns Underground natural Gas Storage (UGS) site, which is an excellent example of an underground storage project in Deimena Formation sandstones. This UGS site provides natural gas to all three Baltic countries.

Additionally, for the Hystories project, data were collected for 17 saline aquifer structures, mostly located in western Latvia. These potential storage sites include 16 onshore and one offshore structure (E6; the largest potential 'trap' in Latvia), all with positive indicators for geological storage. These traps look promising for Underground Hydrogen Storage (UHS) in terms of location, area, reservoir quality, presence of a good seal (clayey rocks – shale – of the Ordovician Zebre Formation), and significant capacity for hydrogen storage. The largest of the onshore structures (Dobele and North-Blidene) are currently under consideration by the largest Latvian energy and industrial companies, for CO_2 storage. Given the large potential capacity of the identified storage sites, these structures should provide enough capacity both for CO_2 and hydrogen storage, sometimes working in synergy.

15.1.1. Data availability and collation

During the 1960's and 1970's, a number of wells were drilled, single–fold seismic data were acquired, and airborne magnetic and marine magnetic surveys were performed during hydrocarbon exploration activities offshore and onshore, and UGS exploration onshore. These data can also be used to analyse the underground storage potential in Latvia. As a result of these surveys, multiple aquifer structures were discovered.

There are no public databases available to inform assessments of Latvian storage sites (Table 28). However, available publications and reports prepared by the EU GeoCapacity, CO_2StoP and ESTMAP projects, and data collected for other research projects, Master and PhD studies are available.

The largest estimated CO_2 storage capacity in Latvia lies in the Cambrian Series 3 Deimena Formation (Sliaupa et al. 2013, Shogenov et al. 2013a, b, Shogenova et al. 2019). This geological formation would also potentially be suitable for UHS.

Since 2013, onshore storage capacity has been re-estimated and static geological models were constructed for four Latvian onshore structures (Dobele, South-Kandava, Blidene and North Blidene) and for E6 offshore structure (Shogenov et al. 2013a, 2013b, Shogenov 2015, Simmer 2018, Shogenova et al. 2019). Three-dimensional structural models were constructed using structure maps of the top reservoir and wells cross sections and static capacities for geological storage of CO_2 were estimated (Shogenov et al. 2013b).

Table 28: List of key data sources for the Latvian Hystories database

Source name / URL	Description	Version / Date
LEGMC Pakalpojumi (lvgmc.lv) https://videscentrs.lvgmc.lv/geologijas-pakalpojumi/geologiska-informacija	Not a public database. Old reports are available on paper mainly in Russian and can be copied (not for free). More recent reports are in Latvian. Digital copies can be also ordered to be sent by e-mail (much more expensive than paper copies) Old seismic data are reinterpreted and available for purchase. Well data and lithological columns are also available for purchase.	As of 05/09/2022
Latvian University.	Research database of Latvian wells, location and geology. Not in the public domain.	
Old books in Russian, more recent in English and very rare in Latvian. Research articles, Masters and PhD studies (mainly in English).	Available in the Baltic libraries, in the publications and in Universities databases (Master and PhD theses).	
Public reports and databases of EU projects: EU GeoCapacity, CO_2StoP and ESTMAP.	Reporting of potential for subsurface storage, including CO_2 storage capacity	

The capacity of the largest offshore structure E6 was additionally re-estimated recently for two different formations (Upper Ordovician Saldus F. and Cambrian Deimena F.). This was part of an assessment for the potential for a CO_2-EOR cycle in this offshore structure in the Upper Ordovician Saldus Formation (Shogenov and Shogenova 2017, 2021).

There is no national storage atlas available. There has been no application for a CO_2 storage exploration permit yet.

15.1.2. Availability of detailed data for further site characterisation

More detailed data could be collected (purchased) from the Latvian Environment, Geology and Meteorology Center, LEGMC. Additional wells were drilled for the Dobele structure; in total 23 wells are available. About 187 wells were drilled at Inčukalns UGS (Connexus[28]), half of which are operational.

For other structures, few data are available for a limited number of wells. Old seismic data that have been recently reinterpreted are available via LEGMC (for purchase).

[28] https://www.conexus.lv/enhancement-incukalns-ugs

15.1.3. Identified gaps in data availability

Data for four Latvian onshore structures (Dobele, South-Kandava, Blidene and North Blidene) and for the E6 offshore structure, were reassessed for the Hystories project. Data were available from Андрющенко et al, 1985, Shogenov et al. 2013a, 2013b, Shogenov 2015, Simmer 2018, Shogenova et al. 2019, 2021. Geological data for other structures were available from the EU GeoCapacity project and these data were updated with petrophysical properties reported by Pomeranceva (2003) and Cambrian mineralogy data collected during research projects and published in research books.

15.2. Geological opportunities for hydrogen storage

15.2.1. Geological summary

The main target for the Underground Hydrogen Storage (UHS) study in the Baltic Region (Estonia, Latvia, and Lithuania) is the Baltic sedimentary basin or Baltic Syneclise, a 700 km × 500 km synclinal structure located in the western part of the East European Craton.

The Estonian-Latvian and Lithuanian monoclines are the marginal structures of the Baltic Syneclise. Several structures within the Baltic Syneclise appear to offer potential for UHS:

- The Liepaja Depression is a distinctly asymmetrical depression (length 200 km, width up to 70 km, trough amplitude 800 m) with a gentle northern and a steep near-fault southern edge.
- The Liepaja-Saldus High crosses the Baltic Syneclise. This zone stretches about 400 km from the Swedish offshore and across north-east Latvia. The width of the zone is 25 – 80 km. From southwest to northeast, the basement becomes progressively shallower; from 1900 – 500 m. The Liepaja-Saldus zone is a complex system of blocks and basins. Fault amplitudes reach 600 m.

The Cambrian Series 3 aquifer offers good potential for geological storage of CO_2 or hydrogen in the Baltic sedimentary basin. The Cambrian aquifer contains saline water (up to 120 g/L) in the central part of the basin at depths of more than 800 m. Geochemical and thermodynamic properties will enable the use of the Cambrian Series 3 aquifer for geological storage of gases. The geological conditions are most favourable in the uplifted structures in Latvia on the Liepaja-Saldus High. However, prospective structures are located both onshore and offshore the Baltic area (Grigelis, 1991; Sliaupa et al., 2008a; Shogenova et al., 2009a; Šliaupa et al., 2013).

The Cambrian Series 3 stratigraphy is similar both onshore and offshore Latvia (Grigelis, 1991). The lithofacies implies the deepening of the sedimentation environment and maximum transgression at the beginning of the deposition of the Cambrian Series 3 (Kybartai times). Rocks of the Cambrian Series 3 Deimena Formation were deposited in a shallow regressing marine basin and subject to tides and storms. These deposits are dominated by quartz sandstones with subordinate claystone layers.

The major Deimena reservoir rocks are 50 – 70 m thick and were deposited during a marine regression on top of the Kybartai Formation. The regression deposits have a higher sand percentage compared with the underlying Kybartai Formation. The Cambrian reservoir is sealed by Ordovician claystones and marlstones with low-porosity carbonates, except for the in the northern and southern extremes of the basin where rocks were exposed to intense meteoric water infiltration (Paškevičius, 1997). The Deimena Formation is covered by up to 46 m thick shales and clayey carbonate caprocks of the Lower Ordovician Zebre Formation in the studied structures in Latvia. Shale rocks are dark with thin layers (0.5 – 2 mm) and highly fissile. A layer of greenish-grey glauconite-bearing sandy marlstones (0.5 m thick) was observed at the base of onshore formations. The reservoir rocks are further sealed by 130 – 230 m-thick Ordovician and 100 – 225 m-thick impermeable Silurian clayey carbonate caprocks.

15.2.2. Storage assessments

The most promising reservoir properties for gas/CO_2/hydrogen storage in the Baltic Basin are found in the Cambrian series 3 Deimena Formation sandstones (Shogenova et al., 2009a; Shogenov et al., 2013; Sliaupa et al., 2013).

In addition to the underground storage capacity of the Inčukalns UGS (Deimena Formation sandstones), which could become available for storage of hydrogen after 2040 – 2050, the largest 16 potential onshore storage structures in Latvia (already assessed as prospective for CO_2 storage; Shogenova et al., 2009a), are proposed as options for UHS in the Hystories database.

In the Latvian offshore area, the smaller E6-B area within the largest in the Baltic States structure (E6) with an areal extent of 47 km^2 is also considered prospective for hydrogen storage. The E6-B part is bounded by faults that are expected to be sealing and this structure is therefore deemed more promising for storage than the larger adjacent block E6-A which is disrupted by several faults (Shogenov and Shogenova, 2017, 2022). The same approach could be proposed for the Blidene and North Blidene structures (Figure 49). The Larger North Blidene structure could be used for CO_2 storage, while the smaller Blidene structure could be used for hydrogen storage.

The proposed anticlinal structures ('traps') identified in the Hystories database include one UGS site, 16 onshore and one offshore structure (E6) in the top of the Cambrian Deimena Formation. Depth to top reservoir is 650 – 1125 m, average reservoir thickness is 30 – 70 m and areal extent of these traps ranges from 10 – 95 km^2. Deimena sandstones have good reservoir properties, including average porosity of 20 – 28%, average permeability of 300 – 360 mD in the onshore structures and 150 mD in the E6 structure offshore. Average permeability in the Inčukalns UGS is 465 mD. The Deimena Formation has a low temperature (16 – 25 ˚C onshore and 36 ˚C in the offshore E6 structure) which would result in a higher density of stored gases compared with higher temperature reservoirs. The Deimena Formation is immediately overlain by up to 46 m thick shales and clayey carbonate caprocks of the Lower Ordovician Zebre Formation in the studied structures. Overall, the seals comprise 130 – 230 m thick Ordovician and 100 – 225 m thick Silurian impermeable clayey carbonates.

Only the largest structures available in Latvia were mapped (Table 29, Figure 50, Figure 51). Additional small structures could be assessed as the demand for hydrogen and UHS evolves.

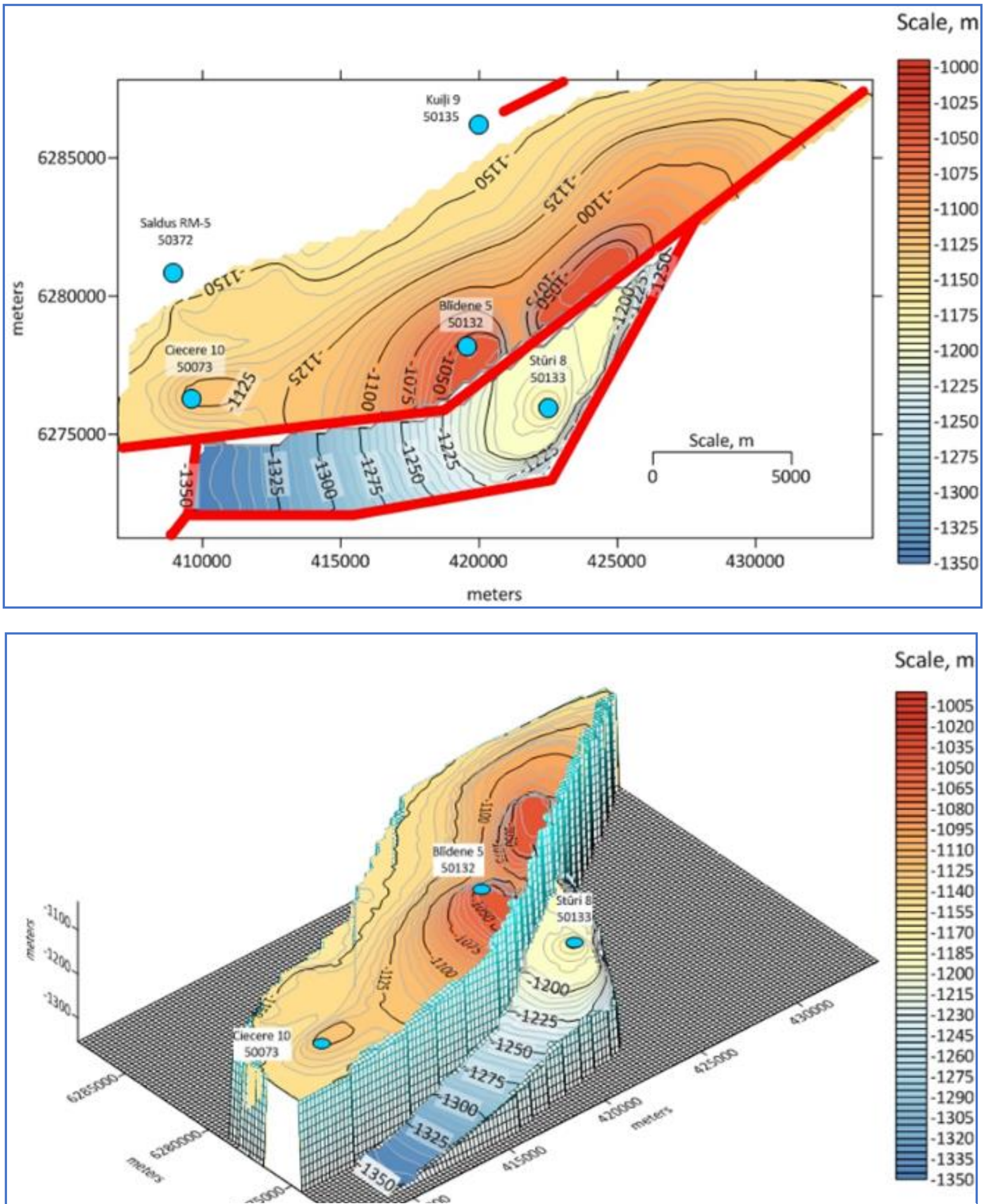

Figure 49: Example of a site where CO_2 and hydrogen storage could be applied in synergy. Contour maps and 3D structure maps of the structures within the Deimena Formation in onshore North Blidene (upper block) and the Blidene (lower block). Colour scale indicates depth. Models prepared using Golden Software Surfer 15 software. Fault line is indicated with red line on the top figure (Simmer, 2018, Shogenova et al, 2019). The Larger North Blidene structure could be used for CO_2 storage, while the smaller Blidene structure could be used for hydrogen storage.

Table 29: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	17	Main reservoir type. Locally-defined closures. The largest onshore Dobele, North Blidene and Blidene sites were recently considered for CO_2 storage by large emitters (e.g., Latvenergo, Schwenk Cement). The largest capacity (Baltic Region offshore structure E6) is prospective both for CO_2 and for UHS. CO_2 capacity estimates were made in CO_2StoP and ESTMAP projects. One of the aquifer traps (Inčukalns) is used for UGS	Confirm operational capacities and performance. Investigate and assess alternative potential including Hydrogen Energy Storage. Regional exploration may reveal other trap structures.
Hydrocarbon reservoirs	1	There is a Hydrocarbon field in the offshore E6 structure in Upper Ordovician strata. The field has not yet been exploited. Information is available only in research articles and estimation is made only for CO_2-EOR case.	Confirm operational CO_2 capacities and performance. Investigate and assess alternative potential including Hydrogen Energy Storage. Regional exploration may reveal other trapped structures.

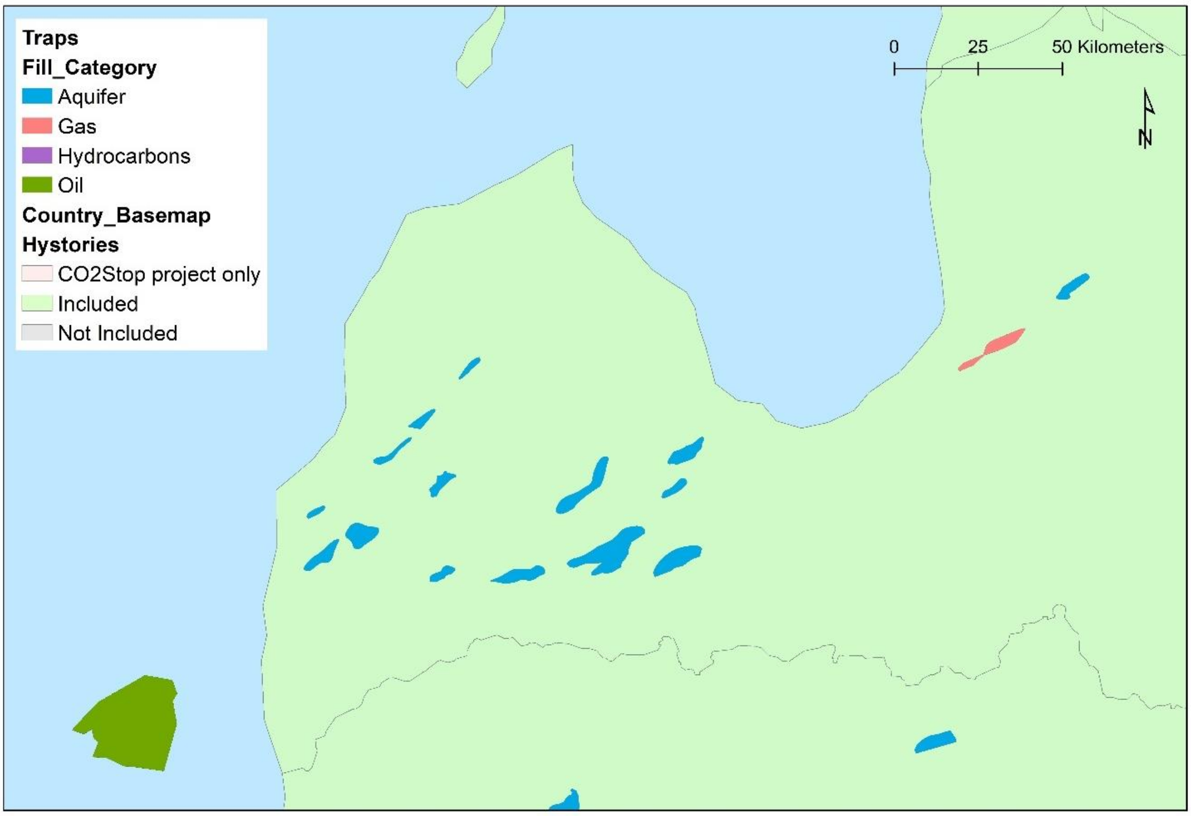

Figure 50: Overview of identified potential traps in the Hystories database within Latvia (and surrounding areas). .

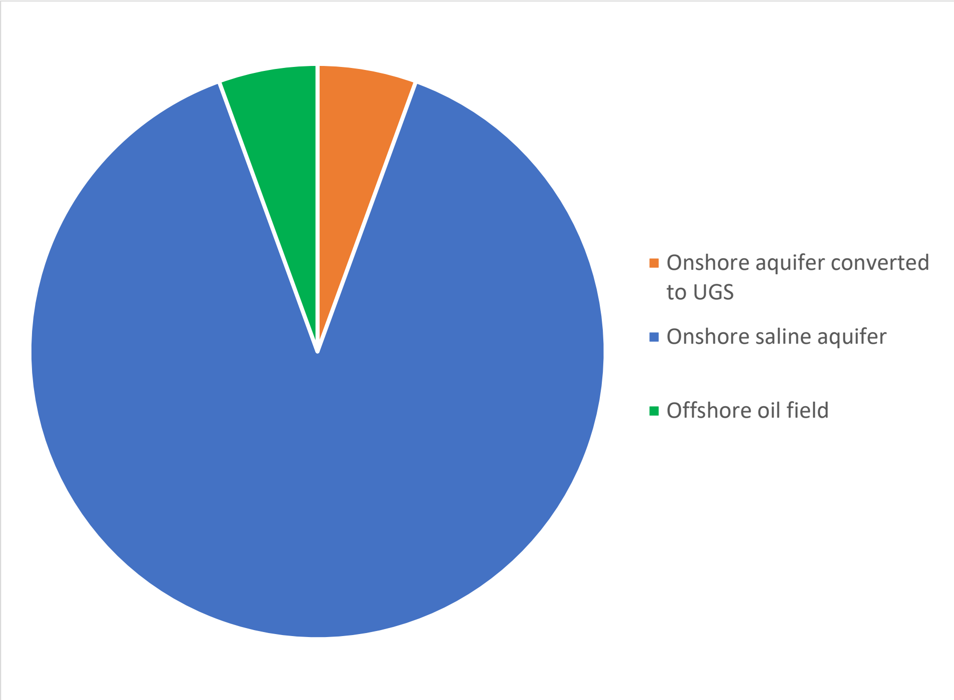

Figure 51: Frequency pie chart showing categories of identified potential storage traps in Latvia. These are all within the same storage formation/unit

15.2.3. Existing storage sites

There is only one onshore porous media UGS site in Latvia. This is a saline aquifer closure. The Inčukalns UGS site, owned by CONEXUS, is an excellent example of an underground storage project in the Deimena Formation sandstones. This site provides natural gas to all three Baltic countries and proves high storage efficiencies can be achieved for underground storage of gases. The Deimena Formation sandstones are located at depths of 680 – 800 m and are around 50 m thick.

The total gas storage volume in this UGS site is 4.445 billion m^3, with an active gas volume of 2.30 billion m^3 and a cushion gas volume of 2.145 billion m^3. The areal extent of the UGS site gas deposit is about 20 km^2. The area of the gas deposit is about 20 km^2.

Design capacity is as follows; daily injection 12 million m^3, daily withdrawal 24 million m^3. Working pressure is minimum 24 bars and maximum 105 bars. The capacity of the compressor stations is 33.5 MW (45 600 horsepower). There are 187 wells (including 93 producers) and three gas collection stations.

15.2.4. Potential future development opportunities

Potential future development opportunities are offered by onshore and offshore aquifer structures. The largest structures could be considered for development for UHS and CO_2 storage in adjacent blocks.

Latvia could provide storage not only for national stakeholders, but also for neighbouring countries. Storage could be provided for Estonia, where suitable storage options are not available. Storage could also be offered for Lithuania, where CO_2 injection is currently forbidden, and reservoir and injection properties are poorer.

Latvia has available UGS capacity and significant experience acquired during 50 years of successful operation. CONEXUS, the owner of Inčukalns UGS site, is also looking for future business opportunities and storage of hydrogen and CO_2 could be options of interest.

15.3. Discussion and conclusions

In Latvia, the most promising geological conditions for UHS are found in the Cambrian Series 3 Deimena Formation sandstones. This formation is effectively sealed by shales of the Ordovician Zebre Formation. Successful operation of the Inčukalns UGS site for 50 years proves good reservoir/seal quality and high storage efficiencies are achievable. By extension, it would be expected that UHS could also be successfully operated in Latvia.

For Hystories, 17 structures, mostly located in the western Latvia were identified as 'traps' worthy of further investigation for UHS. These traps, including 16 onshore and one offshore structure, look promising in terms of location, areal extent, reservoir, and seal quality. These traps are expected to offer significant capacity.

The largest onshore structures Dobele and North-Blidene which were previously assessed for UGS, are now under consideration by the largest Latvian energy and industrial companies for CO_2 storage. Considering that this stakeholder group includes companies that are planning to produce hydrogen, it seems plausible that UHS will also be of interest.

The large capacity offered by structures in Latvia could provide enough storage for both CO_2 and Hydrogen storage, potentially both at some sites. As an example, a recent study assessed part of the large offshore E6 structure for UHS alongside CO_2 storage and geothermal energy recovery (Shogenov and Shogenova, 2022).

16. Lithuania; geological assessment of storage opportunities

Underground Hydrogen Storage (UHS) potential was assessed for 12 oil fields and three aquifer structurers in the Cambrian Series 3 Deimena Formation sandstones. One small Upper Permian salt dome is also available to develop for storage.

The oil fields are located at depths of 1800 – 2100 m and have areal extents of 3 – 31 km^2. These reservoirs have sandstone with thicknesses of 16 – 59 m, porosity of 6 – 11%, permeability of 11 – 110 mD, and temperatures of 75 – 87˚C.

Two onshore and one offshore saline aquifer structures have been identified as potential stores during Hystories. These structures lie at depths of 0.9 – 1.6 km and have areal extents of 43 – 91 km^2. The capacity of these saline aquifer traps is greater than that of the oil fields. The saline aquifers have higher porosities and permeabilities and lower temperatures than the oil fields.

To increase UHS capacity, the most prospective opportunity may be to access transboundary storage projects in Latvia in the Cambrian Deimena Formation, located close to the Lithuanian border.

16.1.1. Data availability and collation

A List of the publicly available data sources used to assess storage potential for Lithuania is provided in Table 30.

16.1.2. Availability of detailed data for further site characterisation

More detailed data are available from the Geological Survey of Lithuania and at NRC (Saulius Sliaupa). There is no public database for storage sites.

16.1.3. Identified gaps in data availability

Additional publicly available data could be transcribed, however, this would require visits to the Lithuanian geological survey or further collaboration with NRC. Many of the older publications are in Russian and more could be translated given further resources.

Overall, detailed data such as seismic and well data are only available by special request from oil and gas companies on a project-by-project basis.

Seismic coverage is good overall in the Lithuanian part of the Baltic Basin. Acquisition of new well and 3D seismic data at promising sites would improve storage assessments if these data were made public. There is also scope to improve seismic coverage in eastern Lithuania.

Table 30: List of key data sources for the Lithuanian Hystories database

Source name / URL	Description	Version / Date
INSPIRE dataset for Geology Geological Survey of Lithuania.	INSPIRE dataset for Geology theme represents geological information for the territory of Lithuania. Layer with Active well objects is not public, in order to obtain data you need to contact the Lithuanian geological survey under the Ministry of Environment which is the resource provider, lgt@lgt.lt. Layers GE.AquiferSystems, GE.Aquiclude, GE.Aquifer, and GE.Aquitard are shown at a scale of 200 000:100 00 000. INSPIRE dataset for the Geology theme was created using input datasets provided by the Lithuanian Geological Survey under the Ministry of Environment of Lithuania: 1) neo-tectonically active faults, 2) borings, 3) hydrogeological borings, 4) groundwater bodies, 5) hydrogeological objects, 6) underground water monitoring facilities and borings, 7) seismic monitoring stations, 8) Lithuanian Quaternary geological map M 1:200 000, 9) Lithuanian geomorphological map M 1:200 000, 10) Lithuanian Pre-Quaternary geological map M 1:200 000, 11) Hydrogeological map M 1:200 000. The output data set is created by State Enterprise GIS-Centras, Lithuania.	05/09/2022
Nature Research Centre, Institute of Geology and Geography (NRC), Lithuania	Research database of Latvian wells, location and geology. Not public.	
Old books in Russian, more recent publications in English and in Lithuanian. Research articles, Master and PhD studies (mainly in Lithuanian).	Available in the Baltic libraries, in journal publications and in University databases (Master and PhD theses).	Zdanavičiūtė O ., Sakalauskas K., 2001. Petroleum geology of Lithuania and Southeastern Baltic. Vilnius: GGI. 204 pp. Rasa Šliaupienė, Saulius Šliaupa. Prospects for CO_2 geological storage in deep saline aquifers of Lithuania and adjacent territories. geologija. 2011. Vol. 53. No. 3(75). P. 121–133 © lietuvos mokslų akademija, 2011. Unpublished exploration report of E7-1/82 offshore well. 1983. LEGMC), Latvia, Riga. (In Russian). 2) Shogenov et al, 2013, 2015.
Public reports and databases of EU projects: EU GeoCapacity, CO_2Stop and ESTMAP.	Reporting of subsurface storage uses	GeoCapacity 2008 CO_2StoP 2013 ESTMAP 2016

16.2. Geological opportunities for hydrogen storage

16.2.1. Geological summary

Lithuania is situated in the south-eastern part of the Baltic sedimentary basin overlying the western periphery of the East European Craton of the Early Precambrian consolidation. The basin sediments have experienced very little tectonic deformation owing to the underlying stable craton. The Baltic basin was established during Cambrian times (about 520 Ma) and is basin fill comprises sediments from all the geological systems of the Phanerozoic. The thickness of sediments varies from 200 m in southeast Lithuania to 2300 m in west Lithuania.

Lithuanian territory has good coverage in terms of seismic and deep well data. A number of sandstone aquifers have been defined in the sedimentary sequence. Furthermore, a salt pillow was discovered in south of west Lithuania which could offer storage opportunities. The Baltic Basin is therefore considered prospective for UHS.

The Cambrian Series 3 Deimena Formation reservoir has been extensively studied owing to the presence of extensive oil exploration in western Lithuania territories, which has been exploited over the past 50 years.

Onshore

Onshore, the aquifer comprises quartz sandstones with rare shales and siltstones which do not exceed 15% in abundance. The porosity of the sandstones shows strong correlation with depth. Porosity varies from 20 – 25% in the shallow eastern periphery of the Baltic basin to 5 – 15% in the west. Permeability varies with porosity, ranging from 500 – 1000 mD in the east to 10 – 200 mD in the west. This trend is mainly attributed to late diagenetic quartz cementation. The thickness of the reservoir is about 50 – 70 m. Reservoir depths range from 300 m in the east to 2200 m in the west. The Cambrian aquifer is sealed by a very thick shale package of Ordovician and Silurian age (Sliaupa et al, 2013). Previous studies identified 76 onshore structures in Cambrian reservoir rocks. However, most these structures are relatively small, although some are probably still of interest for hydrogen or gas storage. The largest Syderiai and Vaškai structures are located in the northern part of Lithuania; the Syderiai structure and the Vaškai structure. The small nature of the potential trapping structures is a result of structural deformation of the sedimentary cover of Lithuania being relatively weak (owing to the cratonic basement). Tectonic stresses that resulted in deformation were most intense during latest Silurian-earliest Devonian (Late Caledonian stage) times (Sliaupiene, 2014).

Lithuanian onshore oil production started in 1991. It reached its production peak in 2004 with 2.8 Mbbl per day. In Lithuania, 15 commercial oil fields lie within Cambrian sandstones, three are located in Silurian reefs, and one lies in an Ordovician reservoir. The oil is light. Twelve presently operating oil fields in western Lithuania are close to depletion and UHS could be considered for UHS in the in the Deimena Formation reservoirs.

There are abundant salt layers in the Kaliningrad district in south-west Lithuania. The salt is exploited in the Gusev area at depths of 630 – 700 m, where the thickness of the salt layer is 140 m. Average purity of salt is about 95%. By contrast, only one Upper Permian salt pillow has been discovered in the Usėnai area close to the Kaliningrad district border (Figure 52). Two wells were drilled. The top of salt dome was found at the depth of 459 m. The thickness of the dome is 75 m, the resources of salt were calculated as 549 Mt. The size of the dome is 2 by 3 km. The dome is underlain by 63 – 90 m-thick anhydrites and overlain by Triassic shales around 200 m-thick. The following parameters were established for the Usėnai salt pillow: salt pillow gas 60 m height, 1.8 km diameter; maximum allowed height of cavern 24 m, minimum allowed distance from cavern to pillow wall 72 m, minimum distance between walls of neighbouring cavers 72 m. The volume of a 24 by 24 m cavern is 10,857 m^3 (cylindrical) and 7238 m^3 (spherical). An alternative approach is creating a gallery-type cavern of diameter 250 m and height 10 m. The volume of such a gallery cavern is evaluated at 500,000 m^3 (Shogenova et al., 2022).

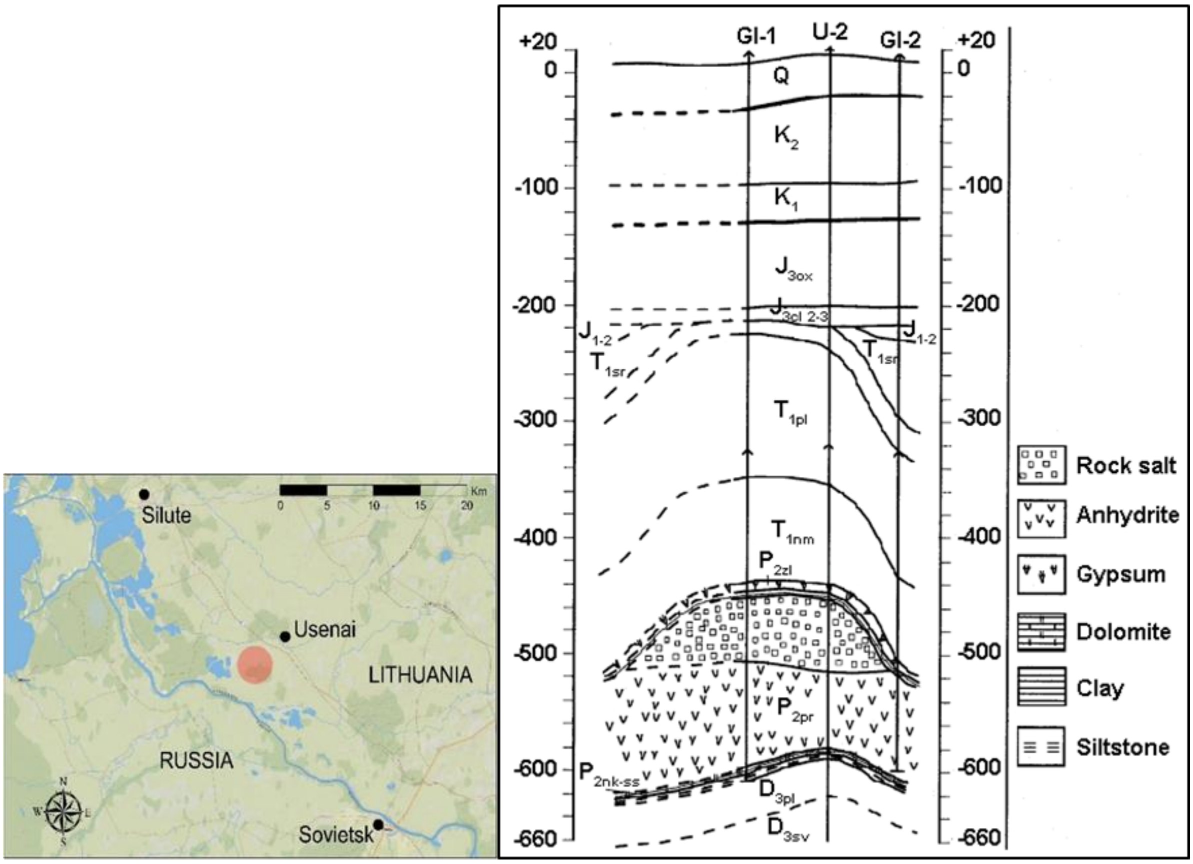

Figure 52: Location of the salt dome in the Usėnai area, b) Geological cross section across Usėnai salt dome. Q-Quaternary, K2-Upper Cretaceous; K1-Lower Cretaceous, J3ox- Oxfordian Upper Jurassic, J3cl - Callovian Upper Jurassic; J1-2-Lower-Middle Jurassic, T1šr- Šarkuvos Fm. Lower Triassic, T1tr- Tauragės Fm. Lower Triassic; T1pl- Palangos Fm. Lower Triassic, T1nm-Nemuno Fm. Lower Triassic, P2pr-Prėgliaus Fm. Upper Permian Series (Lopingian), D3pl- Pļavinas Fm. Upper Devonian; D3šv-Šventosios Fm. Upper Devonian.

Offshore

The offshore area has dense coverage in terms of seismic profiles. Several dozens of hydrocarbon exploration and exploitation wells were drilled in the Baltic Sea area. The first offshore wells for hydrocarbon exploration were drilled in the 1970s. Prospective local traps have been defined during earlier studies (e.g. CO_2StoP). The traps are characterised by low storage capacity values owing to their relatively small size (area 5 – 20 km^2, vertical amplitude 20 – 40 m) and poor reservoir properties (porosity of Cambrian sandstones is predominantly <8%). The largest trap (D11) is located close to coastline still offers a relatively low-capacity storage opportunity, which will be challenging to exploit given the higher costs for offshore exploration. A larger capacity trap (E7) lies on the border with Latvia. This structure was included in Hystories database.

16.2.2. Storage assessments

The best reservoir properties for gas storage in the Baltic Basin are found in the Cambrian series 3 Deimena Formation sandstones (Shogenova et al, 2009b, Sliaupa et al, 2013, Shogenov et al., 2013). However, Lithuanian storage sites have a poorer quality primary cap rock compared with neighbouring Latvia. In Lithuania, reservoir rocks in aquifer traps and oil fields are covered by interlayers of mainly argillaceous carbonate rocks.

The Vaškai structure, located in in eastern Lithuania in the Pasvalys region, is the largest potential storage structure found in the Deimena Formation sandstones (Figure 53, *Table 31*). Five wells were drilled and a number of seismic profiles were acquired in order to investigate this structure that was considered prospective for Underground Gas Storage (UGS). The structure is bounded by a 200 m amplitude fault in the south. The sandstone has an average porosity of 22% and permeability of 800 mD. This structure has an areal extent of 4 by 10 km and vertical amplitude of 35 m.

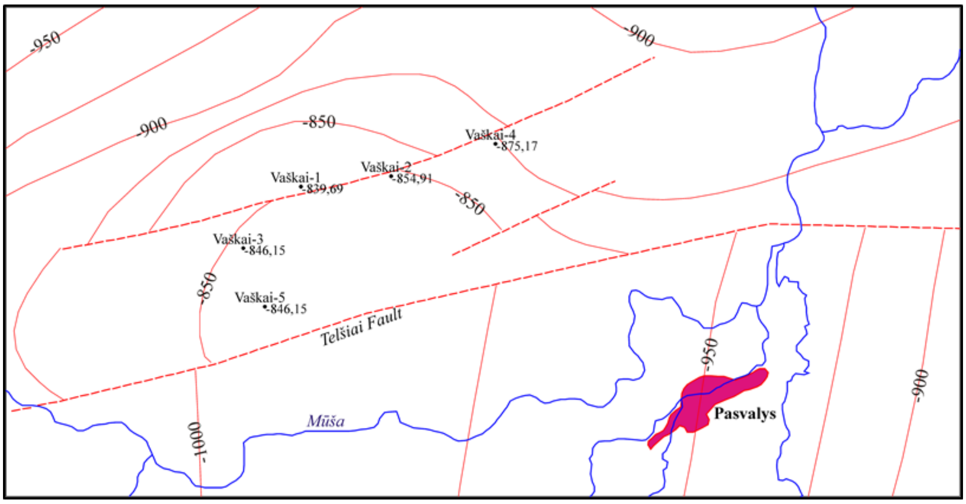

Figure 53 Map of Vaskai structure showing contours of the top of Cambrian Series 2-3 Deimena Group Vergale-Deimena (sandstones) Wuliuan Stage (red line) and faults (dashed red lines).

The Syderiai structure is the largest identified prospective storage opportunity in Lithuania. This potential trap has an area of 91 km^2 area and reservoir thickness of 50 m (Figure 54, *Table 31*). This trap could considered as prospective for hydrogen or natural gas storage.

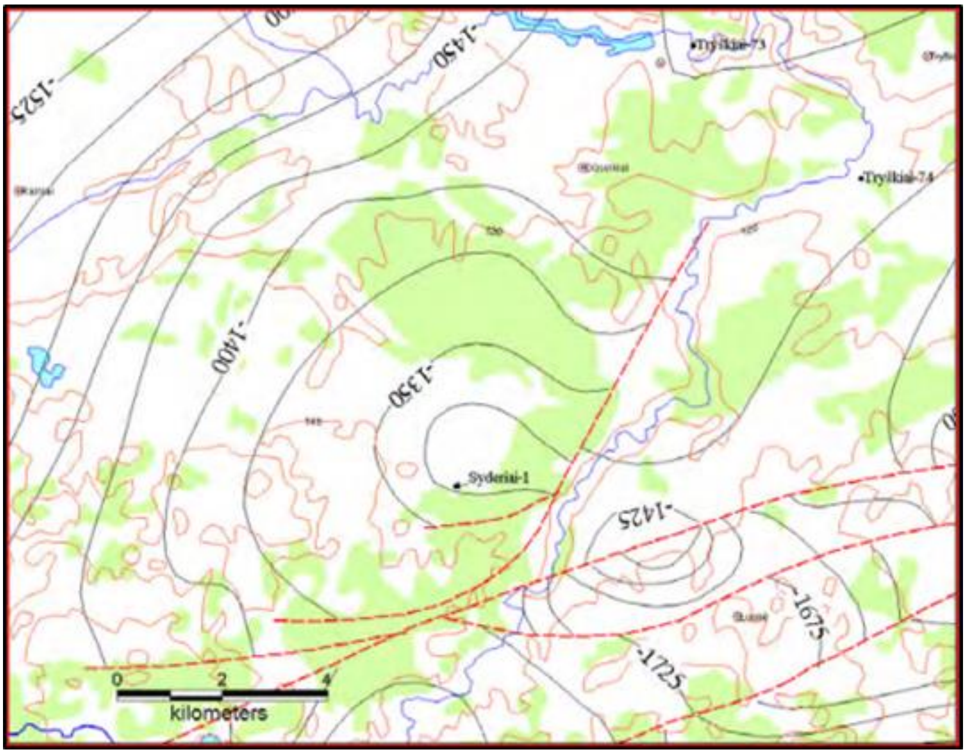

Figure 54: Depth of top of Cambrian Deimena Group sandstones in Syderiai structure. Faults are shown (red lines). Contour lines in 25 m (Vangkilde-Pedersen, T. et al. 2009).

The smaller offshore E7 structure has lower porosity and permeability than mapped Lithuanian onshore structures and is located relatively far from the shore, but its volume is larger than that of Vaskai because it has a greater reservoir thickness of 58 m (Figure 55, Shogenov et al, 2013 b).

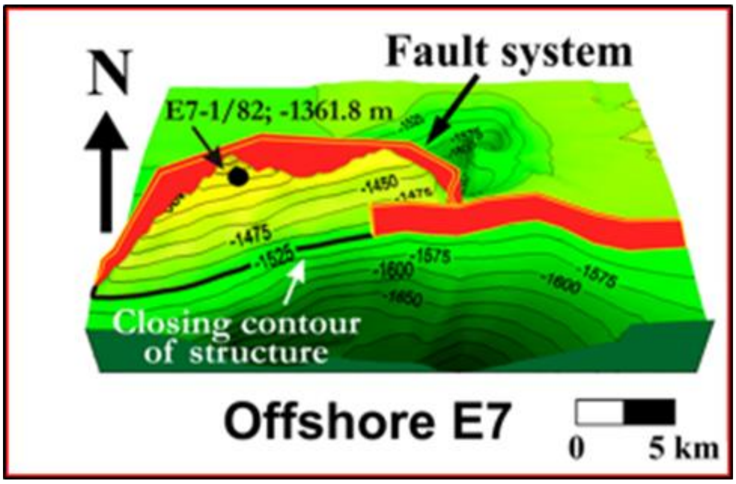

Figure 55: 3-D model of the top of Cambrian aquifer for offshore E7 structure that straddles the boundary between Latvia and Lithuania (Shogenov et al, 2013 b)

Lithuanian onshore oil production started in 1991. It reached peak production peak during 2004 with 2.8 Mbbl per day. In Lithuania, 15 commercial oil fields are found in Cambrian sandstones, three are in Silurian reefs, and one lies in Ordovician strata. Oil of all fields is light.

Twelve presently operating oil fields that lie in the Deimena Formation in western Lithuania are close to depletion and could be considered for UHS (*Table 31*, Figure 56, Figure 57).

Table 31: Summary of storage capacity options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	3	Onshore Syderiai and Vaskai entries available in ESTMAP. Offshore E7 was included in Latvian database, as it is located at the Latvian-Lithuanian onshore border. Syderiai site is planned for UGS.	Regional geological mapping and assessment of aquifers may reveal further potential for energy storage, including hydrogen
Hydrocarbon reservoirs	12	Main reservoir type. Local-defined with approximate capacity determination. All sites could be used for CO_2 storage and theoretically may represent alternative potential for UHS	Investigate and assess alternative potential including HES. Regional exploration may reveal other trapped structures.

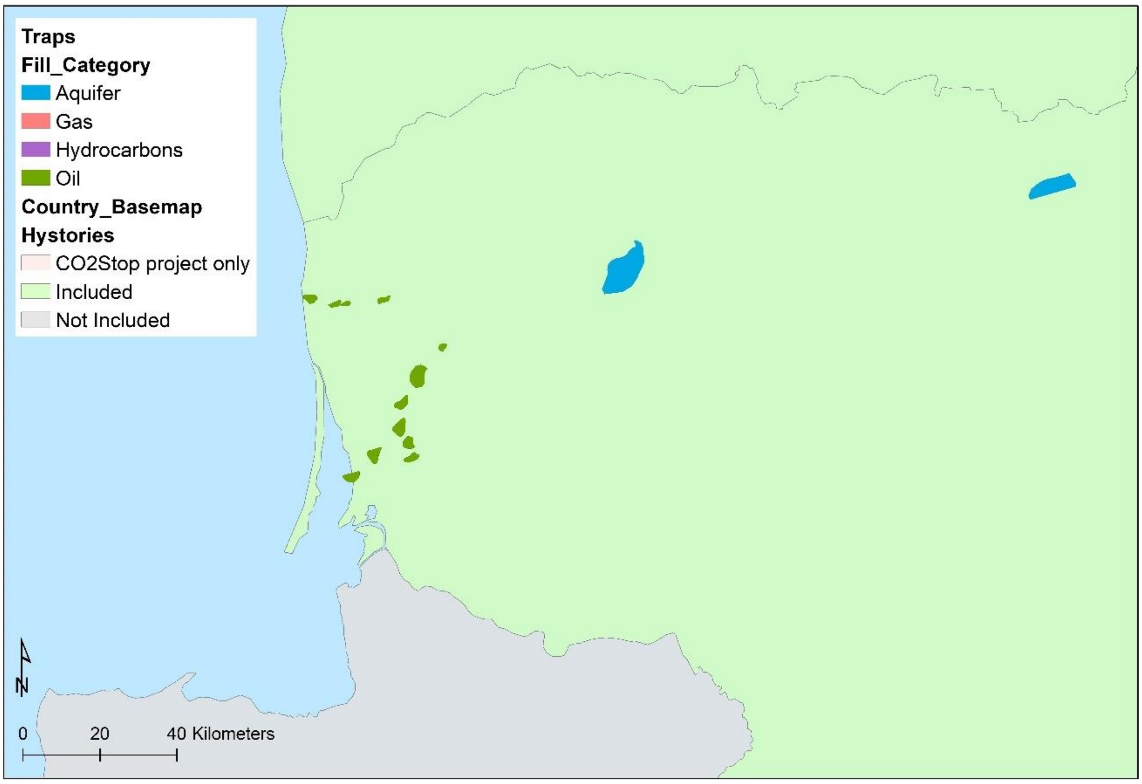

Figure 56: Overview of identified potential traps in the Hystories database within Lithuania.

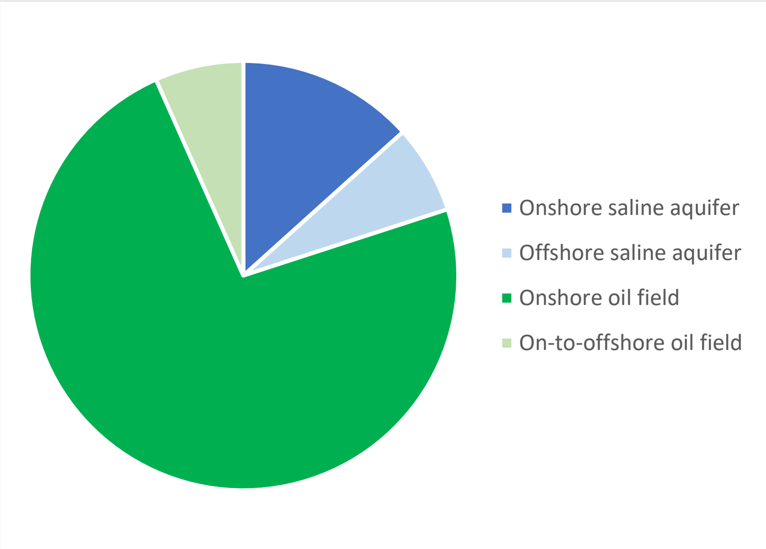

Figure 57: Frequency pie chart showing categories of identified potential storage traps in Lithuania. These are all within the same storage formation/unit in the database

About 10 years ago, the Ministry of Energy of Lithuania launched a project to assess the possibility of constructing an underground gas storage facility in the Syderiai structure (Figure 58). The Syderiai saline aquifer structure in Telšiai region, occurring at a depth of about 1400 m, was selected as it is the largest identified trap structure available in onshore Lithuania. Additional detailed seismic campaigns and geological exploration work were undertaken to determine whether a UGS facility of strategic importance for Lithuania's energy security could be constructed in the Telšiai region.

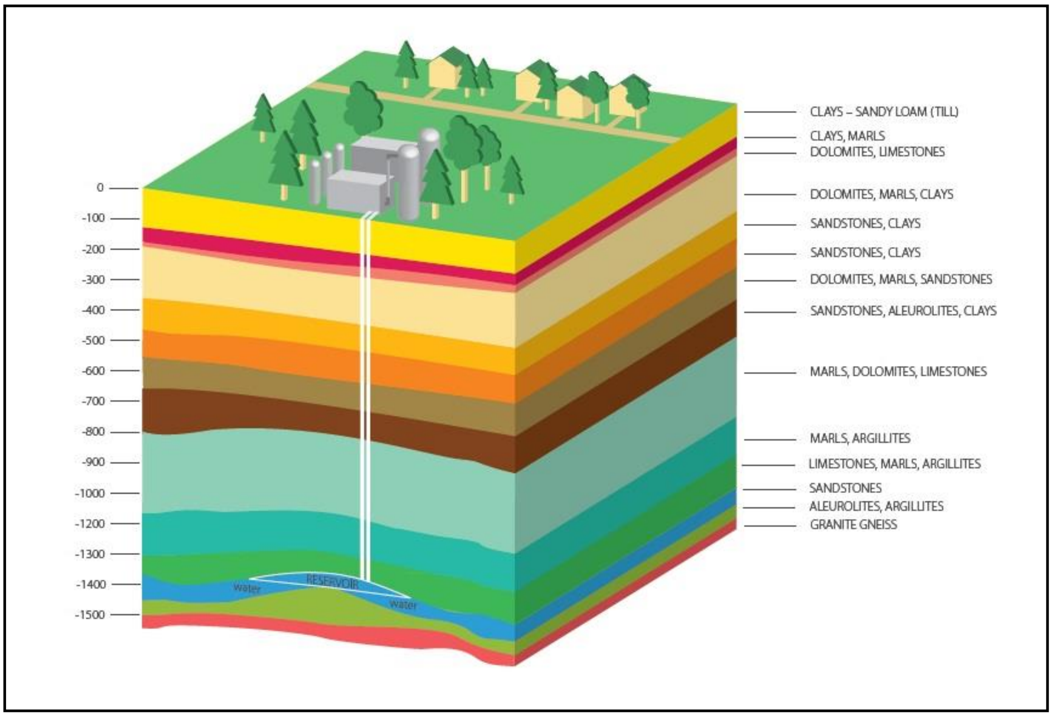

Figure 58: Syderiai Underground Gas Storage, Ministry of Energy of the Republic of Lithuania

16.2.3. Existing storage sites

There are no existing gas or hydrogen storage sites in Lithuania. The Ministry of Energy of the Republic of Lithuania[29] plans to use Syderiai structure[30] for UGS of LNG (Enmin, 2022; Figure 58).

16.2.4. Potential future development opportunities

Lithuanian territory has good coverage in terms of seismic and deep well data and has been extensively characterised during oil exploration and exploitation. Seventy-six potential structural traps were identified in Cambrian age reservoirs by earlier studies (e.g. CO_2StoP). However, capacity of the individual structures appears to be very small except the largest two structures, Syderiai and Vaškai, which are in the northern part of Lithuania. Given that natural gas and hydrogen could be considered valuable commodities, even the small structures may be plausible for development where the traps lie onshore and near relevant infrastructure such that a positive business case could be developed.

16.3. Discussion and conclusions

The geological conditions in Lithuania are not very promising for geological storage. The Cambrian Deimena Sandstone (the main hydrocarbon-bearing formation) has poorer reservoir properties than neighbouring Latvia and generally lies at depths greater than 2 km with correspondingly high temperatures in the west of Lithuania, where most of 75 structures and oil fields are located. Additionally, most the potential traps are very small and therefore, would not offer a large storage capacity if developed.

The primary caprock also appears to be of low quality. The caprock comprises low permeability primary and secondary cap rocks comprising Ordovician and Silurian carbonates which are argillaceous to varying degrees (limestones, dolostones, marls, clays, argillites (Figure 58). However, the large thicknesses of overlying reservoir rocks reduce the risk of gas seepage and the ability of these caprocks to contain buoyant fluids is suggested by the presence the Cambrian Deimena Formation reservoir sandstones.

The potential storage capacity of the three identified aquifer structures is higher than that of the 12 depleted oil fields, based on their size and reservoir properties.

[29] https://lrv.lt/

[30] https://enmin.lrv.lt/en/strategic-projects/gas-sector/syderiai-underground-gas-storage

17. Norway; geological assessment of storage opportunities

Geologically, continental Norway mainly comprises Palaeozoic metamorphic and intrusive rocks covered by thin, discontinuous accumulations of Pleistocene-Holocene sediments. Natural geological onshore storage opportunities in porous formations on the mainland can therefore be considered non-existent. Porous sedimentary rocks are present onshore in Svalbard, but apart from local studies on CO_2 sequestration in a semi-sealed aquifer in Longyearbyen[31] the potential for sub-surface storage remains largely unexplored and is not covered here.

In contrast to the mainland, the Norwegian continental shelf areas comprise substantial and varied sedimentary successions hosting one of the World's large petroleum provinces. From its beginning in the late 1960s, offshore petroleum exploration and production has encouraged extensive mapping and characterisation of subsurface reservoirs on the Norwegian continental shelf. As required by national regulations, a significant amount of the collected data is publicly available through a centralised database which is operated and maintained by the Norwegian Petroleum Directorate. Public access and sharing of data have stimulated extensive academic research and benefitted the offshore hydrocarbon and CO_2 storage industries.

The lack of potential onshore sites constrains identification of storage at suitable depths. Most identified traps are located more than 50 km offshore which would present a more challenging business case. This is also largely the case for identified offshore storage formations and -units at suitable depth.

As offshore infrastructure to some extent is still present or located nearby, decommissioned oil and gas fields are the most obvious candidates for hydrogen storage on the Norwegian continental shelf. Additional potential is offered by Jurassic to Miocene-age saline aquifers in the North Sea at suitable depths, which have been mapped as part of Norway's ongoing CO_2 storage effort. For the latter, only a limited number of potential well-defined traps have been identified as yet.

17.1. Data availability and gaps

17.1.1. Data availability and collation

The present assessment is limited to the Norwegian continental shelf south of the 62nd parallel, which corresponds to the area covered by the CO_2StoP database.

[31] http://CO2-ccs.unis.no/

All data used in this compilation are open access and available through the public portal of Norwegian Petroleum directorate – NPDFactpages[32]. The main references used are listed in Table 32.

This database, consisting of tabulated fact pages and a GIS-based map service with exportable shapefiles, is continuously updated and includes descriptions of all sedimentary units, structural maps, type-well sections, field footprints, and detailed descriptions of all exploration wells. The latter may include comprehensive final well reports, analysis of well data and samples and detailed descriptions of the drilling operation. The database also includes summary descriptions of production wells, fields, field production data, and information about license owners, surveys, and exploration activities. A complete list of depleted fields located in the study area was retrieved and screened with respect to the Hystories project selection criteria. All of these are located more than 50 km offshore.

Additional data on saline aquifers, compiled as part of the national CO_2 atlas, was retrieved from the same website[33]. The Norwegian CO_2 storage atlas contains contoured maps of thickness, depth, and spatial distribution of individual geological formations. The depth maps were used to create shapefiles for storage units and to modify existing polygons from the CO_2StoP database so that they conform to the depth selection criteria defined by Hystories (recommended below 500 m, see Hystories D1.1).

Table 32: List of key data sources for the Norwegian Hystories database

Source name / URL	Description	Version / Date
Norwegian Petroleum Directorate Website https://npd.no	Central repository for Norwegian Petroleum-related data. Searchable database and interactive GIS-based maps	2021 (Website is continuously updated)
Norwegian Petroleum Directorate, CO_2 Atlas https://www.npd.no/en/facts/carbon-storage/	Central repository for Norwegian CO_2 storage information.	2021

17.1.2. Availability of detailed data for further site characterisation

The Norwegian National Repository for Petroleum Data (DISKOS[34]) offers seismic, well data and production data on demand. Access to some datasets requires membership, which is free for research institutions. Cores from exploration and development wells can be inspected and

[32] https://factpages.npd.no/

[33] https://www.npd.no/en/facts/carbon-storage/

[34] (https://www.npd.no/en/diskos/about

sampled through the Geobank[35] service administered by the Petroleum Directorate. There is also a wealth of scientific publications available relating to specific fields and formations.

17.1.3. Identified gaps in data availability

There are comparatively few detailed and readily accessible descriptions of well-delineated traps in the saline aquifer storage formations/units. These have been of little interest to the petroleum community, and CO_2 storage efforts so far have mainly focused on identifying suitable sites based on assessment of storage at formation scale rather than targeting specific traps.

17.2. Geological opportunities for hydrogen storage

17.2.1. Geological summary

The geology of the Norwegian sector of continental shelf covered here is largely a product of Upper Jurassic to Lower Cretaceous rifting controlled to some extent by older structural elements. The strata comprise a variety of mainly siliciclastic formations of Carboniferous to Pleistocene age representing aeolian, fluvial, shallow- and deep-marine as well as glacial depositional environments. Many of these formations exhibit substantial storage resource potential as demonstrated by ongoing petroleum exploration and production. There are currently 70 producing petroleum fields in this area with a further three approved for production as time of writing. Hydrocarbon accumulations predominantly occur in structural traps located in Devonian to Jurassic strata as well as stratigraphic/ structural traps in Late Cretaceous Early Palaeocene (chalk) and Early Eocene strata. Thick, Early Cretaceous, Mid Eocene, and Oligocene claystone and shale formations form very competent seals for these reservoirs.

17.2.2. Storage assessments

There are no identified, subsurface storage opportunities for hydrogen in mainland Norway. The potential for onshore subsurface storage in porous formations in Svalbard is underexplored, with the exception of the Longyearbyen CO_2 laboratory[36].

There are opportunities for offshore storage in porous formations in the North Sea as demonstrated by present petroleum E&P and ongoing CO_2 sequestration studies, but for Norway, nearly all of these of these are located more than 50 km offshore, lie at depths >2500 m or are not fully sealed and thus do not match the site-selection criteria employed by Hystories. However, given that hydrogen in the near future may become to store offshore

[35] https://www.npd.no/en/facts/geology/geobank/

[36] http://CO2-ccs.unis.no/

wind energy, decommissioned oil and gas fields and offshore aquifer traps could present opportunities for offshore hydrogen storage.

There is limited information available about the location and extent of saline aquifer traps which could be suitable for hydrogen storage. Only a few closures have been identified as part of previous CO_2 storage studies.

A summary of identified offshore traps in the Norwegian Hystories database are presented in Table 33, Figure 59 and Figure 60.

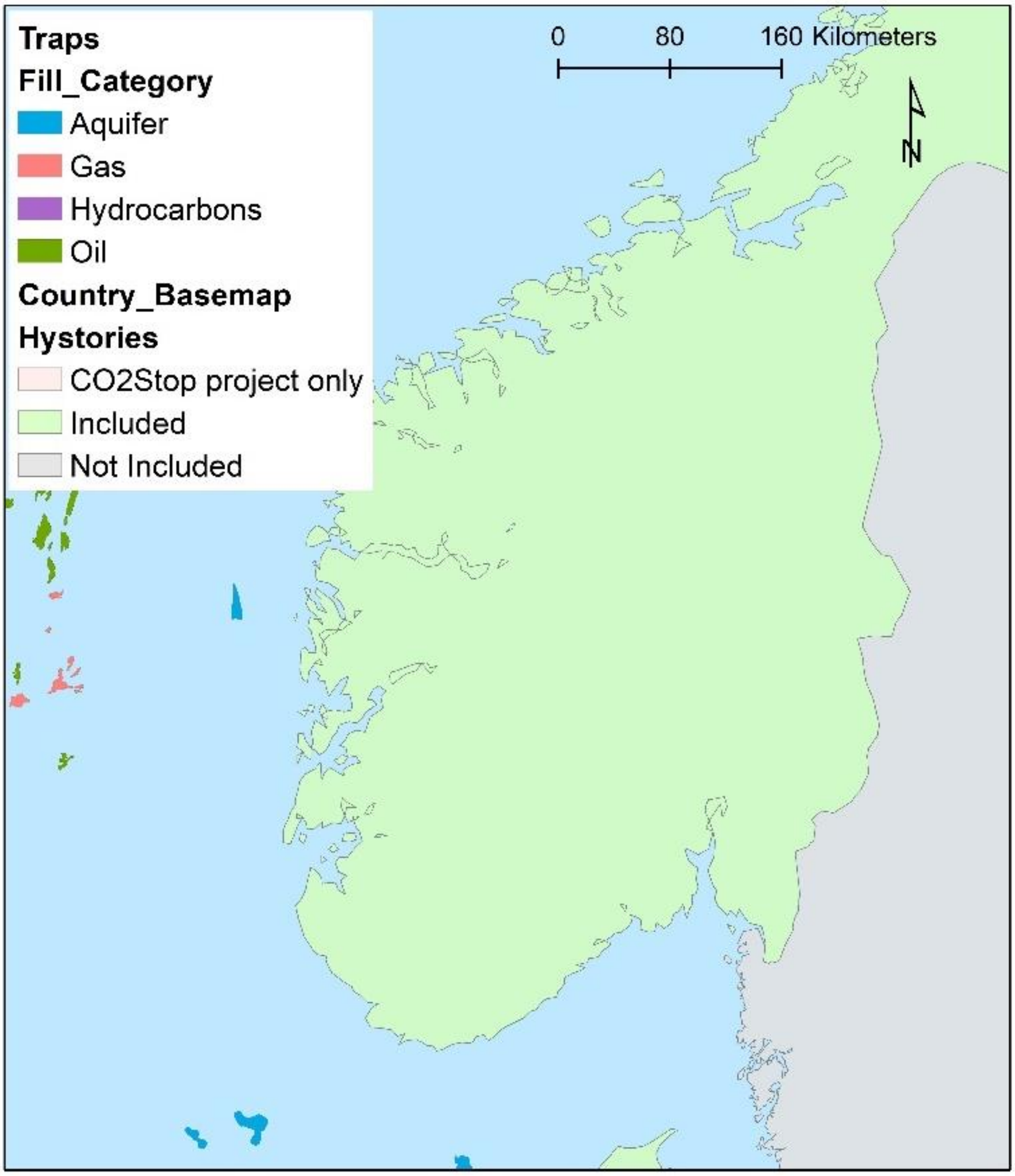

Figure 59: Overview of identified potential traps in the Hystories database within Norway (and surrounding areas).

Table 33: Offshore traps in the Norwegian Hystories database

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Depleted offshore gas fields	5	Exploited from 1971 to 2004. Installations have been removed. All fields are distant from shore and therefore infrastructure costs could be large. Plans for redevelopment are being considered, either for CO_2 storage or to restart production using more cost-efficient sub-sea installations.	Site specific studies required. Additional data could be added with further resources.
Depleted offshore oil fields	3	Exploited during the period from 1994 to 2016. Installations have been removed. All fields are distant from shore and therefore infrastructure costs could be large.	Site specific studies required. Additional data could be added to database with further resources.
Offshore aquifers	-	Aquifer stores have been identified at several stratigraphic levels, but most are far from shore and therefore infrastructure costs could be large. Few specific traps have identified	Site specific studies required. Identifying trap structures may be possible using available databases.
Offshore aquifer traps	3	Identified as part of CO_2 storage screening.	Site specific studies required

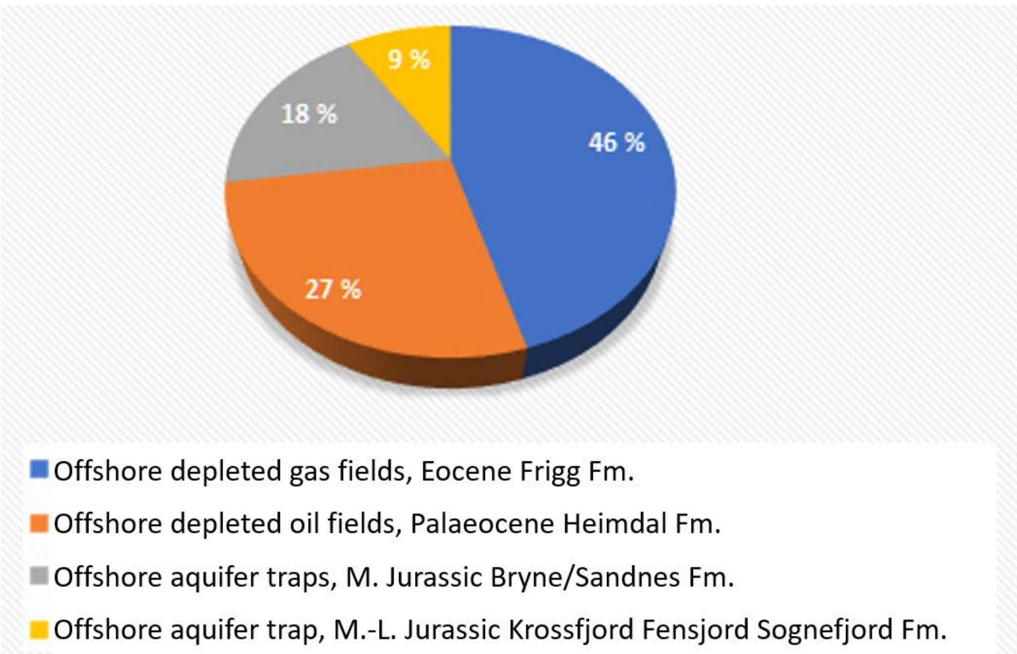

Figure 60: Frequency pie chart showing categories of identified potential storage traps in Norway

17.2.3. Existing storage sites

There are no existing onshore storage sites in porous media. The petroleum industry employs storage in excavated caverns at several locations along the coast.

Offshore storage of CO_2 in porous media is presently conducted on the Snøhvit field in the Barens Sea and in the Sleipner Field in the central North Sea. For the latter injection of CO_2 into the Utsira Formation has been ongoing since 1996. Currently the Johansen Formation in the area west of Bergen is being developed as a commercial storage site as part of Norway's Longship project[37]. Both the Utsira and Johansen Formation are relevant as storage formations for hydrogen.

17.2.4. Potential future development opportunities

Although storage potential in terms of volume is large, the bulk of storage opportunities are located more than 50 km offshore. Development of stand-alone storage sites to service onshore hydrogen production and consumption will require significant investment in infrastructure. Establishment of offshore subsurface hydrogen is therefore most likely to happen as part of a larger effort, involving the re-use of existing infrastructure and co-development with offshore wind energy production.

17.3. Discussion and conclusions

Hydrogen storage in porous media in Norway will likely be focused solely offshore. There is substantial potential in utilising existing petroleum fields before they are decommissioned at the end of production or even after they have been decommissioned. Redeveloping depleted fields as hydrogen storage sites linked to offshore wind farms might present an attractive option.

Identification of specific storage opportunities in saline aquifer is thus presently hampered by a lack of information about location and size of specific traps for containing injected hydrogen. Identification of suitable sites should be possible however, given the wealth of data accessible for further studies.

[37] https://ccsnorway.com/

18. Poland; geological assessment of storage opportunities

Good storage conditions for Underground Hydrogen Storage (UHS) in deep aquifers are found in north-west and central Poland. This area comprises a Palaeozoic platform with the thick sediments deposited in the Permian-Mesozoic epicontinental basin of the Polish Lowlands. Here, sedimentary rocks have significant thickness and good reservoir properties. In this part of Poland, sedimentary rocks of Lower Triassic, Lower Jurassic, and Lower Cretaceous age comprise sandstone aquifers suitable for UHS. The tectonic structures that are suitable for UHS storage are in the area of uplifted Pomeranian and Kuyavian Swells and the Cretaceous deposits filling the troughs adjoining it on both sides. These are the Pomeranian and Warsaw Troughs in the northeast and the Szczecin and Mogilno-Łódź Troughs in the southwest.

In Poland, the main area with identified natural gas fields in the Polish Lowlands. Gas fields have been also documented on the Carpathian Foreland. Minor resources occur also in small fields within the Carpathian Mountains area and in the Polish Exclusive Economic Zone of the Baltic Sea. About 75% of the documented gas resources are found in the Miocene and Rotliegend formations. The remaining resources are found in the Cambrian, Devonian, Carboniferous, Zechstein, Triassic, Jurassic, Cretaceous and Paleogene formations, and part of one field in the Precambrian of the Carpathian Foreland.

Oil fields in Poland are located in the Carpathian Mountains, on the Carpathian Foreland (in the Carpathian Foredeep), within the Polish Lowlands and in the Polish economic zone of the Baltic Sea. The oil fields occurring in the Carpathian Mountains and Carpathian Foreland have a long history as this area is world's oldest crude oil mining region. Nowadays, these fields are almost depleted. Currently, the Polish oil fields of the largest economic importance are situated in the Polish Lowlands.

18.1.Data collation and collection

18.1.1. Data availability and collation

The Hystories database of potential 'traps' for hydrogen storage in Poland includes both aquifer structural closures and hydrocarbon fields. The Central Mining Institute (GIG) prepared the part of the database on potential opportunities in depleted hydrocarbon fields. The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI-PAS) prepared the part of the database on saline aquifers.

Data collected during the CO_2StoP project was checked and updated. New data reported in Hystories includes five geological traps considered too shallow for CO_2 storage (i.e., above 800 m), which may be considered for hydrogen storage. The updated Polish Hystories database contains 38 geological structures in total. Formation and Storage Units remain the same as in the CO_2StoP database.

For all traps, the following data have been updated:

- Projection information. Location of trap centrepoint and shapefiles have been developed according to the new map projection;
- Subsurface and Surface issues were added;
- Lithology and Environment of deposition for the reservoir and seal were given;
- Minimum depth to top of trap and seal thickness were added;
- Number of wells penetrating storage unit and their age were given,
- Updated data availability and quality database fields.

For some traps, information on the presence of sulphates or iron in the rocks, was available.

The main sources of information used are listed in Table 34. The data sources used for each potential storage trap are listed in the database. The ‘Remarks’ field was used in the Hystories database to emphasise any remaining uncertainties.
Data for potential porous media hydrogen stores that were collated includes basic reservoir and petrophysical data, lithology and fluid fill, and information from oil field data lithology pressure and temperature, where such data are available in the public domain.

Data on the results of geophysical surveys carried out during the drilling of deep wells are included in the wells documentations of the National Geological Archive (NGA). Use and publication of these data requires the consent of the Ministry of the Environment. A list of other studies carried out in connection with deep wells drilling can be found in the well documentation in the NGA.

If the deep wells have been described in the PGI-NRI publications "Deep wells logs," we can expect more detailed documentation of the storage trap considered for UHS.

More detailed data on the reservoirs considered for UHS and the layers of sealing overburden can also be found in the PGI-NRI regional publications.

There are gaps in the sampling of reservoir rocks and, more often, of the sealing overburden that could be considered for UHS (no cores or outcrops). There are no detailed data on porosity and permeability, and no interpretation of wells logs.

Separate permissions must be obtained to access NGA data and copy the geological documentation. Obtaining permission to disclose data for scientific purposes is allowed for Polish research institutions. For external clients, the use of the geological information and geological well cores can be accessed for a fee.

Table 34: List of key data sources for the Polish Hystories database

Source name / URL	Description	Version / Date
MEERI PAS publications	Publications about CCS and UHS	Tarkowski, R., 2005; Tarkowski, R. & Uliasz-Misiak B., 2005; Tarkowski, R., & Uliasz-Misiak, B., 2006; Tarkowski, R., 2008; Tarkowski, R., Uliasz-Misiak, B., Wójcicki, A, 2008; Tarkowski, R., (ed.), 2010; Tarkowski, R., Dziewińska, L., Sylwester, M., 2014
National Geological Archives https://www.pgi.gov.pl/en/narodowe-archiwum-geologiczne-2.html	Boreholes	1965-2022
Deep Wells Logs PGI-NRI The Polish Geological Institute – National Research Institute DEEP DRILLING HOLE PROFILES PIG-PIB (In Polish: Profile głębokich otworów PIG-PIB) https://www.pgi.gov.pl/oferta-inst/wydawnictwa/serie-wydawnicze/profile-otworow-pig.html	A detailed description of deep wells logs in the Polish Lowlands	Zeszyt 11: Strzelno IG 1 Zeszyt 43: Choszczno IG 1 Zeszyt 125: Brześć Kujawski IG 1, IG 2, IG 3 Zeszyt 156: Bodzanów IG 1
Statutory reports of MEERI PAS	Detailed reports on geological structures in terms of CCS and UHS (MEERI PAS studies)	Reports from 2003-2022
Polish Geological Institute – National Research Institute http://geoportal.pgi.gov.pl/css/surowce/images/2021/bilans_2021.pdf	Reporting raw mineral deposits in Poland (the report is available in Polish).	31.12.2021 (report is updated annually)
System of management and protection of mineral resources in Poland – MIDAS http://geoportal.pgi.gov.pl/portal/page/portal/midas	The main source of information on two closely related topics: mineral resources of Poland and the exploitation of deposits. The service provides access to three groups of information: • deposits • mining areas as well as related concessions • mineral resources management The present application allows the user to browse and display all data that are publicly accessible, including their presentation on the map (the application is available only in Polish).	2021 (website is regularly updated)
Mineral resources – mineral raw materials deposits (Spatial data) https://dm.pgi.gov.pl/	Spatial data (polygons of deposits) presented on MIDAS website relating to: mineral deposits, mining area and mining country are available as a SHP files. The Central Geological Database (CBDG) is the largest Polish collection of digital geological data, such as detailed information on boreholes, archival geological reports and various types of geophysical research.	2021 (website is regularly updated)
The underground gas storage facilities in Poland https://www.gie.eu/transparency/databases/storage-database/	The Storage Database shows the operational data such as working gas volume, injection and withdrawal capacities of storage facilities as well as the under construction and planned storage sites. The database is available in an open format and includes also details on the operators and facilities.	July 2021
Other sources	Other available data from reports, scientific papers, websites and other reputable sources.	

18.1.2. Availability of detailed data for further site characterisation

The Polish Geological Institute manages the National Geological Archives (borehole profiles, geological documentation[38]), which contains more detailed information.

Data on boreholes commissioned by private investors remain their property and are accessible after obtaining the permission of the investor/owner.

Most data on depleted hydrocarbon fields included in Hystories comes from Poland MIDAS and were collected by the Polish Geological Institute-National Research Institute (PGI-NRI).

The underground gas storage facilities in Poland are owned by PGNiG and managed operationally by Gas Storage Poland sp. z o.o., a PGNiG Group company which has the status of storage system operator and, as required by applicable regulations, offers third party access on equal contractual terms (PGNiG, 2022).

18.1.3. Identified gaps in data availability

The gaps in the availability of detailed information on the porosity and permeability of reservoir and seal rocks can be filled through interpretation of existing well logs. The poor condition of drill cores, often collected several decades ago, makes it impossible to carry out most of the detailed testing relevant to UHS. The few deep boreholes drilled in recent years by private investors are related to the exploration of geothermal waters. Data from these recent boreholes but remain the property of the company that contracted the drilling of the well and are not available in the public domain.

The Hystories database was completed using publicly available data and therefore there are gaps data availability, since some information remains confidential. Details on the reservoir, oil/gas composition, seal, fault density and well data were frequently unavailable.

Further work and site-specific investigation would be needed to develop these potential hydrogen storage sites.

18.2. Geological opportunities for hydrogen storage

18.2.1. Geological summary

The deep saline aquifers of the Central Polish Permo-Mesozoic Basin are the most promising opportunity for UHS storage in Poland: the Baltic and Pomorska formations (Lower Triassic), Komorowo and Borucice formations (Lower Jurassic) and the Mogilno Formation (Lower Cretaceous) (Figure 61).

[38] https://www.pgi.gov.pl/en/narodowe-archiwum-geologiczne-2.html

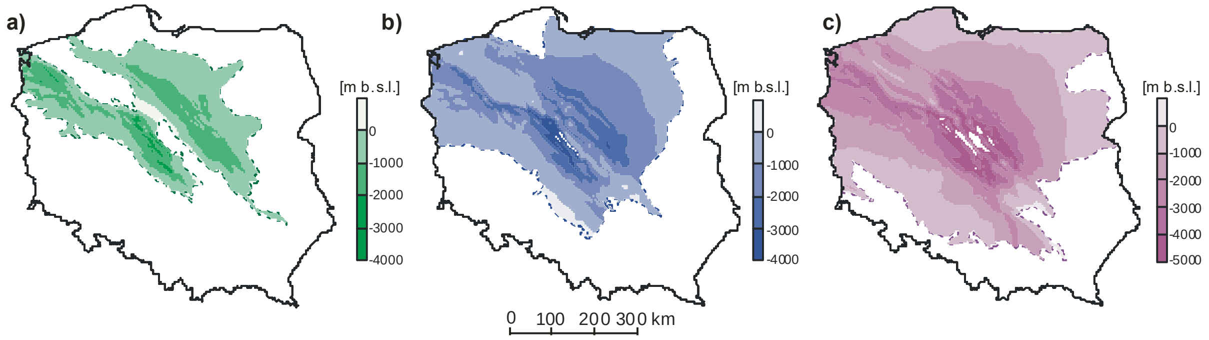

Figure 61: Structural map of the base of the Lower Cretaceous (a), Lower Jurassic (b) and Lower Triassic (c) aquifers (Tarkowski et al., 2008)

The sandstone reservoirs of the Baltic and Pomeranian Formations are sealed by fine-grained clastics of the Połczyn Formation and by clay/evaporitic rocks of the Barwice Formation. The Lower Jurassic Komorowska Formation is sealed by clays of the Ciechocek Formation, and the Borucice Formation is sealed by fine-grained clastics of Aalenian and Bajosian age. In Lower Cretaceous strata, the Mogilno Formation sandstones are sealed by Upper Cretaceous marls, limestones, opokas and chalk.

Interest in the same structures in deep aquifers for purposes other than UHS (CO_2 storage, natural gas storage) is possible. However, owing to the large number of aquifers and depleted hydrocarbon fields, it is anticipated that there will be sufficient available storage resources.

In the Polish Lowlands, gas fields are found in strata of Permian and Devonian-Carboniferous age in the Fore-Sudetic and Wielkopolska regions. Gas fields are found in Carboniferous, Permian and Cambrian strata in the Western Pomerania area. In these regions, gas occurs in massive- and block-type fields with water- or pressure driven production-. In the Polish Lowlands only a few gas fields contain high-purity methane gas, the majority contain a mixture of nitrogen and natural gas with the content of methane ranging from about 30% up to over 80%.

On the Carpathian Foreland, natural gas fields mainly occur mainly in Miocene formations. Gas fields also occur in Jurassic, Cretaceous, Devonian, Carboniferous, Triassic and Precambrian strata. The fields commonly contain high-purity methane natural gas with low nitrogen content, though a few fields have a high nitrogen concentration. In this region gas occurs in structural-lithological multi-layer traps or sometimes, massive-type reservoirs with gas pressure depletion-drive (expansion of natural gas dissolved in the oil drives production).

In the Carpathians, natural gas occurs in self-contained fields or as an accompanying element in crude oil or condensate fields in Cretaceous and Paleogene formations. The gas is characterised by a high content of methane (usually over 85%) and a few percent of nitrogen (PIG, 2021a).

In the Polish Lowlands, documented oil fields occur mainly in Permian sediments. A few isolated fields are found in Carboniferous, Cambrian and Devonian strata. The majority of these fields are of the massive type, with an underlying passive aquifer and with a gas cap depletion drive.

In the Carpathian Mountains, oil fields occur in several tectonic units, but mainly in the Silesian strata. Oil fields are mainly in structural traps and more rarely in structural-lithological traps. Fields mainly comprise laminar strata type with a water leg. Production is initially driven by the expansion of natural gas dissolved in the oil and subsequently by gravity driven drainage.

Carpathian hydrocarbon fields are mainly of the oil-gas type. The resources of the Carpathian oil fields are generally minor, depending on the size and a character of the structures in which they occur. The resources of the Carpathian fields have been nearly exhausted as a result of many years of exploitation.

In the Carpathian Foredeep, oil fields are mainly found in Mesozoic platform sedimentary rocks (Jurassic carbonate rocks and Cretaceous sandstones) and in the autochthonic Miocene strata. Most of these fields are multi-layered hydrocarbon reservoirs with various types of hydrocarbon traps (stratigraphic, lithologic or tectonic). Some of the fields located in the regions mentioned above contain dissolved gas components forming an oil condensate (PIG, 2021b).

Natural oil seeps are fairly common in south-east Poland, especially in areas of Carpathian Flysch series exposures. The first records of such seeps may be traced back to the first half of the sixteenth century. Rapid development of the oil industry in Poland was triggered by the discovery of a method of distillation of kerosene from seep-oil and by the invention of an effective modern kerosene lamp by Ignacy Łukasiewicz in 1853. When the first oil well was drilled at Titusville (Pennsylvania) in 1859, several dozen wells were already producing oil in the Carpathians. The oil and gas industry in Poland began with the first oil well in the world, at Bóbrka Field in 1853, followed by the first refinery in 1854 (Wołkowicz et al., 2016).

18.2.2. Storage assessments

The assessment of the CO_2 storage potential for Poland has been presented in several articles (Tarkowski, R., 2005; Tarkowski, R. & Uliasz-Misiak B., 2005; Tarkowski, R., & Uliasz-Misiak, B., 2006; Tarkowski, R., 2008; Tarkowski, R. et al., 2008; Tarkowski, R., (ed.), 2010; Tarkowski, R. et al., 2014). Since the same structures and storage levels are included in the UHS database, these studies can be used to consider the potential for hydrogen storage.

Overall, the part the Hystories database for Poland contains 14 formations, 16 storage units and 102 onshore traps as indicated in Table 35 and Figure 62. Figure 63 shows a frequency pie-chart showing the number of identified trap records for each storage unit name contained in the database. The databased indicates where storage potential may be present and site-specific investigations will be required to develop potential stores. Most the hydrocarbon traps are in the Carpathian Foredeep (Oligocene to Miocene), Carpathian Mountains (Mesozoic), Zechstein (Permian) and Rotliegend (Permian) strata. Most the saline aquifer traps are in Mogilenska (Cretaceous), Borucicka (Jurassic) and Komorowska (Jurassic) strata.

Of the 38 aquifer traps included in the database (Figure 64), three have detailed data and characterisations available (Figure 65).

Table 35: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	38 More detailed data and geological models available for the following closures: Konary: PL_T_20210701104250119 Sierpc: PL_T_20210719094739455 Suliszewo: PL_T_20120926180033633	MEERI PAS assessed the hydrogen storage potential for three structures (Konary, Sierpc, and Suliszewo) included in the Hystories database. The assessment of the hydrogen storage potential for the remaining structures, owing to the lack of geological data to develop a geological model, will be subject to significant uncertainties.	Regional geological mapping and assessment of aquifers may reveal further energy storage potential.
Hydrocarbon reservoirs	64	In total 64 defined depleted hydrocarbon field traps are included in the database. Seven of these are operational Underground Gas Storage (UGS) facilities (including two UGS facilities for nitrogen-rich gas). Most of reservoirs are located in the southern and western parts of the country.	Site specific studies required. Confirmation of location-specific suitability and expected capacities. Assessment of if there is future scope to investigate alternative use potential of UGS sites.

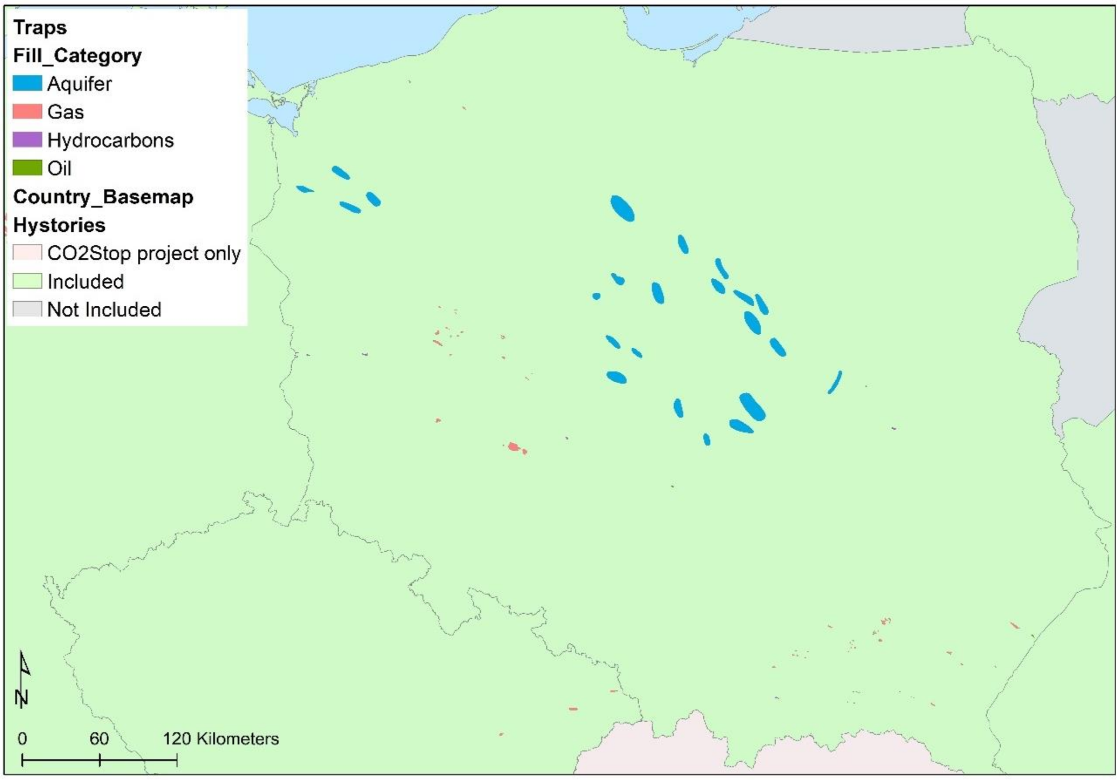

Figure 62: Overview of identified potential traps in the Hystories database within Poland.

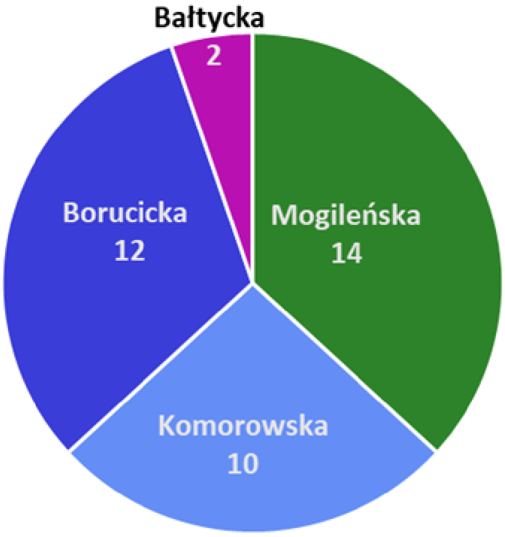

Figure 63: Frequency pie chart showing categories of identified potential storage traps different storage units in Poland.

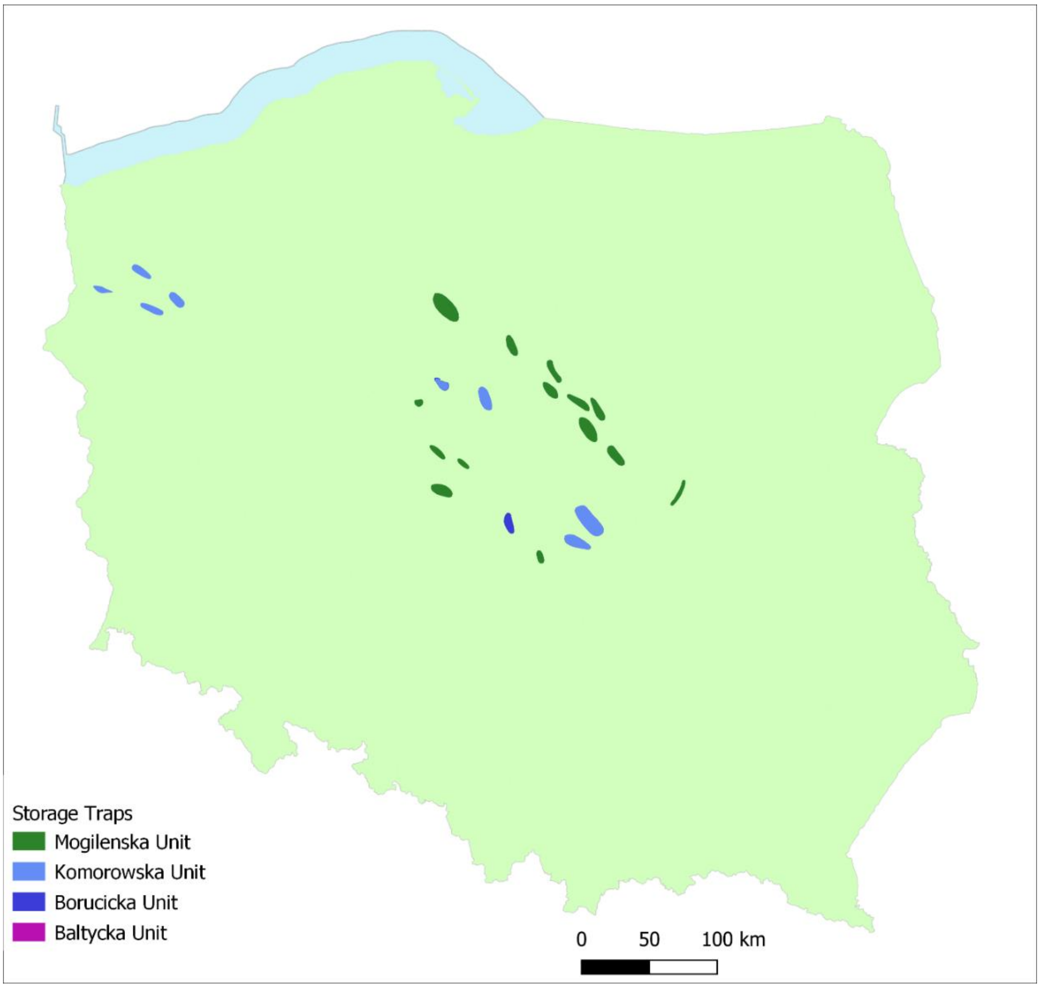

Figure 64: Main stratigraphic units of saline aquifer storage 'traps' in the Hystories database

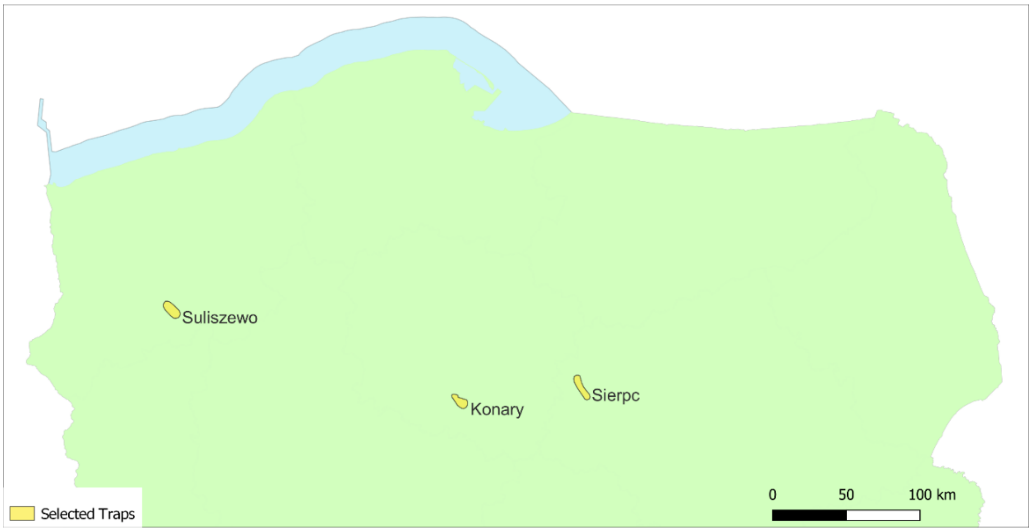

Figure 65: The most studied saline aquifer geological structures in the Hystories database for Poland

18.2.3. Existing storage sites

In Poland, there are five operational underground natural gas storage (UGS) facilities utilising porous rock reservoirs. They lie in different reservoir formations than most the potential traps being considered for UHS in Hystories (Figure 66).

Four UGS sites, UGS Husów, UGS Strachocina, UGS Swarzów, and UGS Brzeźnica, are located in depleted natural gas deposits in south-eastern Poland. Gas is stored in sandstones and limestones of varying ages (Jurassic, Cretaceous, and Miocene). The storage reservoirs are sealed by overlying slates and marls. The working capacity of these individual UGS facilities is 500, 360, 90, and 100 million m^3, respectively.

The largest Polish UGS site is Wierzchowice, in the Fore-Sudetic Monocline area. Gas is stored in a depleted natural gas reservoir in Rotliegend sandstones and Zechstein limestones. The storage formation is sealed by anhydrite and the oldest rock salt of the Werra cyclothem. The working capacity of UGS Wierzchowice is 1,300 million m^3.

No information on the planned use of identified traps in deep saline aquifers for energy storage or other purposes is available.

In addition to underground gas storages in depleted gas deposits, there are two UGS in salt caverns, UGS Kosakowo in bedded salt deposit in northern Poland and UGS Mogilno in salt dome in Central Poland. Their working capacity is 297 and 581 million m^3 respectively.

The UGS facilities in Poland are owned by PGNiG and operated by Gas Storage Poland sp. Z o.o. which is a PGNiG Group company. Data from the UGS sites located in depleted hydrocarbon fields has been added to Hystories database.

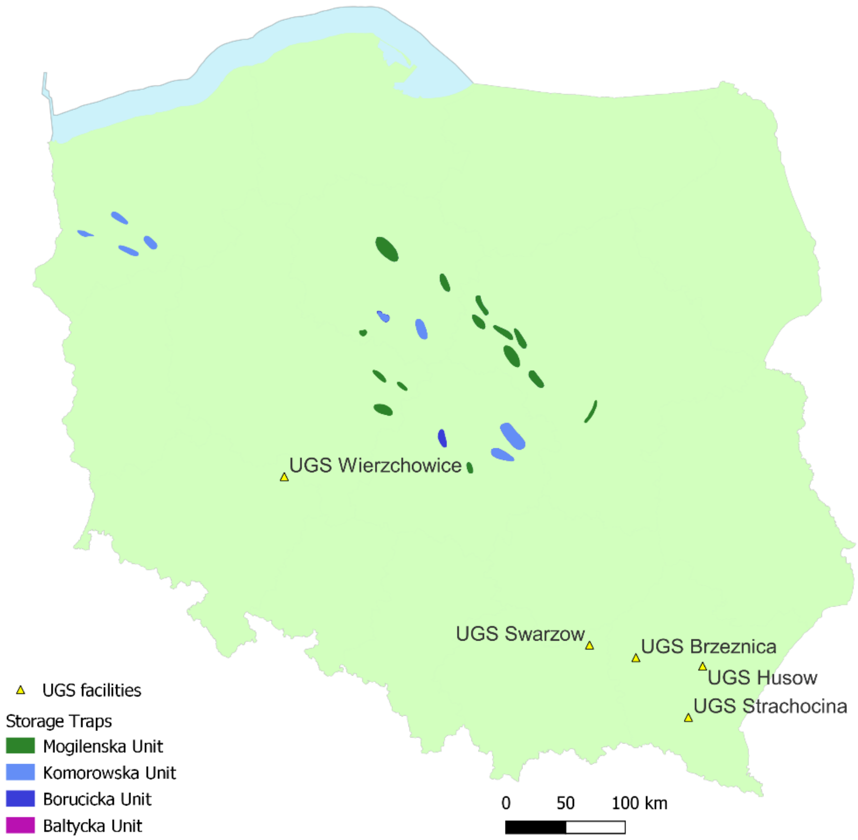

Figure 66: Overview of identified potential aquifer traps and UGS sites in the Hystories database within Poland.

18.2.4. Potential future development opportunities

Because of the geological recognition level and research results, the aquifer traps of Konary and Suliszewo seem particularly promising for UHS. The UGS sites have been successfully operating for decades and offer insight and experience in storage and retrieval of resources from depleted Polish gas fields. The UGS fields are mainly located in south Poland, and the most promising UHS traps appear to be located in north Poland. There are many depleted gas fields available which could also be considered for storage. However, given that some of the fields are nitrogen-rich, an assessment of the expected reactions in the reservoir is required.

18.3. Discussion and conclusions

The interest in underground hydrogen storage in deep aquifers in Poland is only moderate. There is more interest in UHS in salt caverns. The mixing of hydrogen with natural gas when using depleted fields also requires further consideration, particularly in nitrogen-rich gas fields.

19. Portugal; geological assessment of storage opportunities

Despite the petroleum exploration efforts that took place as recently as 2016 (Martins and Silva, 2021), no exploitable hydrocarbon fields have been identified in Portugal. Hence, the possibilities for hydrogen storage in porous media in Portugal are restricted to saline aquifers. Furthermore, the assessment conducted in Hystories only considered the onshore possibilities, which, unlike the offshore areas, can be cost-competitive with respect to hydrogen storage in salt domes for which there are several onshore possibilities.

Data coverage for deep geological formations is relatively small and mostly restricted to the Lusitanian Basin area. The Hystories assessment focused in this area and in total, two formations and five units were identified as potential storage units. The Torres Vedras Group and the Silves Group offer storage potential in west-central Portugal, extending from Alcobaça to Monte Real. However, the quality of the available data does not allow, at this stage, identification of specific traps.

19.1.Data availability and gaps

19.1.1. Data availability and collation

The geological assessment built on previous EU projects on subsurface energy storage opportunities, such as ESTMAP (van Gessel, 2017), and on screening for CO_2 storage in deep saline aquifers in FP7 COMET (Martínez, 2013), H2020 STRATEGY CCUS (Veloso, 2019) and the ongoing H2020 PilotSTRATEGY project. The CO_2StoP database was also checked, but the data is the same as compiled in COMET and has been superseded by assessments conducted in STRATEGY CCUS and PilotSTRATEGY.

To address the fact that hydrogen can be stored in porous media at shallower depths than CO_2 (i.e. shallower than 800 m) academic studies (MSc and PhD thesis) focusing on Compressed Air Energy Storage (CAES) were revisited, as these had previously addressed the possibilities of storage in aquifers shallower than 800 m (e.g. Cavaco, 2013; Matos et al., 2019; Susano, 2015).

Additionally, to ensure that all latest petroleum exploration data was collected, a meeting was held with the Directorate General for Energy and Geology. The main data sources used for Hystories are shown in Table 36.

Table 36: List of key data sources for the Portugal Hystories database

Source name / URL	Description	Version / Date
Acervo do Petróleo – national repository of petroleum exploration data (visualization of existing data at DGEG webGIS; https://portalgeo.dgeg.gov.pt/arcgis/apps/webappviewer/index.html?id=de764a4a5ccd446292cb26a7e5c2e725)	Database of all geological and geophysical information collected in the scope of petroleum exploration efforts in Portugal. Maintained by Directorate-General for Energy and Geology (DGEG)	Consulted in 2022
LNEG Geoportal and online Databases	WebGIS and set of databases on geological activities in Portugal, including mining and groundwater exploration. Allows downloads of information such as geological maps, main features of boreholes, geothermal resources, etc.	Consulted in 2022
KTEJO Project: Feasibility Study of CO_2 Capture and Storage (CCS) at Pego Coal Power plant	Includes first assessment of CO_2 storage possibilities in the onshore Lusitanian basin	2011
COMET project: Integrated infrastructure for CO_2 transport and storage in the west Mediterranean; https://cordis.europa.eu/project/id/241400	Identifying and assessing the most cost-effective CO_2 transport and storage infrastructure to serve the West Mediterranean area, namely Portugal, Spain and Morocco. Includes storage capacity estimates for onshore and offshore sedimentary basins in Portugal.	2013
ESTMAP Project: Energy Storage Mapping and Planning.	Compiled information on developed and future potential subsurface and above-ground storage reservoirs and well as existing storage facilities linked to these reservoirs, for the various energy options (natural gas, compressed air, heat, pumped hydro, hydrogen, etc.)	2016
STRATEGY CCUS: Strategic planning of regions and territories in europe for low-carbon energy and industry through CCUS	Support the delivery of carbon capture, utilisation and storage (CCUS) in eight promising regions. Identified as such because they feature strategic elements, such as clusters of industry, potential CO_2 storage sites, opportunities for CO_2 usage, and options for hydrogen production and use.	2022
PilotStrategy: Geological CO_2 storage pilot in strategic territories; https://pilotstrategy.eu/	Assessment of regions of Southern and Eastern Europe to support development of carbon capture and storage (CCS). It includes the onshore Lusitanian basin as one of the target areas.	2022 (Ongoing)

19.1.2. Availability of detailed data for further site characterisation

In Portugal the information about deep geology of sedimentary basis is held by the DGEG[39] and can be consulted in their interactive webGIS[40], as part of the national repository of petroleum exploration data (Acervo do Petróleo). The webGIS locates all the seismic surveys, both 2D (5,865 km onshore and 67,009 km offshore) and 3D (580 km^2 onshore and 9,752 km^2 offshore), of petroleum exploration boreholes (175 boreholes, of which 27 are offshore), and additional information such as aeromagnetic and gravimetric surveys and piston-core sampling. The webGIS also includes information unrelated to petroleum exploration, such as mining activities, geothermal resources, spring and mineral groundwater. Although this information is not essential for energy storage assessments, it provides insights into potential conflicts or synergies between activities. The webGIS does download of any raw or processed data, which must be requested from DGEG and is subject to confidentially agreements. DGEG usually cooperates readily with research institutions and are willing to provide access to petroleum exploration data for research project or academic studies such as MSc and PhD theses.

The National Laboratory for Energy and Geology (LNEG[41]), also runs a webGIS, the GEOPORTAL[42], and several databases[43] with information on geological activities in the country, including some data coming from petroleum exploration. LNEG also runs the national core repository, where records and samples for deep boreholes and wells are kept. GEOPORTAL allows downloading of information from the databases, as well geological maps.

19.1.3. Identified gaps in data availability

Although the onshore 2D seismic coverage is significant (Figure 67b), many of the seismic lines were acquired decades ago thus data quality of these lines is not ideal for defining geological structures. The 2D seismic surveys conducted by Mohave Oil & Gas Corporation from the 1990's onwards offer better quality data, but coverage does not allow for definition of traps. The 3D onshore surveys, also acquired by Mohave Oil & Gas Corporation are much higher quality, but coverage is restricted to three relatively small areas (Figure 67c) and only one of these is located in a region which may be of interest for hydrogen storage.

Most of the legacy boreholes targeted potential oil and gas reserves, but having found no evidence of commercially viable resources, recorded little information about the permeability,

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39 https://www.dgeg.gov.pt/

40 https://portalgeo.dgeg.gov.pt/arcgis/apps/webappviewer/index.html?id=de764a4a5ccd446292cb26a7e5c2e725

41 https://www.lneg.pt/

42 https://geoportal.lneg.pt/mapa/

43 https://geoportal.lneg.pt/en/databases/

porosity, or formation water chemistry of the target reservoirs, much less data on the caprocks lying above. Geophysical logs are available for several wells, allowing estimation of porosities and net-to-gross ratios, but the number of hydraulic tests available to compute permeabilities is very small.

The exploration efforts conducted by Mohave Oil & Gas Corporation from the 1990's onwards in the onshore sector of the Lusitanian basin currently provide the best information about the sedimentary sequence, with the geophysical logs being particularly useful, but still with almost no drill stem tests conducted.

19.2.Geological opportunities for hydrogen storage

19.2.1. Geological summary

Portugal's morpho-structural units includes five major sedimentary basins: two Mesozoic sedimentary basins that extend from the onshore to the offshore, the Lusitanian basin, in the western Iberian margin, and the Algarve basin, along the south margin of the country; two entirely offshore basins, the Porto basin and the Alentejo basin (Figure 67a) and; the onshore Cenozoic Tejo/Sado basin, which spreads along west-central Portugal, and has important groundwater resources.

The Mesozoic basins, and particularly the Lusitanian basin, both onshore and offshore, have plentiful of salt formations (salt layers, salt domes, etc.) that provide opportunities for storage of hydrogen in salt dissolution cavities. Given the maturity of gas storage in salt caverns, dissolution cavities are expected to be the primary target for hydrogen storage (UHS), as indicated by LNEG (2022) and in accordance with the knowledge gained by the national Transmission System Operator (*REN-Redes Energéticas Nacionais*) that operates the existing natural gas storage facilities.

The possibility of storage of hydrogen (H_2) in porous media is much more likely to be exploited if cost-competitive storage resources can be defined in onshore saline aquifers. The offshore areas were not screened, as it was considered that this option lacks economic viability compared with the several salt domes available onshore and offshore.

Furthermore, it was decided to screen only saline aquifers onshore in the Lusitanian Basin, as the existing data for the onshore Algarve basin is very scarce Figure 67a & b). In any case, the Algarve region is less industrialised, and it is not identified in the Atlas for Sustainable H_2 production to be amongst the "*very favourable areas for implementation of green H_2 facilities*" by the national research institute for energy and geology, Laboratorio Nacional de Energia e Geologia (*Sustainable Green H_2 Atlas for Mainland Portugal*; LNEG, 2022).

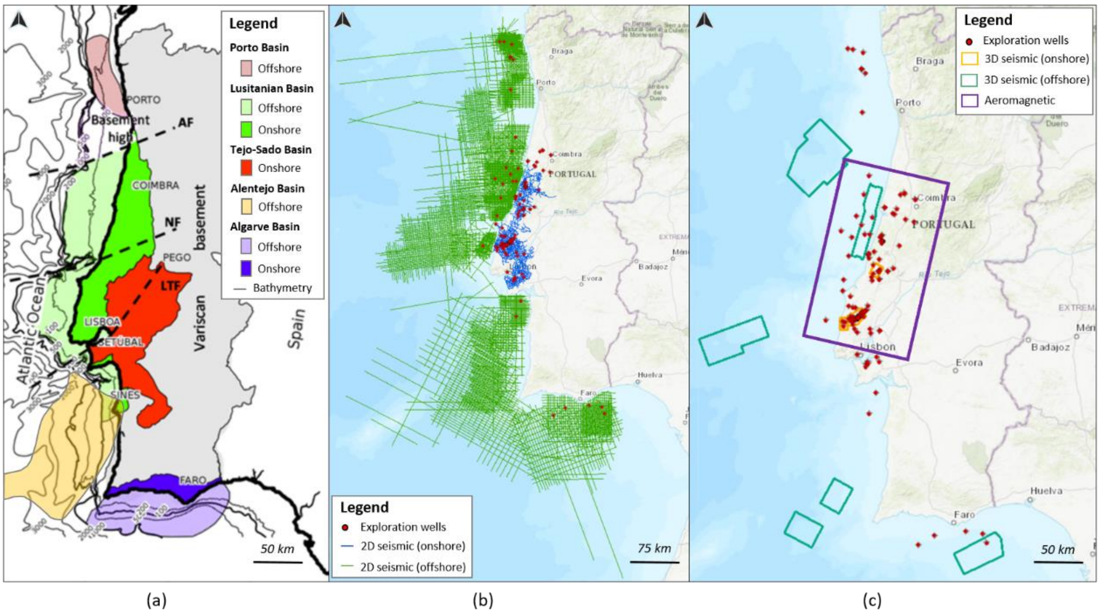

Figure 67: (a) Sedimentary basins in Portugal and some of the major faults subdividing them (AF- Aveiro Fault, NF – Nazaré fault, LTF – Lower Tagus Fault) (b) 2D seismic surveys and petroleum exploration wells in the DGEG database, (c) 3D seismic and aeromagnetic surveys and petroleum exploration wells in the DGEG database. After Pereira et al. (2021)

19.2.2. Storage assessments

The Lusitanian Basin extends along the West Iberian Margin, trending NNE-SSW, and covering approximately 20,000 km^2 in the west-central part of mainland Portugal and the adjacent continental shelf. This basin is defined as the area between the coastal town of Aveiro, in the north, and the coast south of the Arrábida Chain. The Lusitanian Basin has an extensive onshore area in which Mesozoic sedimentary formations outcrop. For details about the Lusitanian basin refer to, for instance, Kullberg et al. 2006 or Rasmussen et al. 1998. The storage options included in the Hystories database are summarised in Table 37 and Figure 68.

From the simplified porosity-depth profiles, two formations stand out as potential storage targets:

1) The Torres Vedras Group, of Lower Cretaceous age, comprising siliciclastic sediments, predominantly sandstones. The Torres Vedras Group is overlain by the Cacém Formation limestones and marls that could act as the primary caprock, although its heterogeneity raises concerns of lateral continuity. A more laterally extensive seal may be provided by the facies variations in the vertical sequence of the Torres Vedras Group itself, with layers of clays and siltstones several metres thick.
2) The Castelo Viegas and Penela formations of the Silves Group, Upper Triassic. The two formations are in vertical continuity and will act as a single reservoir, thus they are refered here as a same storage target, and generically referred to as a part of the Silves Group. Both the Castelo Viegas and Penela formations are characterised by siliciclastic deposits (sands and sandy-conglomeratic sediments), capped by evaporites (halite) with intercalations of dolomitic shales and anhydrite of the Dagorda Formation.

It is worth highlighting that the formations identified in this sector of the Lusitanian basin exhibit a considerable heterogeneity and variation in thickness through the basin, thinning at the structural highs

The Torres Vedras Group, or lateral equivalents, either has been eroded across much of the onshore sector of the Lusitanian Basin or is too shallow to be considered for UHS purposes. This Group only occurs at suitable depths for UHS in the Monte Real area. However, this area has suffered considerable halokinetic deformation and is structurally complex. Although, structural traps may exist for small-size UHS, the existing 2D seismic data are too sparse to allow identification of traps. Thus, a single unit area was defined for the region (Figure 68), based only on the depth of occurrence of the top of the Torres Vedras Formation in the Monte Real region, as provided by boreholes MRW-5, MRW-8 and MRW-9. In some boreholes, such as MRW-5, the upper Jurassic Alcobaça Formation which comprises mainly sandstones, seems to be in hydraulic connection with the Lower Cretaceous Torres Vedras Group, and may offer combined storage capacity. However, the region has suffered tectonic deformation, and the Alcobaça Formation is not identified in other wells in the area.

The Torres Vedras unit area included in Hystories database extends to encompass the Top Lower Cretaceous seismic horizon mapped by the 2D seismic surveys conducted by Mohave Oil & Gas Corporation in 1995 (Mohave Oil & Gas Corporation, 1995) and 1996 (Mohave Oil & Gas Corporation, 1996). This storage 'unit' included in Hystories does not indicate the whole area offers storage potential, but rather an area where, if additional geological and geophysical data are acquired, more detailed studies should be performed to identify traps.

In the Castelo Viegas and Penela formations of the Silves Group, four storage units were defined within a relatively small area in the north sector of the Lusitanian basin, related to the depth of occurrence of the top of the Silves Group, ranging from 800 m to 3000 m depth (Figure 68). All four units encompass the Castelo Viegas formation and the Penela formation divided by the presence of the major faults (identified from 2D seismic data) that seem to compartimentalise the storage units. The units are overlaid by an excellent cap-rock comprising extensive salt, marl, and clay layers from the Hettangian Stage (the Dagorda Formation) which can be hundreds of metres thick. It should be noted that while seal quality looks excellent, there is considerable uncertainty on reservoir quality in these four storage units. In addition, it is not possible to define traps from the sparse 2D seismic data. There is a 3D seismic data survey in the area that is currently being interpreted within the PilotSTRATEGY CO_2 storage project that may shed some light on the existence of traps in one of the units (the Alcobaça unit).

Table 37: Summary of storage options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore aquifers	2 formations, 5 units	Two formations (Torres Vedras and Silves) were identified in regional scale assessments as possible targets for UHS. High uncertainty remains on reservoir quality owing to lack of permeability data. Seismic data does not allow definition of traps	Further assessment required if new geological and geophysical data can be acquired. Interpretation of the existing 3D seismic survey data may help clarify the existence of traps in the Alcobaça unit.

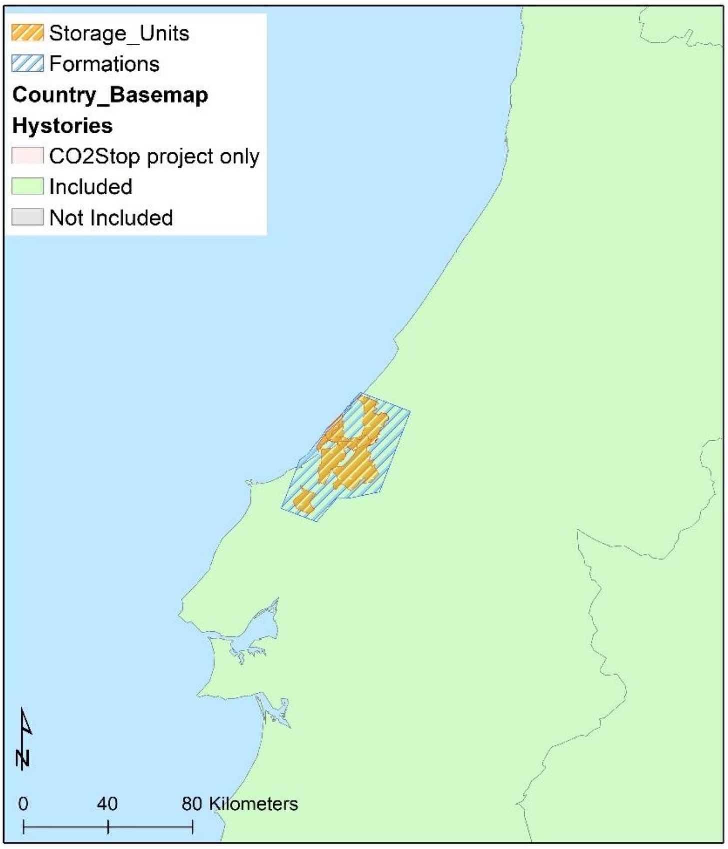

Figure 68: Overview of identified potential storage formations and units in the Hystories database within Portugal. Offshore options were not assessed given the availability of relatively low-cost H_2 storage available in on and offshore salt domes

19.2.3. Existing storage sites

There are no gas storage sites in porous media reservoirs in Portugal. The natural gas storage industry in Portugal utilises six salt dissolution cavities in west-central Portugal, at Carriço, in the Monte Real salt dome. The operator is the Portuguese company *REN-Redes Energéticas Nacionais*. The government has recently announced plans to build two other salt cavities, in the same salt dome, as a national natural gas reserve.

A further geological storage facility is found in the engineered cavity in gabbroic rock of the Sines Sub-Volcanic Complex. The cavity is used for Liquified Petroleum Gas (LPG) storage and is located just ashore from the deep-water port and LPG Sines terminal, in south-west Portugal. The engineered cavity is located at 130 m below ground level, has a storage capacity of 80,000 km^3, and has been operating since 2001.

19.2.4. Potential future development opportunities

Portugal has an ambitious National Hydrogen Strategy, EN-H2 (DGEG, 2020). The EN-H2 aims to use large amounts of renewable energy sources (solar and wind) for the production of green hydrogen and other Renewable Fuels of Non-Biological Origin (RFNBO), such as methane (mainly to inject into the natural gas grid) and aviation kerosene. The EN-H2 does not directly address the storage of the produced hydrogen, and several scenarios can be considered depending on the centralisation/decentralisation options for green H_2 production and utilisation. Nevertheless, the *Sustainable Green H_2 Atlas for Mainland Portugal* (LNEG, 2022) recognises the need for underground storage of hydrogen.

The existing data about the deep geological conditions in Portugal has already been incorporated in the geological assessment conducted in the CO_2 storage projects, in ESTMAP, and now in Hystories. The identification of suitable traps for UHS in porous media will probably require investment in acquisition of geophysical data (2D and/or 3D seismic) in the target areas.

The lack of data about the permeability of the saline aquifers in the Torres Vedras and Silves Groups is also impairs certainty about the feasibility to inject hydrogen in these reservoirs.

The EN-H2 can provide an incentive for further detailed studies and investment in acquisition of new data. However, it is likely that such efforts will be initially directed to evaluation of the storage potential in the several salt diapirs identified offshore.

Storage of hydrogen in porous media may become of interest depending on the locations selected for green hydrogen production. If such locations are within zones of the Lusitanian basin in which salt rocks are less common, interest for the storage of hydrogen in porous media may arise.

19.3. Discussion and conclusions

Portugal has the incentive to screen and characterise underground sites for UHS in connection with the government strategy EN-H2. However, given the many salt domes and diapirs in the country (both onshore, and offshore) and the experience in storing natural gas in salt dissolution cavities, it is likely that the primary target will be salt domes.

Portugal has several decades of experience in storing natural gas in salt caverns, and it is expected this type of facility will also be the primary target for onshore UHS. The possibility of storing hydrogen in saline aquifers should not be discarded since opportunities may arise depending on the location of facilities for green hydrogen production if these are developed in regions with an absence of salt domes. There are no opportunities for storage in depleted oil and gas fields since they are not found in the country.

Although general mapping of potential suitable geological formations has been accomplished, with the identified opportunities located in the onshore Lusitanian basin (i.e. the region extending from Alcobaça to Monte Real), the definition of traps is not possible owing to the quality and density of the legacy seismic and boreholes. The definition of traps will require investment in geophysical and geological data acquisition.

20. Romania; geological assessment of storage opportunities

Romania was among the first countries in the world to begin hydrocarbon exploitation, dating back to 1857. For this reason, many of the hydrocarbon fields are depleted or nearly depleted, providing good opportunities for storage.

The potential storage reservoirs (depleted hydrocarbon fields and deep saline aquifers) are located in sedimentary basins which cover the entire country with the exception of the Carpathians: Transylvanian Depression, Pannonian Basin, Scythian and Moldavian Platform, Moesian Platform, Getic Depression, Diapyre Fold Zone, Dobrudjan promontory and Black Sea Shelf. Unlike the well-characterised hydrocarbon fields, deep saline aquifers are less known, particularly onshore where fewer data are available. Offshore, non-productive structures could be considered for aquifer storage.

For storage, different lithologies are available in the aforementioned basins. Most of the reservoirs comprise sandstones, but calcareous facies are also encountered.

20.1. Data collation and collection

20.1.1. Data availability and collation

The Romanian database for the Hystories project builds on the CO_2StoP and ESTMAP databases. In addition, data from a nationally funded project was used. This national project focused on finding energy storage solutions in the sedimentary basins of Romania, including storage potential in the Black Sea.

For this project, data from CO_2StoP database were assessed in terms of potential for hydrogen storage and some of the data were retained. New data, including new traps, that were previously considered not suitable for CO_2 storage but could be suitable for hydrogen storage, were added.

The data sources used are listed in Table 38. Considerable effort was required to find the requested information. Much of the requested data are not publicly available and are held under strict confidentiality agreements. All information in the Hystories database is from public sources. Books presenting all hydrocarbon fields of Romania and the lithofacies maps with good descriptions offer valuable information (e.g. Beca and Prodan, 1983). These data sources were published in the 1970's and 1980's. Since then, a few good PhD theses and articles were published, which were used to update the database. Not all sedimentary basins are covered by publicly available data.

No detailed site data were available for the Hystories assessment, only basic reservoir data and administrative information were available. Seal data was very sparse, as well as data on heterogeneity. Most publicly available information relates to basic reservoir properties.

Table 38: List of key data sources for the Romanian Hystories database

Source name / URL	Description	Version / Date
Acorduri de concesiune pentru explorare-dezvoltare-exploatare NAMR 2021 http://www.namr.ro/wp-content/uploads/2021/03/Postare_AP_-EDE_martie-2021.pdf	Oil development-operation and exploitation concession agreements.	2021
Gas Storage database https://www.gie.eu/transparency/databases/storage-database/	European UGS database	July 2021
Information on one UGS site http://www.depomures.ro/despre_depozit.php	Information on UGS Targu Mures in the Transylvanian Depression	2021
Depogaz website https://www.depogazploiesti.ro/ro	UGS in Romania	2022 (website is regularly updated)
Various PhD theses and articles	PhD theses and articles	
Paraschiv D., 1975, Geologia zăcămintelor de hidrocarburi din România, Prospecţiuni şi explorări geologice Nr. 10, Bucureşti	Geology of oil and gas fields from Romania - Book, hardcover	1975
Paraschiv D., 1979, Platforma Moesică şi zăcămintele ei de hidrocarburi, Editura Academiei R. S. România, Bucureşti	Moesian Platform and its oil and gas fields - Book, hardcover	1979
Săndulescu, M., 1984, Geotectonica României, Editura Tehnică, Bucureşti	Geotectonics of Romania - Book, hardcover	1984
Saulea et al., 1970	Lithofacies maps for Neogene and Paleogene produced by the Geological Institute of Romania in 1970 - Paper maps	1970

20.1.2. Availability of detailed data for further site characterisation

For Romanian hydrocarbon fields, few data are available in the public domain. There is no public database in Romania and access to subsurface data is very restricted. Much of the information is classified as confidential and can only be accessed under strict conditions as dictated by Romanian legislation.

Research parties can request access to data but usually cannot disclose the data. In some cases, after the approval of NAMR (National Agency for Mineral Resources), some data can be disclosed, but usually anonymised. Even operators cannot disclose data without the consent of NAMR.

To access specific reservoir data, the best option is to request data from the operator and then ask for NAMR approval. Alternatively, one can make a formal request to NAMR, and then wait for their approval or redirection to the operator.

Access to data is currently the biggest hurdle in conducting research into geology, geological CO_2 storage or hydrogen storage.

20.1.3. Identified gaps in data availability

Most of the data was challenging to find, except for basic reservoir properties and licence owners. This is mainly a result of the data access issue described above.

To improve future assessments, specific data must be requested from NAMR and operators for each of the identified potential storage solutions. This process takes a long time and may prove very difficult to execute without dedicated funding.

For all the storage options included in the Hystories database, the greatest uncertainties relate to the caprock formations, since these were not examined in detail during hydrocarbon exploration. The lack of publicly available data leads to other uncertainties, such as the mineralogy, the presence of sulphates/sulphides and iron, the number of wells, the presence of geological faults.

20.2. Geological opportunities for hydrogen storage

20.2.1. Geological summary

Romania offers good storage possibilities both onshore and offshore, in many sedimentary basins: Pannonian Depression, Transylvanian Depression, Moldavian Platform, Getic Depression, Diapyre Fold Zone, North Dobroudjan (Dobrogea) Promontory, Moesian Platform (including Focsani Basin) and Histria Depression (Black Sea). These sedimentary basins contain a wealth of hydrocarbon fields, some depleted, with a track record of more than 160 years of hydrocarbon exploitation (first documented production as early as 1857). It is worth mentioning that in 1900, Romania was the third largest oil producer of the world. After the Second World War, production declined a little but recovered and reached a peak in in 1976. Nowadays, Romania is still among the top hydrocarbon producers in the Eastern Europe and interest in the Black Sea hydrocarbon reserves has been growing over the past few years.

The Pannonian Depression lies is in Romania, on the border with Hungary. The sedimentary strata comprises littoral and calcareous formations of Badenian and Sarmatian age, and terrigenous deposits, sometimes with marly – calcareous intercalations, of Pannonian age (Rabagia, 2009). The During the Neogene, sediments were deposited on a landscape with an irregular relief, resulting in deposition on unconformable surfaces and variations of lithofacies which in turn offered favourable conditions for the creation of a great diversity of traps for oil and gas accumulations (Paraschiv, 1975, 1979a, Maţenco and Bertotti, 2000).

The Transylvanian Depression is a large molassic depression bordered to the north, east and south by the Romanian Carpathians and by the Apuseni Mountains to the west. The Depression has important gas accumulations in Badenian, Sarmatian and Pannonian-age strata Colțoi, 2010). There are reservoir rocks of Paleogene age (sandstones and limestones), in the Lower Miocene strata (sandstones) as well as in the Badenian, Sarmatian and Pliocene deposits (sands, marly sands and sandstones) (Paraschiv, 1975, 1979a).

The Moldavian Platform is the south – western part of the East European Platform and it is bordered to the west and south by major fractures, separating it from the Central European Platform. The sedimentary cover begins in Romania with detrital deposits of Vendean age, followed, with many breaks in deposition, Silurian, Devonian and Mesozoic calcareous rocks, Palaeozoic clays and quartz sandstones, molassic Neogene deposits, and by Pleistocene strata. So far, in the Moldavian Platform, only gas fields have been found in the Sarmatian reservoirs (Paraschiv, 1975, 1979a). Reservoir rocks of Neogene age are mainly siliciclastic, while the older formations present fissured carbonate reservoir rocks.

The Diapyre Fold Zone has hydrocarbon accumulations in rocks of Oligocene to Neocene age (Burdigalian, Helvetian, Sarmatian, Meotian, Pontian, Dacian and Romanian). These reservoirs are mainly siliciclastic and have good reservoir properties (Paraschiv, 1975, 1979, a).

The North Dobroudjan (Dobrogea) Promontory represents the north – western extension of the North Dobroudjan Orogen which outcrops in the northern Dobrogea. This is a folded area that comprises metamorphic rocks with granitic intrusions and Palaeozoic and Mesozoic sedimentary formations (Ionesi, 1994). Hydrocarbon accumulations are mainly found in Neogene formations. Most of the discovered fields are oil, condensate and a few gas accumulations, located along the promontory ridge. The majority of these accumulations lie in Sarmatian and Pliocene age reservoirs (Paraschiv, 1975, 1979a).

The Moesian Platform is situated on the north and south sides of Danube River in Romania and Bulgaria. The main hydrocarbon reservoir rocks are fissured carbonate rocks (dolomites and limestones) of Middle – Upper Devonian to Lower Carboniferous age, as well as of Middle Triassic, Malm – Neocomian and Turonian – Senonian age. Hydrocarbons are also found in calcarenites of Barremian and Albian age, gritty rocks of Permian – Triassic, Lower and Upper Triassic age and the Dogger Formation. Other reservoir rocks include glauconitic sandstones of Albian age, gritty limestones in Lower Sarmatian strata. Poorly cemented sands and sandstones in Sarmatian and Pliocene strata and sandstones and orthoquartzites of Middle Devonian – Ordovician age are also productive. The traps are very diverse in terms of tectonic or lithological type. Most hydrocarbon fields that have been discovered in the Moesian Platform are oil fields (58 %), the remainder being gas (37%) and gas–condensate (5%) (Paraschiv, 1979 a, b, Maţenco et al., 2003).

The Histria Depression is the offshore region in which the most important hydrocarbon fields from Romanian black sea shelf are present and exploited starting from 1980. The hydrocarbon reservoirs are contained mainly in siliciclastic and limestone formations of Albian, Upper Cretaceous and Eocene age (Ţambrea, 2007; Dudu et al., 2017).

20.2.2. Storage assessments

The Romanian onshore Hystories database contains hydrocarbon fields, and the offshore part of the database contains saline aquifers. No onshore deep saline aquifers could be identified from the available data. Additional data are required to delineate and characterise onshore saline aquifer traps. The identified offshore saline aquifers are structures that were explored for hydrocarbons and found to be non-productive. These potential storage solutions were also investigated for CO_2 geological storage potential within a national project, funded by the Ministry of Research of Romania.

As there are many onshore hydrocarbon fields, it is anticipated that saline aquifer traps will offer onshore storage potential. Currently, the most readily available solution for onshore hydrogen storage seems to be the depleted hydrocarbon fields. However, natural gas storage is a strategic priority, and it is important that onshore hydrogen storage does not conflict with this use of the subsurface. Effective gas transport networks are available onshore.

The exploitation of offshore hydrocarbon fields is relatively recent and new fields are being discovered. For this reason, on the short and medium term, no hydrogen storage could be considered in the offshore hydrocarbon fields since they are not yet depleted.

The Romanian Hystories database does not present the full potential for hydrogen storage. A significant amount of additional data is required to fully understand the available storage resource. Many uncertainties remain related to the current status of identified traps/fields.

A summary of the potential 'traps' included in the Hystories database is presented in Table 39, Figure 69 and Figure 70.

Table 39: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore gas fields	20	The oldest gas field from the database was discovered in 1928. From a total of 20 fields, 2 are abandoned, one suspended from production, 7 gas storage sites (with associated gas production) and 11 producing gas fields. All reservoir formations are sandstones and the seals are represented in general by shales. All associated data is from public sources. These fields were selected based on existing data from CO_2StoP project. Natural gas storage sites were added.	Site specific studies required. Additional data could be added to database with further resources
Onshore oil fields	17	From 17 oil fields selected for the database, 1 is abandoned. These fields were selected based on existing data from CO_2StoP project.	Site specific studies required. Additional data could be added to database with further resources
Onshore aquifers	-	There is surely potential onshore, but more studies are needed in order to confirm the traps. The potential has not yet been assessed. Only two potential aquifers were identified for CO_2 storage, within GETICA CCS demonstration project. These were not included in the hydrogen storage database since the traps are not confirmed.	Regional geological mapping and assessment of aquifers may reveal further potential for energy storage
Offshore aquifers	4	No entries available in CO_2StoP and ESTMAP projects. The identified traps correspond to non-productive (for hydrocarbons) structures discovered during Black Sea exploration which started during 1980's. Initially, these aquifers were identified as possible solutions for energy and CO_2 storage within a national funded project. Surely more aquifers exist offshore.	Regional geological mapping and assessment of aquifers may reveal further potential for energy storage

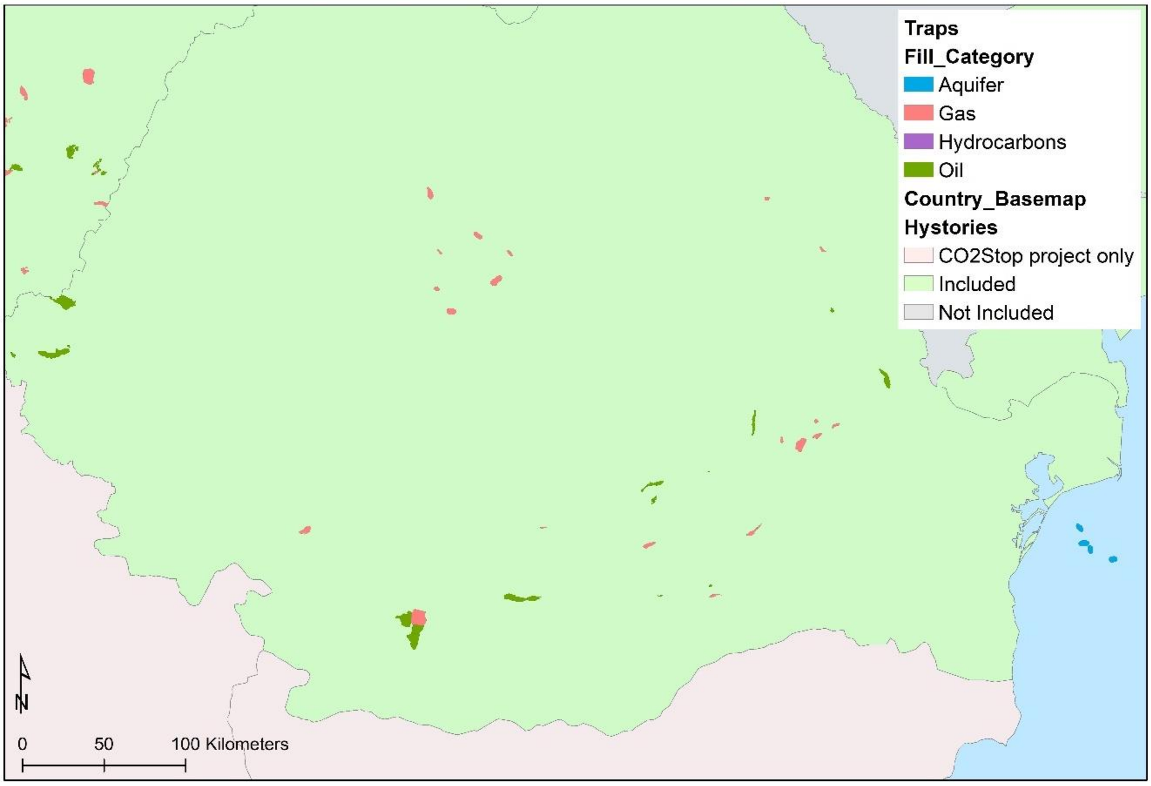

Figure 69: Overview of identified potential traps in the Hystories database within Romania.

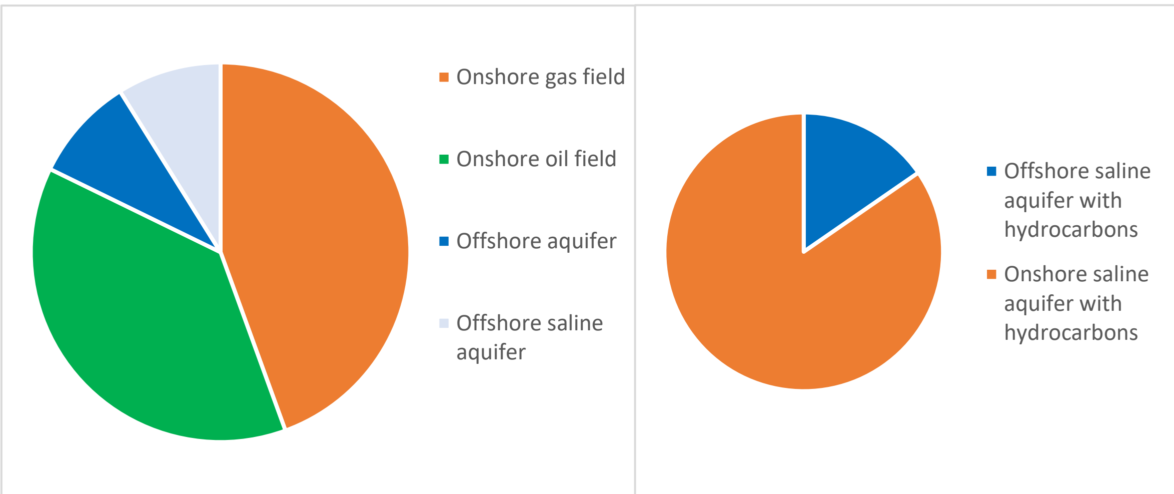

Figure 70: Frequency pie chart showing categories of identified potential storage opportunities in Romania; traps (left) and units (right).

20.2.3. Existing storage sites

In Romania, the subsurface is used for hydrocarbon exploitation, natural gas storage, and exploitation of geothermal resources. Currently there is no hydrogen storage implemented or planned.

Gas storage is an important industry in Romania. The first attempt to create a gas storage site dates back in 1958, the Ilimbav site operated until 1985 at which point it was abandoned owing to technical issues. The first modern gas storage operation began in 1979 at the Urziceni site in a depleted natural gas field. Romania currently has seven gas storage sites in operation, six in the Moesian Platform (operated by Depogaz Ploiesti) and one in the Transylvanian Depression (operated by Depomures). The sites were previously operated by ROMGAZ S.A., the largest gas producer in the country. There are plans to extend gas storage operations, with the development of a new site in Moldova (eastern part of the country) and extension of an existing site (Targu Mures in the Transylvanian Depression). Little information is available on these reservoirs.

No CO_2 geological storage projects exist in Romania at present. In 2010, the GETICA CCS full chain demonstration project was proposed. A feasibility study was finalised and the project was submitted for the EU NER300 programme. The proposal was placed on the waiting list and subsequently stalled owing to the lack of governmental support and the lack of financing.

20.2.4. Potential future development opportunities

Romania presents many opportunities for hydrogen storage, both in hydrocarbon fields and deep saline aquifers. In order to assess the full potential for storage, a significant campaign of data collection is required, and of course, dedicated funding.

The most promising option for hydrogen storage appears to be onshore, particularly in the Moesian Platform and in the Transylvanian Depression. Selection of future hydrogen storage sites must also consider proximity of hydrogen sources.

20.3. Discussion and conclusions

The Romanian onshore offers good storage opportunities in near-depleted and depleted hydrocarbon fields. Depleted gas fields offer the most obvious option. However, particularly in the current regional context, conflict of interest with natural gas storage operations could be a major problem.

Storage potential may also exist in onshore deep saline aquifers, but this potential has yet to be confirmed. New data and detailed characterisation are required.

The Romanian offshore also could present good opportunities for storage, but not in the near future. Gas fields in the offshore are not yet mature or depleted. Some fields have only recently been discovered. Offshore, structures that did not contain hydrocarbons have been identified but these potential saline aquifer traps require further characterisation.

21. Slovenia; geological assessment of storage opportunities

Geological and geophysical data are sparse, making the assessment of geological storage opportunities challenging. Hydrocarbons have been exploited in the Slovenian part of the Pannonian Basin in Miocene strata and potential hydrocarbon storage traps have been identified here. Thick sequences of carbonates and clastics are present in in the Pannonian Basin (north-east Slovenia), the Gorenjska-Posavje basin (central Slovenia) and the Gorica - Vipava Basin (south-west Slovenia) which may offer saline aquifer storage potential. Green hydrogen is of growing interest in Slovenia which may prompt more interest in acquiring new data to improve assessments of the subsurface for subsurface storage of fluids.

21.1. Data availability and gaps

21.1.1. Data availability and collation

Data are sparse, with very few reliable data sources available. The assessment of potential storage locations has been performed through interpretation of available data, and expert extrapolation to assess regions worth further exploration.

Oil and gas exploitation took place over several decades, ending in 1963 when the federal research programme ceased (Lorencic, 2013). Oil and gas were produced from the Mura subbasin of the Pannonian Basin. The Pannonian Basin extends into neighbouring Croatia where oil and gas are still produced. The main data sources used are published papers including an assessment of aquifer storage potential of Slovenia. In some cases, data such as porosity, were estimated using data from the same geological formations in neighbouring Croatia. The main data sources are listed in Table 40. Based on available sources, data from the earlier CO_2StoP and ESTMAP projects assessing potential for geological storage of CO_2 and underground energy storage, respectively, have been updated. The number of identified traps and storage units in Slovenia is shown in Figure 72.

Table 40: List of key data sources for the Slovenia Hystories database

Source name / URL	Description	Version / Date
Geological Research data, maps and reports	Aquifer mapping and research	December 2008
Mioc and Znidarcic 1996 https://hrcak.srce.hr/61178	Geological characteristics of the oil fields in the Slovenian part of the Pannonian Basin	1996
Well database https://e-vrtina.si/	Geological survey of Slovenia – data on wells drilled. Includes some more recent (2010) geotechnical wells	Website presumably updated regularly. Includes wells drilled

21.1.2. Availability of detailed data for further site characterisation

Some well data from hydrocarbon exploration are available from the national geological survey (Table 40). Seismic data are not freely available. A few 2D seismic lines have been shot for oil and gas exploration, mostly dating back to the 1950s.

21.1.3. Identified gaps in data availability

Additional data would need to be acquired to advance the assessment of geological storage potential in Slovenia. This would include collection of primary seismic data and drilling of new wells.

21.2. Geological opportunities for hydrogen storage

21.2.1. Geological summary

This geological synopsis is summarised from Vrabec et al., 2009.

Slovenia has a complex geological history and the country spans four major Alpine structural units; the Dinarides, the Southern Alps, the Eastern Alps, and the Pannonian Basin. The Palaeozoic strata suggest deposition on a continental margin.

The remains of Ordovician, Silurian and Devonian deep-water fossils are found where rocks have been only weakly metamorphosized. These rocks are believed to have been deposited in a deep-water environment in the transition zone from the continental margin to the abyssal plain.

During the Palaeozoic, Slovenia resided on the northern margin of Gondwana or on an independent continental strip in the Paleotethys Ocean.

Devonian limestones are found in the Southern Karavanke Mountains near the northern border of Slovenia. Lower Devonian strata are interpreted to be deepwater deposits. By Mid-Devonian, deposition was occurring on a shallow water carbonate platform. By the end of the Devonian, a drop in sea level exposed the carbonate platform, resulting in erosion and karstification of the carbonate platform.

At the onset of the Variscan Orogeny, early Carboniferous flysch-like strata were deposited in foreland basins. These strata comprise shales, sandstones and greywackes and outcrop in the Karavanke mountains. These strata are truncated by a mid-Carboniferous erosional unconformity that marks the Variscan orogenic uplift. Late Carboniferous post-orogenic molasse-type sediments were deposited, comprising conglomerates, sandstones, and shales. Continental swamps and shallow-marine environments are also indicated by strata in the Karavanke Mountains and Sava Folds. Vrabec et al. (2009) mentions the occurrences of volcanoclastics in early Carboniferous sediments, indicating the volcanic activity. However, in other places in Mediterranean, occurrences of volcanics are mainly associated with post-orogenic volcanism in late Carboniferous-early Permian, as reported by Cortesogno et al. (1998).

During Early Permian, carbonate-siliciclastic deposition continued on a coastal shelf, bordered by reefs as indicated by strata found in the Karavanke Mountains. The Saalian orogenic event, characterised by vertical block motion along steep faults, terminated deposition of these reef limestones. The Saalian event was followed by continental deposition of Middle Permian breccias, conglomerates, sandstones, siltstones and mudstones in alluvial fans, rivers, and shallow marine environments. In the Late Permian, Slovenia was entirely covered by a shallow Sea, which marks the initiation of the Slovenian Carbonate Platform and deposition of limestones. The Upper Permian succession also contains evaporites. Late-Permian granitic intrusions related to post-collisional magmatism related to the Variscan Orogeny are also observed.

During Mesozoic times, Slovenia lay on the northern margin of the Adria. The Adriatic domain was bounded by the Alpine Tethys Sea to the north and west, and the Vardar Ocean to the east.

During the Early Triassic, the Slovenia Carbonate Platform persisted. Mixed siliciclastic-carbonate sediments were deposited. Occasional reef deposited also occur. In the Middle Triassic, the new Meliata Ocean started to open along the Eurasian margin, which in Slovenia resulted in Mid-Ansian to Ladinian extensional tectonics and associated volcanism. Middle Triassic extension split the Slovenian Carbonate Platform into three major palaeogeographic units; The Julian Carbonate Platform (north, today found in the Karavanke Mountains and Alps); the Dinaric Carbonate Platform (south); and the Slovenian Basin (deep water domain between the two platforms). Multiple small shallow basins formed in central Slovenia, with deposition of shales, sandstone, breccia and tuff intercalations. Middle Triassic volcanism and magmatic activity are also identified. Extension ended in Upper Ladinian times. The basins filled and carbonate deposition prograded across parts of central Slovenia. Tectonic activity renewed during Middle Carnian times and limestones deposition began across the platforms. In Norian to Rhaetian times, the underwater topography was relatively level and limestones were deposited across the Julian and Dinaric Carbonate platforms, and dolomite with chert was deposited in the Slovenian Basin.

At the end of the Triassic, a major rifting episode began resulting in the breakup of Pangea and the opening of the Atlantic Ocean. A system of transform basins formed in the Alpine domain, which evolved into the Alpine Tethys Trough. Slovenia was located on the northern passive continental margin of the Adriatic microplate. Jurassic extension created extensive deep-water basins and submarine plateaus.

Subsidence at the end of the Triassic to early Jurassic times resulted in deepening waters over the Julian and Dinaric Carbonate platforms and deposition of several hundreds of meters of shallow-water limestones. The Slovenian Basin water also deepened and accumulated deposits of carbonate gravity flows. Shales and marls were deposited during the Toarcian ocean anoxic event. Thermal subsidence in the Mid Jurassic resulted in the Julian Carbonate Platform subsiding to become a pelagic plateau known as the Julian High, with limestone deposition. The Slovenian Basin deepened further which favoured deposition of cherts and calcareous turbidites. At the end of the Jurassic, deposition of limestones with cherts was taking place in the Slovenian Basin and the Julian High. The Dinaric Carbonate Platform was not significantly affected by thermal subsidence, and shallow water deposition continued until the formation of a barrier reef in the Late Jurassic. In the Late Jurassic, compression occurred, and the carbonate platforms show localised uplift and subsidence.

During the Early Cretaceous, subduction and closure of the Meliata Ocean led to orogeny in the eastern part of the Alpine Orogen. Compression and extensive north-west to north thrusting of Austroalpine nappes and associated metamorphism occurred. Metamorphic rocks formed in north-east Slovenia and were subsequently deeply buried (Early Cretaceous) and then exhumed almost to surface (Late Cretaceous). Early Cretaceous compression was followed by Late Cretaceous extension which is interpreted as the collapse of the Austroalpine orogen, deep water sediments were deposited in eastern Slovenia. Shallow water sedimentation persisted in the Dinaric Carbonate Platform (south Slovenia) throughout most of the Cretaceous until this platform was drowned by a eustatic sea level rise. Shallow water limestone sedimentation resumed in Upper Turonian times. In the area north of the Dinaric Platform, the Austroalpine orogeny was reflected by the deposition of Early Cretaceous clastic flysch-like deposits, which unconformably overly Jurassic limestones. Deep water sedimentation continued into the Cenomanian when limestones were deposited. In the late Cretaceous, the north-eastern margin of Adria collided with continental lithosphere. In the Slovenian Basin (Central Slovenia), this resulted in the deposition of carbonate turbidites, followed by mixed siliciclastic-carbonate flysch deposits which filled the Slovenian Basin. Flysch sediments were deposited in a flexural foreland basin setting. By the end of the Cretaceous, the flysch sediments had covered the northern margin of the Dinaric Carbonate Platform. Further south, rocks of the Dinaric Carbonate Platform were subaerially exposed and karstified.

During the Paleogene, flysch deposition in the Dinarides ahead of the advancing foreland basin continued. Carbonate sedimentation persisted on the Paleogene Adriatic Carbonate Platform to the south-west until it was drowned in Lower to Mid-Eocene times. Thousands of metres of deep-water clastic flysch deposits were laid down. The oldest flysch deposits found in north-east Slovenia are of Late Cretaceous age, whereas the youngest flysch deposits in south-west Slovenia are of Late Eocene age. No early Paleogene strata are observed in central and northern Slovenia, the oldest known are of Eocene age.

At the beginning of the Oligocene, the rising mountain chains of the Alps, Dinarides and Carpathians isolated the Paratethys Sea which spanned across central and eastern Europe. Deposition began in northern and central Slovenia, central Hungary, and Slovakia in a retro-arc flexural basin of the subduction-collision zone that runs along the northern margin of the Alps and Carpathians. In Slovenia, conglomerates with some coal intercalations were deposited, transitioning to shallow marine limestones then to basinal fine-grained clastics. Subduction of the Alpine Tethys ended in the Paleogene, which resulted in continental collision of Adria and Eurasia.

At the transition of Early to Middle Miocene, major lithospheric extension occurred in the intra-orogenic region between the Carpathians, Dinarides and Eastern Alps. The resulting structurally complex Pannonian Basin contains kilometres of predominantly clastic sediments. Across the Sava Folds area, the Pannonian Basin sediments reach westwards all the way to central Slovenia. Cretaceous Austroalpine thrusts were reactivated as low-angle normal faults. It is believed a granodioritic intrusion and associated volcanism are associated with this

Miocene extension. Continental and shallow marine-clastic sediments prevailed in western Slovenia. At the beginning of the Middle Miocene, the combined effect of tectonic activity and eustatic sea level fall resulted in the formation of an erosional unconformity.

Rapid subsidence began again in the Middle Miocene. Shallow carbonate platform deposition began again, followed by deep water mudstones and turbidites. By the end of the Middle Miocene, the next eustatic sea level fall resulted in shallow marine, brackish and continental environments of deposition. In the Sava Folds area, these are the youngest strata, and the succession is terminated by an erosional unconformity.

During Late Miocene times, the final phase of subsidence stated. In eastern Slovenia, a thick succession of predominately clastic sediments was deposited. The lower deposits are of marine origin, the upper deposits are deltaic deposits that filled up the basis and marked the end of deposition in the Slovenian part of the Pannonian Basin.

Dextral motion of the Periadriatic faults continued until Miocene and Pliocene times, with displacement estimated to be 100 km. Additionally, the area to the north was stretched during extrusion and the Pannonian Basin extension, resulting in a 300 km separation of the pre-Oligocene units.

The Neogene shortening in the Adriatic-Eurasia collision resulted in thrusting in the Alps during Middle Miocene to Pliocene times. This thrusting continues in the Julian Alps.

At the transition from Miocene to Pliocene, the final closure of the ocean embayment in the Carpathians stopped eastward movement of the Eastern Alps and a major change in the tectonic regime. In the Sava Folds region and in eastern Slovenia, a reverse reactivation of normal faults with uplift and erosion removed most of the Cenozoic strata. In central and northern Slovenia, the inversion resulted in dextral transpression. The uplift of the Karavanke mountains probably also occurred during the Pliocene – Quaternary inversion. Small local intra-montane basins formed along the strike slip faults. During the Neogene, subduction of Adria under the Dinarides began.

In the Pleistocene, the Alpine glaciers from the Julian Alps and Karavanke mountains were reaching into the foreland. Partially tectonically controlled depressions were filled with fluvial and lacustrine strata up to 120 m thick. The compressional tectonic regime continued from the Pliocene into the Quaternary. Ongoing tectonic activity is evidenced by significant seismic activity.

21.2.2. Storage assessments

Geological data are sparse, therefore storage assessment is challenging and retains high uncertainty. A summary of identified opportunities is shown in Table 41, Figure 71 and Figure 72.

Pannonian Basin

The Pannonian Basin (north-east Slovenia) may offer saline aquifer and hydrocarbon storage potential. Traps have been identified here in the Hystories database. The Slovenian part of the Pannonian Basin comprises the Mura-Zala depression.

There are two hydrocarbon fields in the Pannonian Basin. Commercial quantities of hydrocarbons have not been identified elsewhere in Slovenia. The onshore Petišovci field produces gas and oil from multiple horizons, comprising Miocene age sandstones. Most gas was produced from deep reservoirs between 1963 and 2017. The Dolina hydrocarbon field produces from clastic Neogene strata.

Saline aquifer storage may be possible in the Pannonian Basin. In the Hystories database, traps have been identified in carbonates of Triassic to Cretaceous age and Miocene-age sandstones.

Gorenjska-Posavje Basin

The Gorenjska-Posavje basin (central Slovenia) has some tentatively identified storage potential. Only potential storage units have been identified since there are insufficient data to identify traps. Potential saline aquifer storage units have been identified in Mesozoic clastic and carbonate units.

Gorica - Vipava Basin

The Gorica - Vipava Basin (south-west Slovenia) has some tentatively identified storage potential. Only potential storage units have been identified since there are insufficient data to identify traps. A potential saline aquifer storage unit has been identified in carbonates of Cretaceous to Paleogene age.

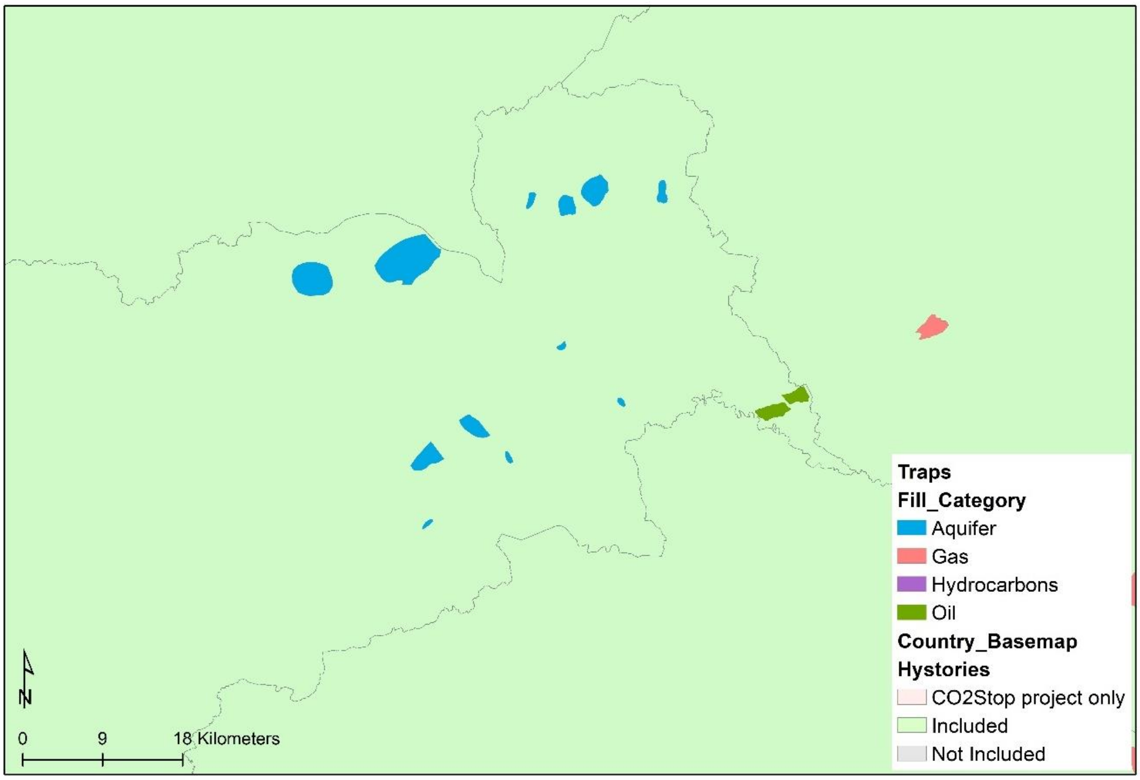

Figure 71: Overview of identified potential traps in the Hystories database within Slovenia (all in the east) plus surrounding areas.

Table 41: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore hydrocarbon traps	4		Additional studies required
Onshore saline aquifers	17		Additional data collection required (seismic/wells)

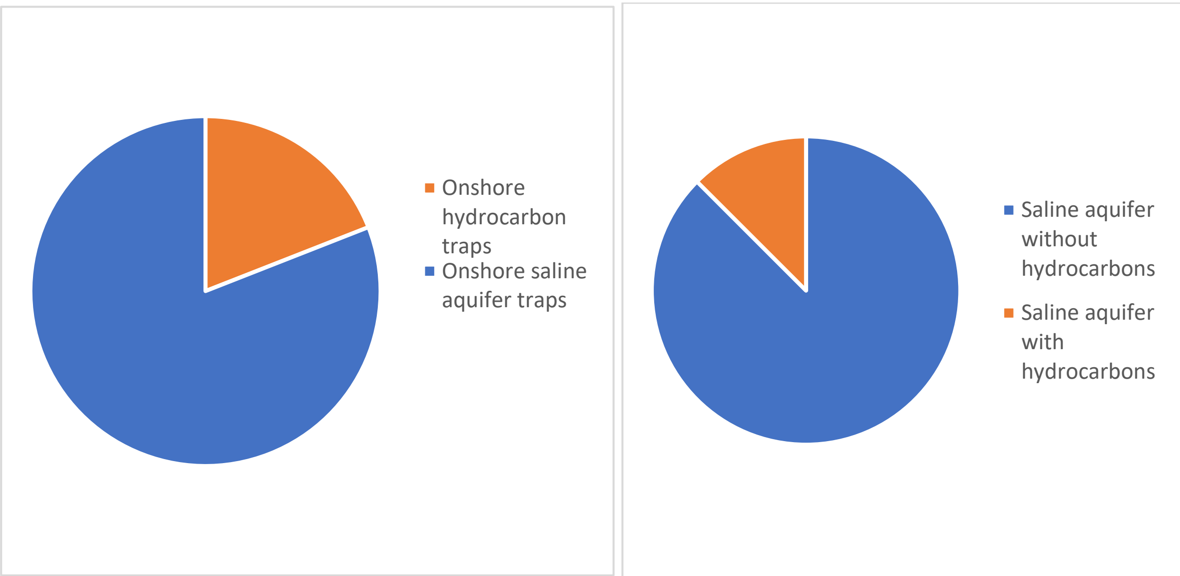

Figure 72 Frequency pie chart showing categories of identified potential storage opportunities in Slovenia; (left) and units (right). Please note that some of the traps are different geological horizons in the same trap and that traps could only be identified in the Pannonian Basin owing to scarcity of data.

21.2.3. Existing storage sites

There are no geological underground natural gas storage sites in Slovenia (Geoplin[44]; the largest natural gas trader in Slovenia).

[44] https://www.geoplin.si/en/natural-gas/natural-gas-in-slovenia-and-worldwide accessed 27/06/23]

21.2.4. Potential future development opportunities

The 2020 complete national energy and climate plan of the Republic of Slovenia[45] indicates a role for hydrogen in the energy sector, with an indicative target of 10% of renewable-sourced methane or hydrogen in the gas transmission and distribution network by 2030. The use of hydrogen to help decarbonise the transport sector is also mentioned.

Green hydrogen is of growing interest in Slovenia. The North Adriatic Hydrogen Valley project, led by the Slovenian energy company HSE, has won a €25 million grant from the EU's Horizon Europe Programme (Slovenia Times[46]). This transnational project involving Slovenia, Croatia and Italy covers the entire value chain from production through storage and distribution to the end use of hydrogen. The aim is to develop projects to produce more than 5,000 tonnes of green hydrogen a year in a bid to decarbonise key industrial sectors (e.g. steel and cement), and transport.

The data included in the Hystories database should be considered as an initial estimate of the opportunities for underground hydrogen storage. More data are required in promising regions to enable to better understand the properties of both the reservoir and sealing rocks to establish their effective storage potential.

21.3. Discussion and conclusions

The Slovenian sector of the Pannonian Basin has identified storage potential. This region also contains the only commercially viable hydrocarbon fields in Slovenia, so the ability of strata to trap buoyant fluids is arguable here. Saline aquifer potential has been identified in the Pannonian Basin (north-east Slovenia) and tentatively identified in the central region of Slovenia. More primary data are required for a thorough assessment including acquisition of new seismic data and drilling of new wells. Green hydrogen is of growing interest to decarbonise the energy, industry, and transport sectors, and perhaps this will engender interest in geological storage of hydrogen.

[45] https://www.energetika-portal.si/dokumenti/strateski-razvojni-dokumenti/nacionalni-energetski-in-podnebni-nacrt-2024/ [accessed 27/06/23]

[46] https://sloveniatimes.com/north-adriatic-hydrogen-valley-wins-eu-funds/ [accessed 27/06/23]

22. Spain; geological assessment of storage opportunities

Oil and gas exploration campaigns were carried out in Spain from the 1950s to the 1980s. A few onshore hydrocarbon deposits were discovered in the Ebro and Guadalquivir basins, and offshore fields were identified in the Bay of Biscay, the Mediterranean Sea and the Gulf of Cádiz. Although these campaigns did not identify huge volumes of oil or gas, this subsurface information has been key in identifying deep saline aquifers with potential for geological storage. A total of 86 deep saline aquifer traps have been included in the Hystories database. This information on the subsurface is public. The potential for geological storage of CO_2 was assessed during the national ALGECO_2 project (García Lobón et al., 2010) (Arenillas et al., 2014) and made available in an online database and Atlas[47] which was utilised as an information source for the Hystories project. Although only a few oil and gas fields have been commercially developed, five of them have been converted to gas storage sites, and two of these, with publicly available data, are also included in the Hystories database.

22.1. Data collation and collection

22.1.1. Data availability and collation

The Hystories database builds on the ALGECO_2 project, carried out by the Spanish Geological Survey (IGME) in 2010 with the objective of identifying geological structures with potential for CO_2 storage. During the ALGECO_2 project, significant effort was expended to collect existing subsurface information and to consider the potential for CO_2 geological storage. This work was undertaken following the guidelines of the transposition of Directive 2009/31/CE on the CO_2 storage law approved by Law 40/2010 of 29th December. Digitisation of data, and evaluation and classification of these data resulted in the identification of 103 structures based on expert-defined criteria. This project was focused on saline aquifers of the main onshore sedimentary basins.

Information collected during the ESTMAP and CO_2StoP projects were reviewed and updated. In the CO_2StoP database, only 45 structures compared with the 103 identified during the more recent ALGECO_2 project. In the online CO_2StoP GIS, the information was also incomplete, including only 43 Storage Units. Some errors were identified, with only six formations considered, and no trap layer included. In short, a complete review of existing data sources was made, coding was corrected, and new GIS trap layer with 60 additional potential stores, was built for the Hystories database.

As requirements for potential storage of hydrogen are different from those of CO_2, the results of the aforementioned projects were adapted to the particular needs of hydrogen storage.

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47 https://info.igme.es/algeco2/

The new information included in the Hystories database, mainly number and extent of reservoir formations and geological unit definition, comes from new reviews of existing data and new data from in-house projects. It was decided to keep the traps already considered as possible CO_2 stores and the search was expanded, within each basin, for other possible favourable formations. Missing data, particularly geochemistry, seal features, and faults, were added to the Hystories database.

The layers for the Hystories GIS were created from scratch with the delimitation of the formation polygons from isobath maps of the geological formation tops from previous studies carried out by the IGME. A minimum depth of 300 m was applied. The Storage Unit GIS layer was also created from scratch by identifying expanded regions that contain favourable structures from the Traps GIS layer.

The main challenge encountered was the distinction between storage traps and units, and between units and formations. During CO_2StoP, defined closures were included as storage units, but these are considered as traps by the Hystories project and had to be reclassified and additional data added since the Traps table is much more detailed than the Units table. For Hystories, the storage unit outlines were defined from the group of traps that share the same storage rock in the same basin. An added issue was the attribution of geological basins. For example, a Triassic formation that belongs to four geological basins. In these cases, three formations with the same characteristics but belonging to three different basins were created. Adding the Basin name to the Observations field in these cases.

Thus, the GIS layers are made up of the following elements: the traps are the same as those considered in ESTMAP, with the addition of several absent traps and the three active gas stores in Spain. The unit layer was created considering a suitable extension around the traps.

The basic gas storage data were provided by ENAGAS (national operator of gas infrastructure), and completed from literature sources, national hydrocarbons database[48] or national statistics database[49] (Table 42).

Most geochemical data and detailed information on faults were not available. For some parameters, only one value was available, which has been considered as average value. For some parameters, a range between a maximum and minimum value was given, in which case this range was reported (for example, depths, temperatures, permeabilities and porosities). The data contained in the survey reports, from the site or nearby, have been used.

All utilised data are public, and access is open. No confidential data have been included.

48 https://geoportal.minetur.gob.es/ATHv2/ , *Archivo de hidrocarburos*

49 https://www.cores.es/es

Table 42: List of key data sources for the Spanish Hystories database

Source name / URL	Description	Version / Date
https://info.igme.es/geologiasubsuelo/portada/Default.aspx	Assessment of CO_2 storage potential	2010
InfoIGME – Sistema de Información Geofísica (SIGEOF) http://info.igme.es/SIGEOF/	Geophysical Information System data	2016
Archivo Técnico de Hidrocarburos https://geoportal.minetur.gob.es/ATHv2/	Hydrocarbon Research Permits, exploitation concessions and data from surveys and seismic surveys	2020
https://www.cores.es/es	Reporting of oil and gas production in Spain	2022
Almacenamientos Subterráneos Gas – Infraestructuras – Enagás (enagas.es)	Subsurface gas storage	2022

22.1.2. Availability of detailed data for further site characterisation

The IGME has been the national repository since 1850 for national geological information such as documents, analysis, reports and maps. Most of this information can be consulted and reviewed. IGME also manages the main lithotech database in Spain, populated from oil and gas, geothermal, and other exploration campaigns. The IGME also collects thousands of cores, cuttings and thin sections, which can be also consulted via the online lithotec databbase [50].

Hydrocarbon data, including the location of permits and data from drilling campaigns and seismic surveys, is updated and provided by the Technical Archive of Hydrocarbons. Applications for access can be processed at the hydrocarbon archive[51] of the Ministry of Ecological Transition.

22.1.3. Identified gaps in data availability

Recent exploration campaigns onshore or offshore have been (or are being) carried out and the data are owned by private companies and are not available in the public domain. Exploration activity has been particularly intensive in the offshore of the Peninsular Spain. This has resulted in the discovery and development of oil and gas fields in the Bay of Biscay, Gulf of Valencia and Gulf of Cadiz.

[50] https://info.igme.es/litoteca/ Litoteca IGME – Consulta Documentos No periodicos

[51] https://geoportal.minetur.gob.es/ATHv2/ – Archivo Técnico de Hidrocarburos

A more detailed assessment using legacy information would require use of confidential data held by private exploration companies. Most of the oil fields found in Spain are located offshore, and it is there that the most intensive exploration campaigns have been carried out, with a dense mesh of seismic lines and exploration wells in these locations. There are also already exploited oil and gas deposits that would be interesting to analyse as potential stores if the exploration data were made available.

In general, geochemical data and detailed information on faults were not available for the Hystories database. Publicly available information available is scarce and of insufficient quality to aid in the evaluation of potential stores.

22.2. Geological opportunities for hydrogen storage

22.2.1. Geological summary

Spain, as part of the Iberian Peninsula, has four main geological domains related to potential formations for underground hydrogen storage (UHS): Cantabrian Range and Duero Basin; Pyrenees and Ebro Basin; Iberian Range, and Tajo and Almazán Basins; and Betic Cordillera and Guadalquivir Basin (Rodríguez Fernández et al., 2004) (Figure 73).

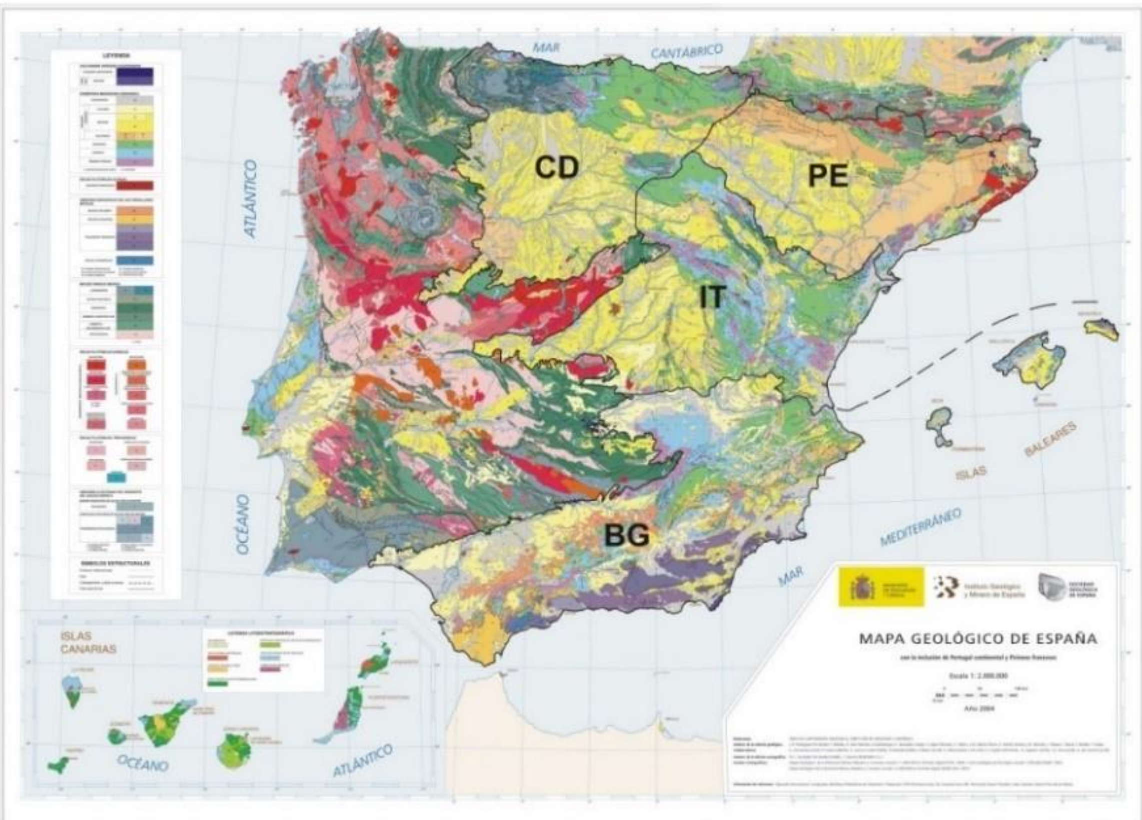


Figure 73: Overview of Spanish geological domains with potential for geological storage. Cantabrian Range and Duero Basin (CD); Pyrenees and Ebro Basin (PE); Iberian Range, and Tajo and Almazán Basins (IT); and Betic Cordillera and Guadalquivir Basin (BG)

The highest potential for geological storage is found in Triassic (Buntsandstein) facies and Jurassic deposits comprising the Lias, Dogger and Malm series. Storage potential has also been identified in the Cretaceous Utrillas Formation and carbonates. In the Guadalquivir Basin, the Neogene (Tortonian-Messinian) Guadalquivir Sands Formation also offers storage potential, as indicated by the presence of commercial-scale gas accumulations.

Sedimentary basin fill generally comprises strata of Triassic to the Neogene age with total thicknesses exceeding 3,000 m. The main identified storage potential in Spain is in saline aquifers. Additional potential is offered by onshore and offshore oil and gas fields in the Guadalquivir Basin (gas), Ebro Basin (oil and gas), and the Cantabrian Range and Duero Basin (oil and gas).

Oil has been produced from 11 fields in Spain. Production started in 1966 from Ayoluengo field and continued for 50 years. The other ten fields are offshore. Activity ceased in 2021, when the last remaining field in the Mediterranean Sea (Boquerón, Casablanca and Rodaballo) closed. Gas production has followed similar evolution: ten fields have been commercially exploited, with the first producing well in 1963 (Castillo). Currently, there are two onshore gas assets in production, El Romeral (Guadalquivir) and Viura (La Rioja).

Hydrocarbon production data in Spain can be consulted at the Corporation of Strategic Reserves of Petroleum Products[52].

22.2.2. Storage assessments

Spain has not extensively exploited its national resources of natural gas and oil. As a result, coverage of the publicly available subsurface information is not complete and therefore a thorough assessment of the potential for UHS in depleted hydrocarbon fields is not currently possible. The available subsurface data have been used to identify structures in saline aquifers which may be suitable for UHS, but given the limited data, the accuracy of these assessments is also limited.

During the GeoCapacity project, assessments considered areas of Spain where there are porous sedimentary formations (such as sandstones, sands and fractured carbonate rocks) present at sufficient depth to store CO_2 in highly dense phase; that is, at depths greater than about 800 m. This criterion, in general terms, rules out the easternmost third of Spain, in addition to the Canary Islands, for geological storage. This leaves four large sedimentary basins (Duero-Almazán, Ebro, Tajo and Guadalquivir) as well as in some areas of the Iberian Range, the Basque-Cantabrian Range, the Betic Range and Campo de Gibraltar. Formations suitable for storing CO_2 were identified in each of these areas based on very limited geological knowledge. Areas where the formations were at depths greater than 800 metres were delimited, and pore volumes and storage efficiency factors were calculated.

The IGME has also participated in other European projects on CO_2 storage, such as COMET and CGS-Europe, as well as in national projects such as CENIT CO_2, INNSONDA and ALGECO$_2$

[52] https://www.cores.es/es

(García Lobón et al., 2010) (Arenillas et al., 2014). ALGECO$_2$ built on previous projects and to date is the most complete CO_2 storage potential assessment carried out in Spain.

Currently, there are no specific research programmes for identifying new potential CO_2 geological storage sites in Spain. Research into CO_2 storage is usually carried out through European projects within the H2020 programme and private industry initiatives. The ENOS project was an initiative of CO$_2$GeoNet in which the IGME participated in collaboration with CIUDEN as the Spanish partners. The SENSE project (2020 – 2022) researched the use of ground motion to understand pressure changes within the reservoir, a technique which can be applied at CO_2 storage sites. The STRATEGY (2024 – 2020) and follow-on Pilot STRATEGY (2021 – 2016) projects are advancing CO_2 storage assessments in Spain using previously identified sites. In Spain, all these studies have only considered saline aquifer storage.

In the Hystories traps database, 56% of the potential stores are in sandstones and 43% in carbonate rocks. It is worth noting that traps have not been identified in all storage units; 17 units do not have defined traps. The updated Hystories database includes 40 Formations (1,263,582 km^2), 95 Storage Units (78,381 km^2) and 85 Traps (10,198 km^2).

Currently, there is insufficient data to evaluate storage potential of depleted hydrocarbon fields or offshore saline aquifers, so the number of potential storages sites may be larger than reported here. In Table 43, the current strategic gas stores that could be possible hydrogen stores in the future have been incorporated into the database. The location of all these potential stores is shown in Figure 74 and a frequency chart is presented in Figure 75.

To advance these potential storage sites, specific studies would be required to provide missing data that would confirm these sites all meet the requirements for hydrogen storage.

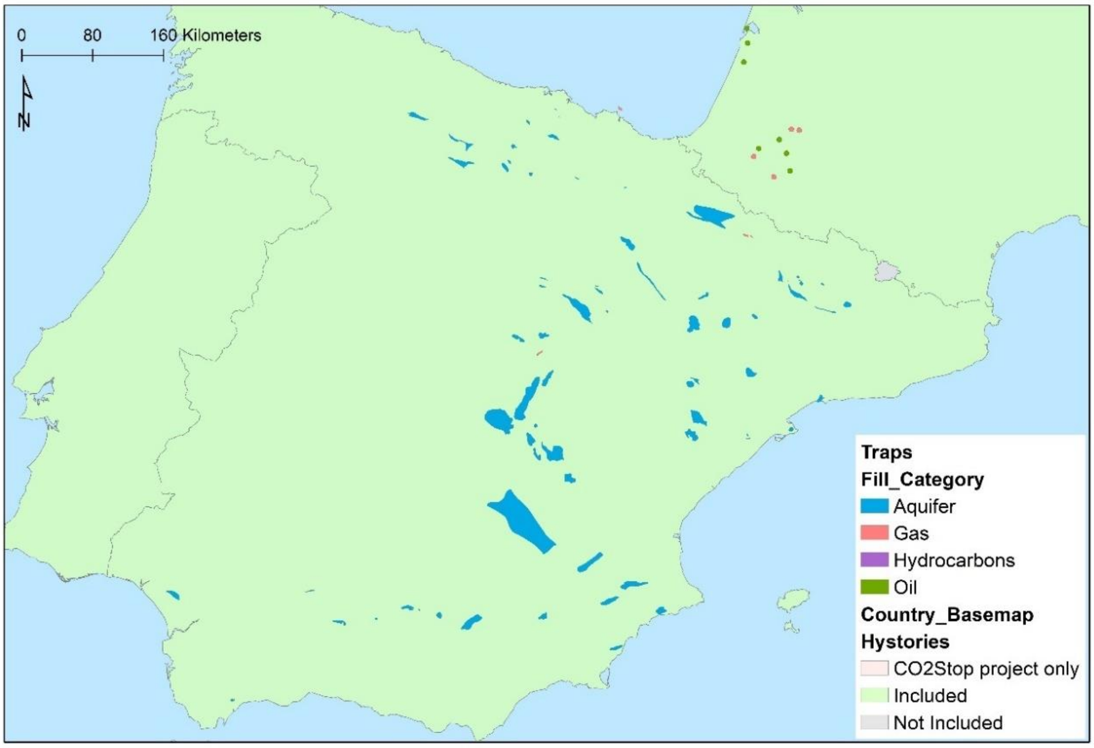


Figure 74: Overview of identified potential traps in the Hystories database within Spain.

Table 43: Summary of identified storage traps *and development actions*

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore aquifers	85	Previous assessment based on legacy data	Further assessment required
Onshore gas storage	3	Natural gas storage in saline aquifers and depleted gas field	
Offshore gas storage	1	Natural gas storage in depleted gas field	

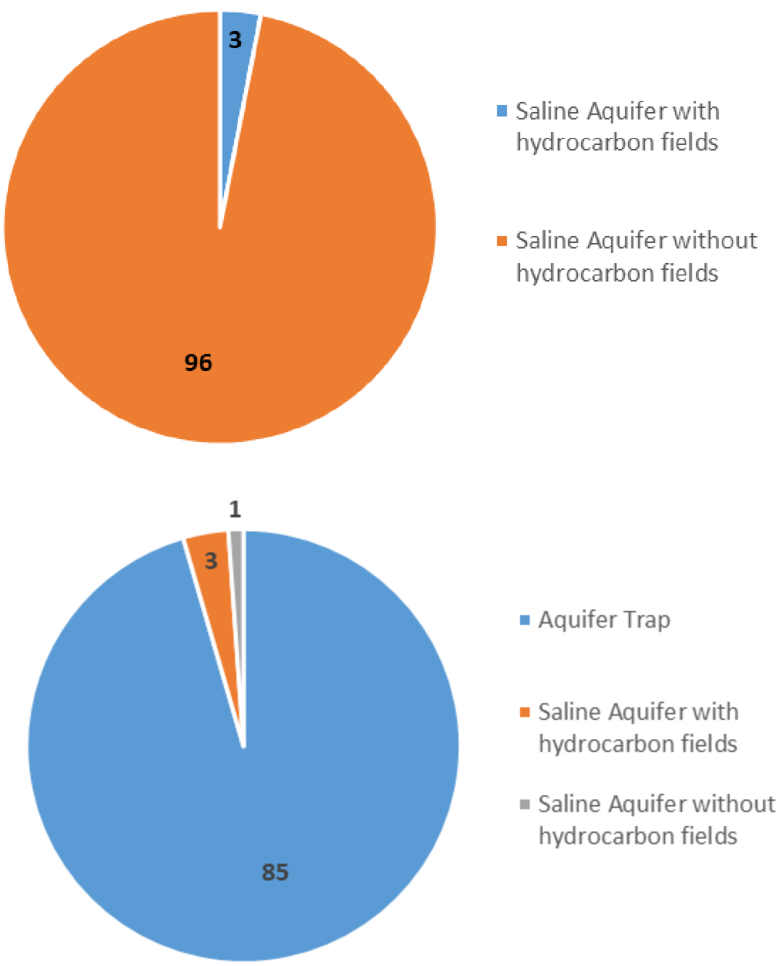


Figure 75: Frequency pie chart showing categories of identified potential storage opportunities in Spain; number of units (upper figure) and traps (lower figure) for onshore saline aquifers and hydrocarbon fields

22.2.3. Existing storage sites

Three gas stores have been included in the Hystories database that are currently in operation. All are owned by ENAGAS. The operational licence for these stores is valid until 2037. Two of the natural gas stores are depleted gas fields, offshore (Gaviota) and onshore (Serrablo). The third store is in a saline aquifer structure (Yela) that was not included in previous project results. Successful storage in this structure supports the idea that there may be unidentified storage potential in saline aquifers. Assessment of this potential and identification of more saline aquifer storage traps would require new data acquisition campaigns.

There are two additional gas storage sites in the Guadalquivir basin (former gas fields), but no public information is available. Another gas store using a depleted oil field (Castor) is in the Mediterranean Sea. The latter site is being abandoned owing to issues with induced seismicity.

22.2.4. Potential future development opportunities

Given the large number of stores already identified during Hystories and previous projects, it seems very likely there is additional potential for UHS that has not yet been identified. For example, favourable stores could probably be found offshore, but no national screening studies have been carried out yet. The ALGECO$_2$ project did study the most promising offshore areas for CO_2 storage, but this information is not public. Most the detailed data (e.g. seismic data) is held by private companies and not available in the public domain. If these detailed data could be accessed, additional storage assessments could be carried out.

Of the total number of depleted fields (six gas, nine oil and two oil and gas reservoirs) only a few have been reused as natural gas storage. There is the possibility these reservoirs could be reused for energy storage. There are evaluation projects currently underway such as the assessment the storage opportunity for green hydrogen in the Guadalquivir Basin (UNDERGY project Call Misiones-CDTi MIG-20211018).

22.3. Discussion and conclusions

In Spain there is favourable legislation that promotes the transition towards clean and renewable energy sources. Hydrogen plays a very important role in this energy transition. This is clear from the National Integrated Energy and Climate Plan (Plan Nacional Integrado de Energía y Clima 2021-2030, PNIEC) and in the government's Hydrogen Roadmap (Hoja de Ruta del Hidrógeno) (MITERD, 2020). The hydrogen roadmap includes the production of green hydrogen from electrolysers with at least 4 GW of energy by the year 2030, and geological storage for long periods and large volumes.

In addition to European funding, at the national level there are financial instruments for research projects on renewable hydrogen that include industries, groupings of companies and research centres.

Until recently, research in this area has been carried out by public centres. The involvement of private companies is rapidly increasing owing to the need to meet the decarbonisation objectives of the national law on climate change and energy transition (Ley 7/2021 de Cambio Climático y Transición Energética).

There are several geological natural gas storage facilities in operation. Presently, there are no other types of geological storage, although possible CO_2 stores have been investigated by research projects. Given the scarcity of hydrocarbon deposits, the search for storage opportunities in Spain has focused on deep saline aquifers onshore. However, there could be favourable sites in saline aquifers in the offshore. Already depleted oil and gas fields (both on and offshore) could offer storage opportunities.

The existing natural gas distribution infrastructure covers the entire country and could help enable the deployment of a hydrogen distribution network. The network also connects to other countries in Europe and Africa. The transport network is being expanded to increase transport capacity to Europe, and the possibility of reusing the infrastructure for transporting hydrogen is being studied.

23. Turkey; geological assessment of storage opportunities

Türkiye is located in a structurally complex area where the Eurasian and African plates collided during Cretaceous to Eocene times. The Anatolian Plateau is sandwiched between these continents. Southeast Anatolia is on the northernmost edge of the Arabian plate and Black Sea region is situated on the southern part of the Eurasian plate. Owing to this collision, several onshore and offshore geological basins have formed. To date, the Southeast Anatolian Basin, Thrace Basin, Adana Basin and Black Sea Basin have been found to contain hydrocarbons. Deformation occurred during the collision and several structural traps developed. Producing formations in south-east Anatolia mainly comprise carbonates with low porosity, but relatively high permeability owing to their fractured nature. The reservoir rocks in the Thrace Basin mainly comprise sandstones with low permeability. The depleted gas fields in the Thrace Basin and oil reservoirs in south-east Türkiye could have potential for geological storage of hydrogen.

23.1. Data collation and collection

23.1.1. Data availability and collation

As a state company, the Turkish Petroleum company holds the majority of licences and information about the petrophysical and geological properties of the subsurface required to assess possible underground storage sites in Türkiye. These data are held as confidential and are very difficult to access. For the Hystories project, data were collected from publicly available reports and documents. Thanks to a recent study, some of the required data have been made available, including current reservoir pressure, temperature, oil formation volume factor, salinity of brine, and pore volume. This project report, 'Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions Towards Low Carbon Development', was produced by the Consortium of Human Dynamics, Regional Environmental Center (REC) Türkiye and Agriconsulting Europe S.A. (AESA) with the Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change as the main beneficiary. Location coordinates of the units are taken from publications of the General Directorate of Petroleum Affairs. Key data sources for the Türkiye Hystories database are listed in Table 44. The publicly available geological data do not provide enough detail to understand the heterogeneity of the geology of individual traps and sealing capability of the caprocks. More in depth analysis and studies of data obtained during drilling are required to assess potential for geological storage projects. The data collected for Türkiye mainly comes from depleted, or producing oil and gas fields, and natural gas storage projects.

Table 44: List of key data sources for the Türkiye Hystories database

Source name / URL	Description	Version / Date
Project Report 'Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions Towards Low Carbon Development'	Batman, Adıyaman and Thrace Regions Field Data and Calculated CO_2 Storage Capacities	2019
Sahin, S. et al., Design and status of the only underground gas storage project in Turkey after three years of operation, SPE 158074, SPE Russian Oil and Gas Exploration and Production Technical Conference and Exhibition, 16-18 October, 2012. https://onepetro.org/SPERPTC/proceedings/12ROGC/All-12ROGC/SPE-158074-MS/158856?searchresult=1	Kuzey Marmara and Değirmenköy Field Data	2012
Petroleum Activities in 1998, General Directorate of Petroleum Affairs Journal No:42 (in Turkish)	Coordinates of most of the units in Batman, Adıyaman and Thrace Regions	1998
History of Petroleum and Oil Wells Drilled in Turkey, 1995, General Directorate of Petroleum Affairs, (Report in Turkish)	Coordinates of Kuzey Marmara Underground Gas Storage	1995
Petroleum Activities in 1998, General Directorate of Petroleum Affairs Journal No:43 (in Turkish)	Coordinates of Değirmenköy Underground Natural Gas Storage	1998

23.1.2. Availability of detailed data for further site characterisation

Most data, such as geological and petrophysical data and fluid properties, required to estimate the storage capacity and project economics have not yet been released and are held as confidential by the Turkish Petroleum Company. Some older data can be purchased from the archives of the Mining and Petroleum Affairs General Directorate. These older data mainly comprise raw information of drilling reports and production records. More detailed and interpreted data are available from the hydrocarbon field operators.

23.1.3. Identified gaps in data availability

Hydrocarbon reservoirs have been analysed and assessed for the oil and gas resources they contain. Therefore, the caprock integrity, seal properties, permeability, porosity and data concerning fluid flow and pore volume have been acquired by operators but are confidential. The main data gap is the lack of data to enable assessment of the potential for storage in saline aquifers.

23.2. Geological opportunities for hydrogen storage

23.2.1. Geological summary

Geographically, Türkiye has longitudinal mountain ranges, extending along the Black Sea and the Mediterranean shores. In between these ranges, lie the high Anatolian plateaus. Türkiye lay located between the two mega-continents: Gondwana to the south and Laurasia to the north, continental fragments belonging to one of these mega-continents separated from the main body and amalgamated to the next. These two major plates collided during late Cretaceous to Eocene times, and the Anatolian Plateau is sandwiched between these continents. Therefore, geological features of Anatolia, consisting of several oceanic and continental "terranes", were formed. From south to north the Alpine terranes are: the Arabian Plate, the northern edge of the Gondwanan Arabian-Libyan Platform; the SE Anatolian Ophiolite Belt, remnants of the southern branch of Neotethys; the Tauride-Anatolide Composite Terrane, an Alpine microcontinent; North Anatolian Ophiolite Belt, representing the allochthonous oceanic assemblages and subduction-accretion complex of the Neotethyan Izmir-Ankara-Erzincan Ocean; Sakarya Composite Terrane, another Alpine microcontinent; Intra-Pontide Ophiolite Belt, remnants of a small branch of the Izmir-Ankara-Erzincan Ocean; Istanbul-Zonguldak Terrane another composite terrane of continental crust origin and Istranca Unit, a suspect terrane of Laurasian affinity (Goncuoglu, 2010).

Most petroleum production occurs from Palaeozoic and Mesozoic petroleum systems in south-eastern part of Türkiye. Some of the oil is linked to the Palaeozoic, particularly Silurian strata, which contain organic-rich source rock. The majority of the reservoirs are charged by Middle Cretaceous source rocks. Oil is mainly produced from Cretaceous reservoirs, although there are Paleozoic reservoirs as well. Younger source rocks such as Oligocene and Neogene bituminous shales are also present and generate oil. The Black Sea part of Türkiye contains both Mesozoic and Paleozoic source-rocks. Most gas production is from offshore fields in the region. Recent explorations have shown major biogenic gas accumulations in the Sakarya field. Gas and oil have been produced from the Oligocene petroleum systems of the Thrace Basin. Eocene strata are also productive for oil in the Thrace Basin (Derman 2014).

The Tuz Golu (salt lake), located in middle Anatolia in the Aksaray province, has been identified as appropriate for solution mining. Large underground caverns can be produced using this process. Drilling operations and salt dissolution operations are ongoing in the area. The first phase of the project has a 1.2 billion standard cubic metre working methane storage capacity.

In Türkiye, a major methane storage facility is in Thrace Basin, namely Silivri Underground Natural Gas Storage Facility. The project has 3.19 billion Sm^3 storage capacity.

23.2.2. Storage assessments

Data collected for the Hystories project is more extensive than was collected for the ESTMAP project. The new dataset includes information on hydrocarbon fields located in the south-east area and Thrace region of Türkiye. The data includes the majority of the discovered hydrocarbon fields since most fields belong to the national oil company, Turkish Petroleum. There are some private companies that hold oil field data that are not available in the public domain.

For the Turkish database, there is one trap per storage unit, so the shapefiles are the same. Confirming the location and extent of the traps is challenging; some coordinates are available from hydrocarbon field reports, some have been estimated from Google Earth. There were some additional storage units where locations could not be provided, and these were excluded from the database to provide a consistent view between the database and the GIS.

Alongside the mostly still producing oil fields, the traps that are currently used for underground gas storage are included in the Hystories database.

The availability of pressure data and pore volume data will support storage capacity estimation of the traps for the Hystories project. There are also data on salinity, reservoir temperature and ultimate oil recovery for the oil fields. Saline aquifers are not included as there are no publicly available data. Further studies may reveal aquifers with potential for hydrogen storage. Unfortunately, fault and seal information are not available. However, since the reported traps are hydrocarbon fields, there is a proven sealing capacity.

A summary of identified storage opportunities is presented in Table 45, Figure 76 and Figure 77.

Table 45: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	None	No entries available in ESTMAP. Unknown whether potential exists. Information is either not publicly available or the potential has not yet been assessed to a sufficient degree.	Regional geological mapping and assessment of aquifers may reveal further potential for energy storage
Hydrocarbon reservoirs	92	Main reservoir type. Pore volumes are given for calculation of storage capacities. Mostly found in the South-eastern part of Türkiye and still producing, though some major fields are nearly depleted. There are also some oil fields located in the Thrace Basin.	Site specific studies required. Additional data could be added to database with further resources
Underground Natural Gas Storage Fields	2	Located in the Thrace Basin. Depleted gas fields have been operated as UGS for a long time.	Confirm operational UGS capacities and performance. Investigate and assess alternative potential including UHS. Regional exploration may reveal other trap structures.

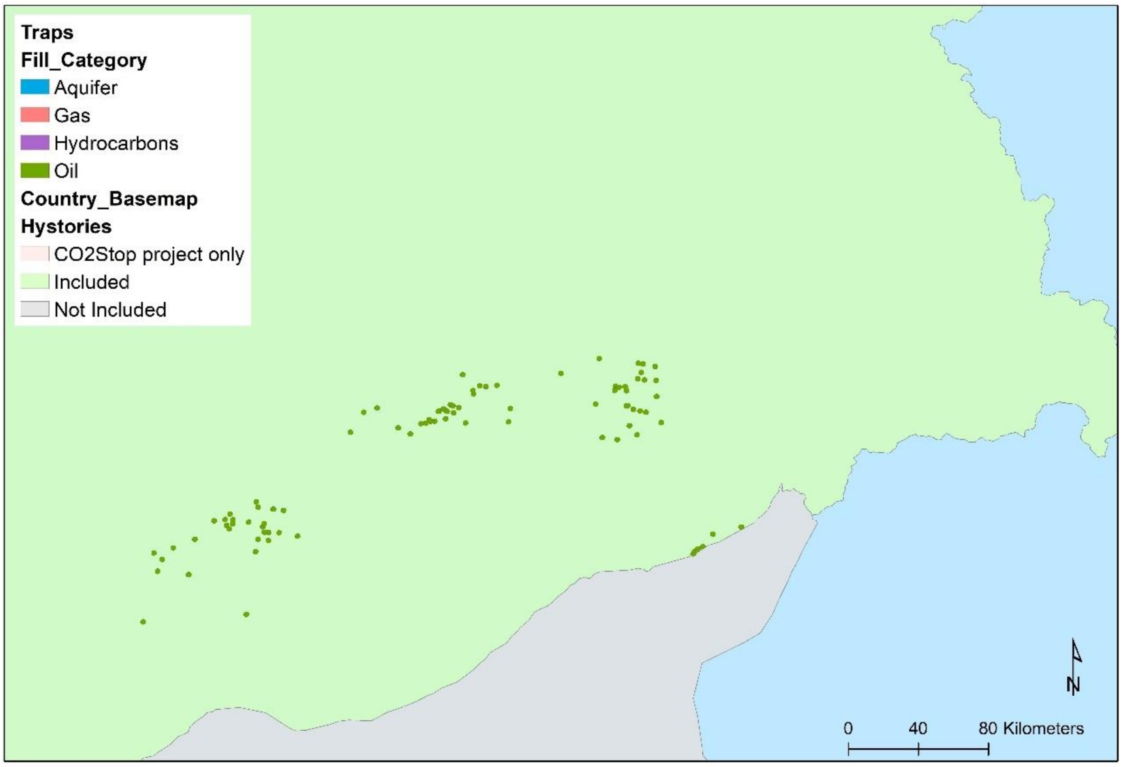


Figure 76: Overview of identified potential traps in the Hystories database within Türkiye (point locations).

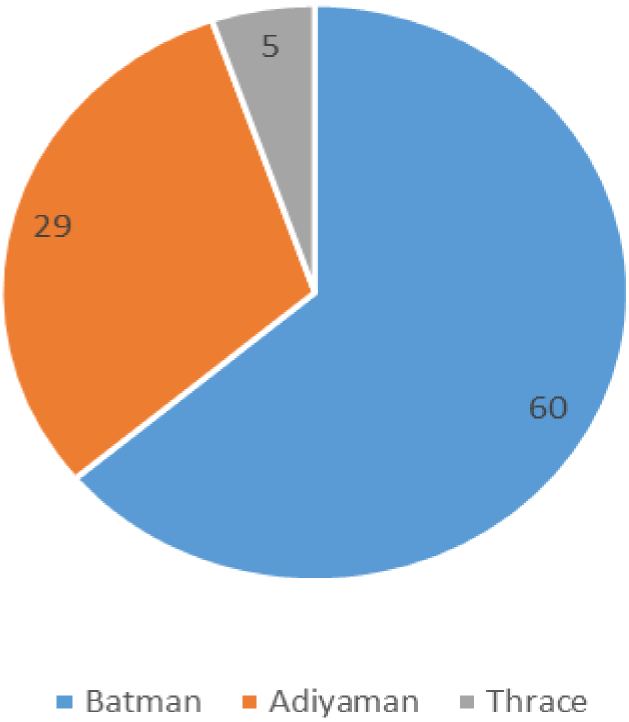


Figure 77: Frequency pie chart showing categories of identified potential storage traps in each geological basin assessed in Türkiye.

23.2.3. Existing storage sites

There are two depleted gas fields included in the Data for Türkiye that are currently in use for underground methane storage. There is a study for the expansion of the Degirmenkoy – Kuzey Marmara fields with new wells and new reservoirs. There is also an ongoing project to construct salt caverns for natural gas storage in central Anatolia.

23.2.4. Potential future development opportunities

The most promising option for hydrogen storage could be the UGS fields as they are close to the most energy intensive regions in Türkiye. Such a change would require a fundamental change in the planned climate change strategies of Türkiye and is very unlikely at least for the time being. Saline aquifers could be a solution if further site-specific work is performed.

23.3. Discussion and conclusions

A significant number of oil fields are present in Türkiye, these could offer potential for geological storage of hydrogen, but further study would be required to assess if the quality of the extracted hydrogen would be sufficient.

Underground natural gas storage is undertaken in two fields and there are plans to expand these projects. A salt cavern construction project is ongoing. These gas storage projects could be converted to hydrogen storage, but this would require a change in the climate policies of Türkiye, and therefore this is unlikely to happen in the near future.

There are insufficient data available to assess the storage potential of saline aquifers. Regional studies including primary data collection are required to assess storage potential.

24. Ukraine; geological assessment of storage opportunities

Ukraine has the largest underground gas storage (UGS) capacity in Europe; about 31 billion cubic metres (BCM). Ukraine leads in Europe in reserves to production ratio, is second in terms of proven natural gas reserves (1.09 trillion cubic metres of natural gas; BP.com, 2019[53]) and fourth in terms of gas production (19.8 BCM in 2021). There are three oil and gas regions in country: East, West and South. The key reserves are concentrated onshore in the Eastern region of Ukraine. Eastern Ukraine is responsible for 90% of national natural gas production.

The decline in production over the last few years suggests that the hydrocarbon fields are becoming depleted. Many fields are around 70 - 90% depleted and some fields are nearing the end of production. One of the promising opportunities for the development of hydrogen storage is the repurposing underground gas storage facilities in Ukraine. Underground Gas Storage (UGS) facilities have been established in depleted gas/gas condensate fields and saline aquifers. The reservoirs have favourable geological and engineering properties, and the overburden has proven effective sealing properties.

24.1.Data collation and collection

24.1.1. Data availability and collation

The ESTMAP database was used as the basis for the database in the Hystories project. During the implementation of the Hystories project, all UGS data indicated in the ESTMAP were checked and updated. In addition, further research was conducted and the Hystories database was supplemented with new formations, storage units and traps comprising depleted fields in Ukraine which can also be considered for hydrogen storage.

All UGS data requested for Hystories project were provided using available scientific publications and reports from the State Research and Development Enterprise ‘GeoInform of Ukraine’ and the fundamental six-volume edition ‘Atlas of Oil and Gas Fields of Ukraine’ (1998—1999), which contains detailed information about all oil and gas-bearing regions of Ukraine, and oil, gas, and condensate fields (Table 46).

These data sources were the main UGS data source used for the Hystories project to identify sites which can be considered for hydrogen storage. The reports include information such as seismic data, wells, cores, and reservoir models for the hydrocarbon fields. The quality of the UGS data can be considered good/excellent, as the traps are confined to the fields of the same name, where detailed site characterisation was carried out.

[53] https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-natural-gas.pdf

Table 46: List of key data sources for the Ukrainian Hystories database

Source name / URL	Description	Version / Date
GeoInform of Ukraine, 2011 Geological and economic assessment of hydrocarbon reserves of the Proletarske oil and gas condensate field (final) (in Ukrainian) Book 1, the text of the report	Scientific publications and reports. Report #63689	2011
GeoInform of Ukraine,1984 The use of field geophysical methods for studying operating wells in order to assess the parameters of reservoirs of gas and gas condensate fields and UGS facilities in Ukraine (in Russian)	Scientific publications and reports Report #47808	1984
GeoInform of Ukraine, 2011 A report on the creation of a permanent geological model of the Solokhivske UGS based on the results of detailed 3D seismic exploration and reinterpretation of well data using modern software complexes (in Ukrainian)	Scientific publications and reports Report #63045	2011
GeoInform of Ukraine, 1978 Results of exploratory drilling in the *Chervonopartyzanska* area and its complex processing (works related to underground gas storage) *(in Russian).*	Report of the Ukrainian thematic group of underground gas storage expedition of deep drilling. Report #40534	1978
GeoInform of Ukraine, 2011 Creation of a permanent operational geological and technological model of the Hlibivske gas field based on the results of detailed high-resolution 3D seismic exploration and reinterpretation of well data in modern software complexes *(in Ukrainian)*	Scientific publications and reports Report #62992	2011
GeoInform of Ukraine, 1987 The use of field geophysical methods for studying operating wells in order to assess the parameters of reservoirs of gas and gas condensate fields and UGS facilities in Ukraine *(in Russian)*.	Scientific publications and reports Report #50794	1987
GeoInform of Ukraine, 1984 The use of field geophysical methods for studying operating wells in order to assess the parameters of reservoirs of gas and gas condensate fields and UGS facilities in Ukraine *(in Russian)*.	Scientific publications and reports Report #47808	1984
GeoInform of Ukraine, 1981 The use of field geophysical methods for studying operating wells in order to assess the parameters of reservoirs of gas and gas condensate fields and UGS facilities in Ukraine *(in Russian)*.	Scientific publications and reports Report #43797	1981
GeoInform of Ukraine, 1986 Report #49389 Analysis, comparison and generalization of the results of exploratory and appraisal and operational drilling for the purpose of geological justification for the placement of wells in the areas of the Ukrburgaz association: Khrestyshchenska, Proletarska area for 1987-1988" (in Russian).	Scientific publications and reports	1986
GeoInform of Ukraine, 1965 Analysis of pilot injection and technological scheme of industrial gas injection into the Bat-Bayosian reservoir of the *Olyshivske* structure *(in Russian)*.	Scientific publications and reports Report #25349	1965

These data were supplemented with information from analysis more than 50 published research publications, papers and open data from energy company websites.

Data for some traps were limited; information on areal extent, reservoir pressure and temperature, sulphate and iron content in the reservoir and seal, fault density and fault compartmentalisation were rarely available. All additional information has been added to the 'Remark' field.

24.1.2. Availability of detailed data for further site characterisation

GeoInform of Ukraine[54], which is part of the Ukrainian Geological Survey (State Geologic and Subsoil Survey of Ukraine[55]) collects, stores and makes available information generated in the process of geological study and subsoil use, including data from seismic exploration and geological core research.

More than 175,000 geological reports with data on more than 20,000 mineral deposits are stored in the archives of GeoInform of Ukraine. In 2021, GeoInform created the National Geological Data Portal[56], which offers free access to all the databases and registries to enable use of the subsurface. This interactive map currently contains data from 6000 sites. To date, 15,000 reports have been scanned, and the database is still being populated.

The subsidiary of Ukrainian Geological Survey – National Joint Stock Company (NJSC) 'Nadra of Ukraine' – south-east ('Ukrnaukageocenter'[57]) stores primary geological information on oil and gas wells that are state and private property. The capacity of the operating core store of south-east 'Ukrnaukageocentr' is calculated at 117 thousand linear metres of core. There are 17,753 boxes of oil and gas core and 743 boxes of coal exploration well cores in storage. Commercial information on gas and oil fields and underground gas storage sites is available from companies such as Ukrtransgaz, Ukrgazvydobuvannya and Ukrnafta.

24.1.3. Identified gaps in data availability

According to the declaration on state of war in Ukraine, dated 24 February 2022, and to remove the threat to national security, access to public registers and databases has been temporarily suspended. The issue of ensuring the functioning of information and communication systems, electronic communication systems, public electronic registers in martial law is regulated by the Resolution of the Cabinet of Ministers of Ukraine of 12 March 2022, No. 263.

[54] https://geoinf.kiev.ua/wp/index.html

[55] https://www.geo.gov.ua/en/main/

[56] https://nadra.gov.ua/

[57] https://ukrnaukageocenter.com/

Given this fact, there are gaps in the database on the reservoir fluids, the density of faults and fault continuity. The coordinates of some depleted fields and their GIS map data are also missing. Data on underground gas storage sites are fully provided.

Most of the hydrocarbon fields have been investigated in detail by means of seismic data acquisition, well interpretation and core testing. Further work will be required to analyse hazardous factors and risks, as well as to investigate the effects of both the gas-hydrogen mixture and pure hydrogen on the porous reservoir media.

24.2. Geological opportunities for hydrogen storage

24.2.1. Geological summary

Onshore Ukraine includes three main oil and gas bearing basins in the western (Pre-Carpathian Depression), eastern (Dniprovsko-Donetska Depression) and southern (Prychornomorska Depression) regions. Existing underground gas storage facilities and depleted oil and gas fields are present in these basins and can be considered as potential hydrogen storage sites. Hydrocarbon reservoirs are most commonly found in Precambrian, Palaeozoic (especially coal-period), Mesozoic (Including the Cretaceous period) and particularly Cenozoic strata.

The age of reservoir rocks which are currently being produced, ranges from Precambrian to Neogene. The reservoirs are represented mainly by sandstones that were formed in coastal-sea, continental alluvial, fluvial, deltaic and lagoon-bay conditions. Owing to the variety of conditions under which the sedimentary rocks were formed, the reservoir properties of layers can vary widely between different fields.

Geological storage formations comprise mainly sandstones of Carboniferous to Neogene age. Traps of existing UGS are of Triassic to Neogene age. The UGS sites with good reservoir properties, that could be converted to hydrogen storage sites, are of Cretaceous - Paleogene and Neogene age. Depleted gas reservoirs are mainly of Carboniferous and Permian age. Neogene reservoirs (Molasses Formation) host the largest UGS capacity and are found in western Ukraine. By composition, these are sandy-clay deposits; interlayers of sandstones, claystones/argillites, and siltstones. Thus, the Molasses Formation offers both seals and reservoirs. In general, trap seals comprise argillites, anhydrites, and salts. For Permian reservoirs, the main seal is the Permian sulphate-halogen strata, which comprises rock salt with layers of anhydrites, salt-rich siltstones, clays, and sandstones, as well as potassium and magnesium salts. The presence of reservoirs and caprocks with good sealing properties ensured the accumulation of large amounts of hydrocarbons in Ukraine over geological time.

The first historically confirmed mentions of oil production appeared as early as the 14th century in the territory of western Ukraine: In 1810 - 1817, oil production began on an industrial scale in the Boryslav city in western Ukraine. The beginning of large-scale production and use of natural gas in Ukraine is related to the discovery of the Dashavske gas field in 1920 in western Ukraine. During 1936, the first oil fields were discovered in the eastern region, after which exploratory drilling became more active. In the southern region, the first oil was extracted from mine wells near the Kostyrin village, in Crimea during 1864. Active drilling operations in Crimea began in 1933. The offshore study of the Black Sea shelf was conducted from 1970 to 1990.

24.2.2. Storage assessments

Ukraine has a developed network of UGS facilities with a capacity of more than 30 bcm, located in the western, central, eastern and southern regions.

The significant capacities of existing onshore UGS sites, established on the sites of depleted gas/gas condensate fields and saline aquifers, make it possible to consider the UGS system as the main potential sites for hydrogen storage in Ukraine (Table 47, Figure 78, Figure 79). The UGS stores are located at depths ranging from 400 to 2000 m.

In addition, hydrogen storage could also be developed in depleted hydrocarbon reservoirs or salt caverns. In Ukraine, there are no UGS stores in salt caverns, but there are large salts deposits. Thus, the prospect of establishing hydrogen storage facilities in salt can be considered in some regions of Ukraine.

Table 47: Summary of storage capacity options and development actions

Reservoir Type	N.o. in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Aquifers	3	Three saline aquifers are used for UGS. Total active gas volume is 1.81 bcm. There may be scope for storage potential in other aquifers.	Regional geological mapping and assessment of saline aquifers may reveal further potential for hydrogen storage
Gas fields (active and depleted)	22	Exploited from 1950s onwards. Most of them are 73-95% depleted or close to depletion.	Site specific studies required
Oil fields (active and depleted)	7	Exploited from 1861-1930s onwards. Most of them are 95-99% depleted or close to depletion.	Site specific studies required
UGS	16	Traps are used for UGS with a total active gas volume of 29.1 BCM (test studies on hydrogen storage were conducted in one UGS site, the information is not public). The remaining depleted hydrocarbon traps can be considered for hydrogen storage development. It is expected that further investigation would reveal additional potential for hydrogen storage based on generic geological assumptions.	The UGS operating capacities have been confirmed. Site specific studies required. Regional studies and investigations may indicate opportunities and additional capacities for hydrogen storage in depleted hydrocarbon traps.

Currently, many hydrocarbon fields in Ukraine are nearing depletion. Accordingly, the number of depleted fields is increasing. Dozens of 'mothballed' or depleted oil and gas fields are present. Some of these storage traps were added to the Hystories database where data is in the public domain. According to official data, oil and gas reservoirs are depleted by 80 to 90%. However, there is insufficient data currently available to confirm these sites have the potential for hydrogen storage. It is necessary to carry out additional further research to determine the specific fields that could be converted to hydrogen storage sites.

The Ukrainian UGS facilities are connected by a system of gas pipelines and connected to the national gas transmission system. The existing network of gas pipelines could be used to transport hydrogen to neighbouring European countries. The possibility of transporting clean hydrogen and hydrogen mixtures through the existing gas transmission system requires additional research on the mechanical strength (fragility) of pipelines depending on the working pressure and materials.

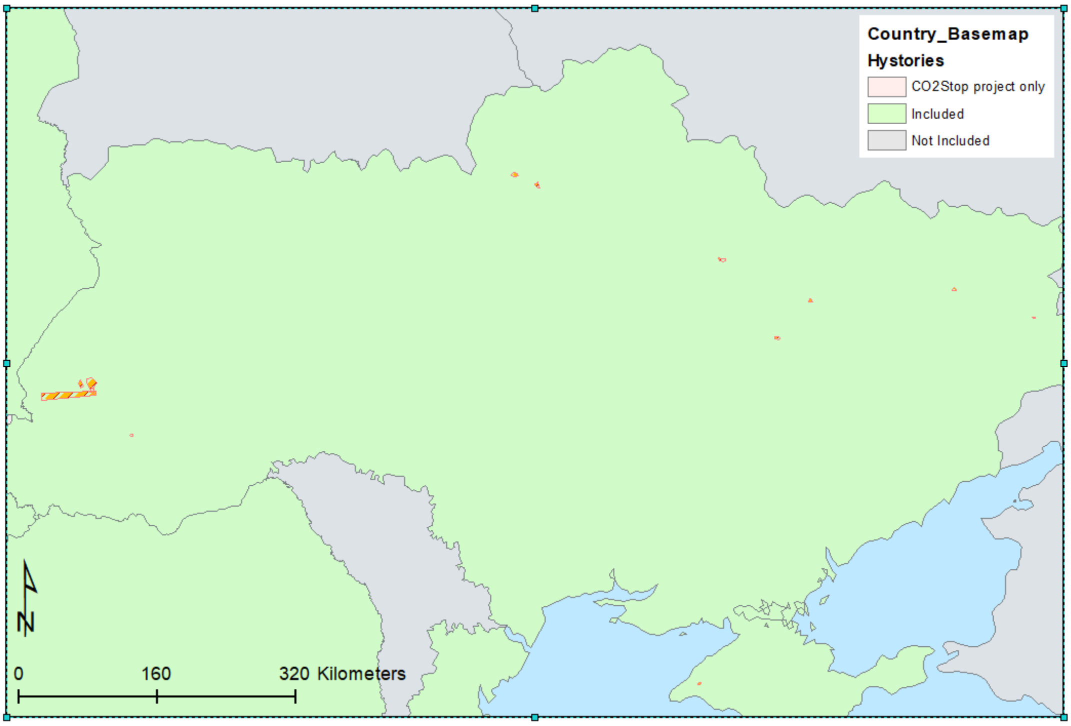


Figure 78: Overview of identified UGS sites in Ukraine that could be converted to UHS

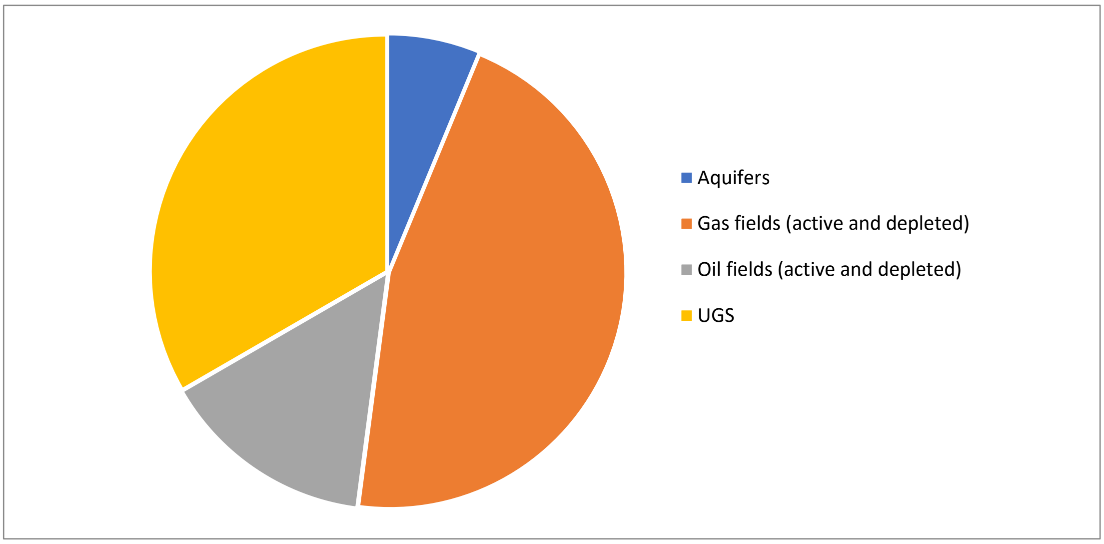


Figure 79: Frequency pie chart showing categories of identified potential storage traps in Ukraine.

24.2.3. Existing storage sites

In total, 13 UGS facilities, with a total capacity of 31.95 bcm, are in Ukraine. Eleven facilities use depleted gas and gas condensate fields, and two use saline aquifers (Table 48). UGS capacity is concentrated in the Western part of Ukraine. All gas storage in Ukraine is divided into four complexes: western; central; eastern; and southern.

The existing UGS facilities are usually used to regulate the unevenness of gas consumption in seasonal periods. Since growth of the hydrogen economy is being observed in Europe, the possibilities of converting UGS sites to hydrogen storage have been studied in Ukraine for the past two years.

The UGS operator, Ukrtransgaz, is researching the possibility of using the Krasnopopivske UGS for storage of hydrogen or a hydrogen-methane mixture (Lugansk region in the east). Within the pilot project, Ukrtransgaz together with the Slovak gas company NAFTA, is examining the technical feasibility of storing hydrogen in the Krasnopopivske UGS site and the impact of hydrogen storage on porous media. Different regimes and volumes of hydrogen in methane are being tested to determine the maximum allowable concentration of hydrogen such that a global reconstruction of equipment is unnecessary. Compressors, shut-off valves, and pipelines are being tested.

More research is needed at current potential UGS sites to examine technical aspects of storing hydrogen.

Table 48: UGS facilities in Ukraine.

#	UGS name	Year	Design indicators of storage capacity, million cubic metres		Production wells stock	Reservoir type	Complex
			Total gas volume (including buffer)	Active gas volume	Number		
1	Uherske	1969	3 850	1 900	88	Depleted gas field	Western
2	Bilche-Volytske-Uherske	1983	33 450	17 050	341	Depleted gas field	
3	Oparske	1979	4 570	1 920	76	Depleted gas field	
4	Dashavske	1973	5 265	2 150	100	Depleted gas field	
5	Bohorodchanske	1979	3 420	2 300	156	Depleted gas field	
6	Olyshivske	1964	660	310	40	Aquifers	Central
7	Chervonopartyzanske	1968	2 973.8	1 500	67	Aquifers	
8	Solokhivske	1987	2 100	1 300	81	Depleted gas condensate field	
9	Kehychivske	1986	1 300	700	53	Depleted gas condensate field	
10	Proletarske	1986	2 980.3	1000	251	Depleted gas condensate field	Southern
11	Krasnopopivske	1973	800	420	40	Depleted gas field	Eastern
12	Verhunske	1975	951	400	73	Depleted gas condensate field	
13	Hlibivske		-	-	-	Depleted gas condensate field	Southern
	Totals		**62 320,1**	**30 950**	**1 366**		

24.2.4. Potential future development opportunities

In Europe, there is some interest in converting UGS sites, including porous media stores, for hydrogen storage sites. There are 13 such UGS facilities in operation in Ukraine, which can be considered as potential hydrogen storage facilities. Depleted hydrocarbon traps are confined to Palaeozoic (Carboniferous, Permian), Mesozoic (Triassic, Jurassic, Cretaceous) and Cenozoic (Paleogene, Neogene) strata.

The UGS facilities of the western region of Ukraine (five facilities) are confined to the Bilche-Volytska zone of the Pre-Carpathian Depression. These facilities could play a key role in hydrogen storage since the western complex is the largest UGS complex in Ukraine, with a total active gas volume of 25.32 billion cubic metres. The main oil and gas-bearing reservoirs belong to Cretaceous (K2-P) geosynclinal and Neogene orogenic geological complexes.

Gas deposits belong mainly to molasse formations of Miocene age (Sarmatian, N1srv and Badenian, N1lan) These are sandy-clay sediments (interlayering of sandstones, clays, and siltstones), so they are simultaneously seals and reservoirs. Sandstones are grey with a greenish and brownish tint, fine- and medium-grained, porous, quartz-dominated, glauconitic, weakly cemented with carbonate and carbonate-clay cement. Siltstones are grey or dark grey with a greenish or brownish tint, and quartz-dominated.

In the Helvetian-Senonian (N1bur-K2) reservoir, one of the world's largest underground gas storage facilities (Bilche-Volytsko-Uherske) has been created. The Senonian (K2) reservoirs comprise sandstones with layers of siltstones, calcareous argillites, marls and pelitomorphic limestones, and they are characterised by sharp changes in lithofacies. The sandstones are overlain by a reliable caprock of Badenian (N1lan) strata which comprises a gypsum-anhydrite horizon.

The UGS reservoirs of Ukraine have good reservoir properties: sandstones and siltstones with porosity of 7 to 27%, permeability 3 to 1283 mD. The strata offer potential stores with layer thicknesses, ranging from 8 to 187 m. Depths range from 580 to 1210. All these characteristics offer favourable conditions for underground hydrogen storage.

UGS facilities of Ukraine are connected to the gas transport systems of neighbouring countries, which in the future may facilitate the export of hydrogen through gas pipelines to the EU.

Within the three main geological basins, there are dozens of depleted gas and oil fields, the reservoirs of which are confined to the oil and gas-bearing strata of Carboniferous, Permian, and Mesozoic age. Traps of such fields are on average at depths of 1000 to 4000 m. The reservoir rock comprises sandstone with an average porosity of 15 to 20%. There are many small, mothballed fields that are not used for commercial purposes.

24.3. Discussion and conclusions

As use and production of hydrogen expands, the need to identify large UHS volumes becomes increasingly urgent. In the Hystories project, a database was populated with the data on the operating UGS facilities in Ukraine, and some depleted hydrocarbon traps that could potentially offer storage capacity. Hydrogen storage is an integral component of the production chain. Fluctuations in consumption and production must be compensated for by temporary storage. Today, Ukraine is considering two options for storing hydrogen.

The first option relates to the use of existing UGS capacities, which use saline aquifers and depleted gas/gas condensate fields and have a total active capacity of 30.95 billion cubic metres (bcm). The western UGS complex is considered a promising region. In recent years, Ukraine has used up to 60% of total underground gas storage capacity for its own needs (approximately 15 bcm of active gas), which confirms the presence of a significant reserve of active underground storage capacity of about 8 to 15 bcm which could be used to store fluids for external markets, including for storing hydrogen.

In assessing the possibility for hydrogen storage by repurposing UGS facilities, it is necessary to first resolve several considerations. In particular, to determine the link to geographical corridors, understand industrial safety, conduct an analysis of risks and mitigations, analysis of the basic legal framework, determine organisational and technical measures, conduct research on the influence of the gas-hydrogen mixture and pure hydrogen on both the porous reservoir and on the existing infrastructure. At the second stage Then, it is necessary to conduct experimental studies to gain practical experience. Additional research is needed to identify storage facilities and implement pilot projects for underground hydrogen storage.

The second option to store hydrogen is to build new infrastructure. European experience shows that hydrogen can be stored in salt caverns. In Ukraine, there are currently no gas storage facilities in salt caverns, but there are large salt deposits in some regions, in which it is promising to develop hydrogen storage facilities.

Studies have shown that technological support is one of the main problems in the future strategic use of hydrogen: Hydrogen can be transported not in its pure form, as this can quickly damage pipelines, but instead mixed with natural gas. Hydrogen concentration up to 10 to 20% by volume is considered acceptable.

The existing network of gas pipelines in Ukraine may be used for hydrogen transportation. These comprise main gas trunklines, gas pipelines-branches, gas distribution stations, compressor stations, underground gas storage facilities, gas metering stations and gas consumption measuring points. Diameters of main gas pipelines vary from 500 to 1400 mm, operating pressures range from 40 to 50 atm.

In Ukraine, the volume of natural gas pumped by pipelines is 30 to 35 bcm per year, so the capacity of this segment of the economy may be 6 to 7 bcm of hydrogen per year, as a methane-hydrogen mixture.

The most significant obstacle to the development of hydrogen energy in Ukraine is the critical condition of storage and gas transport infrastructure. Thus, even the pilot projects for the storage and transportation of hydrogen as an energy carrier are impossible without a "global" redesign of the existing infrastructure.

25. The United Kingdom; geological assessment of storage opportunities

The UK has significant oil and gas resources which offer numerous proven traps, both in depleted fields, and in fields that are nearing the end of production. In addition, the wealth of trapped buoyant hydrocarbons indicates the presence of seals that can trap buoyant fluids for geological timescales, including in saline aquifers. Most of the UK hydrocarbon resources lie offshore, and significant infrastructure has been developed since the 1930s to exploit this opportunity. A few small oil and gas fields are present onshore and may offer early opportunities for development of hydrogen storage. In the onshore UK there are two natural gas stores in porous media.

25.1.Data availability and gaps

25.1.1. Data availability and collation

The UK CO_2StoP database comprised a long list of hydrocarbon fields that could be considered for geological storage of CO_2. During the Hystories project, the BGS team checked, and updated data collated during the CO_2StoP and ESTMAP projects. New data added for the Hystories project mainly comprised onshore hydrocarbon fields, new hydrocarbon field data that had been published since CO_2StoP, and fields that had been excluded from the CO_2StoP database that are too shallow for commercial CO_2 storage (i.e. above 800 m) but could be considered for hydrogen storage.

The Geological Society of London has published three volumes on UK hydrocarbon fields that offer an excellent overview of resources. These memoirs were the main data source used for the Hystories project. Data from these memoirs were supplemented with information from additional published papers and energy company/energy publication websites. In addition, the UK North Sea Transition Authority (NSTA) provides information on UK oil and gas production and well stratigraphy via their website. Data on onshore oil and gas fields is also provided in the BGS directory of mines and quarries[58]. Shapefiles showing the field outlines are available to download from the NSTA website[59]. A list of the main information sources used in provided in Table 49. Data sources used for each potential storage site are listed in the database.

In the three Geological society of London Memoirs included in Table 49, information on individual fields is provided. The amount of available detailed data varies, but usually the memoirs include information on and some examples of seismic data, wells, cores, and reservoir models for fields, including images of the same.

[58] https://www2.bgs.ac.uk/mineralsuk/mines/dmq.html

[59] https://ndr.nstauthority.co.uk/

Some interpretation and interpolation of results was required where limited data were available. For example, reservoir pressure data and data on seal thickness were often not fully available and assessments had to be made based on limited data. The 'comment' field in the database was used in the Hystories database to highlight such uncertainties.

Table 49: List of key data sources for the UK Hystories database

Source name / URL	Description	Version / Date
Geological Society of London, Memoir 14. United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume https://doi.org/10.1144/GSL.MEM.1991.014.01.69	Reporting of oil and gas reserves UK	1991
Geological Society of London, Memoir 20. United Kingdom Oil and Gas Fields Commemorative Millennium Volume https://doi.org/10.1144/GSL.MEM.2003.020.01.01	Reporting of oil and gas reserves UK	2015
Geological Society of London, Memoir 50. United Kingdom Oil and Gas Fields: 50th Anniversary Commemorative Volume https://doi.org/10.1144/M52	Reporting of oil and gas reserves UK	2013
North Sea Transition Authority website. https://www.nstauthority.co.uk/data-centre/data-downloads-and-publications/well-data/ https://www.nstauthority.co.uk/data-centre/data-downloads-and-publications/field-data/	UK oil and gas reporting data. Well data (includes stratigraphy for some wells)	2021 (website is regularly updated)
North Sea Transition Authority website. https://ndr.nstauthority.co.uk/ https://opendata-nstauthority.hub.arcgis.com/documents/-nsta-offshore-zipped-shapefiles-wgs84/about https://opendata-nstauthority.hub.arcgis.com/documents/NSTAUTHORITY::-nsta-onshore-zipped-shapefiles-bng/about	UK oil and gas reporting data. Shapefiles for on and offshore oil and gas fields, wells etc. Equity shares and the owner and operator of each field is listed on the NSTA website.	2021 (website is regularly updated)
BGS Directory of Mines and Quarries https://www2.bgs.ac.uk/mineralsuk/mines/dmq.html	Information on which onshore oil and gas fields are still producing	2020 (publication is refreshed periodically)

25.1.2. Availability of detailed data for further site characterisation

For the UK, onshore seismic data can be viewed and purchased from Lynx-UKOGL[60]. Legacy offshore seismic data are available from the NSTA[61] and scans of legacy seismic data are also available via the BGS[62]. And The NSTA website includes maps of exploration data which show where seismic data have been acquired. BGS operates the UK national geological repository[63] which contains well cores, access for viewing and sampling can be arranged for many wells.

25.1.3. Identified gaps in data availability

As most publications are focused on hydrocarbon resources, data on the reservoir is more easily available than data on overlying seals.

The CO_2Stored database contains information potential storage sites (saline aquifers and hydrocarbon fields) which was prepared through seismic and well interpretation and reservoir modelling. These stores can be viewed through the online CO_2Stored portal and added as a Web Map Service to a GIS. However, these data cannot be downloaded and added into the Hystories GIS as BGS wants to maintain integrity of the database and avoid multiple versions creating that could create uncertainty.

A wealth of data is available for the offshore and onshore UK from decades of oil and gas exploration. Further work would be needed to undertake site-specific investigations to develop potential hydrogen storage sites.

25.2. Geological opportunities for hydrogen storage

25.2.1. Geological summary

The UK offshore comprises large sedimentary basins with hundreds of metres of potential storage formations. "The petroliferous sedimentary basins of the UK Continental Shelf are remarkable for the diversity of their reservoir strata. Reservoir rocks in fields currently in production range in age from Devonian to earliest Eocene, but significant hydrocarbon discoveries have also been made in rocks as young as the mid-Eocene. The reservoirs are

[60] https://ukogl.org.uk/

[61] https://www.nstauthority.co.uk/data-centre/access-to-information-and-samples/

[62] https://www.data.gov.uk/dataset/cb7c667b-25e2-401c-8260-ac8168946235/marine-geophysical-and-seismic-data-from-around-the-uk-1966-onwards

[63] https://www.bgs.ac.uk/geological-data/national-geological-repository/borehole-core-collections/

predominantly siliciclastic rocks, with facies ranging from continental fluvial and aeolian, to marine gravity flow deposits from sub-wave base environments." (Brown, 1991)

Geological storage formations mainly comprise sandstones of Permian to Jurassic age. Sandstones of Devonian to Carboniferous and Cretaceous to Paleogene age are also significant. A few carbonate traps have been identified. Seals comprise thick mudstones and claystones. Triassic evaporite sequences also offer an important seal. The ability of these seals to contain buoyant fluids for geological timescales is proven by the presence of a wealth of hydrocarbon accumulations.

Onshore hydrocarbon exploration in the UK started during the 1840s where oil shale was used for chemical products. Gas was discovered and used for street lighting from 1896 onwards. The Kimmeridge Bay oil field was discovered in 1959 and has been onstream since 1960, this heralded the start of the modern UK oil and gas industry (UKOG, 2022 and UKOOG, 2022).

Offshore gas production began in 1967 with the West Sole field in the Southern North Sea. Offshore oil production began with the Argyll field in the Central North Sea during 1975. During the 1960s and 1970s production was dominated by a small number of very large fields, such as Inde, Leman, Forties, Brent, Ninian and Piper. At the same time, a number of key offshore pipelines were developed (UKEITI, 2022).

25.2.2. Storage assessments

Offshore, the national drive for an overview of CO_2 storage potential has resulted in the CO_2Stored storage atlas which highlights many opportunities. A significant amount of geological storage capacity for CO_2 has been identified and is presented in the national CO_2Stored database. CO_2 storage is mainly expected to take place in saline aquifers in the UK offshore where sufficient capacity is available to safely store many decades' worth of emissions. The Hystories project provides an updated assessment for offshore storage in hydrocarbon fields utilising data that was not available at the time of previous assessments. The majority of storage potential has been identified offshore between the CO_2Stored and Hystories databases.

In the offshore, some regions predominantly contain accumulations of gas; the Southern North Sea, Central North Sea and Irish Sea regions. These regions could be considered for development for hydrogen storage. In the offshore Northern North Sea, oil and condensate dominate. The location of identified potential offshore traps are shown in Figure 80.

The offshore Southern North Sea and Irish Sea both contain gas fields that are within a few tens of kilometres of the shore. Pipelines to connect these assets to the onshore are in place. Offshore hydrogen storage could be considered.

Onshore, the Hystories database identifies storage potential in hydrocarbon fields. Saline aquifer potential has not been investigated as this would require additional resources for interpretation of seismic and well data to identify traps. Onshore hydrocarbon fields are usually quite small, but infrastructure/access costs would be lower compared with offshore sites. Data for some onshore fields was not available for the Hystories project since field exploration started some decades ago and the data for active fields is more easily accessible than for depleted fields. Evans (2007) considered areas where onshore natural gas storage could develop in the UK and highlighted gas provinces in northern England as one of the prospective areas. A research project sought small-scale saline aquifer onshore CO_2 storage opportunities by assessing two regions; Smith et al., 2011, East Midlands (England) and Firth of Forth (Scotland). However, a national interpretation of UK onshore seismic and well data has not been undertaken to identify specific sites for hydrogen storage. The location of identified potential onshore traps included in the Hystories database are shown in Figure 81.

A summary of onshore and offshore traps in the UK Hystories database are presented in Table 50, Figure 81amd Figure 82.

Table 50: Summary of storage capacity options and development actions

Reservoir Type	N.o. traps in Hystories database	Status description, remarks	Recommended actions maturing and extending future potential
Onshore gas fields	11	Exploited from 1960s onwards. Mostly small. Many already depleted.	Site specific studies required and additional well data. Additional data could be added to database with further resources
Onshore aquifers	-	A few possible locations identified in regional project assessing small-scale CO_2 storage opportunities. High uncertainty noted in the report owing to lack of data	Further assessment required if sufficient storage in onshore gas fields is not available. Regional geological mapping and assessment may reveal further potential
Onshore oil fields	16	Main exploitation from 1960s onwards. Mostly small. Many already depleted.	Site specific studies required if insufficient storage in depleted gas fields and saline aquifers is not available. Additional data could be added to database with further resources
Offshore gas fields	128	Exploited from 1970s onwards. Numerous fields but many are distant from shore and therefore infrastructure costs could be large	Site specific studies required
Offshore condensate fields	14	Exploited from 1970s onwards. Numerous fields but all are distant from shore and therefore infrastructure costs could be large	Site specific studies required. Additional data could be added to database with further resources
Offshore aquifers	-	Many aquifer stores identified but most are far from shore and therefore infrastructure costs could be large	Site specific studies required. Regional studies may indicate opportunities since the main assessment has been for CO_2 storage which has different storage requirements
Offshore oil fields	93	Exploited from 1960s onwards. Numerous fields but many are distant from shore and therefore infrastructure costs could be large	Site specific studies required. Additional data could be added to database with further resources

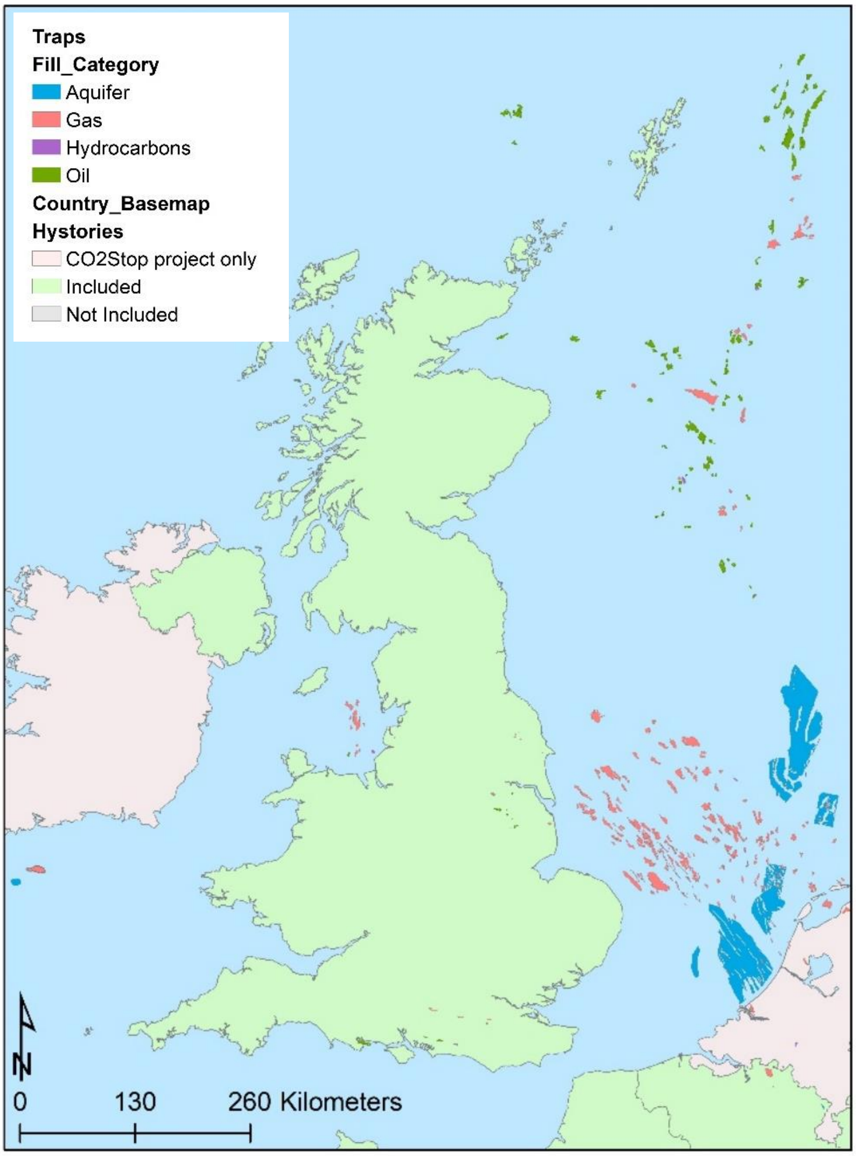
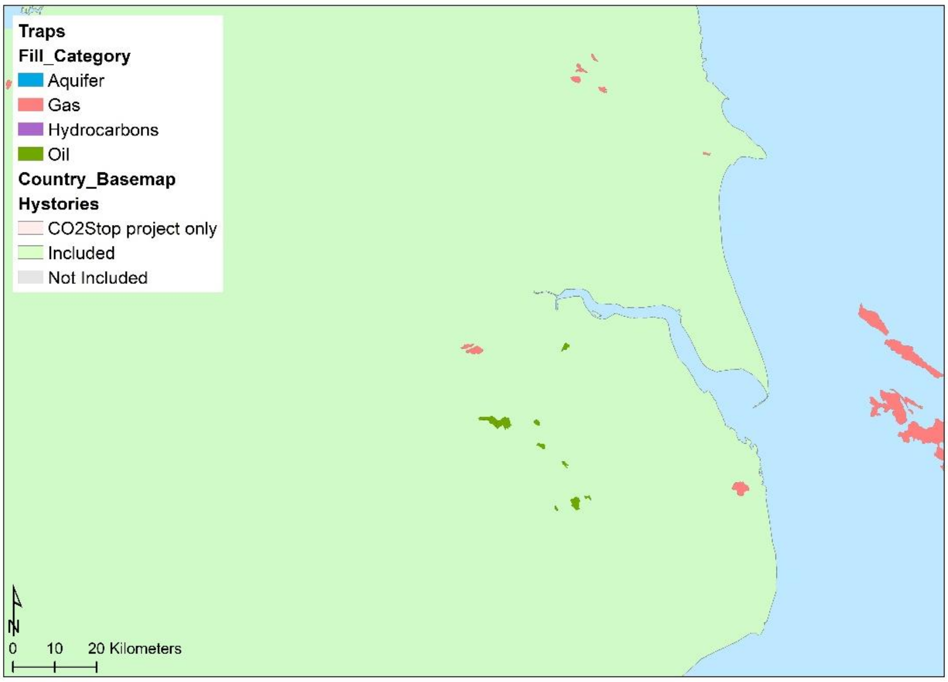


Figure 80: Overview of identified potential traps in the Hystories database within the UK (and surrounding areas)



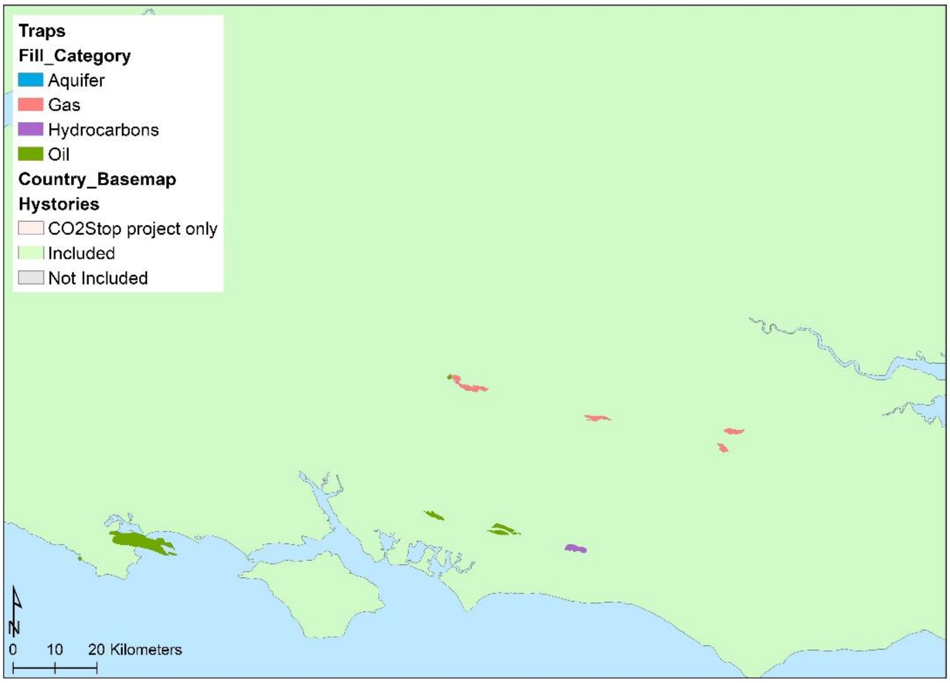
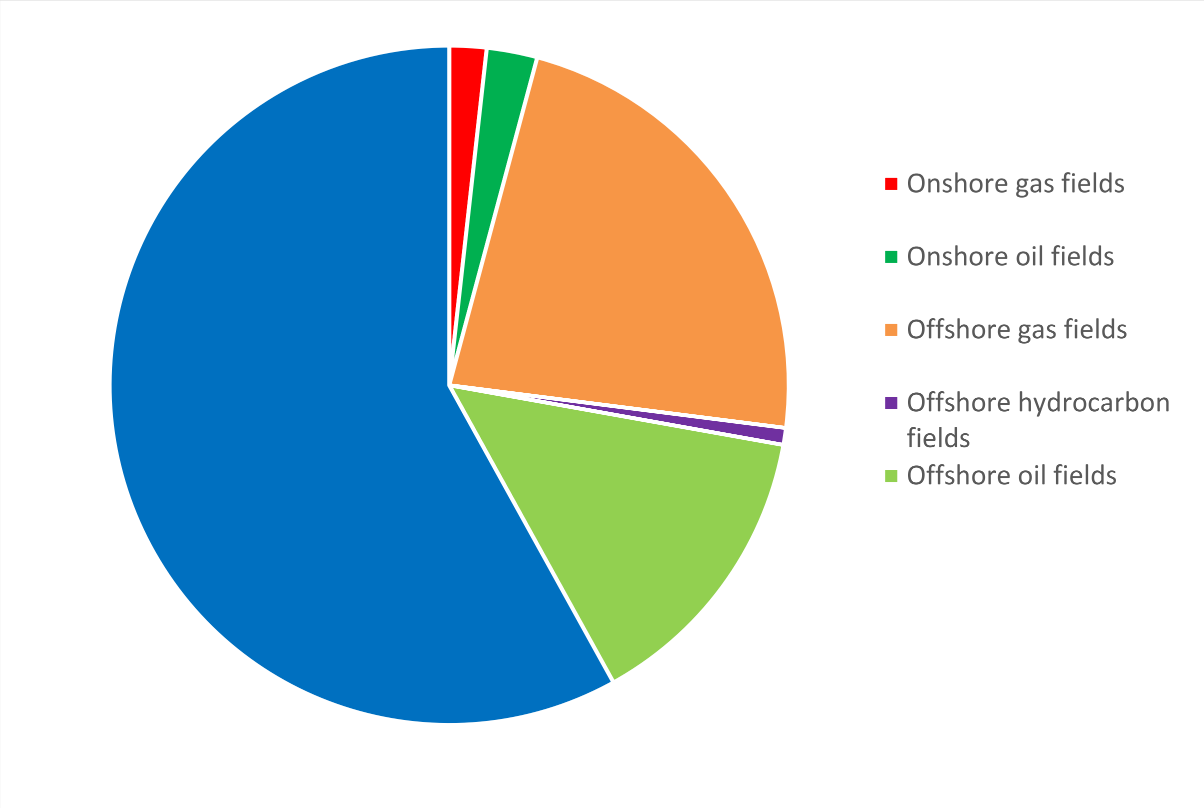


Figure 81: Onshore traps in the UK; north-east England (top) and southern England (lower)



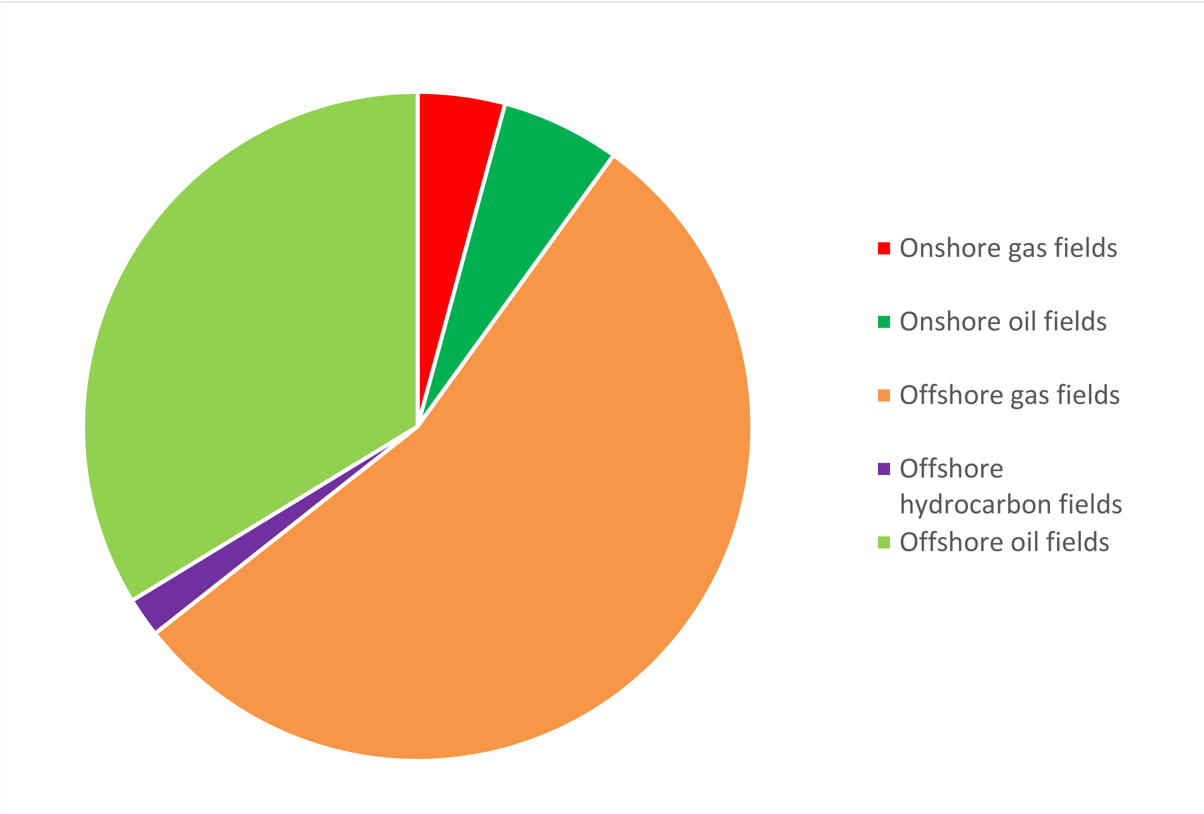


Figure 82: Frequency pie chart showing identified potential storage traps. Top figure includes CO_2 storage saline aquifer traps in the CO_2Stored database. Lower figure shows data in the Hystories database for on and offshore hydrocarbon fields

25.2.3. Existing storage sites

There are two onshore natural gas storage sites in porous media; Hatfield Moors and Humbly Grove (north-east England). Natural gas is also stored onshore in salt caverns in Hornsea (Atwick), Aldbrough, Holford, Hill Top Farm and Stublach (Ofgem, 2022). An offshore natural gas storage site is being considered in the depleted Rough gas field in the Southern North Sea Basin (Centrica, 2022).

There has been hydrogen storage in three caverns in Teesside since 1977. These sites may have been 'mothballed' but official information could not be found to confirm this.

25.2.4. Potential future development opportunities

Legacy data are available to enable identification of potential stores. Further site-specific work would be required to advance the potential storage sites identified during Hystories towards active storage of hydrogen.

In the onshore UK there are a few geological basins/regions where oil and gas resources are found. North-east England in particular has a number of gas fields that could be considered for hydrogen storage.

25.3. Discussion and conclusions

The UK onshore has existing natural gas stores in both salt caverns and porous media. There are onshore near-depleted and depleted gas fields and salt reserves that could be utilised for onshore storage of hydrogen. There may also be onshore opportunities for storage in saline aquifers, but these have not been identified on a national basis though there are some projects that have looked at regions to examine potential for natural gas or CO_2 storage that could be used when looking for hydrogen stores. There are (near-) depleted oil fields onshore which could also be considered.

The UK offshore has a wealth of opportunities for hydrogen storage, though infrastructure costs will be higher. The UK oil and gas industry largely operates offshore, and significant infrastructure has been installed and there may be potential for re-use. An offshore natural gas storage site may be developed through re-use of a large gas field which lies 27 km offshore, suggesting that if needed, offshore hydrogen storage is not completely excluded.

26. Conclusions

Data that is linked to geographical location, also known as geodata, is key in making strategic decisions on the role for the subsurface in meeting energy and climate demands. Having access to data and the knowledge on how to process, manage and manipulate these data will have a wide-ranging impact on the capacity for strategic decision making. Hystories Work Package 1 generated a comprehensive, cross-border, database of potential opportunities for geological storage of hydrogen. The database represents a significant new knowledge deliverable. The purpose of the database is to highlight locations that may be suitable for development for the geological storage of hydrogen, from a geological perspective, across the countries involved in the Hystories study.

Where geological data are available in the public domain, it is possible to identify opportunities where the subsurface could play a role in meeting climate targets. The wealth of data collated during the Hystories project indicates that there is significant potential for geological storage of hydrogen in depleted hydrocarbon fields and saline aquifers across Europe. However, storage opportunities are not evenly distributed and will require varying amounts of effort to realise.

Where the required data are available for assessment, geological traps which could be used to store hydrogen have been identified. The geological traps identified through the Hystories project will require further assessment to confirm their suitability for storage of hydrogen. It is important to note that an absence of identified storage sites does not necessarily mean an absence of opportunity. The Hystories database collates publicly available data, and this means that confidential data that can support assessment of the subsurface were not included.

All countries, except Estonia, were able to identify formations and storage units for potential Hydrogen storage. Sufficient data were available to identify geological traps in 20 of the 22 countries assessed by Hystories. Locations/polygons for some traps were considered confidential so some potential stores are included in the database but not displayed in the GIS.

The Hystories webGIS and desktop GIS contains 311 formations, 581 units and 917 traps collated by the Hystories team. Overall, the final webGIS contains 381 formations, 665 storage units and 1088 traps when CO_2StoP data were added to provide data for countries that were not covered by the Hystories team. Data availability was variable across Europe and for different storage types. Overall, the Hystories database contains 311 formations, 581 storage units and 965 traps (Table 3). With the addition of the CO_2StoP data to infill countries not covered by Hystories participants, the database then contained 386 formations, 665 storage units, and 1136 traps.

Not all potential stores could be included in the GIS since some locations were confidential, therefore the database and GIS have a different number of potential traps.

There was significantly more data available for hydrocarbon fields (with identified, operational or depleted status) compared to saline aquifers, with four countries declaring good public data availability and all other countries indicating at least some public domain data (Figure 15).

Data on saline aquifers was more difficult to access with four countries declaring good public data availability, two countries declaring no or poor data availability, and the remaining countries declaring some public data availability (Figure 16). Detailed data, such as well logs and seismic data, to further assess potential for hydrogen storage are available in several countries (Table 5 – France, Hungary, Italy, Latvia, Lithuania, Norway, Poland, Portugal, Romania, Spain, Ukraine, UK) although sometimes these data have to be purchased, the raw data cannot be published, and in some cases there is an embargo period so that only older data can be accessed. In most countries, the data to carry out further assessments are held confidential, often by the company that owns the hydrocarbon field.

27. Potential future development opportunities and next steps

The database relies on publicly available data. To improve this database, additional resources and data are required. Detailed data, such as well logs and seismic data, to further assess potential for hydrogen storage are available in several countries but are not always free to access or possible to publish in the public domain. There are confidential data that could be purchased and interpreted to enhance the database further. There are also confidential data that have not been released. If access to more data could be secured, then further work could be undertaken. New data could also be acquired in the most promising areas where there are insufficient data; ideally, new seismic data and well data including cores.

Underground natural Gas Storage (UGS) in either porous media stores or salt caverns is undertaken/planned in 17 of the 22 countries studied during Hystories (Austria, Belgium, Czech Republic, Denmark, France, Germany, Hungary, Italy, Latvia, Lithuania (planned), Poland, Portugal, Romania, Spain, Turkey, Ukraine and UK. Natural gas storage in depleted gas fields and saline aquifers is undertaken in many countries where UHS could be of interest (Austria, Belgium, Czech Republic, Denmark, France, Germany, Hungary, Italy, Latvia, Lithuania (planned), Poland, Romania, Ukraine, Turkey, UK). This experience of porous media storage will support development of geological stores for hydrogen.

The sites identified in Hystories require further investigation to confirm their suitability and to advance the potential stores closer to deployment as UHS sites. A range of actions are required depending on the maturity of site investigation and development. Actions to identify potential UHS sites include obtaining permissions to use data to perform basic potential trap identification and interpretation of seismic and well data to confirm storage opportunities, and site-specific geological assessments. To develop sites analysis of the detailed geological data, economic conditions and other logistical aspects are required. The European Hydrogen Backbone (EHB) initiative[64] considers how a network of hydrogen infrastructure could develop in Europe, mirroring the interconnectedness of the natural gas network and highlighting where early opportunities in the hydrogen market could develop. Hydrogen infrastructure may develop near existing gas infrastructure to accelerate deployment. Techno-economic assessments have been performed in the Hystories projects in work packages 5 to 8, considering development of a hydrogen transport and storage network at European scale.

Potential future development opportunities for geological storage of hydrogen were identified in nearly all countries studied by Hystories, additional work is now needed so geological storage can play its role in helping countries meet their national climate targets.

[64] https://ehb.eu/

Appendix 1: data tables

27.1. Formation data table attributes

Please note that these storage 'formations' are not necessarily the same as geological formations. These have been selected in some cases to align with major sandstone bodies, so caution is required when looking at the database.

Table 51: Parameters for the Formation level of the database.

Name of Attribute	Type	Size	Description
OBJECTID	Long Integer	4	A unique identifier for each feature record within the dataset generated by ArcGIS
FORMATION_ID	Text	255	Unique ID of the formation (automatically generated by Access)
FORMATION_NAME	Text	254	Name of the Formation
ASSESS_UNIT_TYPE	Text	255	Assessment Unit type -options are saline Aquifer with or without hydrocarbon fields
ONSHORE or OFFSHORE	Text	255	Is the formation onshore or offshore (if both, label as wherever the majority of the formation lies – onshore or offshore) (select from list)
CHRONOSTRAT_PERIOD_MIN_RES	Text	255	Minimum period of reservoir formation (select from list of geological periods)
CHRONOSTRAT _PERIOD_MAX_RES	Text	255	Maximum period of formation (select from list – Cambrian etc.)
CHRONOSTRAT_MIN_RES	Text	255	Minimum age of reservoir formation (type in text) (Lower Permian etc.)
CHRONOSTRAT _MAX_RES	Text	255	Maximum age of reservoir formation (type in text) (Lower Permian etc.)
STRAT_GROUP_RES	Text	254	Stratigraphic Unit Group of reservoir
STRAT_FORMATION_RES	Text	255	Stratigraphic Unit formation of reservoir
LITHOLOGY_RES	Text	254	predominant lithology of reservoir (select from list)
GEOGRAPHIC_AREA	Text	255	(select from list)
GEOLOGICAL_BASIN	Text	255	(select from list)
ON_OFFSHORE	Text	254	Whether onshore or offshore or both (Dictionary)
WATER_DEPTH	Long Integer	4	Mean average water depth
REP_THICK_RES	Long Integer	4	Representative thickness of reservoir
REP_POR	Long Integer	4	Representative Porosity of reservoir
SEAL	Text	255	name of most widespread primary seal for the reservoir formation
REP_THICK_SEAL	Long Integer	4	Representative thickness of seal

REMARKS	REMARKS	254	Any other relevant information
COUNTRY	Text	254	(Drop down list)
COUNTRYCODE	Text	50	(Drop down list)
LAMBERT_E	Double	8	Eastings in Lambert projection (only one clear set of coordinates and projection information must be supplied, conversions can be carried out in the database)
LAMBERT_N	Double	8	Northings in Lambert projection
X_DD	Double	8	X co-ord in decimal degrees (WGS84)
Y_DD	Double	8	y co-ord in decimal degrees (WGS84)
X	Double	8	X co-ords in any given projection
Y	Double	8	y co-ords in any given projection
Projection_Info	Text	50	Details of projection used for X and Y coords
NO_STORE_UNITS	Double	8	Number of storage units within the formation (automatically generated by Access)
NO_DAUGHTER_UNITS	Double	8	Number of traps within the formation (automatically generated by Access)

27.2. Unit data table attributes

Table 52: Parameters for the Unit level of the database.

Name of Attribute	Type	Size	Description
OBJECTID	Long Integer	4	A unique identifier for each feature record within the dataset generated by ArcGIS
FORMATION_ID	Text	255	Foreign key – Unique ID of the formation
STORAGE_UNIT_ID	Text	255	Unique storage unit id (auto populated)
STORAGE_UNIT_NAME	Text	255	Name of the storage unit
ASSESS_UNIT_TYPE	Text	255	Storage unit type – drop down list saline Aquifer with or without hydrocarbon fields
ONSHORE or OFFSHORE	Text	255	Is the unit onshore or offshore (if both, label as wherever the majority of the unit lies – onshore or offshore) (select from list)
PERIOD_MIN_RES	Text	255	Minimum period of formation (select from list of geological periods)
PERIOD_MAX_RES	Text	255	Maximum period of formation (select from list)
AGE_MIN_RES	Text	255	Minimum age of reservoir formation (type in text) (Lower Permian etc.)
AGE_MAX_RES	Text	255	Maximum age of reservoir formation (type in text) (Lower Permian etc.)

LITHOLOGY_RES	Text	254	predominant lithology of reservoir (select from list)
SUBSURF_INTERF	Text	255	Interference with other uses of subsurface, seismicity etc. (yes/no)
SURF_ISSUES	Text	255	Any surface issues (drop down selection list)
GROSS_THICK_MIN_RES	Double	8	Minimum Height / thickness of the reservoir (m)
GROSS_THICK_MEAN_RES	Double	8	Mean Height / thickness of the reservoir (m)
GROSS_THICK_MAX_RES	Double	8	Maximum Height / thickness of the reservoir (m)
PERM_MIN	Double	8	Minimum effective permeability mD
PERM_MEAN	Double	8	Mean effective permeability mD
PERM_MAX	Double	8	Maximum effective permeability mD
POROSITY_MIN	Double	8	Minimum porosity % (old Default = 20)
POROSITY_MEAN	Double	8	Mean porosity %
POROSITY_MAX	Double	8	Maximum porosity %
AVE_DEPTH_MIN_RES	Double	8	Minimum average depth of the reservoir (m)
AVE_DEPTH_MEAN_RES	Double	4	Mean average depth of the reservoir (m)
AVE_DEPTH_MAX_RES	Double	8	Maximum average depth of the reservoir (m)
PRESSURE_MIN	Double	8	Minimum Current Pressure of reservoir (bar)
PRESSURE _MEAN	Double	8	Mean Current Pressure of reservoir (bar)
PRESSURE _MAX	Double	8	Maximum Current Pressure of reservoir (bar)
TEMP_C_MIN	Double	8	Minimum Temperature (c)
TEMP_C_MEAN	Double	8	Mean temperature (c)
TEMP_C_MAX	Double	8	Maximum temperature (c)
MIN_DEPTH_TO_TOP	Double	8	Depth to highest point of storage unit (that hydrogen could theoretically reach if it could migrate that far due to buoyancy)
FIELD_EXTENT_MEAN	Double	8	Mean Areal Extent of the storage Unit (km2) (area of the whole available geological storage unit, surface and subsurface)
VERT_NET_GROS_MIN	Double	8	Minimum vertical net:gross (%)
VERT_NET_GROSS_MEAN	Double	8	Mean vertical net:gross (%)
VERT_NET_GROSS_MAX	Double	8	Maximum vertical net:gross (%)
SALINITY_BRINE	Double	8	Total dissolved solids (g/l)
SULPHATES_RES	Text	3	Sulphates/sulphides in rock or fluid of reservoir (Yes/no)
IRON_RES	Text	3	Iron in rock / fluid of reservoir (Yes/no)
CO_2_RES	Text	3	CO_2 in reservoir fluid (Yes/no)

STATUS	Text	254	Status i.e. producing, not producing etc.
TOT_PORE_VOL_MEAN	Double	8	Mean Total Pore Volume (m3)
SEAL	Text	255	Name of most widespread primary seal for the storage unit
PERIOD_MIN_SEAL	Text	255	Minimum period of seal formation (select from list of geological periods)
PERIOD_MAX_SEAL	Text	255	Maximum period of formation (select from list)
AGE_MIN_SEAL	Text	255	Minimum age of reservoir formation (select from list)
AGE_MAX_SEAL	Text	255	Maximum age of reservoir formation (select from list)
PRIM_SEAL_OVERLIE	Text	255	Does primary seal directly overlie assessment unit (yes/no)
LITHOLOGY_SEAL	Text	254	predominant lithology of seal(select from list)
SULPHATES_SEAL	Text	3	Sulphates/sulphides in Seal rock (yes/no (constrained))
IRON_SEAL	Text	3	Iron in Seal Rock (yes/no (constrained))
MIN_SEAL_THICK	Double	8	Minimum primary seal thickness (m)
FAULT_DEN	Double	8	Number of faults that cut top reservoir
FAULTS_THROUGH_OVERBURDEN	Text	255	Presence of faults that cut the top reservoir and top seal (was vert extent faults) (Drop down list, Faults present, displacement greater than thickness of the seal; No faults cut the entire primary seal etc.)
AVE_FAULT_THR	Double	8	Average fault throw (m)
MAX_FAULT_THR_RES	Double	8	Max fault throw at top reservoir (m)
RISK_LAT_MIGR	Text	255	Risk of lateral migration out of unit of assessment (low/medium/high)
AVE_DIP_UNIT	Double	8	Average dip of unit of assessment (degrees)
SUSCEPT_RES_DAM	Text	4	Susceptibility of reservoir to formation damage when injecting fluids (low/medium/high)
VERT_STRAT_COMPART	Text	4	Vertical reservoir compartmentalisation (yes/no)
HOR_STRAT_COMPART	Text	4	Horizontal reservoir compartmentalisation (yes/no)
FAULT_COMPART	Text	4	Fault compartmentalisation of the reservoir (yes/no)
FAULT_IN_SEAL	Text	4	Faults present in seal (Yes/no/unknown)
SEAL_OTHER	Text	255	Secondary or other seal names
NO_WELLS_PENETR	Double	8	Number of existing wells penetrating the storage unit
WELL_VINT	Text	255	Well vintage (year)

NO_ABAND_WELL_PENETR	Double	8	Number of abandoned wells penetrating storage unit
AGE_OLD_WELL	Double	8	Age of oldest abandoned well (year)
VINT_PLAT	Text	255	Vintage production platform or site (year)
WATER_DEPTH	Long Integer	4	Mean water depth
SEISMIC	Text	255	Seismic available (drop down list)
WELLS	Text	255	Wells available (drop down list)
MODELS	Text	255	Models available (drop down list)
STATUS_RESEARCH	Text	255	Status of the research on the unit (free text)
AVE_FAU_THR_AVE_SEAL_THI	Text	255	Average fault throw : average seal thickness
REMARKS	Text	254	
COUNTRY	Text	254	
COUNTRYCODE	Text	50	
X_DD	Double	8	X coord of centre of storage unit (WGS84)
Y_DD	Double	8	Y coord of centre of storage unit (WGS84)
NO_AQUIF_DAUGHT	Double	8	Number of aquifer traps within the unit (automatically generated by Access)
NO_HC_DAUGHT	Double	8	Number of hydrocarbon traps within the formation (automatically generated by Access)

27.3. Trap data table attributes

Table 53: Parameters for the Trap level of the database.

Name of Attribute	Type	Size	Description
OBJECTID	Long Integer	4	A unique identifier for each feature record within the dataset generated by ArcGIS
STORAGE_UNIT_ID	Text	255	Foreign key – Unique ID of the storage unit (automatically populated by database)
TRAP_ID	Text	255	Unique id of the trap (automatically populated by database)
STORAGE_UNIT_NAME	Text	254	Name of the trap
ASSESS_UNIT_TYPE	Text	255	Storage unit type – drop down Aquifer trap or hydrocarbon trap Saline aquifers used for underground gas storage to be included as 'saline aquifer' here, with fluid fill attribute = gas. Add notes in Remarks box. Depleted hydrocarbon fields used for e.g. UGS, included as 'hydrocarbon trap' here with e.g. 'gas' in the fluid fill attribute field. Add notes in Remarks box.

ONSHORE or OFFSHORE	Text	255	Is the trap onshore or offshore (if both, label as wherever the majority of the trap lies – onshore or offshore) (select from list)
OPERATOR	Text	254	Field operator name
OWNERSHIP	Text	254	E.g. Private company/state owned etc.
LICENCE	Text	254	Licence owner, type, date
AVAILABLE	Text	8	Could this site be developed for hydrogen storage or is the site not available due to conflict of interest? Yes/no/possibly (drop down)
CURRENT_DEV	Text	255	e.g. operating oil field, abandoned, gas storage, none (drop down)
PLANNED_DEV	Text	255	e.g. gas storage, hydrogen storage, gas production, none (drop down)
EXPLORATION	Text	8	Has site exploration started? i.e. has the site geology been studied with wells drilled and seismic collected; permits obtained etc.. Yes/no/possibly (drop down)
STORAGE_DEVELOPED	Text	8	Has storage (gas, CO_2, hydrogen) storage site been developed – i.e. is it up and running? Yes/no/possibly
END_YEAR	Double	8	Planned year of site closure (including for oil extraction/gas storage etc.)
PERIOD_MIN_RES	Text	255	Minimum/youngest geological period of formation (select from list) (Cretaceous etc.)
PERIOD_MAX_RES	Text	255	Maximum/oldest geological period of formation (select from list)
AGE _MIN_RES	Text	255	Minimum/youngest geological age of formation (select from list) (Albian)
AGE _MAX_RES	Text	255	Maximum/oldest geological age of formation (select from list)
ENV_DEP_RES	Text	254	Primary environment of deposition of reservoir rock e.g. desert
LITHOLOGY_RES	Text	254	predominant lithology of reservoir (select from list)
RES_MINERAL	Text	255	Mineralogy of the reservoir
SUBSURF_ISSUES	Text	255	Interference with other uses of subsurface e.g., gas storage planned, drinking water aquifers above, seismicity etc. – Drop down list)
SURF_ISSUES	Text	255	Any surface issues (drop down selection list) e.g., nature reserve, urban area
GROSS_THICK_MIN_RES	Double	8	Minimum Height / thickness of the reservoir (m) (true vertical thickness)

GROSS_THICK_MEAN_RES	Double	8	Mean Height / thickness of the reservoir (m) (true vertical thickness)
GROSS_THICK_MAX_RES	Double	8	Maximum Height / thickness of the reservoir (m) (true vertical thickness)
PERM_MIN	Double	8	Minimum effective permeability mD
PERM_MEAN	Double	8	Mean effective permeability mD
PERM_MAX	Double	8	Maximum effective permeability mD
POROSITY_MIN	Double	8	Minimum porosity % (% as decimal – e.g., 10% = 0.1)
POROSITY_MEAN	Double	8	Mean porosity %
POROSITY_MAX	Double	8	Maximum porosity %
DEPTH_MIN_RES	Double	8	Minimum average depth of the reservoir (m) (here average depth is depth to the middle of the reservoir. Attribute used to support fluid modelling)
DEPTH_MEAN_RES	Double	4	Mean average depth of the reservoir (m)
DEPTH_MAX_RES	Double	8	Maximum average depth of the reservoir (m)
Minimum depth to Top of Trap	Double	8	Depth to crest of reservoir in trap (m)
PRESSURE_MIN	Double	8	Minimum Current Pressure of reservoir (bar) (at the minimum average depth of reservoir)
PRESSURE _MEAN	Double	8	Mean Current Pressure of reservoir (bar) (at the mean average depth of reservoir)
PRESSURE _MAX	Double	8	Maximum Current Pressure of reservoir (bar) (at the maximum average depth of reservoir)
TEMP_C_MIN	Double	8	Minimum Temperature (°C) (at the average depth of reservoir)
TEMP_C_MEAN	Double	8	Mean temperature (°C) (at the average depth of reservoir)
TEMP_C_MAX	Double	8	Maximum temperature (°C) (at the average depth of reservoir)
MIN_DEPTH_TO_TOP	Double	8	Depth to highest point of storage unit (that hydrogen could theoretically reach if it could migrate that far due to buoyancy)
FIELD_EXTENT_MEAN	Double	8	Mean Areal Extent of the storage Unit (km^2) (If the potential trap crosses country boundaries, consider if you have provided information on porosity, thickness for one country or both)
VERT_NET_GROS_MIN	Double	8	Minimum vertical net:gross (% as decimal – e.g. 10% = 0.1) (i.e. what % of the gross reservoir thickness could be suitable for storage – this is often the % of sandstone within the gross reservoir thickness where the lithology is not homogeneous)
VERT_NET_GROSS_MEAN	Double	8	Mean vertical net:gross (%)

VERT_NET_GROSS_MAX	Double	8	Maximum vertical net:gross (%)
FLUID_FILL	Text	50	Fluid fill of reservoir, e.g. fresh water, gas, hydrocarbons (select from list). Please add notes in 'remarks' field if required. Oil and gas traps; complete with the fluid that is the majority of the fluid in the trap. Use 'hydrocarbons' where there is a relatively even mixture of oil and gas. Aquifers; aquifer can be assigned as fresh water (salinity <1 g/L) or saline (salinity >1g/L) here. Brackish water is included in the 'saline water' category for simplicity – https://www.usgs.gov/special-topics/water-science-school/science/saline-water-and-salinity) 'Dry' hydrocarbon trap – if partner has assigned as a 'hydrocarbon trap', use 'saline water' fluid fill Depleted oil/gas/hydrocarbon field; fluid fill reported as oil/gas/hydrocarbon as is it expected some hydrocarbons remain which could affect H_2 storage
SALINITY_BRINE	Double	8	Total dissolved solids (g/l)
SULPHATES_RES	Text	3	Sulphates/sulphides in rock or fluid of reservoir (Yes/no)
SULPHATES_RES_DETAIL	Text	254	E.g. pyrite nodules, hydrogen sulphide, gypsum in reservoir
IRON _RES	Text	3	Iron in rock or fluid- Yes/no (drop down list)
IRON_RES_DETAIL	Text	254	E.g. iron nodules in reservoir, iron stained sandstone
CO_2_RES	Text	3	CO_2 in Fluid – Yes/no (drop down list)
CO_2_RES_DETAIL	Text	254	Eg CO_2 in oil
STATUS	Text	254	Status i.e. producing, not producing etc. – hydrocarbon traps only
CONNECTIVITY	Text	255	Connectivity to rest of storage unit (yes / no) – hydrocarbon traps only
MIN_UR_GAS	Double	8	Minimum ultimate recovery gas (bcm – billion m3) – hydrocarbon traps only
MEAN_UR_GAS	Double	8	Mean ultimate recovery gas (bcm – billion m3) – hydrocarbon traps only
MAX_UR_GAS	Double	8	Maximum ultimate recovery gas (bcm – billion m3) – hydrocarbon traps only
MIN_UR_OIL	Double	8	Minimum ultimate recover oil (MMcm) – hydrocarbon traps only

MEAN_UR_OIL	Double	8	Mean ultimate recover oil (MMcm) – hydrocarbon traps only
MAX_UR_OIL	Double	8	Maximum ultimate recovery oil (MMcm) – hydrocarbon traps only
FVF_OIL	Double	8	Oil Formation Volume Factor (Rcm / scm) – hydrocarbon traps only
FVF_GAS	Double	8	Gas Formation Volume Factor (Rcm / scm) – hydrocarbon traps only
DISCOV_YR	Double	8	Discovery year
FIRST_YR_PROD	Double	8	First year of production
LAST_YR_PROD	Double	8	Last year of production
TOT_PORE_VOL_MEAN	Double	8	Mean Total Pore Volume (m3)
SEAL	Text	255	Name of most widespread primary seal for the storage unit
PRIM_SEAL_OVERLIE	Text	255	Does primary seal directly overlie assessment unit (yes/no)
PERIOD_MIN_SEAL	Text	255	Minimum period of seal formation (select from list of geological periods)
PERIOD_MAX_SEAL	Text	255	Maximum period of formation (select from list)
AGE_MIN_SEAL	Text	255	Minimum age of seal formation (select from list)
AGE _MAX_SEAL	Text	255	Maximum age of seal formation (select from list)
MIN_SEAL_THICK	Double	8	Minimum primary seal thickness (m)
LITHOLOGY_SEAL	Text	254	predominant lithology of seal (select from list)
SEAL_MINERAL	Text	255	mineralogy of the seal
ENV_DEP_SEAL	Text	254	Primary environment of deposition of seal e.g. Deep sea
SULPHATES_SEAL	Text	3	yes/no (constrained)
IRON_ SEAL	Text	3	yes/no (constrained)
FAULT_DEN	Double	8	Number of faults that cut top reservoir
FAULTS_THROUGH_OVERBURDEN	Text	255	Presence of faults that cut the top reservoir and top seal (was vertical extent faults) (Drop down list, Faults present, displacement greater than thickness of the seal; No faults cut the entire primary seal etc.)
AVE_FAULT_THR	Double	8	Average fault throw (m)
MAX_FAULT_THR_RES	Double	8	Max fault throw at top reservoir (m)
RISK_LAT_MIGR	Text	255	Risk of lateral migration out of unit of assessment (low/medium/high)
AVE_DIP_UNIT	Double	8	Average dip of unit of assessment (degrees)

SUSCEPT_RES_DAM	Text	255	Susceptibility of reservoir to formation damage when fluids are injected (low/medium/high)
VERT_STRAT_COMPART	Text	255	Vertical reservoir compartmentalisation (yes/no)
HOR_STRAT_COMPART	Text	255	Horizontal reservoir compartmentalisation (yes/no)
FAULT_COMPART	Text	8	Fault compartmentalisation of the reservoir (yes/no)
FAULT_IN_SEAL	Text	8	Faults present in seal (Yes/no/unknown)
SEAL_OTHER	Text	255	Secondary or other seal names and thicknesses if available
NO_WELLS_PENETR	Double	8	Number of existing wells penetrating the potential storage unit
WELL_VINT	Text	255	Well vintage (year)
ANNUAL_PRODUCTION_RATE	Double	8	Annual production rate (oil/gas extraction in mmbl/year or mmscf/year – hydrocarbon traps only
Well_flow_rate	Double	8	Million standard cubic feet per day (MMscfd)
NO_ADAND_WELL_PENETR	Double	8	Number of abandoned wells penetrating storage unit
AGE_OLD_WELL	Double	8	Age of oldest abandoned well (year)
VINT_PLAT	Text	255	Vintage production platform or site (year)
WATER_DEPTH	Long Integer	4	Mean average water depth (e.g. depth to seabed for offshore sites)
SEISMIC	Text	255	Seismic data available (even if not in the public domain) (drop down list)
WELLS	Text	255	Well data available (even if not in the public domain) (drop down list)
MODELS	Text	255	Geological/reservoir models available? (even if not in the public domain) (drop down list)
STATUS_RESEARCH	Text	255	Status of the research on the unit (drop-down list), describes stages of site investigation before any industrial operations
DATA_SOURCE	Text	255	Data source (e.g. report name, database link)
DATA_QUALITY	Text	10	Data quality and confidence (excellent, good, fair, poor, low) (drop down)
REMARKS	Text	254	Any additional information – e.g. average porosity for oil field given, polygons not available, trap crosses country boundaries, seal thickness estimated from one well, seismic data held by private companies and not released, saline aquifer used for gas storage, field contains oil and gas, 2% hydrogenS present, key uncertainties in information etc.)

COUNTRY	Text	254	
COUNTRYCODE	Text	50	
X_DD	Double	8	X coord of centre of storage unit (WGS84)
Y_DD	Double	8	Y coord of centre of storage unit (WGS84)
PROJECTION_INFO	Text	50	
DATE_ENTERED	Text	10	Date the database object was created (automatically populated)
HYST_OR_CO_2	Text	50	Note if updated during Hystories, or legacy data from CO_2StoP
GIS_REMARKS	Text	50	Used during GIS creation to check issues with data
ON_OFFSHORE	Text	50	Is trap located onshore or offshore?

Appendix 2: data use statement

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