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Original Paper

Reconnaissance Survey for Potential Energy Storage and Carbon Dioxide Storage Resources of Petroleum Reservoirs in Western Europe

Emil D. Attanasi[1,2] and Philip A. Freeman[1]

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Energy producers and utilities use oil and gas reservoirs for gas storage to meet peak seasonal demand or to supplement intermittent energy production. These reservoirs are also suitable for the long-term storage of carbon dioxide (CO_2), a greenhouse gas. This study reports on a reconnaissance analysis of the potential magnitude of storage resources in 9424 known oil and gas reservoirs from 24 countries within highly industrialized western Europe. To standardize the storage resources of the oil and gas reservoirs, their volumetric capacity is expressed in terms of metric tons (mass) of CO_2. Estimates of recoverable oil and gas at the surface are converted to subsurface volumes and then converted to the equivalent mass of CO_2 at reservoir conditions. The results indicate 36.7 gigatons of CO_2 could be stored, with oil reservoirs accounting for 32% of that total and natural gas reservoirs comprising the remaining 68%. About four-fifths of the reservoir storage resource is offshore, with about three-fourths of that offshore resource at water depths of 200 m or less. Most countries do not have the reservoir storage resources to store 15 years of CO_2 at 2017 emission levels. With few exceptions the bulk of the storage is offshore for countries that do have at least 15 years of storage. The expansion of natural gas storage for strategic purposes in abandoned onshore gas reservoirs is not expected to seriously impact CO_2 storage. The contribution of this analysis is the description of the spatial distribution of potential storage and physical accessibility.

KEY WORDS: CO_2 subsurface storage resource, Petroleum reservoirs, CO_2 emissions, Natural gas storage, Europe.

INTRODUCTION

Energy producers and utilities use oil and gas reservoirs for natural gas storage to meet peak seasonal demand or to supplement intermittent energy production (Platt, 2009). Governments may use depleted oil and gas reservoirs for strategic petroleum storage in the event of national emergencies. Petroleum reservoirs may also be suitable for the long-term storage of carbon dioxide (CO_2), a greenhouse gas (Bump et al., 2022). The use of these reservoirs for storage is appealing because data that characterize the reservoir properties have already been collected, analyzed, and generally preserved by producers and regulatory agencies. Moreover, their original structural integrity is demonstrated having previously held hydrocarbon fluids.

Anthonsen and Christensen (2021) summarize recent studies relating to the potential for CO_2 geologic storage (sequestration) in the European

[1]U.S. Geological Survey, 12201 Sunrise Valley Drive, Mail Stop 954, Reston, VA 20192, USA.
[2]To whom correspondence should be addressed; e-mail: attanasi@usgs.gov

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Union (EU). The earliest studies (Holloway, 1996; Christensen and Holloway, 2004) include partial subsets of the countries. The EU GeoCapacity Project (Vangklide-Pedersen, 2009) includes regional saline aquifers as potential CO_2 storage reservoirs, oil/gas fields, and unmined uneconomic coal beds. Of the grand total of 360 Gt of CO_2 storage resources across 25 EU countries, 326 Gt is estimated to be in saline aquifers, 32 Gt in hydrocarbon fields, and 2 Gt in uneconomic coalbeds, with 116 Gt in onshore storage and 244 Gt in offshore storage (Vangklide-Pedersen, 2009). The CO_2 StoP project (Poulsen et al., 2014) assembled available geographic information system (GIS) based data from previous studies as well as new data in the public domain. It published CO_2 storage estimates for the EU for saline aquifers, structural traps, and hydrocarbon fields, exclusive of Norway's offshore. The estimates total 482 Gt in 418 aquifers, between 31 and 54 Gt in 134 structural traps, and 25 Gt in 513 hydrocarbon fields (Anthonsen and Christensen, 2021). Koukouzas et al. (2022) provide an extensive list of CO_2 storage projects that are operational and in various stages of planning and development.

The contribution of this paper is its characterization of the potential magnitude of western European geologic storage resources in petroleum reservoirs by type; that is, oil or gas, onshore vs. offshore, as well as by depth and by water depth if offshore. An analysis of operating and abandoned reservoirs identifies the number, distribution, and size of potential subsurface storage reservoirs. All reservoirs examined are conventional hydrocarbon reservoirs. Reservoir storage estimates are also aggregated to the field level to demonstrate the degree of clustering of potential storage reservoirs. The storage reservoirs include both operating and known abandoned reservoirs, so that the results of the analysis are estimates of potential storage resource.[1] Reservoir documentation and the structural integrity of legacy facilities are likely to be superior for recently abandoned reservoirs. About 80% of the estimated storage resource is in reservoirs discovered before 1991, suggesting most may have already been abandoned or have limited remaining productive life. Estimates of 2017 CO_2 emissions only from oil-, gas-, and coal-fired electricity generation plants provides the basis for comparing the potential CO_2 storage resource with the mass of CO_2 emissions. These emissions are from the electrical power sector and do not include other industrial emissions.

The first section of this paper describes the reservoir data and how storage resources are estimated and converted on a common unit of mass of storable CO_2. Tables and graphs show the geographic distribution of the storage resources and characteristics of reservoir accessibility. Map displays present the spatial distribution of structures representing potential storage resources. A rough assessment of the adequacy of CO_2 storage resource in petroleum structures is made by comparing estimated resources to the CO_2 emissions of western European fossil-fuel electrical generation plants for 2017. In the second section the structure of natural gas storage in western Europe is reviewed. Implications of expanding onshore natural gas storage for strategic storage are discussed in terms its potential competition with CO_2 storage.

DATA AND COMPUTATIONAL METHODS

Reservoir, Field, and CO_2 Emissions Data

There were 9340 reservoirs with estimates of recoverable oil and gas from IHS Markit (2021; now known as S&P Global, data retrieved September 2021) used in this study. Oil and gas reservoir data for western Europe are from the International Exploration and Petroleum database (IHS Markit, 2021). The reservoirs were mapped to 5704 fields. A reservoir was classified as oil if the natural gas-to-oil ratio, in terms of thousands of cubic feet (MCF[2]) to barrels of oil (bbl[3]) was less than 20 to 1 (Charpentier and Klett, 2005). This criterion resulted in 3943 oil reservoirs and 5397 gas reservoirs. Table 1 provides the salient aggregate statistics. Data consisted of the IHS Markit estimates of recoverable oil and gas, and descriptors such as reservoir depth, water depth of each offshore reservoir, and fluid characteristics. The reservoirs were linked to field names and field locations. Where needed reservoir subsurface depth, water depth, or oil density were

[1] For this study the term storage resource is used to denote pore space in the reservoir occupied by recoverable oil and gas. Because the term CO_2 storage capacity has special technical definition (Society of Petroleum Engineers, 2022), that term is not used here.

[2] 1 cubic foot = 28.317 L.

[3] 1 barrel = 119.2404717 L.

Table 1. Recoverable oil and gas from 9340 identified reservoirs located in western Europe and estimate of the storage mass in terms of CO_2 (hydrocarbon recovery estimates: IHS Markit (2021); MMBL: million (10^6) barrels (1 barrel = 119.2404717 L); BCF: billion (10^9) cubic feet (1 cubic foot = 28.317 L), Mt, megatons, million (10^6) metric tons)

	Number	Oil (MMBL)	Natural gas (BCF)	Condensate (MMBL)	CO_2 storage (Mt)	Percent total storage
Oil reservoirs	**3943**	**95,697**	**127,185**	**728**	**11,579**	**32**
Onshore	2652	17,318	14,215	69	1,156	3
Offshore	1291	78,379	112,969	659	10,423	28
Gas reservoirs	**5397**	**426**	**583,899**	**6384**	**25,098**	**68**
Onshore	4030	84	161,574	578	6,399	17
Offshore	1367	342	422,325	5,806	18,699	51

Bold indicates totals of the rows below

computed based on the values of other reservoirs assigned to the same oil or gas field. There were 87 oil reservoirs out of 3943 oil reservoirs where the API gravity was estimated using the average of the measured gravity of the other oil reservoirs in the field. In the case of gas, a specific gravity default value of 0.8 (Carolus et al., 2018) was used where the IHS Markit (2021) data were missing. For reservoirs missing water depths but which belonged to offshore fields, water depth was estimated by taking the average values of water depth of the other reservoirs in the field. Out of 2601 reservoirs classified as offshore there were 71 reservoirs with water depth assigned using that procedure.

Both the oil and gas reservoir size distributions are highly skewed, that is, a relatively few fields hold most of the estimated recoverable resource while a very large number of fields hold almost a negligible proportion of the resource. For the oil and gas reservoirs studied here, 10% of the reservoirs (representing the largest reservoirs) account for more than 80% of the recoverable resource and the 50% of the reservoirs (representing the smallest reservoirs) account for 1% of the resource. Figure 1a, b shows the frequency distribution by size class of oil and gas reservoirs for oil reservoirs having at least 0.5 million barrels (MMBL) or gas reservoirs having at least 3 billion cubic feet (BCF) of natural gas. The intervals for the horizontal axis are in the form of log base 2. There are 904 oil reservoirs smaller than 0.5 MMBL of oil and 179 gas reservoirs smaller than 3 BCF gas.

One component of the demand for geologic storage resources is for long-term sequestration of CO_2 emitted from various sources. CO_2 emissions for 2017 were derived from estimates of electricity generated by fossil-fuel plants in each country of western Europe (World Resources Institute, 2022). The fossil-fuel based electrical generation plants used coal, oil, or natural gas. Although there are other sources of CO_2 emissions, fossil-fuel based electricity generation is regarded as the largest stationary source for direct capture of CO_2 (Herzog and Golomb, 2004). The electrical generation plants examined operated during 2017 and had generating capacity of at least 25 Megawatts (MW). CO_2 emissions factors computed from net power generation and CO_2 emissions data (U.S. Energy Information Administration, 2022a) were used to estimate the tonnage of CO_2 emitted based on the quantity of electricity generated (see Appendix 1).

Methodology of Estimating Storage Resource

The procedure for estimating storage volume was based on the reservoir estimates of recoverable oil or gas (IHS Markit, 2021) at surface conditions. Historical field level production records were examined to assure that cumulative production did not exceed the estimate of recoverable oil and gas. The volume of potential reservoir storage resource was estimated with standard reservoir formation volume calculations that used reservoir depth, data, and estimates of reservoir temperature and pressure. Details are provided in Appendix 1. Because the field coordinates are proprietary data (IHS Markit, 2021), a grid overlay was constructed where each cell is 25 km (km) by 25 km. The CO_2 storage resource of individual oil or gas reservoirs was aggregated to cell totals. Maps of western Europe show 3943 oil reservoirs (Fig. 2) and 5397 gas reservoirs (Fig. 3) aggregated to 25 km square cells with the color keyed to CO_2 storage resource.

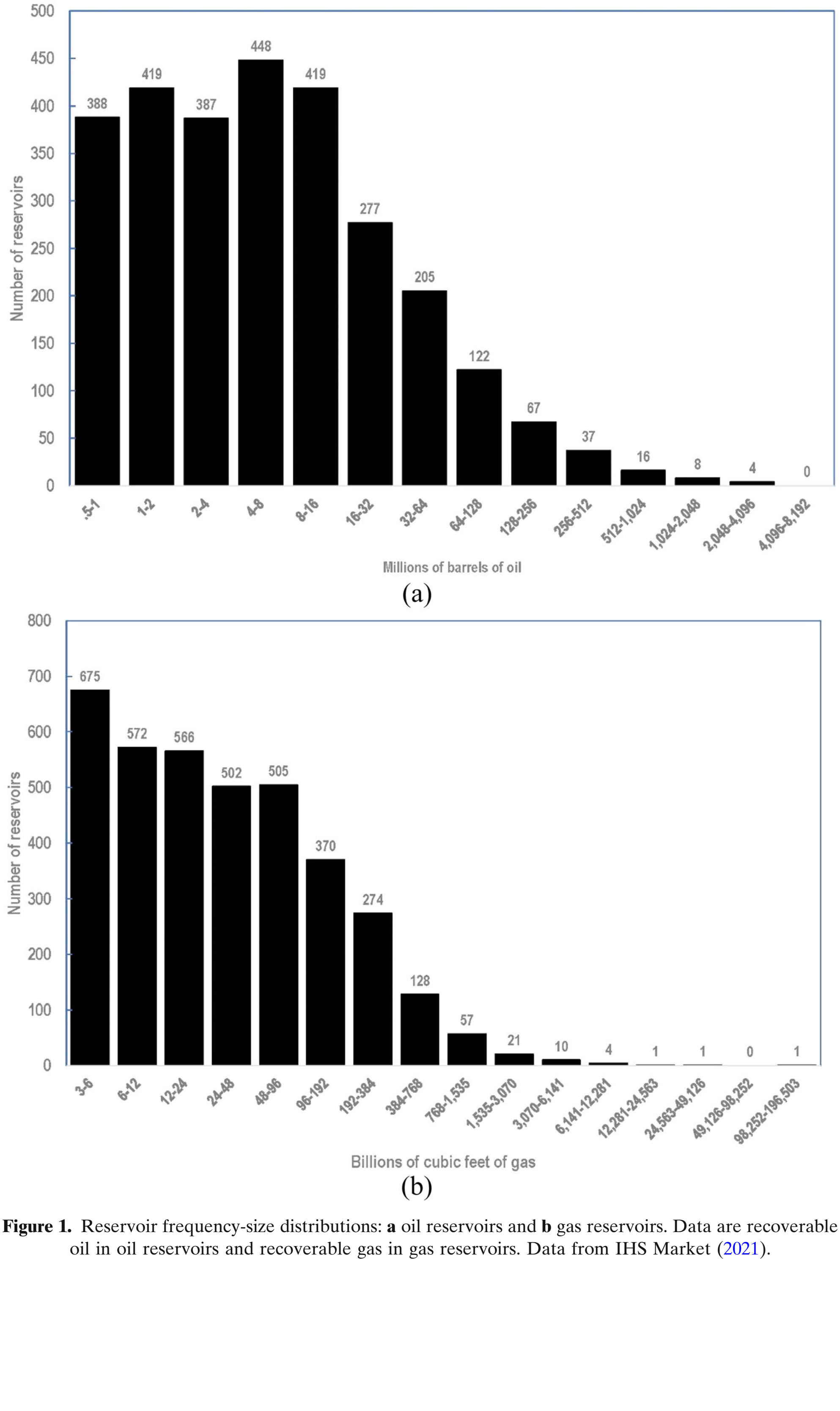

Figure 1. Reservoir frequency-size distributions: **a** oil reservoirs and **b** gas reservoirs. Data are recoverable oil in oil reservoirs and recoverable gas in gas reservoirs. Data from IHS Market (2021).

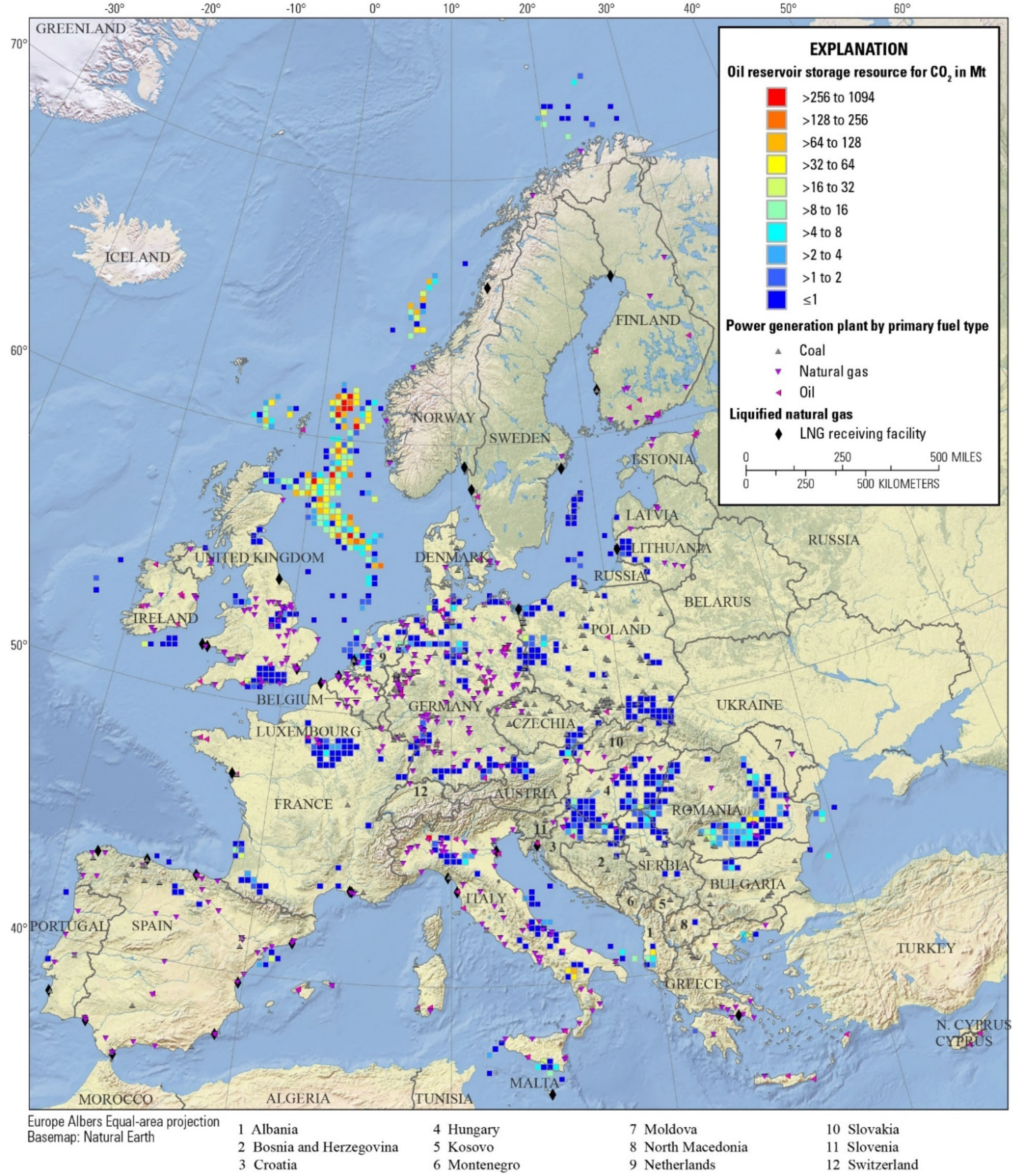

Figure 2. Estimated CO_2 storage resources in mass of megatons (Mt) for oil reservoirs, fossil-fuel electricity generation plants, and liquefied natural gas (LNG) receiving terminals in western Europe. Estimates of CO_2 storage resource are calculated from the estimates of volumes of recoverable oil from IHS Markit (2021). Cells of dimension 25 km by 25 km show the combined CO_2 storage resource of all individual oil reservoirs within the cell. Locations of fossil-fuel plants operating as of 2017 with minimum of 25 Megawatt generating capacity from World Resources Institute (2022) and locations of LNG terminals from International Group of Liquified Gas Importers (2021).

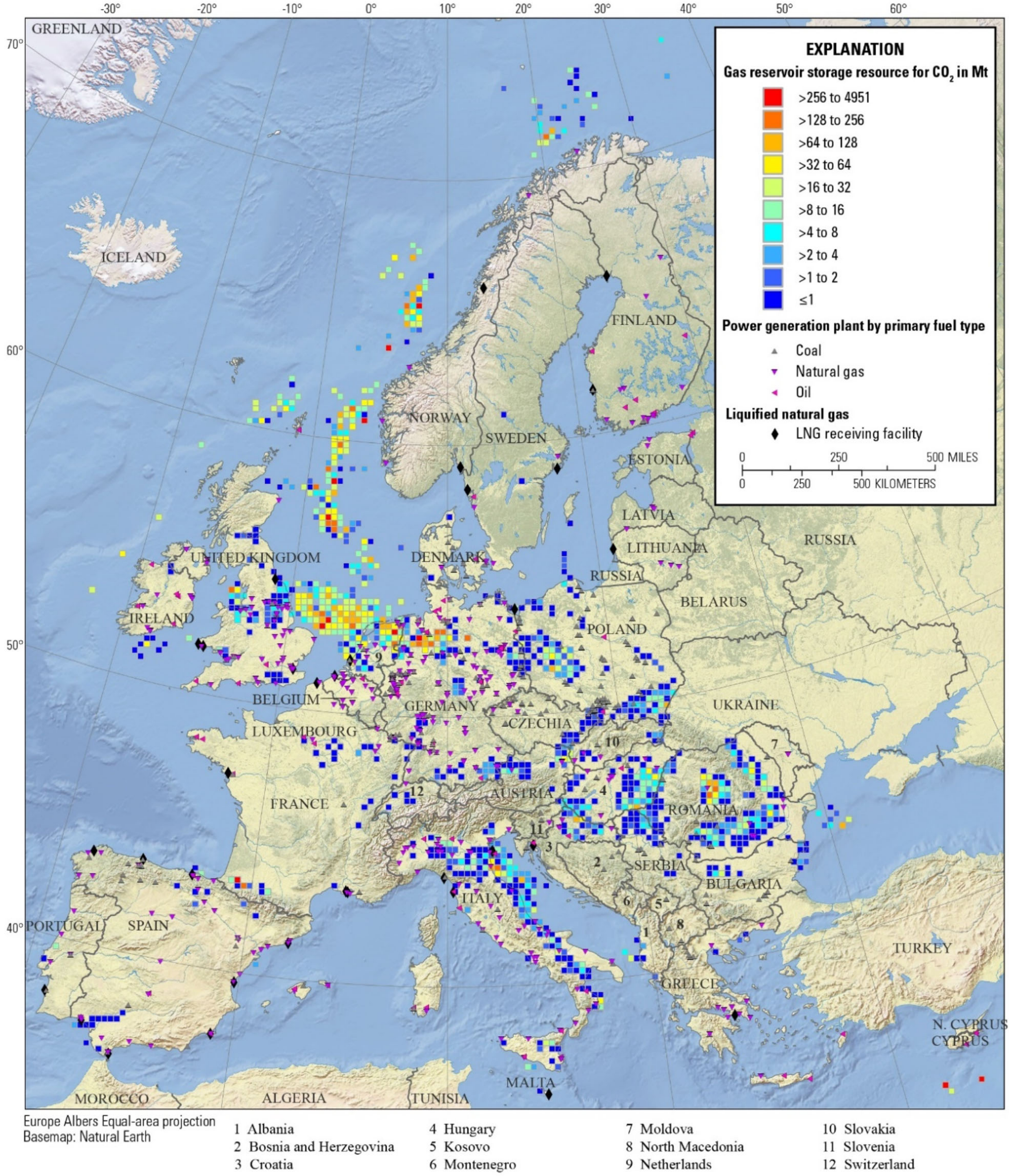

Figure 3. Estimated CO_2 storage resource in mass of megatons (Mt) for natural gas reservoirs, fossil-fuel electricity generation plants, and liquefied natural gas (LNG) receiving terminals in western Europe. Estimates of CO_2 storage resources are calculated from the estimates of volumes of recoverable gas from IHS Markit (2021). Cells of dimension 25 km by 25 km show the combined storage resource of all individual gas reservoirs within the cell. Locations of fossil-fuel plants operating as of 2017 with minimum of 25 Megawatt generating capacity from World Resources Institute (2022) and locations of LNG terminals from International Group of Liquified Gas Importers (2021).

ANALYSIS OF RESERVOIR DATA IN TERMS OF POTENTIAL CO_2 STORAGE RESOURCE

CO_2 Storage Resource and Accessibility

Table 1 shows volumes of the oil and gas with the estimates of CO_2 storage resource for each category. The estimates in Table 1 are based on the designation of the reservoirs as either oil or gas using the criterion explained earlier. In particular, the crude oil is oil volume in oil reservoirs, the gas volume is gas in gas reservoirs, and the condensate is only for gas reservoirs. The results displayed only roughly indicate magnitude and the physical accessibility of the storage resource in producing and nonproducing petroleum reservoirs based on recoverable oil and gas. The storage resources described here do not include pore space in undiscovered petroleum reservoirs.

For clarity of exposition, the discussion focusses on the CO_2 storage estimates. About 79% of the estimated CO_2 storage resource is in reservoirs classified as offshore. Figure 4 shows estimated resource allocation by reservoir depth interval (subsurface depth) and original reservoir type. For onshore reservoirs, about 49% of the estimated onshore storage resource is between subsurface depths of 2000 and 10,000 ft and 72% of the offshore resource is at subsurface depths of 2000 and 10,000 ft. To summarize 79% of the storage resource is offshore and 72% of that offshore resource is at subsurface depths between 2000 and 10,000 ft.

Commercial accessibility of the offshore storage may also depend on the water depth above the reservoir. This is of interest because offshore reservoirs account for almost four-fifths of the estimated

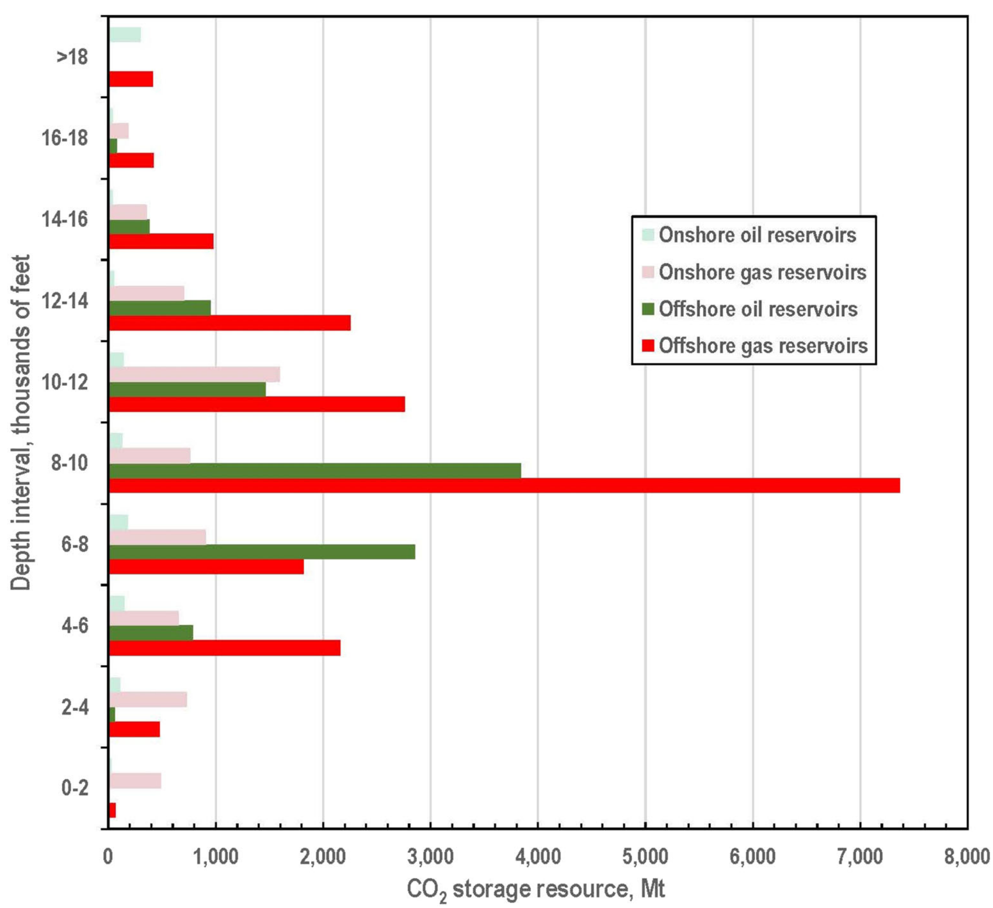

Figure 4. Distribution of carbon dioxide (CO_2) storage resource in Mt (megaton, 10^6 metric tons) by depth interval below-earth surface and reservoir type.

Table 2. Estimated storage resource of CO_2 for offshore reservoirs by water depth interval

Water depth		Oil reservoirs	Gas reservoirs	Percent distribution		
(ft)	(m)	(Mt)	(Mt)	Oil	Gas	Total
< 328	< 100	3280	11,709	31	63	51
328–656	100–200	5177	2202	50	12	25
656–984	200–300	585	322	6	2	3
983–3280	300–1,000	1336	3362	13	18	16
3280–20,000	1000–6098	45	1094	0	6	4
All intervals		10,423	18,699			

storage resource. Table 2 shows the offshore storage resource for the oil and gas reservoirs by water depth. The intervals were set at the equivalent of 100 m (328 ft), 200 m (656 ft), 300 m (984 ft), and 1000 m (3280 ft) and greater than 1000 m. Roughly three-fourths of the offshore storage resource is at water depths less than 200 m (656 ft) water depth.

The reservoir data were tied to fields (IHS Markit, 2021) and the storage resource estimates were summed to the field level to better recognize the possible application of the storage capacity. There were 5407 fields. If a minimum cutoff for the field storage resource is set at 10 megatons (Mt, or million metric tons) of CO_2, then the injection rate could be 1 Mt per year for that field over a 10-year period. The estimate of aggregate storage among all fields in western Europe would drop from 36.7 to about 30.8 Gt, or a reduction of about 16% if that minimum resource cutoff was set.

Storage Resources and CO_2 Emissions by Country and Region

The geographic area of western Europe having potential storage reservoirs was partitioned into three regions: a northern, southern, and eastern regions as shown in Figure 5. The jurisdictions in the northern region include Norway, UK, Sweden, Finland, Denmark, Ireland, Netherlands, Luxembourg, Germany, and Belgium. The southern region jurisdictions consist of France, Switzerland, Austria, Italy, Greece, Portugal, Spain, and Malta. The eastern region includes Latvia, Lithuania, Czechia, Slovakia, Slovenia, Serbia, Bosnia and Herzegovina, Croatia, North Macedonia, Poland, Hungary, Romania, Bulgaria, and Albania. Table 3 shows the estimated offshore and total storage resource of each major jurisdiction, where fields having less than 10 Mt of storage were excluded. Also excluded are hydrocarbon fields where more than one country claimed ownership.[4] For this constrained set of reservoirs, Table 3 shows the northern region accounted for at least 86% of the aggregate reservoir storage resource, of which more than 92% is offshore. The southern region accounted for about 7% of the storage total and the eastern region about 7%.

Table 3 also shows the 2017 country and regional estimate of CO_2 emissions from oil-, gas-, and coal-fired electricity generation plants having capacity of at least 25 Megawatts. The northern region accounted for 46%; the southern region, 26%; and the eastern region, 29%. The fossil-fuel electricity generating plants are stationary facilities that are possible to retrofit with carbon capture technology. The last column of Table 3 compares reservoir storage resource with a rough estimate of 2017 CO_2 emissions by dividing the estimated storage resource by the 2017 estimated emission rate, thus providing a very rough estimate of the sustainability of using the reservoir resource for CO_2 storage. Several countries with only modest storage resources, such as Austria, Hungary, and Sweden, depend heavily on hydropower and other renewable resources. In Albania, operating power plants over 25 MW depend upon hydropower. Most countries do not have the national storage resource to store 15 years of CO_2 at 2017 emission levels. With only a few exceptions the bulk of the storage is offshore for the countries that do have the resource for at least 15 years of CO_2 storage.

NATURAL GAS STORAGE

As of mid-2021 there were about 155 operational natural gas storage sites in European countries (exclusive of Ukraine, Russia, Belarus, and Turkey) with a working storage volume of about 4000 BCF of natural gas (gas infrastructure Europe, 2021). There was another 465 BCF of gas storage under construction and planned. There is a relatively small amount of additional storage at terminals that receive liquified natural gas (LNG). This additional

[4] Table 7 shows the same data as Table 3 without the exclusions.

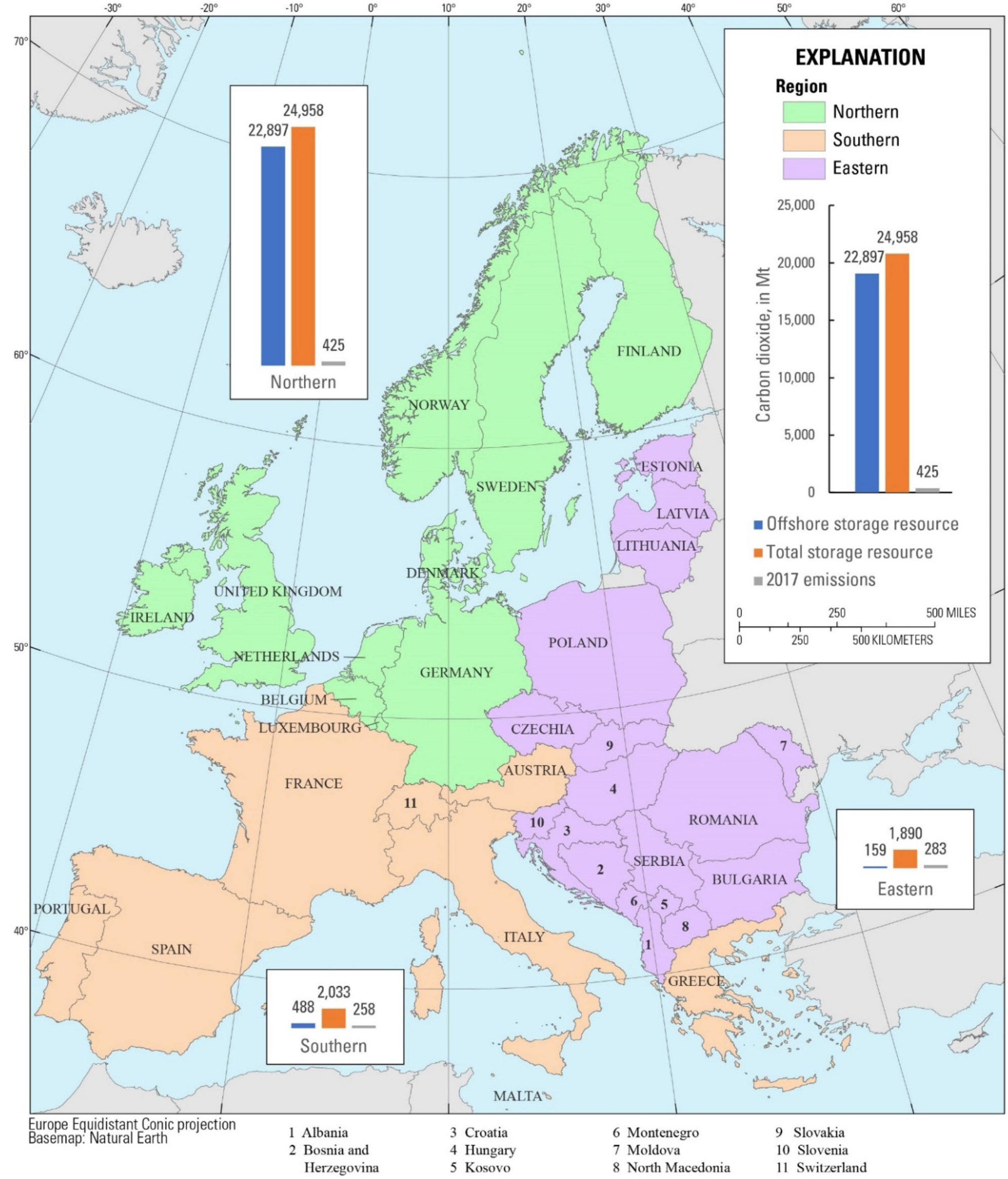

Figure 5. Map showing three regions (northern, southern, and eastern) of Europe with CO_2 resource potential in offshore petroleum reservoirs (blue), in total offshore and onshore petroleum reservoirs (orange), and 2017 CO_2 emissions (gray) as summarized in Table 3. These estimates do not include fields jointly owned by two or more countries nor countries without reservoir capacity or emissions from electricity generation plants at least 25 Megawatts capacity using coal, natural gas, or petroleum as fuel.

Table 3. Total reservoir storage resource for CO_2 by country versus the estimated 2017 CO_2 emissions from oil, gas, and coal-fired electricity generation plants of at least 25 Megawatts capacity and fields of at least 10 MT storage

Jurisdiction names	Offshore reservoir storage resource of CO_2 (Mt)	Total reservoir storage resource of CO_2 (Mt)	Estimated 2017 CO_2 emissions (Mt)	Years of storage at 2017 emission rate
Northern region				
Norway	8467.0	8467.0	1.7	> 30
Sweden	0.0	0.0	0.3	0
Denmark	503.1	503.1	12.9	> 30
Ireland	144.4	144.4	11.3	13
UK	7723.8	7723.8	76.0	> 30
Netherlands	5902.7	6401.8	45.3	> 30
Germany	155.9	1718.3	277.7	6
Northern total	22,896.9	24,958.4	425.2	
Southern region				
France	0.0	807.1	29.3	28
Austria	0.0	82.8	2.5	> 30
Italy	455.6	1110.0	102.5	11
Greece	19.7	19.7	26.6	1
Portugal	0.0	0.0	22.1	0
Spain	12.9	12.9	74.7	0
Southern total	488.3	2032.5	257.7	
Eastern region				
Latvia	0.0	0.0	1.2	0
Lithuania	0.0	0.0	0.3	0
Czechia	0.0	0.0	39.5	0
Slovakia	0.0	13.6	3.7	4
Serbia	0.0	0.0	34.0	0
Slovenia	0.0	0.0	5.5	0
Bosnia and Herzegovina	0.0	0.0	10.8	0
Croatia	0.0	110.4	3.0	> 30
North Macedonia	0.0	0.0	3.3	0
Poland	0.0	331.3	132.1	3
Hungary	0.0	227.3	8.8	> 30
Romania	115.6	1108.6	18.2	> 30
Bulgaria	0.0	17.2	22.3	1
Albania	43.9	81.7	NA	
Eastern total	159.4	1890.1	282.7	
Grand total	23,544.6	28,881.0	965.6	

The table does not include fields jointly owned by two or more countries nor countries without reservoir capacity or emissions
Mt, megaton; 10^6 metric tons; 0 indicates < 0.005

storage is estimated to be 210 BCF. Existing LNG receiving terminals are shown in Figures 2 and 3. The 2021 consumption of natural gas for these same countries amounted to about 17,000 BCF of gas (BP, 2022). The natural gas storage facilities were onshore and at least half the sites were depleted petroleum fields. Salt and rock caverns as well as saline aquifer storage accounted for the remainder of sites. Depleted fields also accounted for more than 60% of the operational working gas storage volume (gas infrastructure Europe, 2021). Table 4 shows the distribution of the number and capacity (estimated from reservoir size) for onshore natural gas reservoirs in the northern, southern, and eastern regions as defined in Table 3. Figure 6 shows a bubble map of the distribution of storage volumes by country. In 2021 the gas storage facilities in the USA had a working gas storage capacity of 4780 BCF during 2020 (U.S. Energy Information Administration, 2022b) supporting annual natural gas consumption

Table 4. Annual natural gas consumption and storage by country and region

Country name	Consumption (BCF/year)	Gas storage (BCF)
Norway	151.3	
Sweden	46.1	
Denmark	81.8	35.7
Finland	72.1	
Ireland	179.7	
UK	2717.4	59.6
Netherlands	1238.4	493.2
Belgium	599.0	30.7
Luxembourg	27.3	
Germany	3197.0	888.9
Northern region total	8310.1	1508.2
France	1520.0	451.4
Switzerland	127.3	0.3
Austria	318.0	324.8
Italy	2560.4	666.6
Greece	246.5	
Portugal	207.1	12.2
Spain	1197.1	116.9
Southern region total	6176.7	1572.2
Latvia	40.9	82.6
Lithuania	78.7	
Estonia	17.2	
Czechia	320.3	147.2
Slovakia	187.9	148.2
Slovenia	31.8	
Serbia	*	15.5
Bosnia and Herzegovina	*	
Montenegro	*	
Croatia	99.8	17.8
North Macedonia	14.4	
Moldova	*	
Poland	820.9	131.1
Hungary	380.9	237.6
Romania	403.8	112.6
Bulgaria	116.6	19.8
Other Europe	220.6	
Eastern region total	2513.3	912.3
Grand total	17,000.1	3992.7

Consumption data from BP (2022) and storage data from gas infrastructure Europe (GIE) (2021)
BCF, billion cubic feet (1 cubic foot = 28.317 L)
*Consumption data reported under Other Europe

of 29,300 BCF. Though annual gas consumption in western European countries in this study area is 60% of that of the USA, the natural gas storage in western Europe is only slightly less than that of the USA.

Natural gas storage in Europe is used to meet large demand increases during winter. It may also be used to arbitrage between current spot and futures prices of natural gas. Because the operating gas storage facilities are used to meet peak seasonal demand and arbitrage opportunities, these facilities are generally located near consumers. Only a select and likely small subset of the onshore gas reservoirs listed in Table 4 may be required to meet expanded seasonal storage. However, the demand for storage increases with increasing volatility of supply volumes from various sources. Pipeline and LNG imports accounted for more than 83% of 2021 European gas consumption. In 2021, Russia accounted for about half of Europe's natural gas imports (BP, 2022).

If the purpose of gas storage is to maintain a strategic inventory of gas for national security purposes, then the larger depleted onshore reservoirs are the more likely candidates. Table 5 shows the number and aggregate capacity of reservoirs by country and by European region at different minimum-sized reservoirs either 20 BCF or 40 BCF in size by region. Although using known gas reservoirs for strategic long-term storage may benefit from existing infrastructure, their disadvantages are they may require a relatively high proportion of the storage capacity to be devoted to cushion gas and rates of injection and withdrawal are relatively slow (Le Fevre, 2013). For an individual gas reservoir about 45% of the overall storage resource must be devoted to cushion gas that must be maintained in the reservoir. The rest of the potential gas storage may be considered working gas. By contrast, salt caverns require only 20% cushion gas while aquifer storage requires 55% cushion gas (Le Fevre, 2013). The maximum daily deliverability of gas is 4.8% of working gas for salt caverns, 1.4% for abandoned gas reservoirs, and 1.1% for aquifers (Le Fevre, 2013). The substantial costs (out of pocket and opportunity costs) and risks associated with strategic storage are such that they might have to be borne by a governmental entity (Ejarque, 2011).

For some countries without significant offshore petroleum reservoirs, there could be competition between CO_2 and strategic gas storage resources in petroleum reservoirs. However, in a case study cited by Bump et al. (2022), there was fierce public resistance to storage of CO_2 in an onshore field in Germany, a country where there is significant onshore natural gas storage. Storage of CO_2 may be perceived by the public as irreversible. Moreover, if CO_2 storage costs are subject to economies of scale, the cost of storage in large offshore reservoirs may undercut costs of storage in numerous small onshore reservoirs.

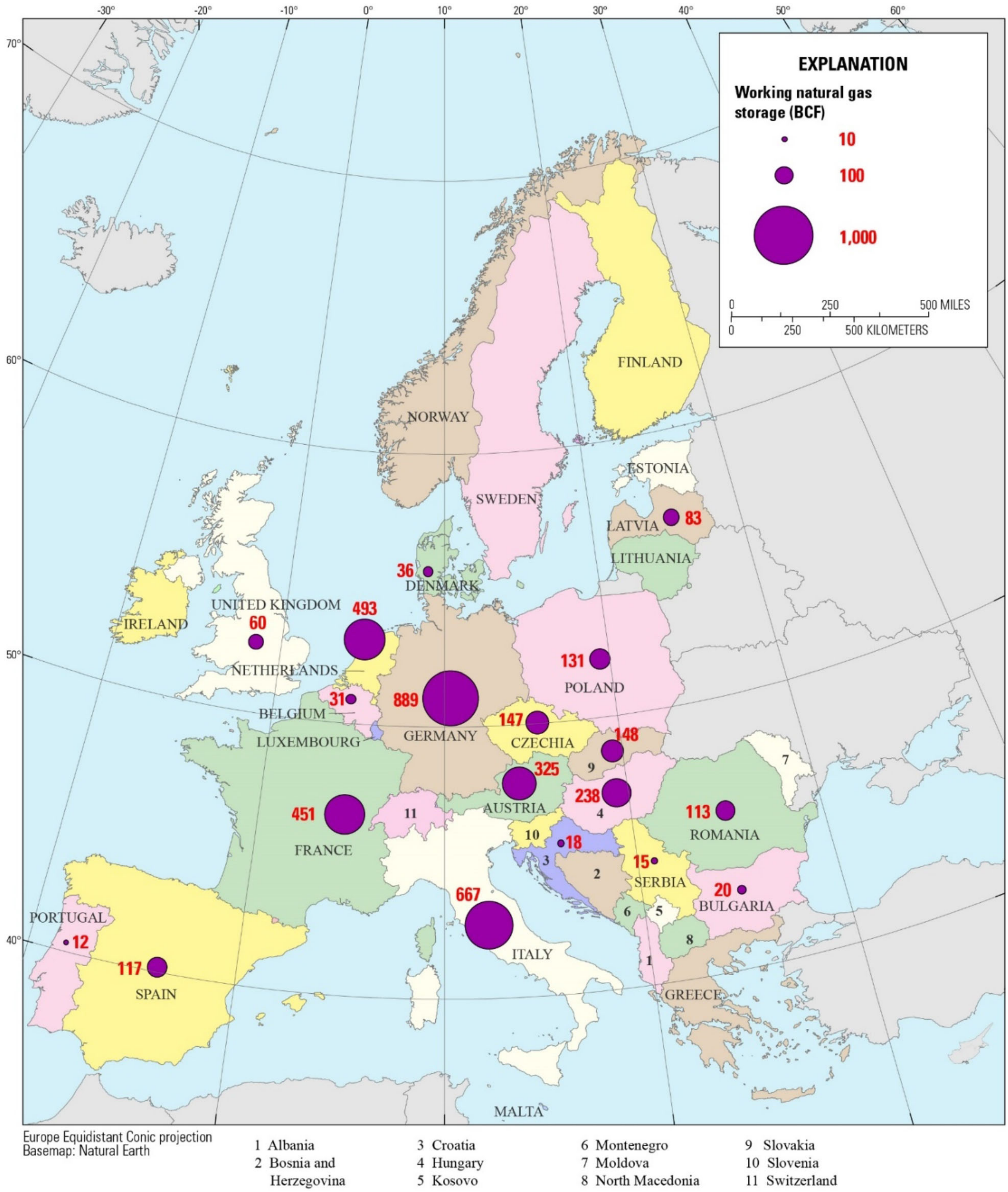

Figure 6. Map showing working volumes of underground natural gas storage as of 2021 in salt caverns, aquifers, and depleted petroleum reservoirs in western Europe, exclusive of storage at liquified natural gas storage facilities. Data are from gas infrastructure Europe (2021).

Table 5. Onshore gas reservoirs having at least 20 BCF and at least 40 BCF recoverable gas

Country	Onshore gas reservoirs > 20 BCF			Onshore gas reservoirs > 40 BCF		
	Number of reservoirs	Total reservoir recovery (BCF)	Total reservoir storage resource of CO_2 (Mt)	Number of reservoirs	Total reservoir recovery (BCF)	Total reservoir storage resource of CO_2 (Mt)
Northern region						
Sweden	0	0	0	0	0	0
Denmark	0	0	0	0	0	0
Ireland	0	0	0	0	0	0
UK	32	2893	73	23	2673	67
Netherlands	113	18,560	548	80	17,616	520
Germany	166	32,347	1081	131	31,396	1050
Northern total	311	53,800	1701	234	51,685	1637
Southern region						
France	8	11,874	420	7	11,836	419
Switzerland	0	0	0	0	0	0
Austria	41	2892	74	22	2370	61
Italy	91	10,150	266	59	9244	243
Greece	0	0	0	0	0	0
Portugal	1	262	7	1	262	7
Spain	2	62	2	0	0	0
Malta	0	0	0	0	0	0
San Marino	0	0	0	0	0	0
Southern total	143	25,240	769	89	23,712	730
Eastern region						
Serbia	15	662	16	8	435	10
Czechia	7	144	4	0	0	0
Slovakia	15	1108	30	11	1005	28
Slovenia	1	35	1	0	0	0
Croatia	16	2258	74	10	2083	70
Poland	100	13,516	354	67	12,673	331
Hungary	77	7675	223	46	6856	200
Romania	301	44,082	1,126	198	41,207	1052
Bulgaria	5	499	17	3	449	15
Albania	2	79	2	1	52	2
Eastern total	539	70,057	1849	344	64,760	1708
Grand total	993	149,096	4319	667	140,157	4075

BCF, billion cubic feet (1 cubic foot = 28.317 L); Mt, megaton, 10^6 metric tons

IMPLICATIONS AND CONCLUSIONS

The focus of this analysis has been on the identification and estimation of potential storage resources in known petroleum reservoirs at the reconnaissance level. The suitability and cost associated with conversion to storage must be established for each site. An advantage of using depleted or soon-to-be depleted oil and gas reservoirs for storage is the access to data filed with regulatory agencies that deal with commercial oil and gas operations. For recent or soon to be-abandoned fields, the wells and pipeline infrastructure may be repurposed resulting in a substantial reduction in storage investment costs (Bump et al., 2022). However, some site-specific conditions can only be revealed by subsurface data. This analysis shows that most of the countries in western Europe would not have 15 years of storage resource at 2017 fossil-fuel-based electrical power sector emissions rates if all the petroleum reservoirs were used exclusively for CO_2 storage. For most of those countries that do have sufficient potential storage resources, a high proportion of their storage resource is offshore.

Several caveats about the magnitude of potential storage resource should be mentioned. The undiscovered reservoirs were not considered or quantified, perhaps leading to understatement.

Alternatively, the magnitude of identified storage resource may be adversely affected by injectivity problems, possible subsidence crushing pore space in pressure depleted reservoirs, or high reservoir pressure at abandonment due to a vigorous aquifer (Bump et al., 2022).

A recent report by the consultancy Wood Mackenzie (Lanthan et al., 2022) identified the North Sea basins (the northern North Sea, Central Graben, southern North Sea) and the Voring basin (offshore Norway) as super basins. These basins are highly favorable not only for future oil and gas production but are also favorable for renewable wind energy production as well as co-location of long-term storage of CO_2. They permit synergies between related geologic storage and the existing infrastructure and facilities that could accommodate sustainable energy production. In fact, storage-related uses compete for depleted reservoirs. Lanthan et al. (2022) project that there will be a demand for hydrogen storage with the growth of offshore renewable power generation. Excess electricity generated at remote locations may be used to produce hydrogen and existing oil and gas infrastructure can be modified to deliver the hydrogen to electrical power generators and to industry. There will be competition between storage for natural gas, hydrogen, and CO_2. Whereas the use of depleted petroleum reservoirs for natural gas or hydrogen storage is reversible, CO_2 sequestration in petroleum reservoirs and aquifers is generally considered permanent. Because of their scale and immense storage potential, large offshore reservoirs appear to be geologically suited for CO_2 sequestration.

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DATA AVAILABILITY

Paper uses published data for emission factors, published fossil-fuel electricity generation data, published gas storage resource referenced, and URL provided. The raw oil and gas reservoir and field data are leased from IHS Markit by the U.S. Geological Survey and contractually cannot be disclosed but may be available for purchase from IHS Markit.

CODE AVAILABILITY

Relevant calculations explained in extensive appendix.

DECLARATIONS

Conflict of Interest The authors declare no conflicts of interest.

APPENDIX 1 ESTIMATION OF CO_2 STORAGE VOLUME AND EMISSION FACTORS

CO_2 STORAGE ESTIMATION

The objective is to find the in situ reservoir volume of hydrocarbons of recoverable oil in oil reservoirs and recoverable gas in gas reservoirs. Next the computed volume is used to calculate the mass for CO_2 that can be stored based on the reservoir temperature and pressure. We used the IHS Markit (2021) estimate of stock tank recoverable oil in oil reservoirs and gas in gas reservoirs as starting data and estimated the volume of the hydrocarbon fluids in the reservoir by calculating reservoir formation volume factors for oil and for gas reservoirs. The procedure for computing formation volume factors generally follows Carolus et al. (2018).

The computation of the formation volume factor requires estimates of the reservoir temperature and reservoir pressure using IHS Markit data or using temperature and pressure gradients if needed. If the reservoir record did not include an estimate of temperature or pressure, the values of these parameters were estimated with default gradients using penetration depth (depth below-earth's surface, d_{on}) and offshore water depth (d_{off}). Note total depth $d_{td} = d_{off} + d_{on}$. In the following the symbol '*' denotes multiplication.

TEMPERATURE AND PRESSURE

A. Onshore reservoir pressure: $P_{on} = 0.433 * d_{on} + 14.7$ psi[5] where d_{on} is penetration depth
B. Offshore reservoir pressure: $P_{off} = 0.455 * d_{td}$ where depth includes water depth and drilling penetration depth where 0.455 was calculated from 0.433 * 1.05 where 1.05 is specific gravity of ocean salt water.
C. Onshore reservoir temperature T_{on} = Temperature at surface + 1.41 per hundred feet of d_{on}, where d_{on} is penetration depth, T_{on} is measured in degrees Fahrenheit (°F[6]) at the surface, assumed 60 °F.
D. Offshore reservoir temperature $T_{off} = 32 + 1.41$ per hundred feet of d_{on} where d_{on} is drilling penetration depth and temperature a measure in degree Fahrenheit.

OTHER DEFAULT AND ESTIMATED PARAMETER VALUES

The default value of the specific gravity of gas is 0.8 when not supplied in an IHS Markit (2021) record. Where the water depth, or penetration depth values were missing from the IHS Markit reservoir records, we used the average depths of reservoirs assigned to the same field. In the few cases where there was no analog reservoir from the same field, the average for the IHS Markit petroleum province is used.

OIL RESERVOIR ESTIMATION OF FORMATION VOLUME FACTORS

Define coefficient (Y_g) for the solution gas–oil ratio equation as:

$$Y_g = 0.00091 * T - 0.0125 * \mathrm{API}$$

where Y_g is coefficient for solution gas–oil ratio equation, 0.00091 is conversion coefficient, T reservoir temperature (°F), 0.0125 conversion coefficient, and API is American Petroleum Institute oil gravity,

The solution gas–oil ratio (RS) is calculated as:

$$\mathrm{RS} = \mathrm{SGG} * \left[\left(P/\left(18 * 10^{\mathrm{Yg}}\right)\right]^{1.204}$$

where RS is solution gas–oil ratio, in standard cubic feet[7] per stock tank barrel[8] (SCF/STB), SGG is specific gravity of the gas, P is initial reservoir pressure, in pound-force per square inch absolute (psia), and 18 and 1.204 are constants obtained by rewriting the Standing correlation equation (Standing, 1948).

The specific gravity of oil (SGO) is calculated as:

$$\mathrm{SGO} = 141.5/(131.5 + \mathrm{API})$$

The coefficient F is calculated for the initial oil formation volume factor equation, thus:

$$F = \mathrm{RS} * (\mathrm{SGG/SGO})^{0.5} + 1.25 * T$$

where F is the coefficient for the initial oil formation volume factor equation, RS is the solution gas–oil ratio, in standard cubic feet per stock tank barrel (Scf/STB), 0.5 is a curve-fitting exponent obtained by Standing (1948), and 1.25 a constant value obtained from curve fitting by Standing (1948).

The initial oil formation volume factor (BOI) is calculated as:

[5] 1 psi = 6.894757 kPa.

[6] °C = (°F − 32) * 5/9.

[7] 1 cubic foot = 28.317 L.

[8] 1 barrel = 119.2404717 L.

$$BOI = 0.972 + 0.000147 * F^{1.175}$$

where BOI is the initial oil formation volume factor (in decimal format), and 0.972, 0.000147, and 1.175 are constants for the correlation equation developed by Standing (1948) as published in Lyons (1999).

NATURAL GAS RESERVOIR ESTIMATION OF FORMATION VOLUME FACTORS

Authors estimated the initial gas compressibility (Z_i) factor using a numerical approximation developed by INTEK Corporation (Carolus et al., 2018) using gas gravity, temperature, pressure and adjusted for impurities and based on correlations described in Standing and Katz (1942) and Wichert and Aziz (1971). The initial gas formation volume factor (BGI, in decimal format) is calculated as:

$$BGI = 520 * P/[14.7 * Z_i * (T_i + 460)]$$

where 520 is the coefficient for the current gas formation volume factor, 14.7 is the standard atmospheric pressure (psi), T_i is the initial reservoir temperature (°F), and 460 is the conversion factor for degrees Rankine (°R).

CO_2 STORAGE CALCULATION

The density of carbon dioxide at each reservoir's pressure and temperature is computed and multiplied by the reservoir's estimated storage volume to calculate the estimated mass of CO_2 that can potentially be stored. The density of the CO_2 will not be under supercritical conditions.

$$\rho = MPRT_k$$

where ρ, the lowercase Greek letter rho, is the density (in gram–liter, gL), M is the molar mass of the gas (for CO_2, this is 44.01 gmol), P is the pressure exerted by the gas in atmospheres (atm),[9] R is the universal gas constant, equal to 0.082057 L atm K^{-1} mol^{-1}, T_k is temperature in Kelvin.

To obtain the absolute temperature of the gas the following equation is used:

$$T_k = (5/9) * (T_F + 459.67)$$

where T_k is the absolute temperature of the gas degrees K, T_F is temperature in Fahrenheit, 5/9 is a conversion constant, and 459.67 is a conversion constant.

Density of CO_2, ρ is found by substituting in values for #atm and T_K in the following eq.:

$$\rho = (44.01\ \text{gmol}) * (\#\text{atm}) * \left(0.082057\ \text{L atm K}^{-1}\ \text{mol}^{-1}\right) * (T_K)$$

where 44.01 is a constant.

EMISSION FACTOR ESTIMATION

According to the U.S. Energy Information Administration (2022c, 2022d), U.S. electric utility and independent power electricity generation 2020 the resulting CO_2 emissions by fuel in 2020 are:

Fuel	Electricity generated (million kWh)	CO_2 emissions (Mt)	CO_2 emission factor (kg/kWh)
Coal	757,763	767	1.01
Natural gas	1,402,438	576	0.41
Petroleum	13,665	13	0.95

Electricity generated is net electricity generated. Million, 10^6; kWh, kilowatt hour; Mt, megaton, 10^6 metric tons; kg, kilogram. Includes electricity-only power plants. Combined heat and power plants are excluded because some of their CO_2 emissions are from fuel consumption for heating purposes. The 2020 annual U.S. emission and generation data was used in estimation (U.S. Energy Information Administration, 2022c, 2022d)

APPENDIX 2 ESTIMATES OF TOTAL AND OFFSHORE OIL, GAS, CONDENSATE AND POTENTIAL CO_2 STORAGE

See Tables 6 and 7

[9] Converting pressure to atmospheric pressure units (#atm) = reservoir pressure (psia)/14.7 psia.

Table 6. Estimates of oil, gas, condensate, and potential CO_2 storage in all hydrocarbon reservoirs in western Europe

Jurisdiction names	Onshore and offshore total					
	Oil (MMBL)	Gas (BCF)	Condensate (MMBL)	Oil reservoir CO_2 storage resource (Mt)	Gas reservoir CO_2 storage resource (Mt)	Total reservoir CO_2 storage resource (Mt)
Northern region						
Greenland	0	3	0	0	0	0
Svalbard, Jan Mayen	0	1	0	0	0	0
Norway	34,402	178,267	2639	4512	4786	9298
Joint UK-Norway	4816	12,683	22	840	230	1070
Joint Denmark-Norway	40	39	0	36	0	36
Sweden	2	38	0	0	1	1
Denmark	3242	10,201	327	378	211	590
Ireland	451	3787	44	31	123	154
Joint UK-Ireland	0	240	0	0	8	8
UK	33,200	144,332	3,161	4407	4971	9377
Joint Netherlands-UK	0	890	5	0	47	47
Joint Faroe Islands-UK	28	13	0	4	0	4
Netherlands	1311	163,793	169	52	7372	7423
Joint Netherlands-Germany	0	118	1	0	5	5
Germany	2522	37,880	42	90	1885	1975
Faroe Islands	0	360	4	0	18	18
Regional total	80,013	552,645	6414	10,351	19,656	30,007
Southern area						
France	939	12,168	107	59	811	870
Switzerland	0	14	0	0	1	1
Austria	939	4698	20	38	114	152
Italy	2604	33,328	62	548	948	1496
Joint Croatia-Italy	0	360	0	0	7	7
Greece	188	182	4	28	2	30
Portugal	0	262	0	0	9	9
Spain	300	740	5	24	19	44
Malta	0	0	0	0	0	0
Cyprus	0	12,027	12	0	830	830
San Marino	0	1	0	0	0	0
Regional total	4969	63,781	209	696	2742	3439
Eastern area						
Latvia	35	1	0	1	0	1
Lithuania	49	11	0	4	0	4
Czechia	85	601	1	3	11	13
Joint Czechia -Slovakia	1	8	0	0	0	0
Slovakia	45	1467	5	1	44	44
Serbia	660	1442	5	19	29	47
Slovenia	6	99	2	0	3	3
Bosnia and Herzegovina	0	0	0	0	0	0
Croatia	824	4463	98	32	176	208
North Macedonia	0	0	0	0	0	0
Poland	416	16,416	19	54	520	574
Hungary	851	11,630	124	51	398	449
Romania	7,189	55,092	117	288	1450	1738
Bulgaria	88	805	4	11	33	44
Albania	893	2623	115	69	36	105

Table 6. continued

Jurisdiction names	Onshore and offshore total					
	Oil (MMBL)	Gas (BCF)	Condensate (MMBL)	Oil reservoir CO_2 storage resource (Mt)	Gas reservoir CO_2 storage resource (Mt)	Total reservoir CO_2 storage resource (Mt)
Regional total	11,141	94,658	489	532	2699	3231
Total, all regions	96,123	711,084	7,112	11,579	25,098	36,676

Hydrocarbon recovery estimates are from IHS Markit (2021)
MMBL, million barrels liquid (1 barrel = 119.2404717 L); BCF, billion cubic feet (1 cubic foot = 28.317 L); Mt, megaton, 10^6 metric tons; 0 indicates < 0.005

Table 7. Estimates of oil, gas, condensate, and potential CO_2 storage in offshore hydrocarbon reservoirs in western Europe

Jurisdiction names	Offshore					
	Oil (MMBL)	Gas (BCF)	Condensate (MMBL)	Oil reservoir CO_2 storage resource (Mt)	Gas reservoir CO_2 storage resource (Mt)	Total reservoir CO_2 storage resource (Mt)
Northern area						
Greenland	0	3	0	0	0	0
Svalbard, Jan Mayen	0	0	0	0	0	0
Norway	34,402	178,267	2639	4512	4786	9298
Joint UK-Norway	4816	12,683	22	840	230	1070
Joint Denmark-Norway	40	39	0	36	0	36
Sweden	0	0	0	0	0	0
Denmark	3242	10,191	327	378	211	589
Ireland	451	3785	44	31	123	154
Joint UK-Ireland	0	240	0	0	8	8
UK	32,991	140,893	3159	4401	4877	9278
Joint Netherlands-UK	0	890	5	0	47	47
Joint Faroe Islands-UK	28	13	0	4	0	4
Netherlands	586	144,005	124	35	6,595	6,630
Joint Netherlands-Germany	0	100	0	0	4	4
Germany	411	3570	26	26	150	175
Faroe Islands	0	360	4	0	18	18
Regional total	76,967	495,039	6351	10,264	17,048	27,312
Southern area						
France	34	10	0	4	0	4
Switzerland	0	0	0	0	0	0
Austria	0	0	0	0	0	0
Italy	829	20,349	3	67	602	668
Joint Croatia-Italy	0	360	0	0	7	7
Greece	188	160	4	28	1	29
Portugal	0	0	0	0	0	0
Spain	282	579	5	24	15	39

Table 7. continued

Jurisdiction names	Offshore					
	Oil (MMBL)	Gas (BCF)	Condensate (MMBL)	Oil reservoir CO_2 storage resource (Mt)	Gas reservoir CO_2 storage resource (Mt)	Total reservoir CO_2 storage resource (Mt)
Malta	0	0	0	24	15	0
Cyprus	0	12,027	12	0	830	830
San Marino	0	0	0	0	0	0
Regional total	1333	33,485	23			1578
Eastern area						
Latvia	31	0	0	0	0	0
Lithuania	2	1	0	0	0	0
Czechia	0	0	0	0	0	0
Joint Czechia - Slovakia	0	0	0	0	0	0
Slovakia	0	0	0	0	0	0
Serbia	0	0	0	0	0	0
Slovenia	0	0	0	0	0	0
Bosnia and Herzegovina	0	0	4	0	0	0
Croatia	2	1168	1	0	26	26
North Macedonia	0	0	0	0	0	0
Poland	76	254	2	4	5	9
Hungary	0	0	0	0	0	0
Romania	191	4106	4	14	129	143
Bulgaria	41	199	0	5	5	9
Albania	80	1043	85	12	32	44
Regional total	422	6771	95	36	195	231
Total, all regions	78,721	535,294	6,469	10,300	17,244	29,122

Hydrocarbon recovery estimates are from IHS Markit (2021)
MMBL, million barrels liquid (1 barrel = 119.2404717 L); BCF, billion cubic feet (1 cubic foot = 28.317 L); Mt, megaton, 10^6 metric tons; 0 indicates < 0.005

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