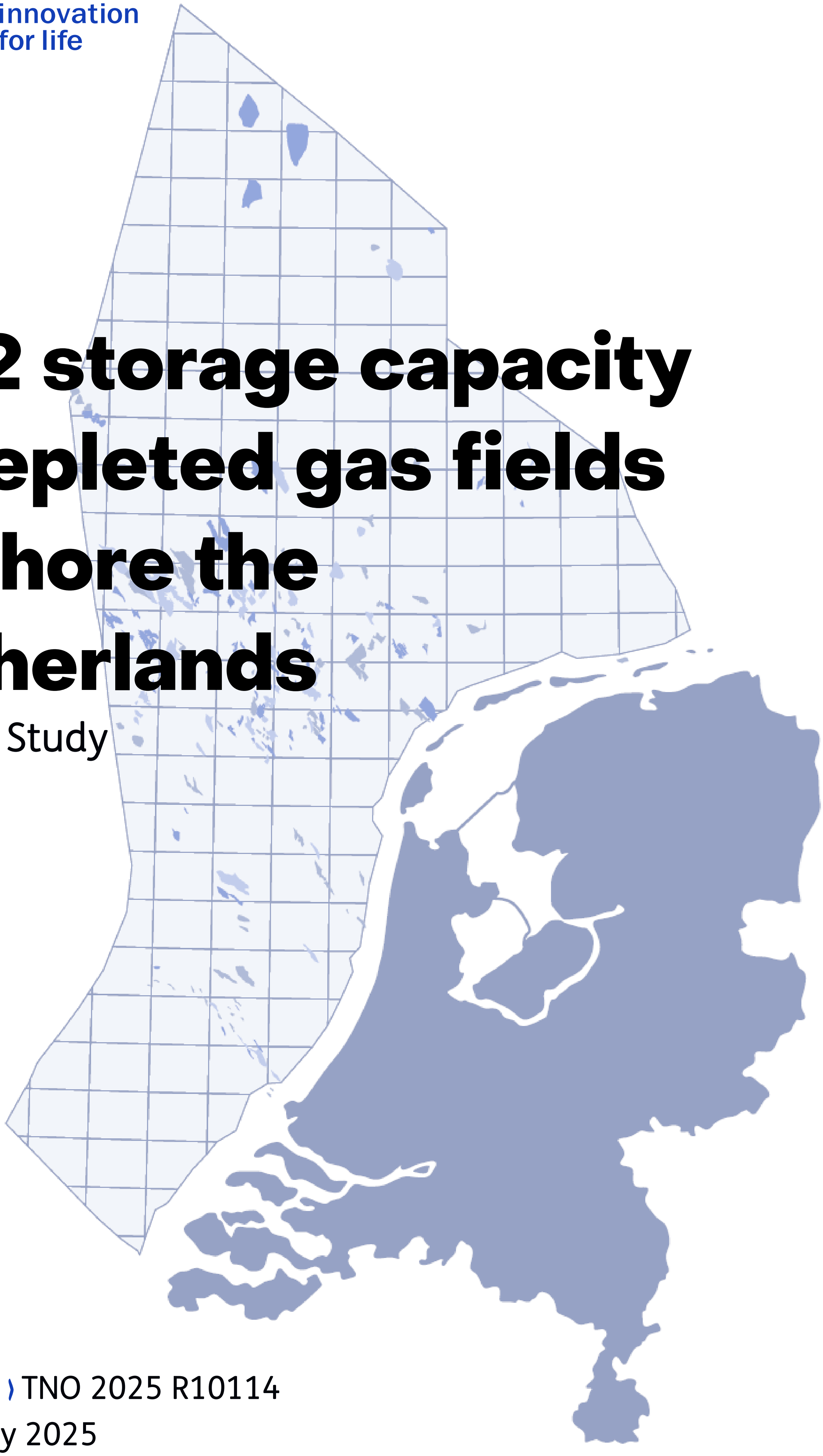

CO2 storage capacity in depleted gas fields offshore the Netherlands

Portfolio Study

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Portfolio Study

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Summary

TNO-Advisory Group (TNO-AGE) prepared this report for the Dutch Ministry of Climate Policy and Green Growth (KGG). The dual aim of this report is to support policy and decision makers in the emerging CO_2 storage industry and to address the EU reporting obligations under the Net Zero Industry Act (NZIA). It provides an initial assessment of the offshore underground CO_2 storage capacity in (nearly) depleted gas fields in the Netherlands, which is estimated at a ~1260 to ~1750 Mt (Mega tons) range for practical storage capacity in 46 and 124 storage sites respectively. It includes an examination of the potential development of available storage capacity through time at portfolio level, which is compared to the currently planned transport capacity development.

In this report we (TNO-AGE) estimate the potential storage capacity in offshore depleted gas fields in the Netherlands following the resource "pyramid methodology". Theoretical capacity corresponds to the maximum physical storage capacity for CO_2 in depleted gas fields, which for the offshore Netherlands we estimate at ~2860 Mt. Effective capacity incorporates additional geotechnical and engineering restrictions. This leads to a reduction of the available storage capacity down to ~2570 Mt. Further analyses are recommended that are likely to have a negative impact on this volume. For practical capacity, economic and legislative criteria are included that can have a significant impact but are not yet fully clear. In this report we consider impactful economic and legislative parameters to generate a high- and a low-case scenario, which together provide a first order uncertainty range of ~1260 to ~1750 Mt, in 46 and 124 storage sites respectively. Most of the practical storage is located in a limited number of medium to large size storage sites. This practical capacity range can be used for policy and stakeholder decisions as capacity range that can be realistically achieved.

The currently planned Porthos and Aramis CO_2 projects are expected to transport 24.5 Mt per annum (Mtpa) and hence contributes substantially to the EU 2030 goal of 50 Mtpa. The EU ambition for 2050 is to increase capture and transport capacity to 550 Mtpa, of which a part will be stored permanently in the subsurface (NZIA). The low case scenario considers a sub-hydrostatic bottom hole injection pressure limit and only includes middle to large depleted natural gas fields in Rotliegend and Lower Triassic formations. The results from the low-case scenario indicate that the annual storage capacity is substantially higher than the transport capacity of the Porthos and Aramis CO_2 projects and could be maintained beyond 2050. This scenario demonstrates that even with fairly conservative criteria the Dutch offshore contains a substantial practical storage capacity.

The main difference between the low-case and high-case practical scenario is the amount of storage sites, 46 versus 124. Increasing the total practical storage capacity significantly will require increasing the number of, mainly smaller, depleted gas fields. The large number of individual projects will requires a significant effort to ramp up CO_2 storage capacity but will also allow the Netherlands to store a larger portion of the CO_2 storage goals defined under the NZIA.

Two main factors are not taken into account in this portfolio study. Spatial restrictions, related to current or planned surface usages and activities, are not considered in the practical capacity estimate. A screening of the overlap between restricted areas and

depleted gas fields show that this might have a large negative impact on the potentially available sites. Only ~310 and ~440 Mt for the low- and high-case scenarios respectively, are located outside a restricted area. Realizing storage sites in currently or planned restricted areas will require early engagements with the relevant stakeholders. The second factor is that aquifer storage capacity is not incorporated in this report.

In this report the portfolio level storage capacity in depleted gas fields is calculated for the Dutch offshore for the theoretical case, and includes a first order estimate for the effective and practical cases. TNO-AGE suggests to update this study with further work including a detailed socio-techno-economical screening. This will give policy makers a more "realistic" storage capacity to base future policy on.

Samenvatting

TNO Adviesgroep Economische Zaken (TNO-AGE) heeft dit rapport opgesteld voor het Nederlandse Ministerie van Klimaat en Groene Groei (KGG). Dit rapport stelt tot doel beleidsmakers en belanghebbenden in de opkomende CO_2-opslagindustrie te ondersteunen. Daarnaast vormt deze evaluatie een onderdeel van de rapportageverplichtingen van Nederland aan de EU onder de Net Zero Industry Act (NZIA). Het biedt een eerste orde inschatting van de ondergrondse CO_2-opslagcapaciteit in (bijna) uitgeproduceerde gasvelden in het Nederlands deel van de Noordzee, die wordt geschat tussen de ~1260 en ~1750 Mt (megaton) voor praktische opslagcapaciteit in respectievelijk 46 en 124 opslaglocaties. Het bevat een inschatting van de potentiële ontwikkeling van beschikbare opslagcapaciteit door de tijd heen op portfolioniveau, die wordt vergeleken met de momenteel geplande ontwikkeling van transportcapaciteit.

In dit rapport hanteert TNO-AGE het voorraadclassificatie systeem conform de "piramide methodologie" om de potentiële opslagcapaciteit in lege gasvelden in Nederland op zee in te delen naar mate van de waarschijnlijkheid dat deze gerealiseerd kan worden. De theoretische capaciteit komt overeen met de maximale fysieke opslagcapaciteit voor CO_2 in uitgeproduceerde gasvelden, die we voor het Nederlands deel van de Noordzee berekenen op ~2860 Mt. De effectieve capaciteit omvat aanvullende geologische en technische beperkingen, wat leidt tot een vermindering van de beschikbare opslagcapaciteit tot ~2570 Mt. Het verdient de aanbeveling om verdere studies uit te voeren naar deze beperkingen aangezien ze waarschijnlijk een negatieve impact op dit volume zullen hebben. Voor de praktische capaciteit zijn economische en beleidsmatige criteria opgenomen die een aanzienlijke impact kunnen hebben, maar zijn nog niet volledig gedefinieerd. In dit rapport hanteren wij economische en beleidsmatige parameters om een hoog en een laag scenario te genereren. Hiermee wordt een eerste orde onzekerheidsbereik van ~1260 tot ~1750 Mt bepaald, in respectievelijk 46 en 124 opslaglocaties. Het grootste deel van de praktische opslag bevindt zich in relatief klein aantal middelgrote tot grote opslaglocaties. De praktische capaciteit kan worden beschouwd als een waarde die realistisch kan worden bereikt.

De Porthos en Aramis CO_2-projecten zullen naar verwachting 24,5 Mt per jaar (Mt per jaar) transporteren en kunnen daarmee substantieel bijdragen aan de EU-doelstelling van 50 Mt per jaar voor 2030. De EU-ambitie voor 2050 is om de opvang- en transportcapaciteit te verhogen tot 550 Mt per jaar, waarvan een groot deel permanent in de ondergrond zal worden opgeslagen (NZIA). Het lage scenario houdt rekening met een sub-hydrostatische injectiedruklimiet en omvat alleen middelgrote tot grote uitgeproduceerde gasvelden in Rotliegend en Onder Trias-formaties. In het lage scenario is de jaarlijkse opslagcapaciteit hoger dan de transportcapaciteit van de Porthos en Aramis CO_2-projecten en kan deze tot na 2050 gehandhaafd worden. Dit scenario toont aan dat zelfs met vrij conservatieve criteria de Nederlandse Noordzee voor de komende decennia praktische opslagcapaciteit bevat.

Het belangrijkste verschil tussen het lage en hoge praktische scenario is het aantal opslaglocaties, 46 versus 124. Hieruit blijkt dat er bij eventuele opschaling van de opslagcapaciteit voornamelijk kleinere, uitgeproduceerde gasvelden moeten worden toegevoegd aan het portfolio. Het grote aantal individuele projecten zou een aanzienlijke

inspanning vereisen om de CO_2-opslagcapaciteit op te voeren, maar zou Nederland ook in staat stellen om een hoger CO_2-opslagpotentieel te realiseren.

Twee belangrijke factoren worden niet meegenomen in deze portfoliostudie. Meervoudig ruimtegebruik, in de vorm van huidig of gepland gebruik van de bovengrond, wordt niet meegenomen in de schatting van de praktische capaciteit. Een screening van de overlap tussen gebieden waar bovengronds een beperking geldt en lege gasvelden laat zien dat dit een grote negatieve impact kan hebben op de potentieel beschikbare locaties. De hoge en lage scenario's bevatten respectievelijk ~310 en ~440 Mt opslagpotentieel in gebieden zonder deze beperking. Het realiseren van opslaglocaties in gebieden met een huidige of toekomstige gebruik van de bovengrond vereist vroege betrokkenheid van de relevante belanghebbenden.
Daarnaast wordt de opslagcapaciteit van de watervoerende lagen niet meegenomen in dit rapport.

In dit rapport wordt de opslagcapaciteit op portfolioniveau in uitgeproduceerde gasvelden berekend voor de Nederlandse Noordzee voor de theoretische opslagcapaciteit, waarbij een eerste orde schatting van de effectieve en de praktische opslagcapaciteit wordt gegeven. TNO-AGE stelt voor om deze studie uit te breiden met een verdiepende studie, inclusief een gedetailleerde socio-techno-economische screening. Dit zal beleidsmakers een meer "realistische" opslagcapaciteit geven om toekomstig beleid op te baseren.

Contents

1 Introduction

1.1 Rationale

The 2015 Paris Agreement (UNFCCC, 2016) provided a milestone for climate action. The main objective is to limit the global average temperature rise below 2 degrees Celsius compared to pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. Article 6 of the Paris agreement also laid the foundation for the development of international carbon markets, allowing Parties to cooperate in achieving their national targets. It also incorporates the 'net zero' concept of balancing anthropogenic greenhouse gasses (GHGs) emissions with GHGs removals by sinks, for example by CO_2 storage in the subsurface.

The Net-Zero Industry Act (NZIA) (EU, 2024) was approved in April 2024. It aims to enhance European manufacturing capacity for net-zero technologies, and addresses barriers to scaling up production in Europe. The act recognizes CO_2 capture, transport and storage (CCS) projects as net-zero strategic projects. It aims to create a Union market for CO_2 storage services by 2030, sets a Union-wide target and requires an annual CO_2 storage capacity of at least 50 Megaton[1] (Mtpa) (EU, 2024). Considering that The Netherlands is among the largest EU oil and gas producers, article 18 of the NZIA is of particular relevance. Article 18 states that companies that hold an oil and gas production license (EU, 1994) must contribute to this storage objective, for instance through the development of CO_2 storage sites. The EU Committee has set a target of 550 Mtpa CO_2 capture for either usage or storage before 2050 (EU, 2024).

1.1.1 Advice question

The Paris Agreement and the NZIA have major implications for the subsurface use. Operators receive additional reporting obligations and are required to develop plans regarding the development of CCS. For the Netherlands this is particularly challenging considering the increasingly complex offshore spatial planning, implying this will require informed and strategic choices by the government.

Given the advisory role that TNO-AGE has for the Ministry (KGG) regarding any activity taking place in the Dutch subsurface, TNO-AGE is in a privileged position to assess and advise on the potential for underground CO_2 storage. TNO-AGE has also access to the extensive historical mining law data on the subsurface and continues to receive and store data from current and future mining projects. Since the most recent report on portfolio level CO_2 storage capacity (TNO, 2020), insights into CO_2 storage methods as well as the development of storage sites has evolved. This report and the underlying analyses have been prepared in anticipation of a request for an update advice from the Ministry to support policy- and decision-makers on the emerging CCS industry, while addressing the EU reporting obligations.

[1] Megaton (Mt) = 10^6 ton. Megaton per annum (Mtpa)

This report provides an initial assessment of the offshore storage capacity in (nearly) depleted gas fields, its temporal development at a portfolio level, and a comparison to the currently ongoing CO_2 storage projects. The storage capacities are calculated following the resource pyramid methodology to arrive at a 'practical' storage capacity, ie. a storage capacity that is considered to be realistically achievable, and are based on available public and confidential mining law data. The results can be used as a basis more detailed future studies and policy decisions.

1.1.2 Scope

Within the CCS framework, the underground CO_2 storage capacity provides an important link in the value chain of CO_2 capture and transport capacity. While offshore transport capacity is briefly discussed in connection with the annual injection capacity analysis, this report focuses primarily on a portfolio-level assessment for CO_2 storage potential in offshore depleted gas fields. Another ongoing project (TNO, in prep) is currently evaluating the offshore aquifer CO_2 storage potential. Currently, CO_2 storage in depleted gas fields is considered a more mature option for the Netherlands, with a shorter path to development. Land-based CO_2 storage and CO_2 capture capacity are outside the scope of this report.

1.2 Current status of CCS

1.2.1 Current status of CCS in the Netherlands

CO_2 capture projections

Carbon capture lends itself to areas of concentrated CO_2 emission. In the Netherlands, industrial clusters have been identified in the 2020 National Climate Agreement (EZK, 2019). Additionally, the German Ruhr Industrial Area and Belgian Antwerp area are frequently referred to as nearby areas of concentrated CO_2 emissions. Combinedly, these industrial clusters are expected to ramp up to a combined annual carbon capture capacity ranging from 4 – 10 Mt (megaton) in 2025, to 13 – 33 Mt in 2030 (Royal HaskoningDHV, 2021).

CO_2 transport projections

Currently there are 2 firm CO_2 transport projects, Porthos and Aramis, with additional proposals in various conceptual phases. Porthos has taken a Final Investment Decision (FID) and is expected to have an annual transport capacity of ~2.5 Mt. Aramis will have an additional annual 22 Mtpa transport capacity, and is in the pre-FID phase.

Underground CO_2 capacity projections

Portfolio studies regarding the CO_2 storage capacity are quite limited. A brief overview is given below for reference. Early reports regarding the CO2 storage portfolio are (TNO, 1995; 1997; 2008). CO2SToP (Poulsen et al., 2014) represent a EU-wide capacity study that for the Netherlands has estimated an average underground storage capacity of 1372 Mt for a combined onshore and offshore portfolio that includes aquifers and depleted gas fields.

EBN and GasUnie (2017) report an offshore theoretical capacity of 2246 Mt in 222 gas fields, and a 1678 Mt practical capacity in 104 gas fields. This reduction is caused by excluding: small fields (<1 bcm), fields with low transmissivity (<100 mD.m), shallow fields in e.g. the A-blocks, and currently abandoned fields. All other fields are considered viable for CO_2 storage.

The storage capacity is calculated based on the Ultimate Recovery (UR), using a conversion factor of 2.5 (Mt CO_2)/(billion Nm^3 of natural gas)[2].

TNO (2020) aimed to asses which offshore locations are suitable for CO_2 storage based on storage locations and transport infrastructure. This was implemented by including small fields (with a storage capacity of >1Mt) as additional storage capacity if these fields were connected to the same platform as a large field (with a >30Mt storage capacity). The storage capacity was calculated based on the Ultimate Recovery (UR) and a conversion factor. In this report, the conversion factor (Mt/bcm) that depended on the depth and Cease of Production (COP) pressure. Additionally, a generic 0.9 multiplier was applied to account for the fall-off in injection rates when approaching the initial reservoir pressure. Up to 2030, this study predicts a cumulative potential storage capacity of 1100 Mt, which could increase up to a maximum of ~1600 Mt in 2036.

Currently, TNO-AGE is working on a portfolio level assessment for Rotliegend aquifers. Preliminary results indicate a theoretical storage capacity of ~1000 Mt and 3650 Mt for the a P90-P10 scenario, respectively (TNO, in prep). Furthermore, GEODE (EBN-TNO, 2030), a joint initiative of EBN B.V. and TNO, is providing much of the underlying data and analyses needed to estimate CO_2 storage capacities in aquifers, but the project itself does not provide any capacity estimates.

1.2.2 Current status of CCS in Europe

CO_2 storage capacity in Europe is mostly concentrated in the North Sea area, with the largest reported portfolio-level resources, generally in aquifers, in Norway and the United Kingdom (UK). The UK has an online database (CO_2Stored) including over 500 potential storage sites and has a total estimated P50 theoretical storage capacity of 78 Gt[3], i.e. 78.000 Mt (e.g. Bentham et al. 2014). The Norwegian Petroleum Directorate has provided CO_2 Atlases per area reporting theoretical storage capacities of ~70 Gt for the Norwegian North Sea, 5.5 Gt for the Norwegian Sea, 7.2 Gt for the Southern Barents Sea (NPD, 2011; 2012; 2013).

The UK and Norway also have the largest capacity in projects that are in various stages of development. Within the EU, the Netherlands and Denmark are currently frontrunners both in project maturity and storage capacity (CATF, 2024).

Country	Injection capacity in 2030 (Mtpa)
Norway	45
UK	29.5
EU	
The Netherlands	14.0
Denmark	9.3
EU others	12.2
EU total	35.5

Table 1-1 Overview of the annual CO_2 injection capacity within Europe. source: CATF, 2024

[2] Nm^3 refers to a cubic meter at a pressure of 1,01325 bar and a temperature of 0°C
[3] Gt represents Gigaton = 10^9 ton

1.3 Resource classification systems

At the International level, CO_2 storage in aquifers has received most attention. The capacity of these systems depends on the methodology and involves very wide ranges of uncertainty. For example, basin or country-scale assessments might estimate the overall pore volume in relevant geological formations and assume a certain percentage (e.g. 2% or 40%) to represent the CO_2 storage capacity. Typically, this fraction is not well justified. Additionally, the areal extent of a basin-scale study might not fully become available for CO_2 storage (cf. Thibeau and Adler, 2022). This is seen in detailed studies of individual storage projects, including detailed mapping and modelling of reservoir pressures and pressure transient effects, which typically yield much smaller capacity estimates. Additionally, not all the estimated potential storage capacity included in large-scale assessments will be matured to actual projects. Hence, to distinguish between the maturity and the associated accuracy of the capacity estimates, a resource classification system is required. Several of such systems are currently in use and are briefly described in the following sections.

In general, CO_2 capacity projections in depleted gas fields have smaller intrinsic uncertainty ranges than those for aquifers. This is because they are based on historical detailed hydrocarbon exploration and production data (e.g. seismic, logging, core and well production data). For the current report, the techno-economical resource pyramid methodology is used.

1.3.1 The resource pyramid

The techno-economical resource pyramid classification is currently the most common reporting standard in portfolios studies. Within this classification, ‘Theoretical capacity’ represents the maximum physical storage capacity, it is generally calculated as the static volume of the storage site. Graphically it is represented as the entire pyramid (cf. Bachu et al., 2007).

‘Effective capacity’ is a subset of the theoretical capacity. It is derived from the theoretical capacity through geological and engineering cut-off limits. This estimate usually changes with the acquisition of new data and knowledge (cf. Bachu et al., 2007). ‘Practical capacity’ is derived from effective capacity, and takes technical, legal and regulatory, infrastructure and general economic barriers to CO_2 geological storage into consideration. ‘Matched Capacity’ is a subset of the practical capacity and corresponds to the (sub) commercial storage resources such as described in e.g. Storage Resources Management System (Bachu et al., 2007) (see also next section 1.3.2 SRMS).

1.3.2 SRMS

The CO_2 Storage Resources Management System (SRMS) (SPE, 2022) is the storage equivalent of the Petroleum Resources Management System (PRMS) (SPE, 2018) that forms the most common international reporting standard for hydrocarbon resources. It emphasizes and subdivides ‘discovered storage resources’ that roughly corresponds to matched capacity of Bachu et al. (2007).

1.3.3 UNFC

The United Nations Framework Classification (UNFC) provides an another project classification scheme that has been updated for CO_2 injection projects in 2024 (UNECE, 2019; 2024). It represents a system where the resource maturity is differentiated along environmental-socio-economic viability (E-axis) and technical feasibility (F-axis) in a tri-axial system with confidence (G-axis). The emphasis of this scheme is placed on the development criteria of projects.

1.3.4 Storage Readiness levels

Storage Readiness Levels (SRL) provide a method to communicate at which level of technical appraisal, permitting and planning activities a project or capacity estimate is generated (e.g. Akhurst et al., 2021). Compared to e.g. the SRMS system that is focused on resources, the SRL system provides a classification for more immature resource estimates.

1.3.5 Portfolio application

For this report, the techno-economical resource pyramid classification is used to establish a bandwidth for the 'practical' portfolio level storage capacity in the depleted gas fields in the offshore of the Netherlands. This method is here considered the most suitable for calculating a portfolio level capacity, whereas the SRMS, UNFC and SRL systems appear more suitable to aggregate a portfolio capacity based on the results from individual storage projects.

In the SRL system, portfolio level studies of depleted gas fields are placed at a SRL level 2 (cf. Akhurst et al., 2021) although the uncertainty in storage capacity is fairly small, and the availability of data and interpretation would allow depleted gas fields to be matured relatively quickly to higher readiness levels.

Clarification is required as to whether the SRMS and UNFC can be properly applied when individual storage sites are not currently defined as projects. Technically depleted gas fields could classify as prospects within the SRMS because prospects are defined as 'a project associated with undiscovered storable quantities that is sufficiently well defined to represent a viable drilling target'. However, because these gas fields are not defined as projects, in is unclear whether they can be included within the SRMS (cf. Akhurst et al. 2021). The UNFC is similarly project based.

2 Method

For this report, a dataset was generated from different data sources in the mining law DINO archive. This included data from all producing, (temporarily) suspended and abandoned natural gas fields of the Netherlands.

In the DINO data archive, natural fields can be defined by one or more accumulations (reservoirs), typically referring to structural compartments and/or stratigraphic layers. Reservoir properties are generally reported at accumulation level in confidential and non-confidential reports/data, which are submitted to TNO-AGE by operators in accordance with various articles of the Dutch Mining Law, as well as supplementary data for license application and research purposes (cf. TNO, 2018; 2020; 2021; 2023). Historical production data is delivered monthly per well or accumulation, and is usually aggregated at field level.

Parameters	DINO_DB Field	DINO_DB Accumulation	OPVIS_1/2 (TNO, 2018, 2021)	OPVIS_3 (TNO, 2023)	OCTO (TNO, 2020)	RO Aquifer study (TNO, in prep)	Main source data	Comments
Ultimate Recovery - (UR) (bcm)	x			x	x		Art. 34 MBW	Contains confidential data
Cumulative Production (bcm)	x						Art 111 MBB	Historic production (public only from 01/01/2003)
Resources PRMS_RC1 (bcm)	x						Art 113 MBB	Data remains confidential for 10 yr
Depth TVD (m)		x	x	x	x	x	Art 34 MBW	Contains confidential data
Hydrostatic pressure						x		Trend based on lower bound of North Sea hydrostatic data, contains confidential data
Initial gas pressure		x	x	x	x		Art 34 MBW Art 113 MBB	Contains confidential data
COP gas pressure				x	x		Art 113 MBB	Extrapolation from data in Art 133 MBB
COP year	x			x	x		Art 34 MBW	Public
Transmissivity (mD.m)		x	x	x	x			Well test in additional reports, core data, etc. (confidential)

Stratigraphic unit		x			x		Art 34 MBW	Public

Table 2-1 Key parameters used to define storage capacity and injection rates, and the corresponding source data sets. Oil and natural gas operators provide confidential and public data under various articles of the Mining Law (MBW). Most relevant are Article 34 of the Mining Law, which governs the production plans, Article 113 of the Mining Decree (MBB) which governs the reporting of the expected annual production profiles (forecast) until the COP. (COP) Cessation of production.

2.1 Application

Dynamic reservoir simulation is considered unfeasible for portfolio studies because of the large number of fields and the detailed input required. The cumulative production, or the Ultimate Recovery (UR) hydrocarbon volumes is used to estimate the (static) storage capacity with the assumption that gas fields can be re-filled to the original pre-production pressure. This approach has been typically used in CO_2 storage capacity studies at a portfolio level (TNO, 1995, 1997, 2008 and 2020).

2.1.1 Theoretical capacity calculation

Theoretical capacity (CAP_{theo}) for depleted gas fields is determined with a conversion of the Ultimate Recoverable hydrocarbon volume (UR) to an equivalent CO_2 volume.

$$\mathrm{CAP_{theo}} = \mathrm{UR} * y_{\mathrm{COP}} \qquad \text{2-1}$$

With CAP_{theo} expressed in Mt, UR expressed in bcm (in Nm^3 at a pressure of 1,01325 bar and a temperature of 0°C), and y_{COP} representing the CH_4 to CO_2 conversion factor.

In TNO (1995, 1997 and 2008) the conversion factor from the Ultimate Recoverable (UR) volume to the storage capacity (in Mt CO_2) was assumed constant at 2.64 Mt/bcm (in Nm^3). For this report, the conversion factor was estimated based on the PVT (Pressure Volume and Temperature) relationship of both CO_2 and the remaining natural gas in the depleted gas fields. A model-based estimate can be established for the relationship between depth, the COP pressure, and the expected conversion factor (EBN, 2019a; Huijskes et al., 2020). This conversion factor is relatively insensitive to the COP pressure (10 to 60 bar range) but shows a strongly non-linear relationship with depth (Figure 2-1).

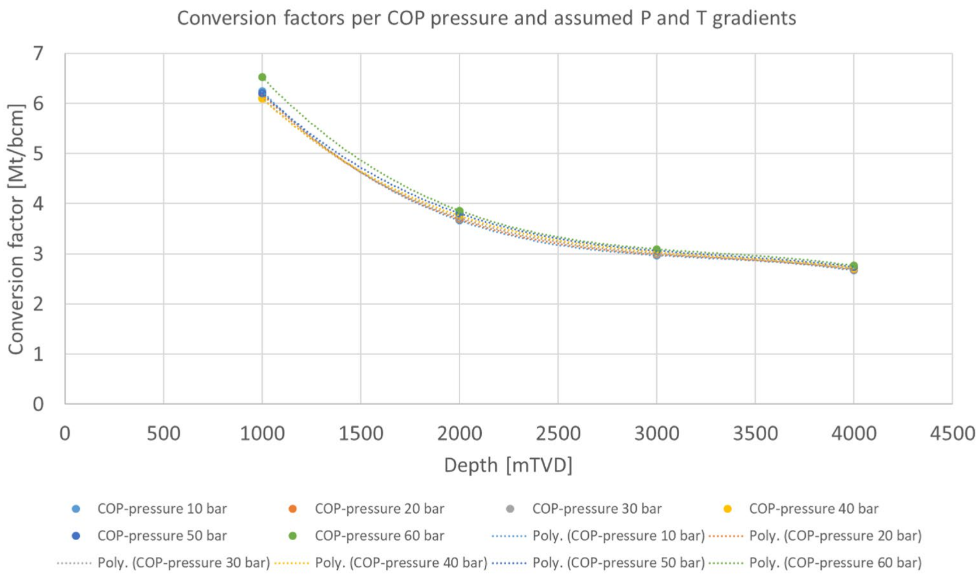


Figure 2-1 Relationship between Conversion factor and depth for various COP pressures. For the assumed pressure and temperature gradients see eq. 2-8 and 2-9.After EBN (2019)

The relationships in (Figure 2-1) can be expressed as third order polynomials:

$$y_{COP=10\ bar} = -0{,}2478\ x^3 + 2{,}4249\ x^2 - 8{,}1131\ x + 12{,}175 \qquad 2\text{-}2$$
$$y_{COP=20\ bar} = -0{,}2339\ x^3 + 2{,}3021\ x^2 - 7{,}7670\ x + 11{,}887 \qquad 2\text{-}3$$
$$y_{COP=30\ bar} = -0{,}2144\ x^3 + 2{,}1290\ x^2 - 7{,}2825\ x + 11{,}484 \qquad 2\text{-}4$$
$$y_{COP=40\ bar} = -0{,}2001\ x^3 + 2{,}0049\ x^2 - 6{,}9475\ x + 11{,}235 \qquad 2\text{-}5$$
$$y_{COP=50\ bar} = -0{,}2051\ x^3 + 2{,}0568\ x^2 - 7{,}1307\ x + 11{,}481 \qquad 2\text{-}6$$
$$y_{COP=60\ bar} = -0{,}2418\ x^3 + 2{,}3949\ x^2 - 8{,}1515\ x + 12{,}521 \qquad 2\text{-}7$$

Here, y_{COP} represents the conversion factor that is calculated for various COP pressures as a function of depth x. Depth is a function incorporating pressure and temperature that both have a significant impact on the PVT behaviour of CO_2 and CH_4. Pressure and temperature gradients have been calculated based on temperature and fluid pressure data sets for the Dutch subsurface in the Southern North Sea (cf. EBN, 2019a).

$$P_{res} = D * 0{,}112 \text{ bar/m} \qquad 2\text{-}8$$
$$T_{res} = 8{,}1765\ °\text{C} + D * 0{,}0318\ °\text{C/m} \qquad 2\text{-}9$$

P_{res} and T_{res} represent the depth and temperature of the reservoir. The methodology incorporates the non-ideal mixing behaviour between pure CO_2 and CH_4 using REFPROP 10.0 (Lemmon et al. 2018; Span and Wagner 1996). The final fluid composition is made dependent on the pressure at the COP, and assumes that reservoir pressure and temperature of the field are in thermal equilibrium (i.e. the situation that will develop over decades).

2.1.2 Effective capacity calculation

TNO (2020) provide an overview of other factors that might significantly affect storage capacity. For the current report these are categorized according to the techno-economical resource classification (Bachu et al., 2007). Additionally, a preliminary screening is done to determine the bandwidth of the potential impact.

Reservoir compaction

Depletion related compaction during gas production decreases the pore volume available for CO_2 storage. The overall compaction consists of an elastic, reversible component, and an inelastic, irreversible component. Laboratory measurements on cores from the Rotliegend Groningen field provide a porosity-compaction trend directly applicable for the offshore fields with similar reservoir characteristics (Roholl et al., 2016). Additionally, it indicates that the inelastic component in the reservoir compaction increases strongly above a porosity of 20%, implying that originally high-quality reservoir streaks and/or fields will suffer most from this effect.

Aquifer influx

During the gas production phase, and the phase between the end of gas production and the start of CO_2 injection, the pore volume of the storage reservoir might decrease due to aquifer influx/expansion. Part of this process might not be reversible on the time scale of CO_2 injection. The gas pressure in the reservoir will have increased accordingly due to the aquifer support, effectively decreasing the amount of CO_2 which can be stored before a maximum pressure is reached. The magnitude of this effect is strongly dependent on both reservoir characteristics and aquifer strength (e.g. Bachu and Shaw 2005). Based on production data, most gas fields in the offshore of the Netherlands can be described as dynamically closed systems with minor aquifer support, hence a limited impact from aquifer influx is expected.

Incomplete penetration of CO_2

Reservoir heterogeneity and quality, and semi-permeable sealing faults can lead to incomplete penetration of injected CO_2 into the depleted reservoir rock on the time scale of CO_2 injection. In pressure depleted reservoirs, volumes associated with e.g. slow-gas production during the production phase of gas fields might not be re-filled during the CO_2 injection phase.

Effects of gas composition on CO_2 density

The current method assumes a pure CO_2 supply for determining the storage capacity, and pure CH_4 as the remaining gas in the reservoir. Impurities in the supply will reduce the storage capacity for CO_2. Additionally, impurities in the CO_2 supply will lead to a lower density related to non-ideal gas mixing behaviour. Similarly, the composition of the natural gas might also have an effect on the mixing behaviour (e.g. Nazeri et al. 2017).

Gravitational separation and mixing processes

The current method models a homogenous mix between CH_4 and CO_2 that in reality will only be achieved in the (very) long term. During injection CO_2 will initially displace the remaining natural gas, implying a gradual transition of non- to partially to homogenously mixed gasses. This will lead to an increase in pressure after injection is ceased due to non-ideal gas mixing behaviour that should be considered in determining at which pressure injection should be stopped.

Final pressure and temperature
The current method assumes reservoir conditions in determining the CH_4 to CO_2 conversion factor. Based on recent projects under development in the Netherlands CO_2 is likely injected 'cold' as compared to reservoir conditions (without preheating on the platform), implying it will take time to achieve thermal equilibrium in the reservoir environment. This process will likely take longer than the injection period and will lead to a gradual pressure increase in the reservoir.

Subject	Reduction factor	Comment
Reservoir compaction	0.98 – 1	Small impact of irreversible compaction based on core data from Rotliegend wells (cf. Roholl et al. 2016)
Aquifer influx	0.97 – 1	Small impact expected for closed systems with volumetrically small aquifers (e.g. most RO and RB fields in the offshore of the Netherlands). Potential range: 0.7 (strong aquifer) – 0.97 (weak aquifer) (Bachu and Shaw 2005)
Incomplete penetration of CO_2	0.8 – 1	Insufficient data available on the efficiency of refilling gas reservoirs with CO_2. Observations of for example 'slow gas' in severely depleted fields, or the discrepancy between static and dynamic volume estimates provide a potential impact estimate (e.g Van Hulten, 2010).
Effects of gas composition on CO_2 density	0.8 - 1	Aramis prescribes a <5% impurity in the CO_2 mixture. Preliminary in-house research indicates a ~20% storage capacity reduction in extreme cases.
Gravitational separation and mixing processes	>0.99	This method assume the end state of homogeneous mixing that in reality will be achieved only after injection is ceased.
Final pressure and temperature	>0.99	Thermal equilibrium assumed that will only be achieved after injection is ceased. Implies a lower 'end of injection' pressure.

Table 2-2 Potential reduction factors for the effective storage capacity.

The initial screening of the technical factors in Table 2-2 suggests that at portfolio level a range of 0.7 – 0.99 could be realistic, which will have an effect on practical capacity estimates. However, the current dataset used in this report does not contain enough field/accumulation detail information to apply these reductions factors. Therefore a generic portfolio-level reduction factor of 0.9 is applied, taking into account that there is a significant range of uncertainty associated with effective capacity.

2.1.3 Practical capacity calculation

Injection cutoff and BHIP limit
CO_2 injection requires a pressure gradient between the injection pressure at bottom hole (BHIP) and the pressure in the reservoir. In current storage projects, the BHIP is limited to the hydrostatic pressure as a preventative measure due to safety concerns. This implies that when the reservoir pressure approaches the hydrostatic pressure, the pressure gradient (the difference between the injection pressure and the pressure in the reservoir) becomes smaller, which reduces the injection rate. Below a certain rate, injection has to be ceased

either for technical reasons (e.g. flow is not constant or stable) or economic viability. In the current report, a cut-off at 0.5 Mtpa was applied.

The consequence of these combined factors is that the hydrostatic pressure (that is already lower than the initial gas pressure) cannot be reached, reducing the storage capacity. How closely a field can approach hydrostatic pressure is controlled largely on reservoir quality. In this report reservoir quality is represented by transmissivity (permeability multiplied by net reservoir thickness). This provides a quantification of the ease of fluid flow through a reservoir and controls the pressure gradient required to inject CO_2 into a reservoir at a certain rate. In good quality reservoirs this pressure gradient is lower than in poor quality reservoirs allowing good quality fields to approach hydrostatic pressure more closely. Relative to the initial pressure this implies a capacity reduction factor of 0.8 – 0.95 for reservoirs with a transmissivity of 0.2 D.m or higher (Table 2-3).

Field size

Small gas fields are economically less viable for CO_2 storage than larger fields since in principle they can store smaller volumes. Therefore, an economic viability threshold can be considered that is partially dependent on field size. EBN & Gasunie (2017) provide economic analyses where the Unit Technical Cost for CO_2 storage sharply rises for fields below the 10 Mt capacity (~ 4bcm). However, TNO (2020) and EBN & Gasunie (2017) included small fields with a storage capacity of respectively >1Mt under specific conditions and >2.5Mt indicating these are considered relevant in optimistic scenarios.

Additional factors determining economic viability such as their location relative to other fields and infrastructure have not been considered in this report.

	Reduction factor	Comment
Injection cutoff and BHIP limit	0.8 – 0.95	0.9 assumed in TNO (2020) Dynamic modeling indicates a reduction factor range of 0.8 - ~0.95 dependent on reservoir quality. <0.2 D.m) cannot be used for CO_2 injection (Bijkerk et al., 2024)
Field size	Cut-off at 1 or 10 Mt	Unit Technical Cost strongly increases below 10 Mt (EBN & Gasunie, 2017)

Table 2-3 Reduction factors for Practical Capacity

2.1.3.1 Practical storage capacity scenarios

Practical storage capacity can change due to e.g. legislative, regulatory and economic boundary conditions. These have a major impact on capacity that is largely independent of the subsurface. Therefore, two scenarios have been used in this report to provide a bandwidth for practical storage capacity.

High-case scenario for practical capacity

- BHIP (Bottom Hole Injection Pressure) limit: BHIP limit is set to hydrostatic pressure (Table 2-3).
- Field size: Field size lower limit is set to 1 Mt (Table 2-3) as very small fields will suffer from poor economic viability. For example, the average annual injection rates in depleted gas fields are expected to vary between ~0.4 to 1.7 Mtpa per well (cf. Section

2.1.5), implying very small fields be filled quickly resulting in a high Unit Technical Cost (e.g. EBN & Gasunie, 2017).

Low-case scenario for practical capacity

- BHIP (Bottom Hole Injection Pressure) limit: BHIP limit is set to hydrostatic pressure (Table 2-3).
- Field size: Field size lower limit is set to 10 Mt (Table 2-3).
- Stratigraphic unit: This case only includes reservoirs from the Rotliegend (RO*), and Lower Triassic (RB*) strata. These represent the most important hydrocarbon producing intervals, and hence the key intervals for CO_2 storage in depleted gas fields. They also represent well-documented, deep stratigraphic units, typically covered by good quality sealing units such as the Zechstein and Rot salt sequences (Figure 3-2).

2.1.4 Preliminary analyses on spatial interference

The current data has not been analysed spatially to define or refine reduction factors regarding practical capacity. In future studies, spatial analysis could be used to refine economic viability, for example by analysing the proximity of depleted gas fields to relevant CO_2 infrastructures.

The expected surface activities defined in the North Sea spatial planning strategy, associated with the North Sea Programme 2022 – 2027 (IenW, 2022), form another important spatial factor. The offshore of the Netherlands has a high intensity of surface activities, with potential ramifications for the realisation of CO_2 storage projects.

Areas allocated for wind parks are intended for combined use including subsurface activities (IenW, 2022). This however would benefit from early engagements to ensure subsurface accessibility. In nature reserves and fishing areas, other activities must comply with specific framework conditions and rules (IenW, 2022). In shipping lanes including a 500 m buffer zone, permanent constructions such as platforms are not allowed. Similarly, fixed objects such as platforms or windfarms are not allowed within military areas (IenW, 2022).

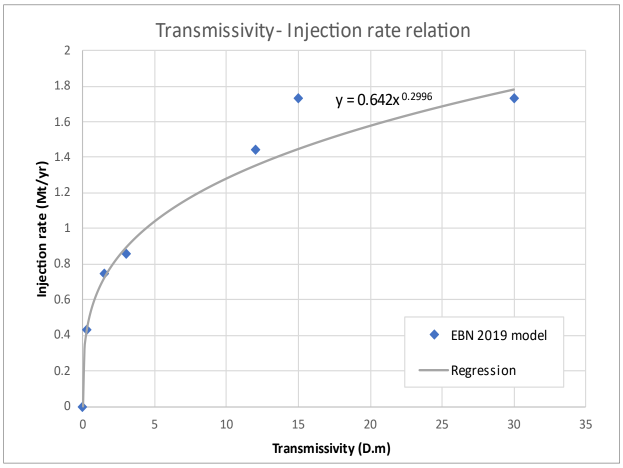
The spatial overlap between activities in the North Sea spatial planning strategy has been analyzed to determine the potentially impact on the CO_2 storage capacity using the intersection tool in ArcGIS PRO (version 3.2.0) including all fields that have a full or partial overlap. The spatial overlap was established between WFS server shapefiles of gas fields outlines projected at surface level (TNO, 2024) with various other surface activities (cf. Section 3.2). These were Natura 2000 areas, shipping areas consisting of the shipping lanes and mooring areas, military areas and wind parks (Geoserver, 2024). The wind park are subdivided into areas that are in-use, under construction and planned (Noordzeeloket, 2024).

The impact of surface activities on the storage capacity will depend on the specifics of the surface activity. Additionally, some storage sites might for example be accessed by e.g. a deviated well. Due to these complicating considerations, surface activities are not included as reduction factors for the practical capacity in this report. Instead for each surface activity the impacted practical storage capacity is calculated to indicate their relative importance.

2.1.5 Injectivity calculation

The Porthos CCS project incorporates different filling rates for gas-phase and dense-phase flow to reduce the chance that undesired thermal and geomechanical effects occur. Additionally, the current wells are repurposed for CO_2 injection, resulting in a dependency on present-day infrastructure for the injectivity estimate. This has lead the TNO (2020) study to incorporate a 'prefill phase' with gaseous CO2 implying a lower injection rate, and to make the field-level injectivity rate dependent on the number of pre-existing wells. However, more recent storage applications do not incorporate a gas-phase injection period with lower injection rates. The current expectation is that operators will generally attempt to ramp up injection rates within a half year to achieve a field-level injection plateau of ~15 yrs based on the duration of the current SDE++ subsidy scheme, and will adjust the injection rate per well, and number of wells per field accordingly. The current study will therefore not assume a gas-phase injection period with lower injection rates.

Injection rates are dependent both on the well design and reservoir parameters. In this report we assumes a tubing diameter that is in line with the reservoir quality, such that the well design does not form a limiting factor (EBN, 2019b). The key reservoir parameters influencing injectivity rates are the reservoir pressure evolution during injection and the transmissivity (kh), ie. permeability multiplied by the net reservoir thickness. EBN (2019b) provided an injectivity estimate based on modeling for transmissivity values of between 0.3 to 30 Dm, and reservoir pressures between 20 to 350 bar. In EBN (2019b) injection rates decrease with increasing pressure, and injection rates decrease with decreasing transmissivity. The pressure dependency is simplified by averaging the injection rate over the injection period, resulting in a relation depending only on reservoir quality (Figure 2-2).



Kh (D.m)	Maximum injection rate per well (Mtpa)
0.3	0.43
1.5	0.75
3.0	0.86
12	1.44
15	1.73
30	1.73

Figure 2-2 Data points from EBN (2019b) indicating the relation between injection rate in Mtpa, and transmissivity in D.m. Power law regression of this data provides an approximation for the applicable transmissivity range.

Injectivity is calculated by assuming a constant injection rate, and is based on a power law regression of the data from EBN (2019b).

$$I_{well} = 0.642 * k.h^{0.2996} \qquad 2\text{-}10$$

With I_{well} representing the Injection rate per well (Mtpa), and where k.h is the transmissivity of the reservoir (D.m).

2.1.6 Portfolio injection capacity profile

Injection rate per well, based on transmissivity data are combined with the storage capacity per field to determine the number of wells per field, and field-level injection rate. Subsequently, these are aggregated to estimate the potential development of the annual CO2 injection capacity at portfolio level.

For this purpose, two required key assumptions are involve the number of included fields (cf. Section 2.1.3.1), as well as the moment in time these fields become available for CO_2 injection. In this report, the start date of CO_2 injection is based on the COP date reported in the production plan (Art 34 MBW). Fields with a COP date in the future, will be converted into an CO_2 storage sites 5 years after this date. Fields with a past or present COP data, can start CO_2 injection in 5 years time.

Projects that are currently in the storage license application process typically >5 year preparation and application process (e.g. Akhurst et al., 2021), but this duration is here assumed to reduce for future storage projects. An additional assumption is made that ~85% of capacity is injected during a ~15 year plateau, with the remainder at decreasing rates over the subsequent 10 years.

The injection duration per field when using one injection well is calculated with:

$$I_{1well\ duration} = 0.85 * CAP_{prac} / I_{well} \qquad 2\text{-}11$$

With $I_{1well\ duration}$ in years, and CAP_{prac} representing the practical capacity in Mt, and I_{well} representing the Injection rate per well (Mtpa). The assumption of a 15 year plateau is used to derive the number of required wells.

$$\#_{Wells} = I_{1well\ duration} / 15 \qquad 2\text{-}12$$

The outcome of equation 2-12 is rounded to an integer ($\#_{Wells\ Int}$), with small fields at least containing 1 well. Based on the rounded number of wells, the duration of the plateau is adapted from the initial 15 years by dividing the plateau injection capacity (85% of the practical capacity) by the field-level injection rate.

$$I_{plateau\ duration} = 0.85 * CAP_{prac} / \#_{Wells\ Int} * I_{well} \qquad 2\text{-}13$$

The outcome of equation 2-13 is rounded to an integer $I_{plateau\ duration\ Int}$), after which the volume injected during the plateau is recalculated.

$$I_{plateau\ capacity} = \#_{Wells\ Int} * I_{well} * I_{plateau\ duration\ Int} \qquad 2\text{-}14$$

With $I_{plateau\ duration\ Int}$ in years, and $I_{plateau\ capacity}$ in Mt. Two thirds of the remaining capacity is injected in the successive 5 years and one third in the final 5 years.

$$I_{field.tail\_1\text{-}5} = 2/3\ (CAP_{prac} - I_{field.plateau\ capacity}) / 5 \qquad 2\text{-}15$$
$$I_{field.tail\_5\text{-}10} = 1/3\ (CAP_{prac} - I_{field.plateau\ capacity}) / 5 \qquad 2\text{-}16$$

With $I_{field.tail\_1\text{-}5}$ and $I_{field.tail\_5\text{-}10}$ in Mtpa.

3 Results

3.1 Capacity

3.1.1 Theoretical capacity results

Theoretical capacity is calculated for all offshore fields separately, and subsequently aggregated according to various categories such as reservoir quality, the stratigraphic level, field size and field production status that are used to inform decisions regarding the effective and practical capacity.

- At portfolio level, the theoretical capacity obtained for the commercially nearly depleted offshore gas fields in The Netherlands is ~2860 Mt in 218 fields (Figure 3-1).
- Field status indicates the current status of the gas field. Producing fields are the largest category (Figure 3-1). Therefore, CO_2 storage within these fields implies either a delayed start of CO_2 injection, or a lower hydrocarbon recovery if these fields are re-developed for CO_2 storage before the expected COP date. Meanwhile, these fields are actively managed, implying up-to-date knowledge that would facilitate an efficient conversion to CO_2 stores.
- Stratigraphic group data shows that the Rotliegend (RO*), and Lower Triassic (RB*) represent the key hydrocarbon producing intervals, and hence the key geological formations for CO_2 storage in depleted gas fields. The Rotliegend and Lower Triassic reservoirs represent deep stratigraphic units, typically covered by good quality sealing units such as the Zechstein and Rot salt sequences (Figure 3-1).
- It is noted that for aquifers, CO_2 storage potential might be significant (e.g. TNO, in prep).
- Reservoir quality represents a key metric for CO_2 storage and can be represented by transmissivity (permeability multiplied by reservoir net thickness). It provides a quantification of the ease of fluid flow through a reservoir. A majority of the depleted gas field portfolio falls within the fair (0.5 – 1 D.m) to good reservoir quality (>1 D.m) (Figure 3-2).
- A subset of the depleted gas field dataset currently does not contain transmissivity data (81 fields with ~515 Mt theoretical capacity) (Figure 3-2).
- Field size represents another key metric for CO_2 storage. Fields are aggregated in categories of <5 Mt, >=5 - <10 Mt, >=10 - <30 Mt, and >=30 Mt. A large majority of depleted gas fields is larger than 10 Mt (Figure 3-3).

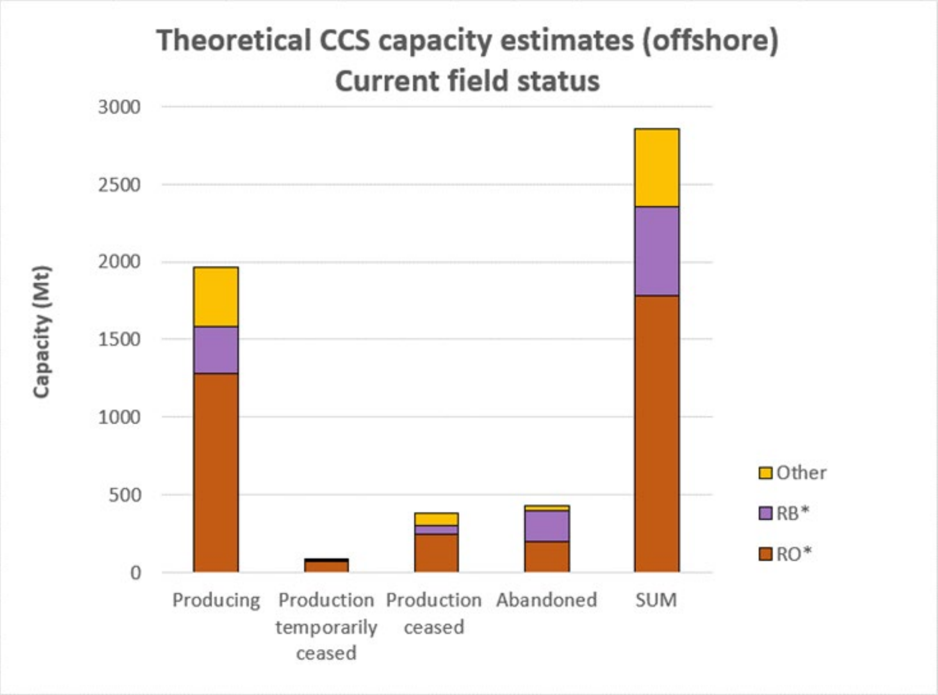


Figure 3-1 Theoretical capacity, categorized according to field status as of 2023. Colours indicate the key stratigraphic reservoir intervals (group level): Rotliegend (RO*) and Lower Triassic (RB*). SUM indicates the total Theoretical storage capacity.

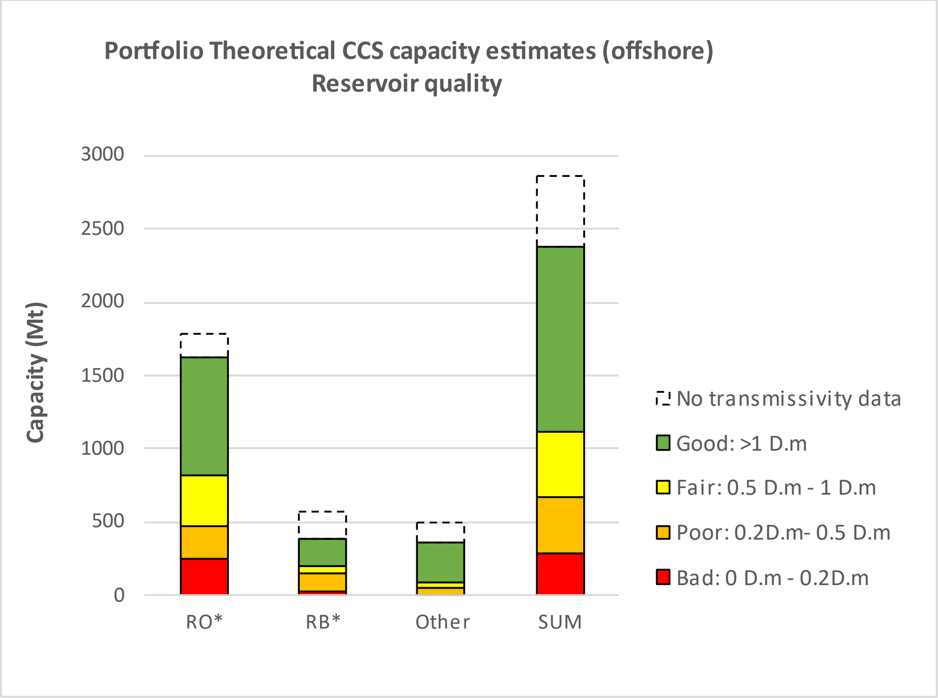


Figure 3-2 Theoretical capacity, categorized according to stratigraphic reservoir intervals. Colours indicate the transmissivity as proxy for reservoir quality. SUM indicates the total Theoretical storage capacity.

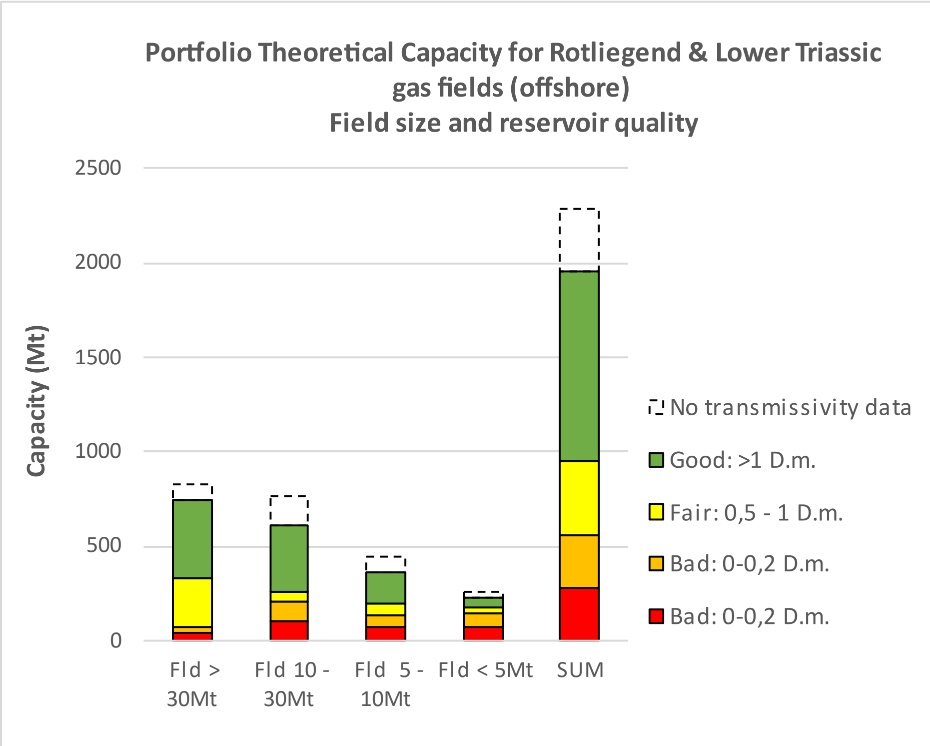


Figure 3-3 Theoretical capacity for Rotliegend and Lower Triassic reservoirs, categorized according to field size, with large fields (>30 Mt) and moderate size fields (10 – 30 Mt) considered the most likely fields for CO_2 storage. Colours indicate the reservoir quality. SUM indicates the total Theoretical storage capacity in the Rotliegend (RO*) and Lower Triassic (RB*) reservoirs.

3.1.1.1 Key assumptions impacting theoretical capacity

- Condensate fields, and oil fields are not considered in this report, but could be potential candidates for CO_2 storage sites.
- Theoretical capacity is intended to capture the maximum capacity. The current method assumes that fields are repressured to the initial natural gas pressure. Technically, some fields might be able to be repressured to a higher geomechanical limit. This has not been evaluated.
- Fields not (yet) in production have not been included as these do not have storage capacity below the initial natural gas pressure.
- All offshore natural gas fields that have been produced are currently incorporated in this report, including those that have been abandoned and might have become less suitable since that time, for example through aquifer influx.

3.1.2 Effective capacity

- Effective capacity is estimated here by applying a generic 0.9 multiplier to the entire depleted gas field portfolio (Figure 3-4). This results in an effective capacity of ~2570 Mt in 218 fields.

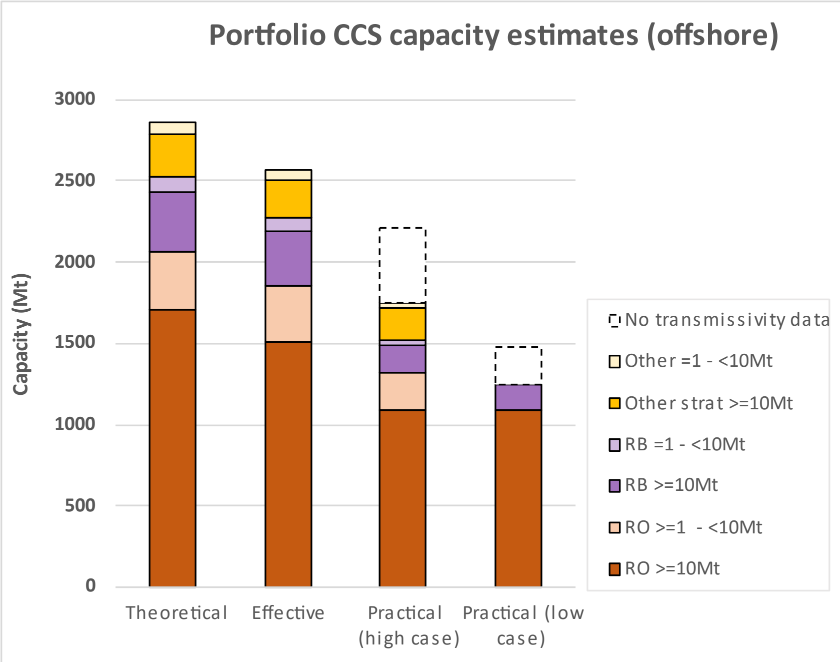


Figure 3-4 CO_2 storage capacity categorisation according to techno-economical resource classification.

3.1.2.1 Key assumptions impacting effective capacity

- Reduction factors acting on effective capacity are field specific, but are currently estimated by using a generic reduction factor of 0.9. Further detailed work is required to quantify the effects of the underlying technical factors at a field-specific level (cf. Section 2.1.2).

3.1.3 Practical capacity

A high- and a low-case practical capacity estimate scenario is given, and differentiated by additional cut-offs for the low- case. The use of a low- and high-case for practical capacity is intended to capture the associated uncertainty range (cf. Section 2.1.3).

- High case practical capacity is derived from the effective capacity using a 1 Mt storage capacity cut-off, and the hydrostatic BHIP reduction factor. It currently contains ~1750 Mt in 124 fields. In addition, this could be increased with a ~460 Mt effective capacity in 64 fields for which the dataset currently contains no transmissivity value.
- The <1Mt field size limit in the high-case capacity excludes 17 fields with a combined effective capacity of 7 Mt.
- The low case practical capacity is derived from effective capacity using a 10 Mt capacity cut-off, the BHIP reduction factor, and is limited to the Rotliegend and Lower Triassic reservoirs. It contains ~1260 Mt in 46 fields. This could potentially be increased with a ~230 Mt effective capacity in 9 fields for which the dataset currently contains no transmissivity value (Figure 3-4; Figure 3-5).
- Because only middle (>=10 – <30 Mt) to large fields size (>=30 Mt) are included in the low-case, it contains relatively large volumes compared to the number of required fields.

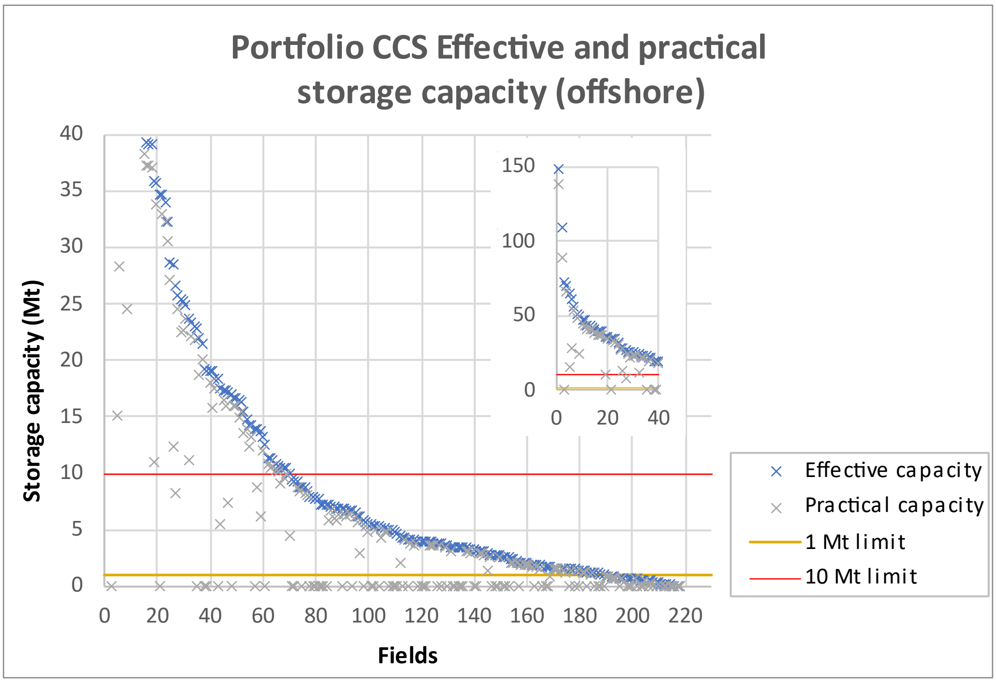


Figure 3-5 Effective and practical storage capacity of individual fields. Inset shows the fields with a higher than 40 Mt storage capacity. Practical storage capacity at 0 Mt, or at approximately half the effective capacity correspond to fields with incomplete data. Note the large number of fields between the 1 – 10 Mt storage capacity.

3.1.3.1 Key assumptions impacting practical capacity

- It is emphasised that these capacity values depend on the reduction factors applied to the 'practical capacity', and might change substantially as they reflect regulatory decisions and economic constraints.
- A subset of the depleted gas fields in the dataset currently contains no transmissivity values (Figure 3-2). Addressing this gap in the data set will increase the practical storage capacity estimates.

3.2 Spatial distribution of CO_2 storage capacity

Offshore storage capacity is concentrated in the P blocks (Porthos), and the K&L blocks (Aramis) (Figure 3-6). This report does not incorporate spatial factors or surface constraints as reduction factors for practical capacity. However, the spatial planning on the North Sea potentially has major implications for the potential use of the subsurface. Shipping lanes, wind parks, nature reserves, and military areas might all restrict the accessibility to CO_2 storage sites and will benefit from early engagement with the relevant authorities and regulatory bodies to optimise the development of activities. A preliminary estimate is given regarding which part of the potential CO_2 storage portfolio might be affected by surface criteria by examining the spatial overlap.

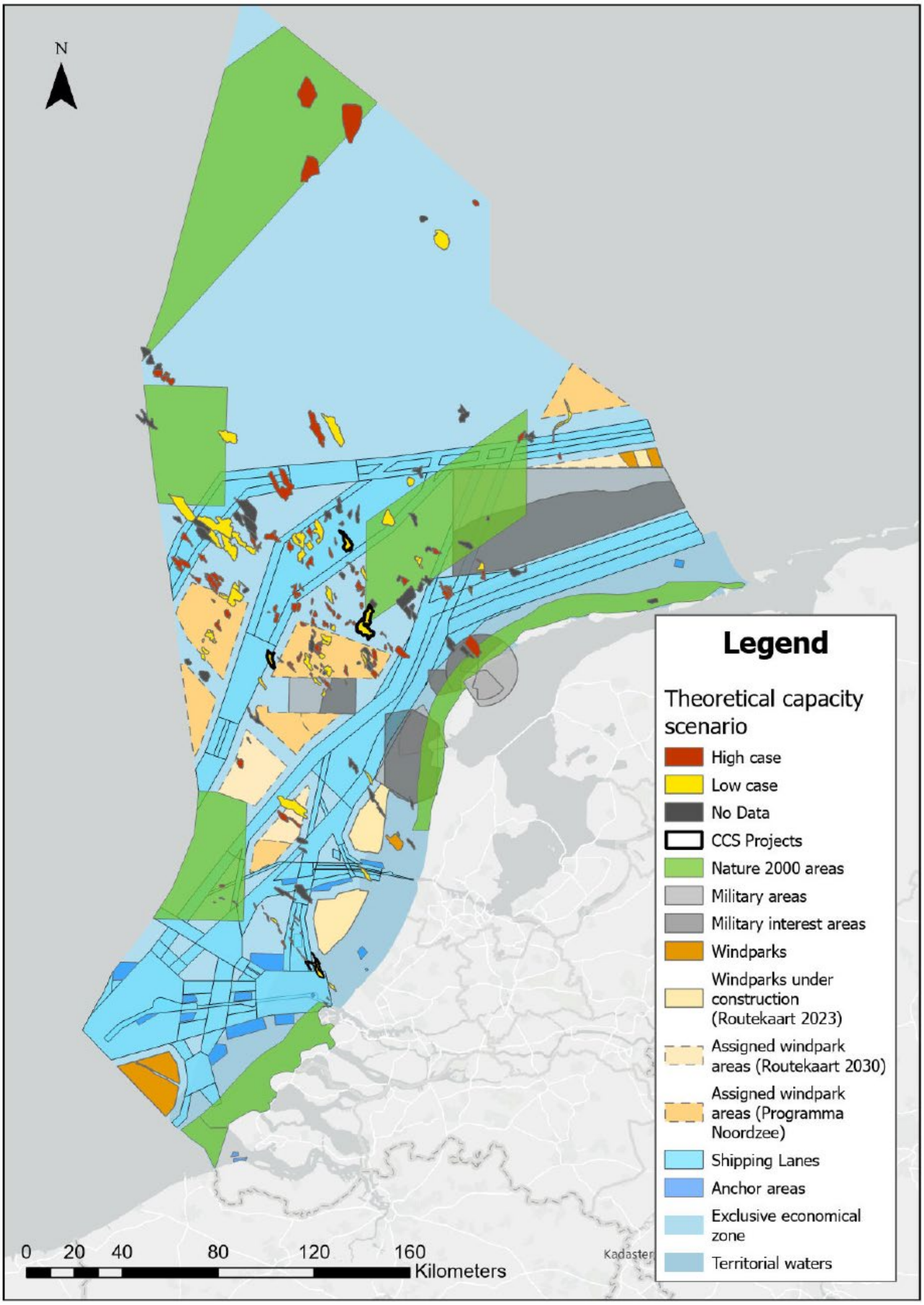


Figure 3-6 Map-based visualisation of high- and low-case practical storage sites. Background indicates the current North Sea spatial planning strategy, associated with the North Sea Programme 2022 – 2027 (IenW, 2022). Note that only producing, (temporarily) suspended and abandoned natural gas fields have been included in this report. Fields not (yet) in production have not been included as these do not have storage capacity below the initial pressure.

	Low case				High case			
	Capacity (Mt)	Fields (#)	No transm. data: CAPeff (MT)	No transm. data: Fields (#)	Capacity (Mt)	Fields (#)	No transm. data: CAPeff (MT)	No transm. data: Fields (#)
Total capacity	1260	46	230	9	1750	124	460	64
No surface activity	310	14	145	5	430	49	240	38
Nature reserves 2030	200	6	20	1	370	14	75	18
Wind parks 2030	400	11	45	2	480	30	80	11
Military areas 2030	75	3	0	0	110	8	5	3
Shipping areas 2030	375	16	20	1	500	33	75	14

Table 3-1 Low- and high-case practical capacity with potential surface restrictions based on the North Sea spatial planning strategy.

- Only a small fraction of ~310 – ~440 Mt (low- and high-case practical capacity) is not constrained by a partial overlap with surface activities.
- Areas allocated as Natura2000 reserves, and (planned) wind parks contain an additional 600 – 850 Mt (low- and high-case practical capacity) that requires early engagements and might be impacted by additional rules and conditions.
- Military areas and shipping lanes could affect an additional 450 – 600 Mt (low- and high-case practical capacity).

3.3 Temporal development of CO_2 storage capacity

Storage capacity is not available directly because it requires a technical, administrative and constructional efforts per storage site. Hence it is considered likely that storage capacity will develop gradually over the coming decades. The simplifications how this is captured for the current portfolio study are described in Section 2.1.6. It is emphasised that the current profiles for the low- and high-case practical capacity scenarios should be seen as a visualisation to highlight potential concerns.

- Both low- and high case practical scenarios assume that capacity is ramped up as quickly as possible given the ambitious EU targets of creating storage capacity. The actual development for storage demand by CO_2 emitters, and the concurrent development of storage capacity is uncertain.
- For the low case practical scenario, yearly storage capacity could be added from 2029 onwards starting with 10 fields and increase to ~60 Mtpa in 2039 – 2044 with ~40 fields, after which growth in storage capacity would gradually decrease (Figure 3-7).
- For the high case practical scenario, storage capacity ramps up more quickly compared to the low-case scenario because it incorporates more fields with a past or current COP data (52 fields in 2029). Yearly capacity increase has a broadly similar pattern but has

higher values with a peak at ~90 Mtpa. Additionally, storage capacity peaks at >80 Mtpa in 2039 – 2044 in ~120 fields, after which growth in storage capacity would gradually decrease (Figure 3-7).

- In line with the overall capacity categorisation, currently producing fields represent a large fraction of the overall storage capacity. Because these fields have a COP date in the future, they initially represent a small fraction of the yearly capacity increase within the portfolio (Figure 3-7).

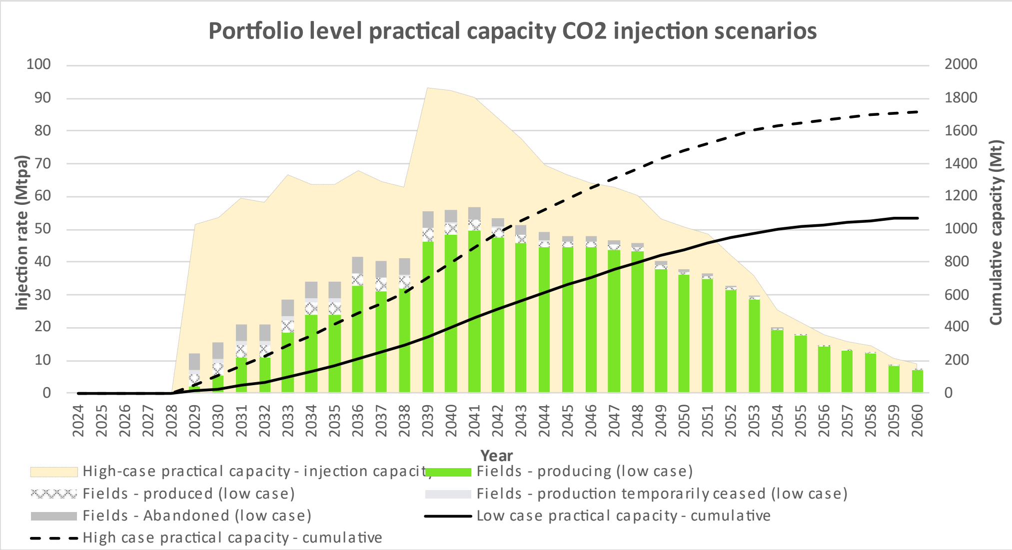


Figure 3-7 Development of yearly and cumulative storage capacity over time, based on the low- and high-case practical storage capacity of ~1260 Mt and ~1750 Mt respectively.

3.3.1.1 Key assumptions impacting temporal development of storage capacity

- The current portfolio injection profile is strongly simplified. One of the key assumptions is that fields will be converted to CO_2 storage locations 5 years after the COP date.
- However, the fields that are currently in the license application process, are producing fields with a future COP date. The Aramis and Porthos project both start with large nearly depleted gas fields upon which the CO_2 transport infrastructure is based. Subsequently, nearby fields (including smaller fields) might be incorporated into these projects.
- The low- and high-cases injection profiles start in 2029 with 10 and 52 fields respectively (Table 3-1; Figure 2-1). Particularly the high-case is here regarded as extremely optimistic, assuming a streamlined license application process without any obstructions, no delays in construction and injecting into small fields that might turn out to be non-economically viable.

4 Discussion

4.1 Portfolio comparison to current status

The development of storage capacity is compared to the current project specific development of offshore CO_2 transport, CO_2 storage capacity (Figure 4-1).

The Porthos project is post-FID and has the intent to transport and store CO_2 at a 2.5 Mtpa rate from 2026 onwards. The Aramis project is pre-FID and has the intent to transport up to 22 Mtpa, commencing in 2029. Currently, 3 additional offshore storage projects are in pre-FID phase and combinedly have a ~10 Mtpa storage capacity that will be supplied by the Aramis pipeline. This implies that at this moment ~12.5 Mtpa storage capacity is in the license application process.

- At combined 24.5 Mt annual storage capacity, Porthos and Aramis can contribute substantially to the 50Mtpa EU goal for 2030 defined in the NZIA (EU, 2024).
- The EU goal of 550 Mtpa CO_2 usage or storage for 2050 will require substantially larger transport and storage capacity systems under the assumption that a significant percentage will have to be stored permanently in the subsurface (EU, 2024).
- With a ~10 Mtpa capacity in pre-FID projects the Aramis pipeline is only at partial capacity. Before 2030, an additional storage capacity at a rate of ~12 Mtpa should be applied for, and receive storage licenses to achieve full capacity (Figure 4-1).
- The low- and high-case practical scenarios demonstrate that the majority of the potential storage capacity is located in a fairly small number of large fields (cf. Figure 3-3; Figure 4-1).
- The low case practical scenario does not ramp up at a sufficient rate to supply the Aramis project at full capacity. The high case scenario would be able to supply sufficient storage space but is considered unrealistic because it requires connecting many small fields and therefore the execution of many simultaneous projects. Similar to the storage sites for the current Aramis launch phase, additional large fields in the vicinity of the Aramis infrastructure and potentially still producing, are required to provide sufficient storage capacity for the Aramis growth phase. This might necessitate choosing between the intent to accelerate natural gas production on the North Sea and reaching the CO_2 storage capacity goals.
- Overall, the low case practical scenario suggests that the potential availability of storage capacity is higher than current transport capacity. This is further amplified in the high-case scenario, or by incorporating other storage types e.g. aquifer storage.
- However, it is noted that the current cases do not incorporate surface constraints and might suffer from further reductions related to e.g. interference of other spatial uses. Only a small fraction of ~310 – ~440 Mt (low- and high-case practical capacity) is not constrained by a partial overlap with surface activities.
- Additionally, achieving and subsequently maintaining storage capacity at the currently projected transport capacity of 24.5 Mtpa will require a continuous addition of new storage sites.
- To ramp up the injection volume at a sufficient rate, an emphasis needs to be placed on the larger fields that are potentially still on production.

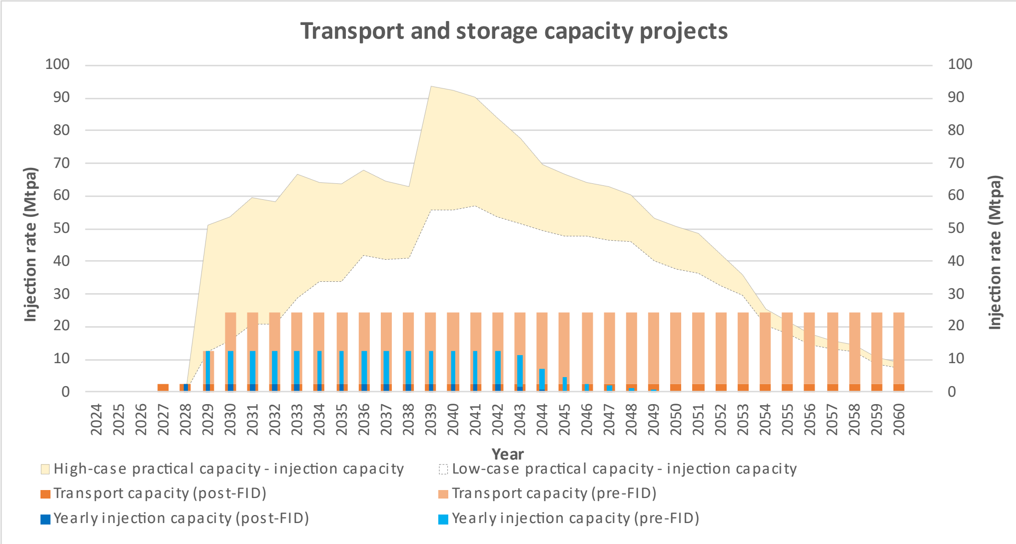


Figure 4-1 Comparison of firm transport and storage projects, and the low and high case storage capacity development

4.1.1 Aquifers

A potentially major positive factor that can affect the offshore CO_2 storage capacity in the mid- to long term is the addition of CO_2 storage capacity in aquifers (TNO, in prep). The quantification of these volumes is less mature but the preliminary estimated volumes are substantial . For example, the theoretical CO_2 storage capacity in only the Rotliegend aquifers varies stochastically between ~1000 Mt and ~3650 Mt (P10-P90 range, TNO, in prep). This implies that the overall offshore storage potential is larger than the ranges for depleted gas field storage documented in this report. However, whether this theoretical aquifer capacity is viable depends on further analysis and regulations regarding e.g. bottom hole pressure constraints and the ability to coordinate effectively with other (surface) activities in the North Sea.

4.1.2 Robustness of capacity estimates

The current results provide an initial insight into the storage capacity of nearly depleted offshore natural gas fields in the Netherlands, and is intended to support policy- and decision-makers and address the EU reporting obligations. The capacity estimates are in line with previous studies such as EBN and GasUnie (2017) that reported a 1678 Mt practical capacity in 104 fields, and TNO (2020) that predicted an available capacity of 1100 Mt in 2030, which increases to a maximum of ~1600 Mt in 2036.

The storage capacity as determined in this report are dependent on many factors. Improvements in the underlying data is expected have a minor impact, for example by reducing the fields with missing transmissivity data, and will be incorporated in updates to this report. Improvements in the methodology particularly regarding the factors impacting effective capacity can have a substantial, mostly negative, effect on the storage capacity that should be captured stochastically. An additional large and positive impact on theoretical capacity is expected from the inclusion of aquifer capacity data.

Developments in offshore natural gas production, and the experiences gained during development of the first CO_2 storage sites can have large, difficult to predict impact. Additionally, results can vary dependent on regulatory decisions and choices regarding e.g. the spatial planning. Therefore, it is recommended to regularly update the CO_2 storage capacity at portfolio level.

5 Conclusions

This report and the underlying analyses were prepared in anticipation of a request for advice from the Ministry (KGG) regarding the portfolio level CO_2 storage capacity in offshore depleted gas fields. It intends to support policy- and decision-makers on the emerging CCS industry, and addresses EU reporting obligations under the Net Zero Industry Act (NZIA). This report provides an initial assessment of the offshore storage capacity in (nearly) depleted natural gas fields, its temporal development at a portfolio level, and a comparison to the currently ongoing CO_2 storage projects.

The storage capacity in depleted natural gas fields is calculated following the resource pyramid methodology to arrive at a preliminary practical capacity that can be used for policy decisions, which falls in a range of 1260 – 1750 Mt. Theoretical capacity, i.e. the physical maximum CO_2 storage capacity in depleted natural gas fields is estimated at ~2860 Mt. Effective capacity, incorporating reductions related to various geotechnical and engineering criteria is estimated at ~2570 Mt. These criteria are still under evaluation and could negatively impact capacity. To determine a preliminary practical capacity range, i.e. incorporating economic and legislative criteria a high- and low-case scenarios were determined. In the high-case the practical storage capacity is ~1750 Mt in 124 fields with an ~460 Mt addition in 64 fields for which not all data is yet incorporated in the data. The low-case practical capacity is ~1260 Mt in 46 fields with a ~230 Mt potential addition in 9 fields. These practical cases demonstrate that the majority of practical storage is found in a limited number of moderate to large capacity storage sites.

The low-case practical capacity shows that with conservative estimates regarding the bottom hole injection pressure limit, use of the well-known Rotliegend and Lower Triassic stratigraphic units, and individual store size, the offshore of the Netherlands contains substantial storage capacity in depleted natural gas fields. If all these fields are developed as storage sites they could provide sufficient capacity to maintain a 24.5 Mtpa rate calculated for the Porthos and Aramis CO_2 transport networks to beyond 2050. However, it would requires large, currently producing fields in the vicinity of the Aramis pipeline to be converted to storage sites to ramp up production at a sufficient rate in the early phase. This contradicts the standing policy intended to accelerate the offshore natural gas production.

Additionally, the practical capacity estimates do not incorporate limitations to spatial planning and surface activities. An preliminary screening of the overlap between surface activities and depleted gas field locations shows that this might have a negative impact on the realisation of many of the potential CO_2 storage sites. In the low- and high-case practical capacity scenarios, respectively ~310 and ~440 Mt are not located in areas designated for surface activities. Realization of the storage sites in restricted areas will require early engagements with the relevant stakeholders. The development of CO_2 storage project in aquifers might depend on legislative and regulatory choices, add substantial storage capacity, but will be similarly affected by restrictions due to surface activities.

In the high-case practical scenario 124 fields are included as storage sites. Increasing the practical storage capacity beyond the 46 storage sites included in the low-case capacity would imply significantly increasing the number of, mainly smaller depleted gas fields. The larger number of individual storage projects will requires a significant effort to ramp up CO_2 storage capacity but will also allow the Netherlands to store a larger portion of the CO_2 storage goals defined under the NZIA.

6 Recommendations & Remarks

6.1 Future work

Data

The current available data has several limitations. When these limitations will be resolved the completeness and accuracy of the results are expected to improve.

- Addressing gaps in the data sets: particularly transmissivity data that is required for calculating the impact of limiting the BHIP. This is missing for 81 fields.
- The report currently uses a North Sea specific hydrostatic pressure trendline in depth. Addition of more extensive datasets containing depth-referenced hydrostatic-, gas- and lithological pressure data will improve the assessment of pressure restrictions to storage capacity.
- COP date: currently a initially expected COP date from the production plans is used while this can change during the production period. This static date can be replaced with a COP date based on the production forecast that is delivered yearly as part of Article 113 reporting.
- Ultimate Recovery and Cumulative Production volumes are most robustly reported and recorded at hydrocarbon field level, while reservoir properties are reported at accumulation level. Currently, volumes are split equally among accumulations if a field consists of multiple accumulations. This assumption can be replaced with a more realistic subdivision.

Methodology

- Theoretical capacity: Cumulative Production could be used instead of Ultimate Recovery to resolve some of the concerns regarding confidentiality. It would additionally imply that the portfolio capacity becomes dependent on the currently produced hydrocarbon volumes, rather than the anticipated ultimate production at the COP.
- Effective capacity: Investigate the field specific impact of key reduction factors that are briefly mentioned in this report but not yet integrated by implementing stochastic ranges or multiple deterministic scenarios. This could be further improved by adopting similar basic dynamic analyses as previously for underground gas storage, and underground hydrogen storage (e.g. Juez-Larré, 2016; 2019)
- Practical capacity: Include spatial and economic analyses and create notional development plans and economic screening of these scenarios. For example the field size cut-off in reality will be dependent on the location. Small fields adjacent to a large CO_2 store might be viable whereas a solitary small field is not. Similarly, there could be synergies between CO2 storage in depleted gas fields and aquifers.
  Development of storage capacity: currently assumptions governing the rate at which storage capacity is developed is very basic and controlled only by the COP year, and could be improved with a more realistic assessment incorporating additional factors such as spatial clustering, limiting the number of simultaneous projects, spatial analyses etc.

Synergies

- Inclusion of aquifer storage capacity
- GSEU CO_2 capacity atlas: The GSEU is undertaking an effort to develop a European CO_2 capacity atlas that has largely similar goals as the current report.
- NZIA legal reporting requirements: currently, the reporting requirements for the NZIA are unclear. Once these are clarified reporting can be adapted. This might include for example:
  - Injection forecasts or changes herein, such as currently determined in Art 113 MBB for conventional oil and gas production.
  - Specification of the reporting standard or classification system. The SRMS is closest to the PRMS reporting standard commonly used by the hydrocarbon industry, while there is a strong EU focus on the implementation of the UNFC for e.g. Critical Raw Materials.

SIGNATURE

Utrecht, 25 Februari 2025

N.H. (Nico) Zornig

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