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Geological and Petrophysical Properties of Underground Gas Storage Facilities in Ukraine and Their Potential for Hydrogen and CO_2 Storage

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Abstract: This article provides detailed geological and reservoir data on the existing underground gas storage (UGS) facilities in Ukraine and their prospects for hydrogen (H_2) and carbon dioxide (CO_2) storage. The H_2 and CO_2 storage issue is an integral part of the decarbonisation of Ukraine and Europe as a whole. A detailed assessment of UGS in Ukraine was carried out in the framework of the EU Horizon 2020 project Hystories, which is about the possibility of the geological storage of H_2. A database of the available geological data on reservoir and caprock properties was compiled and standardised (reservoir geometry, petrophysics, tectonics, and reservoir fluids). General environmental criteria were defined in terms of geology and surface context. The total estimated H_2 energy storage capacity in 13 studied UGS facilities is about 89.8 TWh, with 459.6 and 228.2 Mt of H_2 using the total (cushion and working gas) and working gas volumes, respectively. The estimated optimistic and conservative CO_2 storage capacities in the 13 studied UGS facilities are about 37.6/18.8 Gt, respectively. The largest and deepest UGS facilities are favourable for H_2 and CO_2 storage, while shallower UGS facilities are suitable only for H_2 storage. Studies could be conducted to determine if CO_2 and H_2 storage could be applied in synergy with CO_2 being used as a cushion gas for H_2 storage. The underground storage of H_2 and CO_2 plays key roles in reducing greenhouse gas emissions and supporting clean energy while enhancing energy security. Increasing the share of renewable energy and integrating sustainable development across various sectors of the economy is crucial for achieving climate goals.

Keywords: underground gas storage; hydrogen storage; CO_2 geological storage; cushion gas; reservoir rocks; sustainable decarbonisation

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1. Introduction

Ukraine, as an active member of the UN Framework Convention on Climate Change (UNFCCC), was among the first nations on the European continent to ratify the Paris Agreement on 14 July 2016 and the Kyoto Protocol on 4 February 2004. Ukraine, as a candidate for accession to the European Union (EU), aims to align with EU climate goals, including the European Climate Law's target of climate neutrality by 2050 and a 55% greenhouse gas emissions reduction by 2030. As a country that ratified an Association Agreement with the EU on 16 September 2014 and that is a member of the Energy Community Treaty, Ukraine is dedicated to

(1) Reduce the total amount of greenhouse gas emissions (GHGEs) by 65% by 2030, compared to 1990 levels;
(2) Increase the share of renewable energy sources in the structure of gross final energy consumption to not less than 27% by 2030;
(3) Become climate neutral by 2060, in line with the long-term ambitions of EU members and in accordance with EU policies [1].

In response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, the EU is implementing its REPowerEU Plan [2] in February 2023, focusing on renewable energy and thereby reducing reliance on Russian gas and the effects of climate change. The energy sector is responsible for more than 75% of the EU's GHGEs. The revised Renewable Energy Directive EU/2023/2413 raises the EU's binding renewable target for 2030 to a minimum of 42.5% of consumption, up from the previous 32% target, with the aspiration to reach 45% [3]. Decarbonisation via carbon dioxide (CO_2) geological storage and hydrogen (H_2) production, part of the decarbonisation pillar of the EU Green Deal and Fit-for-55 package REPowerEU plan, will reduce CO_2 emissions, enhance energy security, and create new jobs.

To achieve these goals, Ukraine aims to apply innovative technologies to decarbonise its energy sector and boost energy efficiency. Ukraine's integration into the EU's renewable and decarbonisation frameworks can enhance cooperation and contribute to achieving climate neutrality and sustainable development.

The challenges in decarbonising the energy sector are reported with respect to environmental sustainability, the security of the energy supply, economic stability, and social aspects in [4]. A global carbon tax was reported as the most promising, but very challenging, instrument for humanity to accelerate the process of decarbonisation.

Potential solutions include H_2 energy and CO_2 capture, utilisation, and storage (CCUS) technologies. To ensure energy security and reduce CO_2 emissions, Ukraine's existing underground gas storage (UGS) facilities, currently used for surplus European gas storage, could be repurposed for H_2 and CO_2 storage, efficiently using existing infrastructure. It is, therefore, important to conduct a comprehensive assessment of Ukraine's existing UGS facilities to estimate their capacity for H_2 and CO_2 storage, as no comprehensive studies have been conducted in Ukraine.

UGS facilities are a special case as they could potentially be converted directly into H_2 storage sites since they are already connected to the gas network and have already been well characterised, and pressure and fluid movement in the reservoir is well understood. Although numerous research projects are investigating the potential of underground H_2 storage (UHS), the number of fully operational projects in UGS facilities remains limited. There are existing UHS facilities in salt caverns in Teesside (UK), Spindletop (USA), and Clemens Dome and Moss Bluff (USA). Hydrogen-rich gas was stored in an aquifer in Lobodice (Czech Republic) and in a UGS store in a depleted gas reservoir in Austria. Pure H_2 storage in a depleted gas reservoir started during 2023 in Austria (the Underground Sun Storage project) [5]. Global experience indicates that H_2 storage poses significant safety risks due to its unique properties, such as its high flammability, low molecular weight, and the potential for leaks. As a result, robust safety measures and modelling are essential to mitigate these risks [6]. Extensive experience from many countries on UGS offers important relevant experience in managing these risks. Building on experience from projects like Sleipner [7] and Snøhvit [8] (Norway), UGS facilities also offer a significant potential for long-term CO_2 sequestration. There is currently no experience of CO_2 storage or UHS in Ukraine.

Assuming the cushion gas, which comprises natural gas, is retained during H_2 storage and neglecting any mixing issues, UGS stores offer a promising opportunity for H_2 storage.

Alternatively, CO_2 and H_2 storage could be used synergistically if CO_2 is used as a cushion gas for H_2 storage (Figure 1). More detailed, site-specific simulations of this potential mixing are needed to determine the feasibility of using CO_2 as a cushion gas.

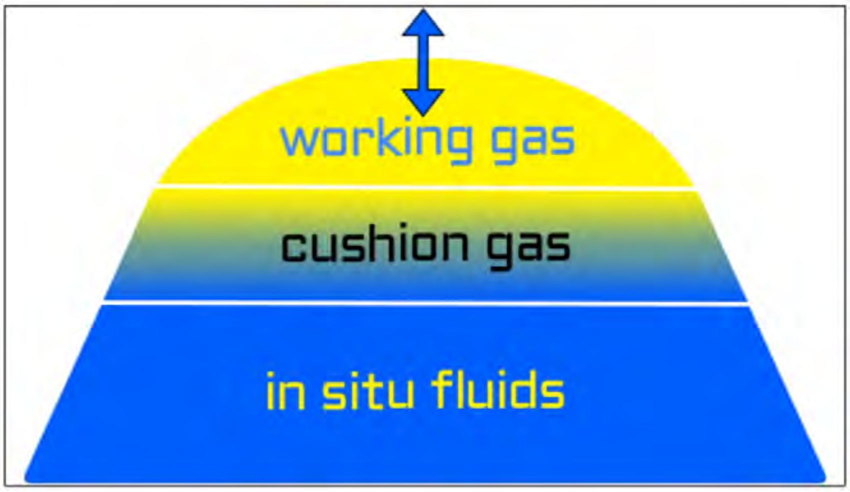

Figure 1. Diagram showing gas distribution within a geological storage site (modified from [9]). The bidirectional nature of the arrow signifies that the working gas is injected and withdrawn as needed.

Accurately estimating the CO_2 storage capacity allows potential emissions reductions to be quantified and sensible storage targets to be made. This information is crucial for demonstrating the feasibility and effectiveness of CCUS projects in achieving emission reduction targets.

The objective of this article is to analyse the geological and petrophysical properties of UGS facilities, estimate their potential for H_2 and CO_2 storage, and assess possible synergies. The careful estimation of H_2 and CO_2 storage capacity is a complex process that requires a multidisciplinary approach and data analyses (reservoir and caprock lithological characterisation, a porosity and permeability assessment, and the evaluation of pressure and temperature conditions) [10].

As a part of the H2020 EU project "HYdrogen STORage in European Subsurface" (Hystories [11]), aimed at supporting technical developments for the storage of pure green H_2 in depleted fields and aquifers, a thorough analysis was conducted on 13 UGS facilities in Ukraine. The purpose of the Hystories project was to assess the potential of these sites for the geological storage of H_2. During the Hystories project, geochemical reactions and microbiological impacts and mitigations were studied [12,13]. Given the potential for geochemical and microbiological reactions concerning UHS, site-specific studies would be required to confirm suitability.

Ukrainian UGS facilities were also included in a recently published techno-economic modelling study of H_2 storage in European UGS facilities [14], in which only working gas volume data of UGS facilities, reported in 2004, were collected and used for calculations, and the total volumes of all the European UGS facilities were not available.

The study presented here used and analysed the total, working, and cushion gas volumes in Ukrainian UGS facilities for H_2 and CO_2 storage and their possible synergy.

2. Geological Background and Location of UGS in Ukraine

The Ukrainian mainland comprises three major oil- and gas-bearing basins in the western, eastern, and southern regions (Figure 2). Existing UGS facilities, as well as most depleted oil and gas fields, belong to these basins and can be considered potentially suitable for H_2 and/or CO_2 storage.

Figure 2. Oil- and gas-bearing regions in Ukraine. Modified from [15].

Ukraine has a developed network of 13 UGS facilities with a total capacity of more than 31 billion cubic metres (BCMs) of natural gas. Eleven of the UGS facilities were built in depleted gas and gas condensate fields (Uherske, Bilche–Volytsko–Uherske, Oparske, Dashavske, Bohorodchanske, Solokhivske, Kehychivske, Proletarske, Krasnopopivske, Verhunske, and Hlibivske), and two were built in aquifers (Olyshivske and Chervonopartyzanske) (Figure 3 [16]).

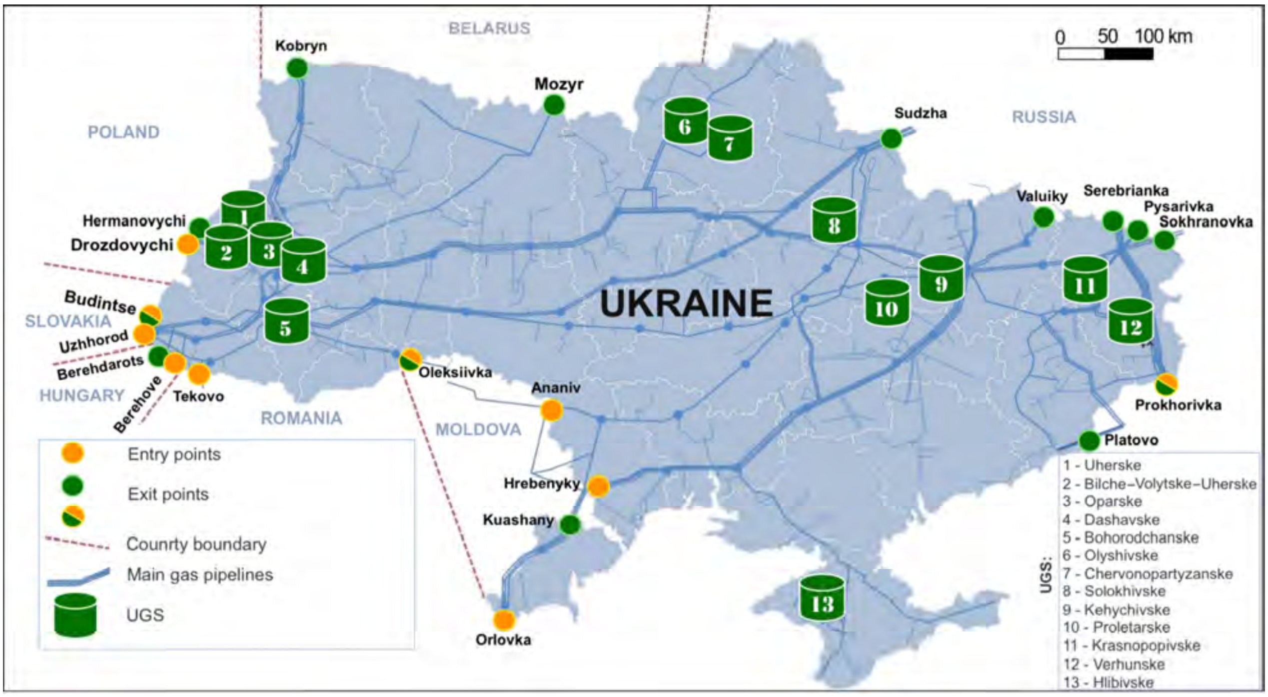

Figure 3. Location of existing UGS facilities in Ukraine. Modified from [16].

The significant capacities of the existing onshore UGS facilities lie at depths ranging from 400 to 2000 m, making it possible to consider the UGS system as an early opportunity in Ukraine for H_2 storage or for CO_2 storage in deeper reservoirs. There are four UGS complexes which can be defined by the location of the UGS facility and its connection to the main gas pipelines in Ukraine: (1) western, (2) central, (3) eastern, and (4) southern (Figure 4).

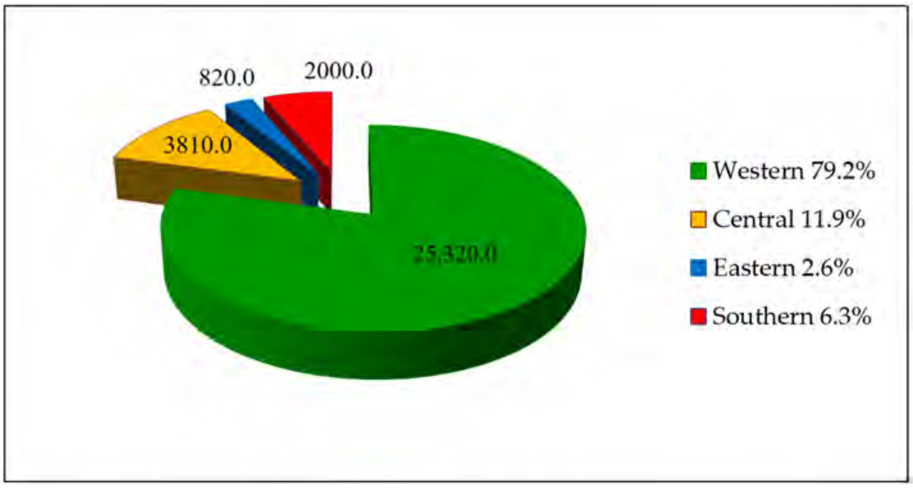

Figure 4. The distribution of the working gas volume across the UGS complexes, Mm^3.

2.1. Western Region

The western UGS region is located in the Carpathian Foreland (Figures 5–7) and is connected to a transcontinental, interstate, and intrastate gas pipeline system. There are five gas storage facilities:

1. Uherske.
2. Bilche–Volytske–Uherske.
3. Oparske.
4. Dashavske.
5. Bohorodchanske.

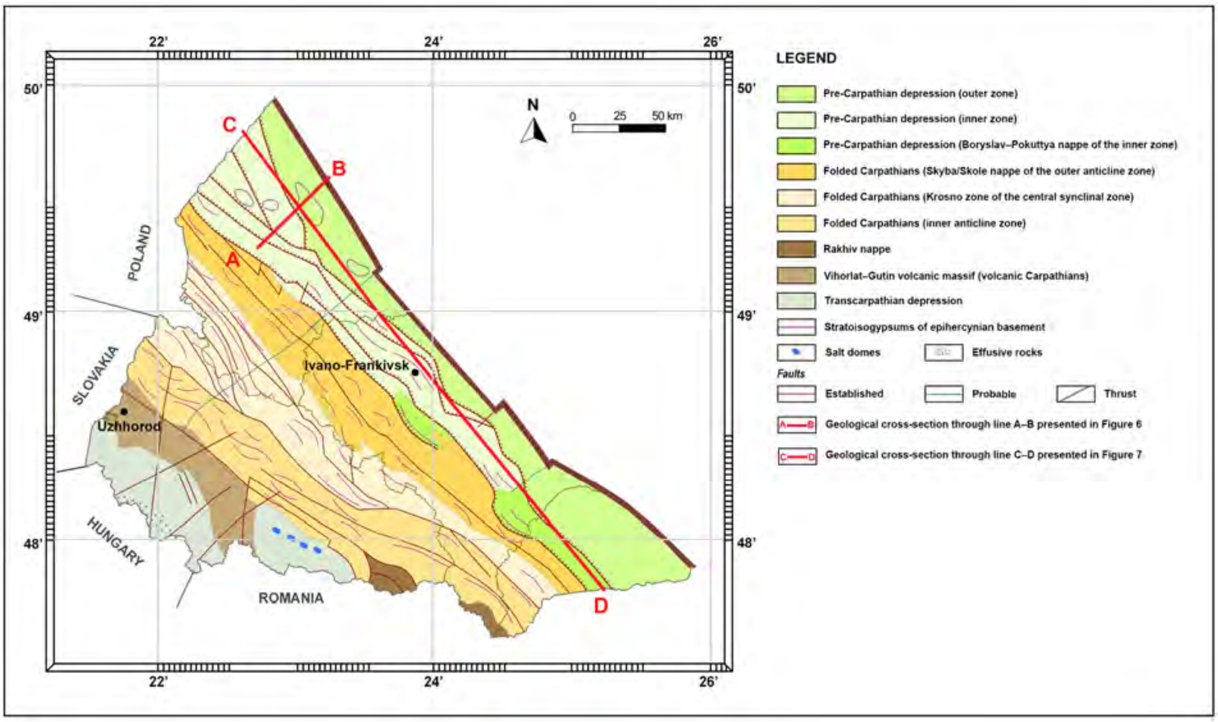

Figure 5. Tectonic map of the Ukrainian Carpathians (modified from [17]).

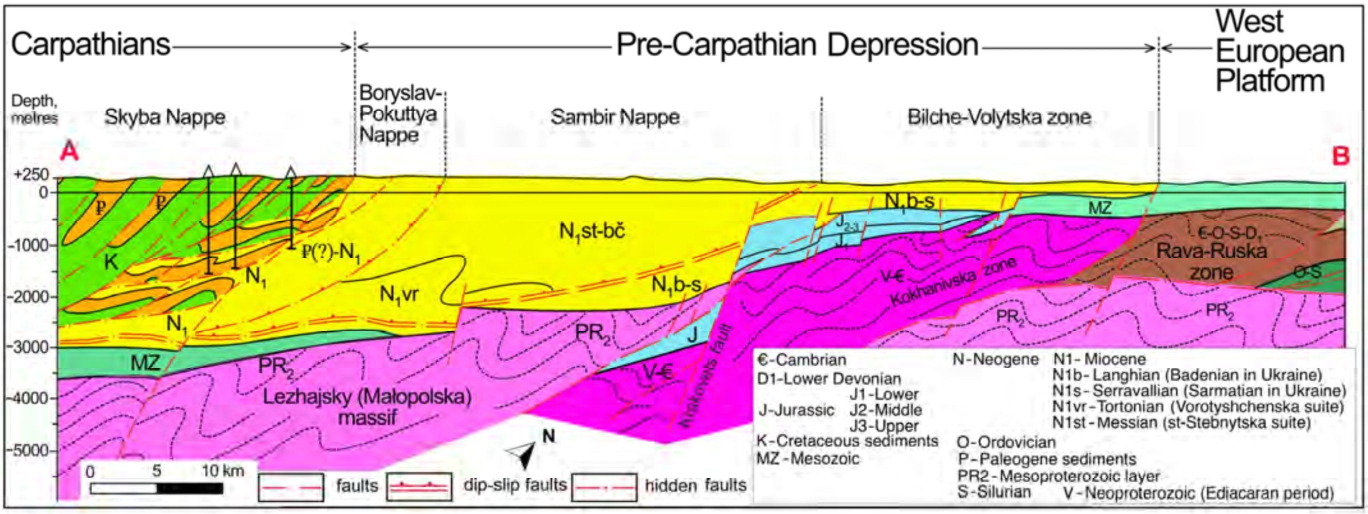

Figure 6. Geological cross-section through the A–B line indicated in Figure 5 (modified from [18]).

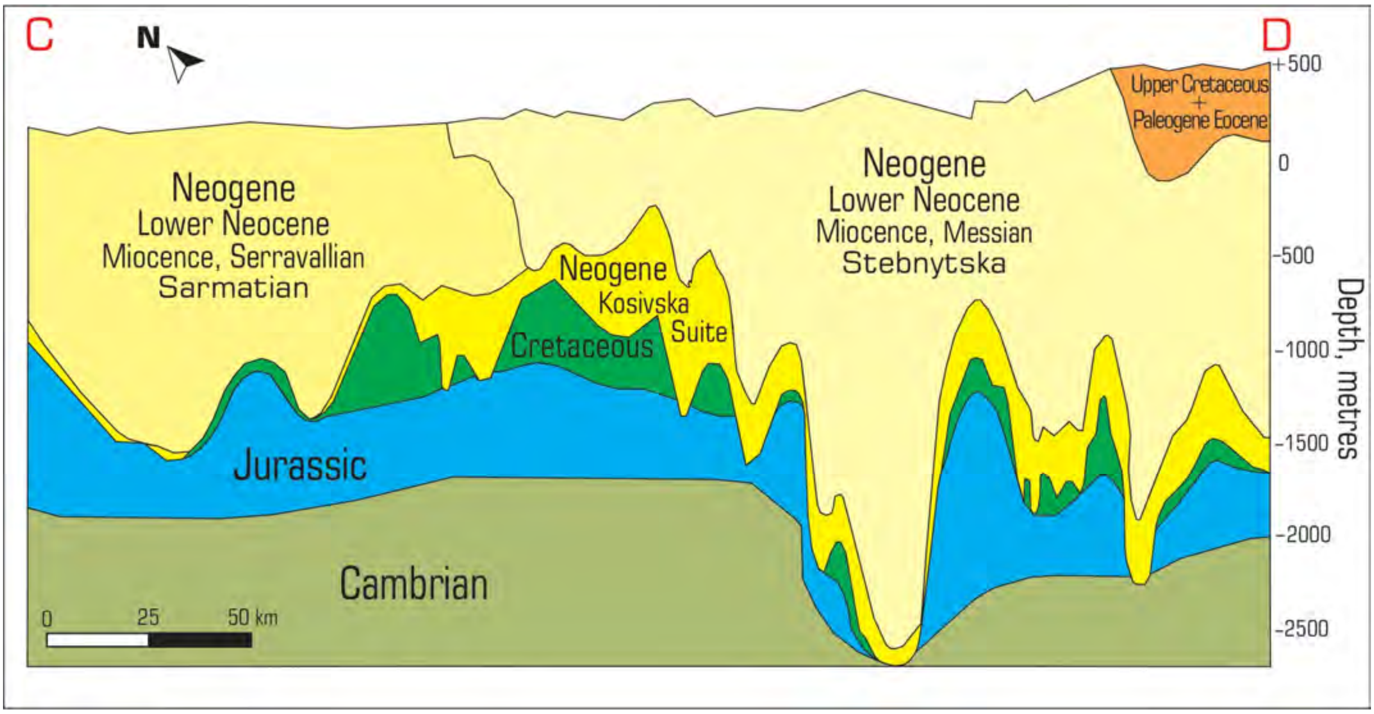

Figure 7. Geological cross-section through line C–D, line indicated in Figure 5 (modified from [19]).

The UGS facilities of western Ukraine are limited to the Bilche–Volytska zone—the outer part of the Pre-Carpathian Depression. The structural–tectonic Bilche–Volytska zone is one of western Ukraine's most important gas-producing zones. It was formed on the submerged southwestern edge of the Eastern European Platform, where layers and lenses of sandstones and siltstones formed traps for hydrocarbon deposits under different geodynamic conditions [20]. Massive gas fields are characteristic of the erosive protrusions of the Jurassic Period and occur occasionally in Cretaceous sediments of the Cenomanian, overlain by poorly permeable Miocene sediments. Proterozoic, Paleozoic, Mesozoic, and Cenozoic sediments are involved in the structure of the Bilche–Volytska zone.

The depression comprises two different layers—basement and sedimentary cover. The basement comprises Proterozoic–Paleozoic formations, while the sedimentary cover comprises Mesozoic–Cenozoic formations (Figure 8). The area of the Bilche–Volytska zone, which was dry for an extended time during the Cretaceous Period, was intensively eroded.

The Neogene sediments overlay Pre-Neogene sediments of varying ages, ranging from Proterozoic to Cretaceous [21].

Era	Period	Epoch	Age	Suite name in Ukraine	Reservoir Horizon	Petrographic characteristics of rocks	Thickness, m
Cenozoic	Neogene (N)	Miocene (N_1)	**Messinian (N_1mes)**	N_1st – Stebnytska N_1s – Sarmatian Dashavska: N_1dš$_2$ – upper sub-suite N_1dš$_1$ – lower sub-suite	Horizon ND-5 (IV) Horizon ND-7 (V) Horizon ND-8 Horizon ND-9	Thick monotonous layer of gray calcareous micaceous clays, siltstones, and sandstones with layers of tuffs and tuffites – molasses formation.	0–4000
			Tortonian (N_1tor)	N_1vr – Vorotyshchenska N_1kos – Kosivska	Kosivska Suite	Layering of clays, siltstones, sandstones, and marls.	100–1900
			Serravallian (N_1srv)	N1tr – Tyraska	Horizon XVI		60–100
			Langian (N_1lan)	N_1b – Badenian N_1bg – Bogorodchanska		Gypsum-anhydrite horizon.	50–100
Mezozoic	Cretaceous (K)	Upper (K_2)	**Maastrichtian**	Senonian		Sandstones, siltstones, argillites, marls, sandy limestones.	0–100
			Santonian				0–450
			Coniacian				0–53
			Turonian				0–123
			Cenomanian				0–60
		Lower (K_1)	**Albian**			Limestones, and calcareous argillites.	0–210
	Jurassic (J)	Upper (J_3)	**Tithonian Kimmeridgian**	Nyzhnivska		Limestones, dolomites with layers of marls, argillites, and sandstones.	150–500
			Oxfordian	Rava–Ruska			150–400
		Middle (J_2)	**Callovian**	Rudkivska Yavorivska		Limestones, sandstones, siltstones, gravelites.	0–60
			Bathonian Bajocian	Kohanivska		Argillites, siltstones, and sandstones.	0–250
		Lower (J_1)	**Pliensbachian**	Medynytska		Sandstones, and argillites with layers of coal.	200–500
Paleozoic	Devonian (D)	Lower (D_1)	**Emsian**	Dnistrovska (D_1*dn*)		Layering of sandstones, siltstones, and argillites.	0–800
			Pragian				
			Lochkovian				
	Silurian (S)	Wenlock	**Homerian**	Clay–carbonate layer (S_{1-2}*gk*)		Argillites, rarely siltstones, sandstones, and limestones. The carbonate increases up the section.	0–1400
			Sheinwoodian				
		Landovery	**Telychian**				
			Aeronian				
			Rhuddanian				
	Ordovician (O)	Upper (O_3)	**Hirnantian**	Molodova series (O_{2-3}*ml*)		Graptolitic argillite.	0–150
			Katian				
			Sandbian				
		Middle (O_2)	**Darriwillian**				
			Dapingian				
	Cambrian (Є)	Series 2	**Stage 4**	Berezhkiv series (Є$_{1-2}$*br*)		Layering of sandstones, siltstones, and argillites.	0–1500
			Stage 3				
		Terreneuvian	**Stage 2**	Baltic series (Є$_1$*bl*)			
			Fortunian				
Proterozoic						Shales, and phyllites with interlayers of sandstones, siltstones, and argillites.	>2000

Figure 8. Stratigraphic section of the Bilche–Volytska zone [21].

The UGS facilities in the western Ukraine complex are interconnected by a system of gas pipelines, which creates favourable conditions for the redistribution of gas flows to meet the needs of both local and distant consumers.

The achieved capacity of the complex in terms of the working gas volume is about 81.4% of the total amount of working gas in the country's gas storage facilities. The inventory of the production wells corresponds to 53% of the total number of production wells drilled in UGS facilities in Ukraine.

The western Ukrainian UGS complex is the most efficient gas storage complex in Ukraine, meeting the needs of the country's western region both in terms of the required gas storage volume and productivity. It ensures the security of gas supply not only in the eastern region but also for transit supplies of export gas to western and eastern Europe. At the same time, there is a considerable shortage of UGS facilities in other regions of Ukraine (northern, central, eastern, and southern). This applies to the eastern and the Dnieper region, where the country's greatest industrial activity is located.

The Neogene sandstones confined to depleted gas reservoirs are grey with greenish and brownish tones. They are fine- and medium-grained, porous, and contain quartz and glauconite with carbonate and carbonate-clay cement, weakly cemented. The siltstones, mainly comprising quartz, are grey and dark grey with a greenish or brownish tint.

The Bilche–Volytsko–Uherske UGS facility lies within the N_1srv–K_2 reservoir. It is the largest store not only in Ukraine but in the whole of Europe and can contain more than 17 billion m^3 of natural gas [22].

The Upper Cretaceous (K_2) reservoirs comprise sandstones with layers of siltstones, calcareous argillites, marl layers, and pelitomorphic limestones. The sandstones are overlain by a reliable caprock of Langian (N_1lan) gypsum–anhydrite horizon. In this region, regional faults have considerable lengths, large amplitudes, depths, and durations of development.

2.2. Central Region

The central UGS complex is located within the Dnieper–Donets Basin (Figure 9). The Dnieper–Donets Basin lies almost entirely in Ukraine and is the main producer of hydrocarbons. The basin is bounded by the Voronezh High of the Russian Craton to the northeast and by the Ukrainian Shield to the southwest. The basin essentially consists of a Late Devonian rift overlain by clastic marine and alluvial deltaic sediments deposited in a Carboniferous to Early Permian postrift sag.

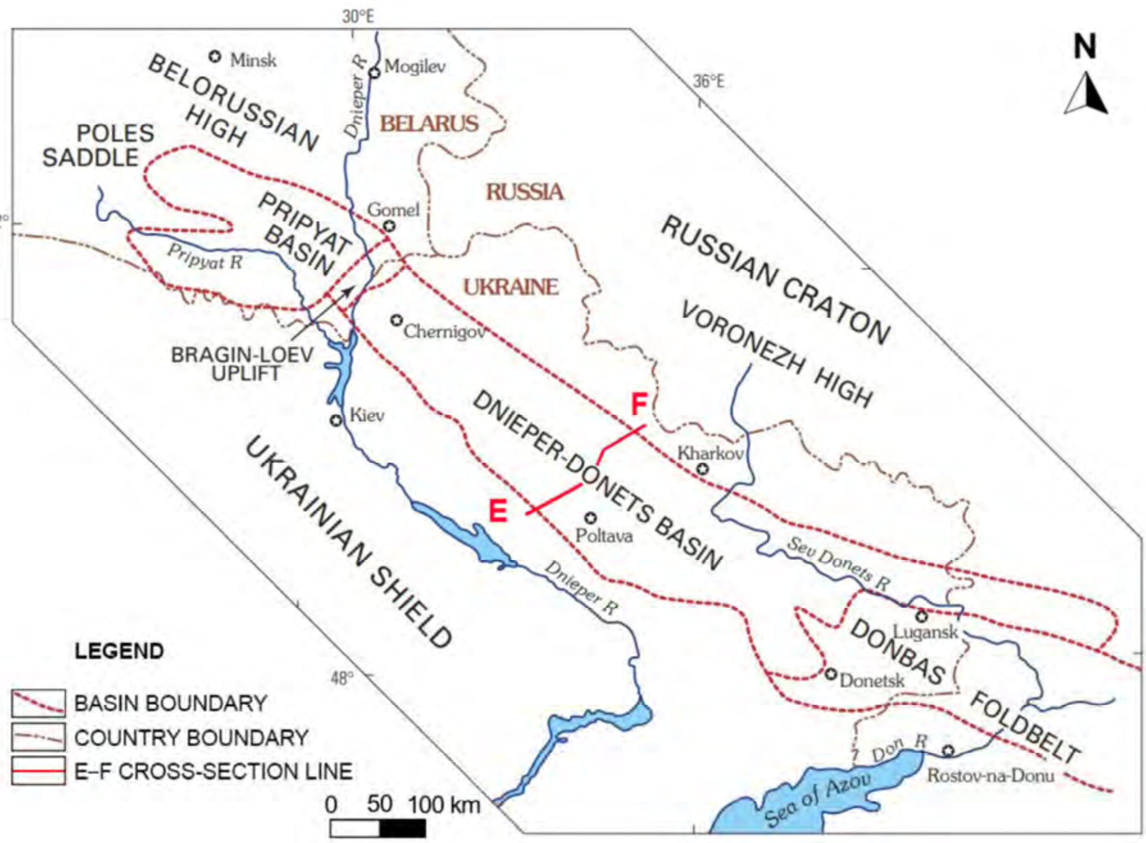

Figure 9. Location of Dnieper–Donets Basin. The indicated cross-section E–F is presented in Figure 10 (modified from [23]).

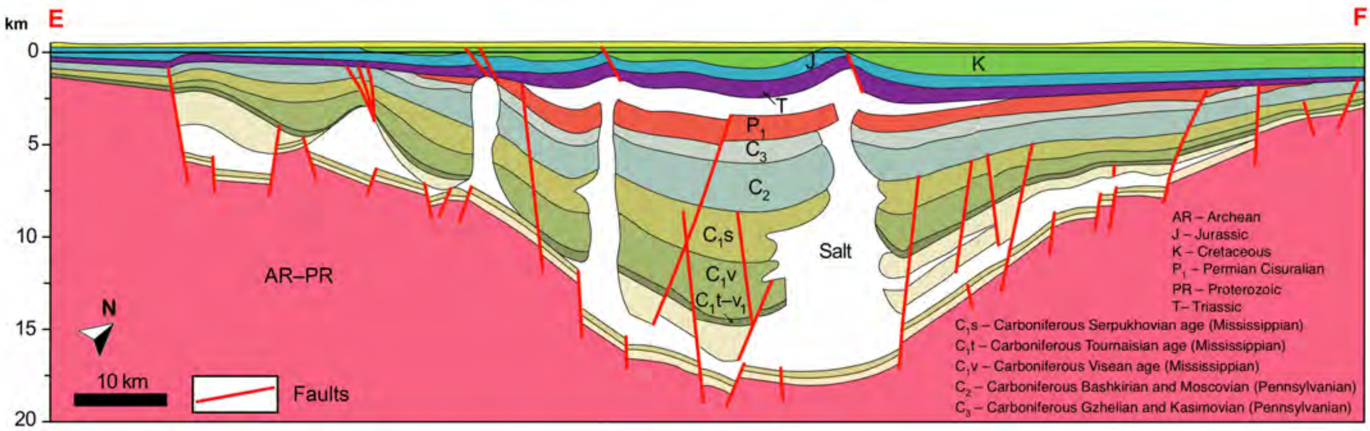

Figure 10. Regional geological cross-section E–F across the Dnieper–Donets Basin (modified from [23]). Location is shown in Figure 9.

The Devonian rift structure extends northwest to the Pripyat Basin in Belarus. The two basins are separated by the Bragin–Loev uplift, which serves as a Devonian volcanic centre. To the southeast, the Dnieper–Donets Basin has a gradual boundary with the Donbas fold belt, an area that has undergone structural inversion and deformation. The sedimentary succession of the basin comprises four tectono-stratigraphic sequences (Figures 9–11).

System / Series / Stage				Lithology	Reservoir Horizon	Maximum thickness (m)	Sequence
Quaternary						700	Postrif platform
Cretaceous						950	
Jurassic					Lower Bathonian Bajocian aquifer	650	
Triassic					Lower Serebryanska	900	
Permian	Cisuralian		Kungurian			1400	
			Artinskian				
			Sakmarian		Under-Bryantsivskiy		
			Asselian				
Carboniferous	Pensylvanian	Upper	Gzhelian			1500	Postrift sag
			Kasimovian				
		Middle	Moscovian		Horizon M-7	1200	
		Lower	Bashkirian		Bashkirian Stage Horizon B-5+B-9	1200	
	Missisipian	Upper	Serpukhovian			800	
		Middle	Visean			1700	
		Lower	Tournaisian			750	
Devonian	Upper		Famennian			3600	Synrift
			Frasnian			2000	
							Prerift platform
	Middle		Givetian			180	
			Eifelian				

LEGEND

Sand, mudstone
Sandstone, sand
Carbonate rock
Salt, anhydrite
Volcanics
Coal
Principal unconformity

Figure 11. Stratigraphic section of Dnieper–Donets Basin (modified from [23]).

The prerift platform sequence comprises Middle Devonian to Lower Frasnian clastic rocks deposited in a large intracratonic basin. The Upper Devonian synrift sequence is approximately 4–5 km thick and consists of marine carbonate, clastic, and volcanic rocks, along with two salt formations. These formations are deformed into salt domes and plugs, as shown in Figure 9.

The postrift sag sequence of the basin comprises Carboniferous and Lower Permian clastic marine and alluvial deltaic rocks, reaching thicknesses of up to 11 km in the southeastern part.

The Lower Permian interval includes a salt formation that is an important regional seal for oil and gas fields. The basin was strongly compressed in Artinskian (Early Permian) time and the southeastern basin areas were uplifted and deeply eroded, forming the Donbas fold belt. The postrift platform sequence includes Triassic to Tertiary rocks deposited in a shallow platform depression that extended well beyond the boundaries of the Dnieper–Donets Basin [24].

There are six oil- and gas-bearing stratigraphic units (complexes) in the Dnieper–Donets Basin with similar formations containing UGS reservoirs:

1. Mesozoic (Olyshivske, Chervonopartyzanske, Solokhivske, and Krasnopopivsle UGS facilities).
2. Upper Carboniferous–Lower Permian (Kehychivske UGS facility).
3. Middle Carboniferous (Verhunske and Proletarske UGS facilties).
4. Lower Carboniferous.
5. Devonian.
6. Precambrian.

The central UGS complex includes

6. Olyshivske (injection has not been carried out since 2012).
7. Chervonopartyzanske.
8. Solokhivske.
9. Kehychivske.

The UGS reservoirs are confined to the Mesozoic and Upper Carboniferous–Lower Permian oil and gas complexes. The Mesozoic sequence comprises depleted Jurassic strata and is the main component of the underground gas reservoirs of the eastern region (Olyshivske, Chervonopartyzanske, and Solokhivske). The Middle Jurassic (J_2) strata comprise clays with layers of sandstones containing shells and lignite lenses. The reservoir strata are sandstones. The Bathonian (J_2)-age clay formations are caprocks.

The Upper Carboniferous and Lower Permian sediments in the eastern region are represented by terrigenous and salt-water deposits. The difference between the salt-water formations is a sharp increase (up to 70%) in the proportion of evaporites (halite and anhydrite). The reservoirs comprise porous sandstones and fissured–cavernous anhydrites and limestones. The youngest Permian stratum comprises a sulphate–halogen layer, which serves as a first-class seal for the Permian reservoirs. Lithologically, it is rock salt with layers of anhydrites, saline siltstones, clays and sandstones, and potassium and magnesium salts.

The central UGS complex was built connected to the Kyiv system of main gas pipelines to ensure a reliable gas supply to consumers in the Kyiv, Khmelnytsky, Vinnytsia, Zhytomyr, Kirovohrad, Cherkasy, Chernihiv, Poltava, Sumy, and Kharkiv regions. The gas storage facilities are interconnected by a system of gas pipelines, which makes it possible to regulate the volume of injection and selection within the complex as needed.

The achieved volume of working gas within the complex is 12.2% of the total volume of working gas in the country's gas storage facilities. The inventory of production wells is 16% of the total number of production wells drilled in UGS facilities.

2.3. Eastern Region

The eastern UGS complex comprises (Figure 3) the following facilities in the Luhansk region:

10. Krasnopopivske.
11. Verhunske gas storage facilities (the injection has not been carried out since 2012).

The eastern UGS complex is in the Dnieper–Donets Basin. The UGS reservoirs are confined to the Mesozoic and Middle Carboniferous oil and gas complexes. The Mesozoic sequence includes the depleted Triassic gas field (Krasnopopivske). The Triassic is represented by the stratification of thin sand–clay layers of the Serebrianska suite (T_2). The reservoirs are sandstones. The Lower Triassic clay formations are the caprocks.

The UGS reservoirs in the Middle Carboniferous strata are confined to the Bashkirian stage (Verhunske). The lower part of the Bashkirian stack (Bashkirian plate) comprises sandy-clay sediments covered by a marine clay–carbonate layer, and the upper part comprises a caprock of sandstones and clays with carbonate and coal layers. The reservoir rocks comprise sandstones, and the seal is formed by a clay layer.

The eastern UGS complex was established in the Donetsk gas pipeline system to ensure a reliable gas supply to consumers in the Donbas. The achieved amount of working gas within the complex is 2.6% of the total amount in the country's UGS facilities. The stock of production wells is 8% of the total number of production wells drilled in UGS facilities.

2.4. Southern Region

The southern UGS complex is being built in the Dnieper region and in the Crimea as a system of gas pipelines that transports towards the Balkans and includes two UGS facilities:

12. Proletarske.
13. Hlibivske.

The UGS facilities in the southern UGS complex are in the Dnieper–Donets Basin (Proletarske) and the Prychornomorska Depression (Hlibivske). These UGS facilities are limited to the southern oil and gas region. The Proletarske UGS reservoir is confined to the Moscovian strata and Bashkirian stages of the Middle Carboniferous strata. The Moscovian strata comprise sandstones and mudstones and occasional limestones. The lower part of the Bashkirian (Bashkirian Plate) contains a pack of sandy-clay sediments covered by a marine clay–carbonate layer, and the upper part comprises a caprock of sandstones and clays with carbonate and coal layers.

The rocks of the UGS reservoir are predominantly sandstones and, to a lesser extent, fractured limestones. According to their evolutionary characteristics, the sandstones belong to layered, lenticular, bar-, channel-, and delta-deposited sandstones.

The Middle Carboniferous caprock is represented by a clay layer, mainly of lagoonal origin. The Hlibivske UGS reservoir is limited to the oil- and gas-bearing complex of the Prychornomorska Depression in strata of the Paleocene–Eocene age. The Prychornomorska Depression (Figure 12) is a geological structure extending from northwest to southeast in the zone where the East European platform is connected to the Scythian platform. The depression was formed by the long-term submergence of the southern slopes of the Ukrainian shield, which was most intense in the late Mesozoic and Cenozoic eras.

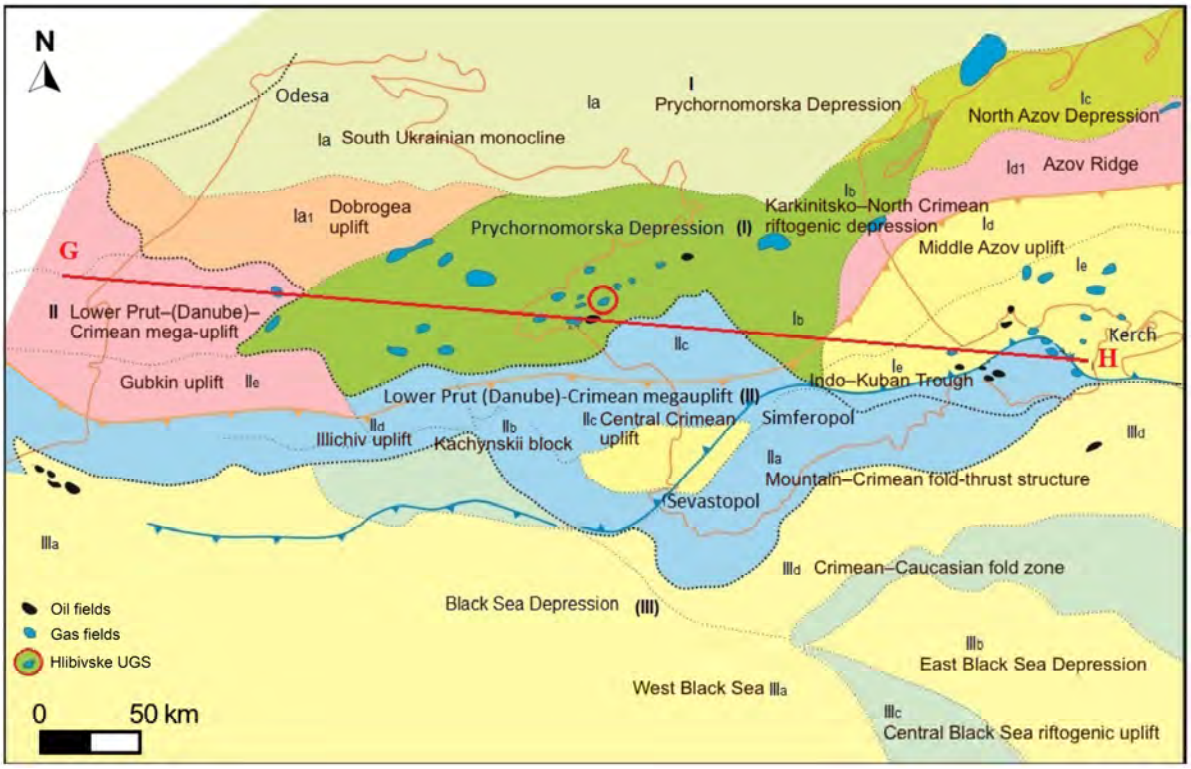

Figure 12. Tectonic map of the Azov–Black Sea region in southern Ukraine (modified from [25]). G–H line: a seismic–geological cross-section of the sedimentary cover is shown in Figure 13.

Latitudinal and meridional faults determined the block structure of the crystalline basement. The Prychornomorska Depression's geological structure comprises Palaeozoic, Mesozoic, and Cenozoic sediments, which can be up to 6000–8000 m thick (Figures 13 and 14) [26]. These sedimentary rocks are related to the primary hydrocarbon regions and comprise various geological formations.

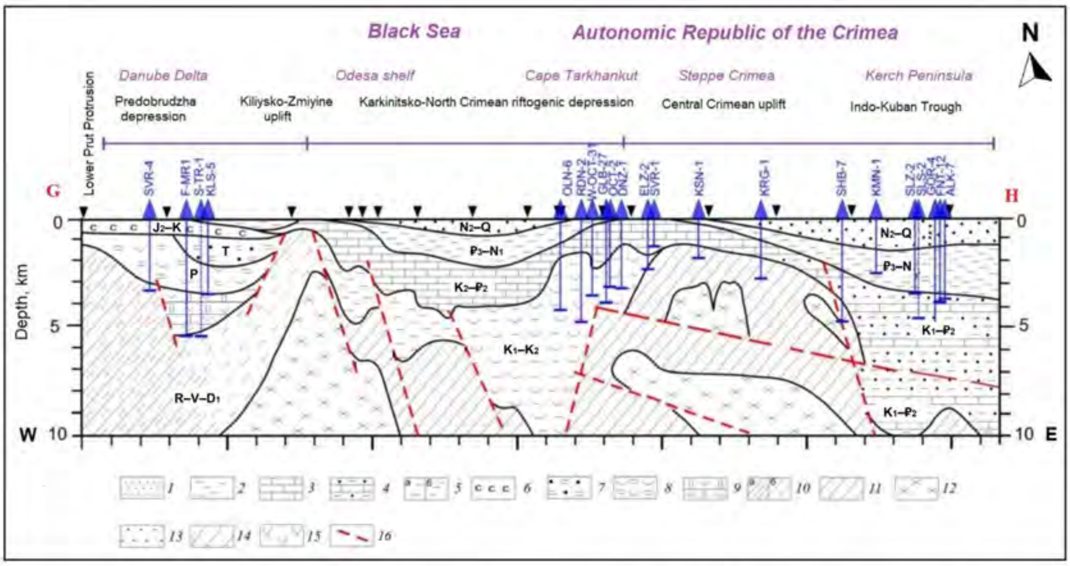

Figure 13. Seismic–geological cross-section of the sedimentary cover in southern Ukraine with probable fault zones along the G–H line that is shown in Figure 12 (modified from [27]): 1—middle Miocene–Quaternary (N_2–Q) sand and mudstone; 2—Eocene–Oligocene (P_2–P_3) and Oligocene–Lower Miocene (P_3–N_1) sediments; 3—carbonate rocks of Upper Cretaceous–Eocene (K_2–P_2); 4—Lower Cretaceous–

Eocene (K_1–₽$_2$) siltstones and marls; 5—terrigenous (a) and terrigenous–volcanogenic (b) rocks; 6—Middle Jurassic–Lower Cretaceous (J_2–K) terrigenous–clay layer; 7—Triassic (T) argillites and anhydrites; 8—Permian (P) argillites and clays; 9—Middle Devonian–Carboniferous (D_2–C) limestones and dolomites; 10—Riphean Lower Devonian undissected platform cover complex (R–V–D_1); 11—Paleozoic Mesozoic basement; 12—Doryphean granite–gneiss layer; 13—sedimentary cover; 14—Paleozoimesozoic basement; 15—volcanogenic complex; 16—faults.

Era	Period	Epoch	Age	Reservoir Horizon	Petrographic characteristics of rocks	Thickness, m
Cenozoic	Neogene (N)	Pliocene (N_2)	Piacenzian		Calcareous clays, sands, and sandstones.	0–200
			Zanclean		Shell, and oolitic limestones.	0–20
		Miocene (N_1)	Messinian		Marl–clay, and sandy-silt rocks, oolitic limestones.	0–100
			Tortonian			0–420
			Serravallian		Sandy–clay shell limestones, marls.	0–750
			Langhian			0–2000
			Burdigalian		A uniform layer of gray, and dark gray slightly calcareous clays, occasionally with layers of siltstones, sandstones.	
			Aquitanian			
	Paleogene (₽)	Oligocene (₽$_3$)	Chattian			0–1750
			Rupelian			
		Eocene (₽$_2$)	Priabonian		Calcareous clays, marls, and argillaceous limestones.	0–410
			Bartonian			0–100
			Lutetian			0–400
			Ypresian			0–120
		Paleocene (₽$_1$)	Thanetian		Fine–grained argillaceous limestones, and blue–gray marls, less often clays, and sandstones.	0–200
			Selandian	Brachyform fold		0–200
			Danian			0–200
Mezozoic	Cretaceous (K)	Upper (K_2)	Maastrichtian		Mostly carbonate rocks: limestones, dolomites.	0–920
			Campanian			0–430
			Santonian			0–320
			Coniacian			
			Turonian			0–950
			Cenomanian			0–600
		Lower (K_1)	Albian		Sedimentary–volcanogenic layer.	0–1100
			Aptian		Silty clays, and argillites.	0–240
			Barremian		Variegated continental sandstones, gravels, and clays.	
			Hauterivian			
	Jurassic (J)	Upper (J_3)	Tithonian			>1500
			Kimmeridgian		Carbonate–evaporite complex: dolomites, limestones, gypsum.	
			Oxfordian		Organic–rich limestones.	
		Middle (J_2)	Callovian		Terrigenous–clay layer of argillites, siltstones.	210–3000
			Bathonian			
			Bajocian			
	Triassic (T)	Upper (T_3)	Norian		Limestones with layers of argillites, and anhydrites.	80–640
			Carnian			
		Middle (T_2)	Ladinian		Siltstones, sandstones, and mudstones.	
			Anisian			
		Lower (T_1)	Olenekian		Coarse–clastic terrigenous rocks.	>200
Paleozoic	Permian (P)	Cisuralian	Kungurian		Argillites, siltstones, and red sandstones with layers of conglomerates, and effusive.	
			Artinskian			
			Sakmarian			
			Asselian			
	Carboniferous (C)	Missisipian Upper	Serpukhovian		Terrigenous clay stratum of gray mudstones, siltstones, and sandstones with layers of coal.	<650
		Missisipian Middle	Visean		Limestones with layers of siltstones, and sandstones.	350
		Missisipian Lower	Tournaisian		Dolomites, and anhydrites with layers of dolomitized limestones, and argillites.	500
	Devonian (D)	Upper (D_3)	Famennian		Dolomites, limestones, and anhydrites.	<850
			Frasnian			
		Middle (D_2)	Givetian		Limestones, and dolomites, anhydrites with layers of argillites, and marls.	600–850
			Eifelian			
		Lower (D_1)	Emsian		Calcareous argillites, and siltstones with thin layers of marls, tuff sandstones, dolomites, limestones.	>2000
			Pragian Lochkovian			
	Silurian (S)	Pridoli			Limestones, and dolomotic.	>650
		Ludlow	Ludfordian		Dolomitic marls.	
			Gorstian			
		Wenlock	Homerian		Limestones.	
			Sheinwoodian			
		Landovery	Telychian		Limestones.	
			Aeronian			
			Rhuddanian			
	Ordovician (O)	Middle (O_2)	Darriwillian		Gray quartz calcareous sandstones, and limestones.	500
			Dapingian			
	Cambrian (Є)	Terreneuvian	Stage 2		Different–grained sandstones, siltstones, argillites, gravelites.	300
			Fortunian			
	Neo-proterozoic				Terrigenous layer of mudstones, siltstones, and sandstones.	
						>300
	Paleo-proterozoic				Igneous, and metamorphic rocks: migmatites, gneisses, granodiorites.	

Figure 14. Combined stratigraphic section of the southern oil and gas region of Ukraine—the Crimean Plain, the Northern Black Sea Coast, and the Northwestern Black Sea Shelf (modified from [26]).

Large uplifts and troughs are complicated by local structures that are often oil- and gas-bearing. Oil and gas are found in rocks from the Neogene to the Devonian age, but gas and gas condensate fields have only been found in the Paleogene and Lower Cretaceous strata at depths of 350 to 4500 m. They are mainly associated with vaulted parts of anticlinal folds. The hydrocarbon reservoirs comprise sandstones, siltstones, and organic-detrital limestones.

The Hlibivske UGS facility, located in the Prychornomorska Depression, includes Palaeocene sediments of fine-grained clayey limestones and marls. The Lower Palaeocene comprises limestones and marls, while the upper comprises carbonate rocks. Dense calcareous clays serve as caprocks.

This facility ensures a consistent gas supply for domestic users, with additional gas transport to Moldova, the Balkan Peninsula, and Turkey through the southern regions of Ukraine. The complex currently holds 3.8% of the total working gas supply. This complex holds 23% of all the production wells drilled in Ukraine's UGS facilities.

3. Data and Methods

For Ukraine, the Hystories data collection exercise built on the primary reservoir data collected as part of the ESTMAP (Energy Storage Mapping And Planning) project [28]. All the UGS facility data collated in the ESTMAP project were checked and updated during the Hystories project. Data on all the analysed UGS facilities were collected from scientific publications and reports [29–39] available in the State Research and Development Enterprise "Geoinform of Ukraine". In addition, the comprehensive six-volume edition of the "Atlas of Oil and Gas Fields of Ukraine" (1998–1999), which contains detailed information on all oil- and gas-bearing regions of Ukraine, as well as oil, gas, and condensate fields, was used.

The reports from Geoinform of Ukraine, which outline the geological properties of UGS facilities, were mainly used to identify appropriate sites for H_2 or CO_2 storage. These reports provide valuable information, including seismic data, details about wells, core samples, and reservoir models for the relevant fields. In addition, over 50 research publications, papers, and open data from energy company websites were analysed and included in the Hystories study of Ukraine.

A high-level estimate of the range of the H_2 storage potential can be estimated by considering the volumetric characteristics of UGS reservoirs. In UGS facilities, the three relevant volumes for this study are the physically unrecoverable gas, the cushion gas, and the working gas capacity. Unrecoverable gas is the volume that is trapped in the pore space and cannot be withdrawn. The cushion gas is used to maintain reservoir pressure and ensure deliverability. The working gas capacity is the gas which is injected and withdrawn to meet demand. This study considers two scenarios: (1) the UGS reservoir would be depleted such that only the physically unrecoverable gas remains and hydrogen is used as the cushion gas, and (2) the UGS facility is converted to pure CO_2 storage. The volumetric capacity ranges are obtained by combining the reported working gas volume in the UGS facilities and H_2 density in situ reservoir conditions (temperature and pressure properties, Table 1).

Table 1. Ukraine's underground natural gas storage system (modified from [16,22,40]).

	UGS Facility Name	Year	Gas Volume, Mm^3		Number of Production Wells	Reservoir Type	Region
			Total Gas Volume (Including Cushion)	Working Gas Volume			
1	Uherske	1969	3850	1900	88	Depleted deposit	Western
2	Bilche–Volytsko–Uherske	1983	33,450	17,050	341	Depleted deposit	Western
3	Oparske	1979	4570	1920	76	Depleted deposit	Western
4	Dashavske	1973	5265	2150	100	Depleted deposit	Western
5	Bohorodchanske	1979	3420	2300	156	Depleted deposit	Western
6	Olyshivske	1964	660	310	40	Aquifer	Central
7	Chervonopartyzanske	1968	2973.8	1500	67	Aquifer	Central
8	Solokhivske	1987	2100	1300	81	Depleted deposit	Central
9	Kehychivske	1986	1300	700	53	Depleted deposit	Central
10	Krasnopopivske	1973	800	420	40	Depleted deposit	Eastern
11	Verhunske	1975	951	400	73	Depleted deposit	Eastern
12	Proletarske	1986	2980.3	1000	251	Depleted deposit	Southern
13	Hlibivske	1983	1881.1	1000	84	Depleted deposit	Southern
	Total		56,366	31,950	1450		

The H_2 capacity in M_{H_2} (cm^3) of the UGS was estimated with different levels of confidence. Using the total volume of the gas reservoir, V_{total} (Table 2), the total H_2 storage capacity (M_{H_2total}) was estimated:

$$M_{H_2total} = V_{total} \times \rho_{H_2r} \quad (1)$$

The H_2 density in in situ reservoir conditions (ρ_{H_2r}) was calculated as a function of pressure and temperature using models for thermodynamic properties of pure fluids [41]. The operating mode of the UGS facilities is determined by the maximum and minimum pressure of the reservoir.

The operating mode of the UGS facilities is determined by the maximum and minimum pressure of the reservoir. The maximum pressure corresponds to the state when the UGS facility is completely filled with gas, while the minimum pressure corresponds to the state when only cushion gas is in the reservoir. There is also an allowable (permissible) maximum gas pressure in UGS facilities, which depends on geological characteristics and technical factors. Typically, the maximum allowable pressure is close to or slightly below the original reservoir pressure before depletion. It is also worth noting that CO_2 storage is usually conducted at depths below 800 m where the CO_2 is a supercritical fluid. H_2 storage and UGS reservoirs can be shallower and, therefore, this brings an additional consideration for the conversion of UGS facilities for CO_2 storage.

Table 2. Geological and technical parameters of UGS facilities in Ukraine.

UGS	Formation Name	Age	Trap Name in Ukraine	UGS Total Area km^2	Temp., °C	Pressure, MPa Avg (Min–Max)	Permeability, Md (10^{-15} m^2) Avg (Min–Max)	Porosity, % Avg (Min–Max)	Top Reservoir Depth, m	Thickness, m Avg (Min–Max)	Reservoir Lithology	Seal Lithology
1. Uherske	Molasse	N_1mes	Horizon ND-8	21.5	30	5.37	30 (12–47)	20	687.5	70	Sandstone	Anhydrite
	Molasse	N_1mes	Horizon ND-9	4.95	30	5.5	39	20	750	45	Sandstone	Anhydrite
2. Bilche–Volytsko–Uherske	Flysch	N_1srv-K_2	Horizon XVI	74	42	5.02 (2.4–7.7)	20 (19.3–60.5)	25	965	187	Sandstone	Anhydrite
3. Oparske	Molasse	N_1mes	Horizon ND-5 (IV)	19.4	27	5.4 (2.6–8.3)	103 (75–131)	27	620	23	Sandstone	Claystone
	Molasse	N_1mes	Horizon ND-7 (V)	10.3	27	5.4 (2.6–8.3)	103 (75–131)	15	715	20.6	Sandstone	Claystone
	Molasse	N_1mes	Horizon ND-8 (VI)	24	27	5.4 (2.6–8.3)	103 (75–131)	10	820	20.4	Sandstone	Claystone
4. Dashavske	Molasse	N_1mes	Horizon ND-8	34.4	25	3.8 (1.9–5.8)	20–1200	26	657	9	Sandstone	Siltstones, Clays
	Molasse	N_1mes	Horizon ND-9	5.49	25	3.8 (1.9–5.8)	20–1200	25	710	15	Sandstone	Siltstones, Clays
5. Bohorodchanske	Molasse	N_1tor	Kosivska Suite	14	44	6.7 (3–10.5)	3	15	1130	150	Sandstone	Claystone
6. Olyshivske	Sandy clay	J_2b-bt	Bathonian-Bajocian aquifer	24.12	25	5.6	2	35	560.5	20	Sandstone	Claystone

Table 2. *Cont.*

UGS	Formation Name	Age	Trap Name in Ukraine	UGS Total Area km^2	Temp., °C	Pressure, MPa Avg (Min–Max)	Permeability, Md (10^{-15} m^2) Avg (Min–Max)	Porosity, % Avg (Min–Max)	Top Reservoir Depth, m	Thickness, m Avg (Min–Max)	Reservoir Lithology	Seal Lithology
7. Chervonopar-tyzanske	Sandy clay	J_2bt	Lower Bathonian	13	25	4.5	2	30	536.5	10–20	Sandstone	Claystone
	Sandy clay	J_2b	Bajocian aquifer	13	25	3.8	2	30	544	10–16	Sandstone	Claystone
8. Solokhivske	Sandy clay	J_2b	Bajocian horizon	57.6	34	7.9	3	25	903.5	67.5	Sandstone	Claystone
9. Kehychivske	Saline	P_1s	Under-Bryantsivskiy horizon	10.9	55	15.8	8	14 (6–23)	2060	5.2	Sandstone	Salt
10. Krasnopopivske	Sandy clay	T_1	Lower Sere-bryanska Sub-Suite	12	22	3.5	1.1	19	455	8	Sandstone	Claystone
11. Verhunske	Terrigenous carbonate	C_2b	Bashkirian Stage	12	30	11.8 (8.2–15.4)	0.6	22	1224	9.7	Sandstone	Claystone
12. Proletarske	Terrigenous carbonate	C_2m	Horizon M-7	13	35	8.7 (6.0–11.4)	104 (63–145)	20 (11–28)	1440	5–26.1	Sandstone	Claystone
	Terrigenous carbonate	C_2b	Horizon B-5+B-9	13	35	8.7 (6.0–11.4)	(0.2–474)	20 (12–25)	1785	6.6–66.2	Sandstone	Claystone
13. Hlibivske	Clay–carbonate	$P_1d\text{-}sl$	Brachyform fold	9.4	68	11.2	0.5	19	1050	120	Limestone	Claystone
Average (Min–Max)				18.2 (4.95–74)	35 (22–68)	6.7 (1.9–15.4)	34.9 (0.2–1200)	21.95 (6–28)	964 (455–2151)	44.8 (5–66)		

Avg—average.

The maximum values of reservoir pressure (Table 2) were used to estimate the H_2 density. The volume of the active zone of the UGS reservoir (V_{active}, Table 1) was used to estimate the active capacity of the storage site ($M_{H_2active}$), considering the reservoir in situ fluids and cushion gas that could be used during H_2 storage:

$$M_{H_2active} = V_{active} \times \rho_{H_2r} \quad (2)$$

The cushion gas volume of the potential H_2 storage site was estimated for two potential cases: (1) if the cushion gas is H_2 ($V_{H_2}cg$), the volume is estimated as the difference between the M_{H_2total} and the $M_{H_2active}$ (Table 3) and (Table 2); (2) if the cushion gas is CO_2 ($V_{CO_2}cg$), the volume is estimated as the difference between the optimistic CO_2 storage capacity (M_{CO_2}Opt.) and the conservative approach (M_{CO_2}Cons.) (Table 4).

Table 3. The potential for the H_2 storage capacity, in Mt, in the studied UGS facilities in Ukraine.

UGS Facility	Total Gas Volume Mm^3	Working Gas Volume Mm^3	Temp., °C	Pressure, MPa (max)	ρ_{H_2r} (kg/m^3)	M_{H_2total} (Mt)	$M_{H_2active}$ (Mt)	M_{H_2}cg (Mt)	M_{H_2} Energy (TWh)
1. Uherske	3850	1900	30	8.5	6.46	24.9	12.3	12.6	4.8462
2. Bilche–Volytsko–Uherske	33,450	17,050	42	10.38	7.47	250	127.4	122.6	50.1956
3. Oparske	4570	1920	27	7.7	5.92	27.1	11.4	15.7	4.4916
4. Dashavske	5265	2150	25	6.65	5.14	27.1	11.1	16.0	4.3734
5. Bohorodchanske	3420	2300	44	10.2	7.36	25.2	16.6	8.2	6.5404
6. Olyshivske	660	310	25	7	5.44	3.6	1.7	1.9	0.6698
7. Chervonopar-tyzanske	2973.8	1500	25	5.3	4.17	12.4	6.3	6.1	2.4822
8. Solokhivske	2100	1300	23	9.6	7.18	15.1	9.3	5.7	3.6642
9. Kehychivske	1300	700	55	15.9	10.61	13.8	7.4	6.4	2.9156
10. Krasnopopivske	800	420	22	5	3.99	3.2	1.7	1.5	0.6698
11. Verhunske	951	400	30	12.4	9.12	8.7	3,6	5.0	1.4184
12. Proletarske	2980.3	1000	35	16.5	11.63	34.7	11.6	23.0	4.5704
13. Hlibivske	1881.2	1000	68	11.2	7.46	14.0	7.46	6.57	2.93924
Average (Min–Max)	4939 (660–33,450)	2458 (310–17,050)	35 (22–68)	9.72 (5–16.5)	7 (4–11.6)	35.4 (3.2–250)	17.5 (1.7–127.4)	17.8 (1.5–122.6)	7.4 (0.7–50.2)
Total	64,201.2	31,950				459.6	228.2	231.27	89.77684

Mt—millions of tonnes; ρ_{H_2r}—the density of H_2 in situ reservoir conditions; M_{H_2total}—the total storage capacity of H_2 in the reservoir, excluding cushion gas and in situ fluids; $M_{H_2active}$—the working or active storage capacity of H_2 in the reservoir, considering cushion gas and fluids in the reservoir; M_{H_2}cg—the volume of the H_2 cushion gas; M_{H_2}Energy—the storage capacity of H_2 in energy units of Terawatt hours (TWh).

Table 4. The potential for the CO_2 storage capacity, in Mt, in the studied UGS facilities in Ukraine.

UGS Facility	Total Gas Volume Mm^3	Working Gas Volume Mm^3	Temp., °C	Pressure, MPa (max)	ρ_{CO_2r} (kg/m^3)	M_{CO_2}Opt. (Mt)	M_{CO_2}Cons. (Mt)	M_{CO_2}cg (Mt)	CO_2 State
1. Uherske	3850	1900	30	8.5	723	2783.6	1373.7	1409.9	Fluid
2. Bilche–Volytsko–Uherske	33,450	17,050	42	10.38	593.85	19,864.3	10,125.1	9739.2	SC fluid
3. Oparske	4570	1920	27	7.7	718	3281.3	1378.6	1902.7	Fluid
4. Dashavske	5265	2150	25	6.65	728.7	3836.6	1566.7	2269.9	Fluid
5. Bohorodchanske	3420	2300	44	10.2	539.7	1845.8	1241.3	604.5	SC fluid
6. Olyshivske	660	310	25	7	700.95	462.6	217.3	245.3	Fluid
7. Chervonopar-tyzanske	2973.8	1500	25	5.3	144.1	428.5	216.2	212.3	Gas
8. Solokhivske	2100	1300	23	9.6	823.9	1730.2	1071.1	659.1	Fluid
9. Kehychivske	1300	700	55	15.9	670.3	871.1	469.2	401.9	SC fluid

Table 4. *Cont.*

UGS Facility	Total Gas Volume Mm^3	Working Gas Volume Mm^3	Temp., °C	Pressure, MPa (max)	ρ_{CO_2r} (kg/m^3)	M_{CO_2}Opt. (Mt)	M_{CO_2}Cons. (Mt)	M_{CO_2}cg (Mt)	CO_2 State
10. Krasnopopivske	800	420	22	5	137.3	409.2	137.3	271.9	Gas
11. Verhunske	951	400	30	12.4	807.7	646.2	339.2	307	Fluid
12. Proletarske	2980.3	1000	35	16.5	829.13	788.5	331.7	456.8	SC fluid
13. Hlibivske	1881.1	1000	68	11.2	327.5	616.1	327.5	288.6	SC fluid
Average (Min–Max)	5295 (660–33,450)	2458 (310–17,050)	35 (22–68)	9.7 (5–16.5)	596 (137–829)	2890 (409–19,864)	1446 (137–10,125)	1444 (212–9739)	
Total	64,201.2	31,950				37,564	18,794.9	18,769.1	

Mt—millions of tonnes; ρ_{CO_2r}—density of CO_2 in situ reservoir conditions; M_{CO_2}Opt.—optimistic CO_2 storage capacity; M_{CO_2}Cons.—conservative CO_2 storage capacity; M_{CO_2}cg—volume of CO_2 cushion gas for H_2; CO_2 state—CO_2 state of aggregation in in situ conditions.

The theoretical CO_2 storage capacity of the structures was estimated using the same approach as for H_2. The optimistic approach, M_{CO_2}Opt., was estimated using the V_{total}, and for the M_{CO_2}Cons., the V_{active} was used:

$$M_{CO_2}\text{Opt.} = V_{total} \times \rho_{CO_2r} \quad (3)$$

$$M_{CO_2}\text{Cons.} = V_{active} \times \rho_{CO_2r} \quad (4)$$

The CO_2 density in in situ reservoir conditions (ρ_{CO_2r}) value depends on the in situ reservoir pressure and temperature and was estimated using a function of the states of CO_2 under in situ conditions [42]. The maximum values of the reservoir pressure (Table 1) were used to estimate the CO_2 density. To calculate the active H_2 storage capacity in energy units, the heating value for H_2 of 39.4 kWh/kg was applied [43].

4. Potential for CO_2 and H_2 Storage

For this paper, the UGS data that were collected as part of the Hystories project were further reviewed and updated (Table 2) with additional details to assess the potential for H_2 and CO_2 storage in UGS facilities in Ukraine (Tables 3 and 4). The 13 assessed Ukrainian UGS facilities are represented by 12 sandstone and 1 limestone reservoir facilities. They are characterised by a wide variation of parameters, including the areas in the range of 5–74 km^2 (average 18.2 km^2), reservoir rock thicknesses in the range of 5–187 m (average 44.8 m), and reservoir top depths in the range of 455–2151 m (average 964 m). The Oparske UGS facility exploits three reservoir layers located at the depth of 620, 715 and 820 m, and four UGS facilities (Uherske, Dashavske, Chervonopartyzanske, and Proletarske) exploit two reservoir layers. The reservoir rocks are characterised by porosities in the range of 6–35%, with an average of 22% for all the reservoir layers. The reservoir temperatures increased from 22 °C at the depth of 455 m (Krasnopopivske) to 68 °C at the depth of 1050 m (Hlibivske), with an average of 35 °C in Proletarske at the depth of about 2 km (Table 2).

In the context of climate change mitigation efforts, CO_2 storage is an important technology for storing CO_2 emissions from industrial processes and power plants. UGS facilities in Ukraine can potentially serve as secure and large-scale CO_2 storage sites by repurposing existing sites for CO_2 storage. Additionally, there could be a potential for utilising the storage capacity in Ukraine for importing CO_2 from other sources outside Ukraine or for transferring CO_2 from one area of Ukraine to another.

Estimating the CO_2 storage capacity accurately is essential for quantifying the potential emission reductions and optimizing subsurface planning. This information is crucial for demonstrating the feasibility and effectiveness of CCUS projects in achieving emission reduction targets. The analysis carried out during this study made it possible to estimate the potential of the CO_2 storage capacity.

Repurposing existing UGS facilities for CO_2 storage can be a cost-effective solution. This approach utilises existing infrastructure, reduces the need to build completely new CO_2 storage facilities, and uses well-understood reservoirs with the proven ability to store buoyant fluids. An H_2-specific evaluation of the sites, particularly the seals, would be required since H_2 can permeate through some materials that could trap CO_2 and natural gas.

In this study, the quantitative range of theoretical H_2 and CO_2 storage capacities of the 13 reported onshore UGS facilities in Ukraine was estimated for the first time (Tables 3 and 4). The amount of cushion gas required for H_2 storage was also calculated. Based on the specific in situ reservoir conditions, the density and state of CO_2 were estimated for each storage site.

The Bilche–Volytsko–Uherske storage site, with the largest area and average reservoir thickness (74 km^2 and 187 m, respectively), offers the largest storage capacity for both CO_2 and H_2 amongst all the structures analysed. The sandstone storage reservoir has excellent average porosity (21%) and permeability (1000–2000 mD). Among all the sites investigated, this storage site is the most suitable and feasible for both H_2 and CO_2 storage.

If the structure was depleted and H_2 was used as a cushion gas, the facility could potentially store over 127 Mt of H_2 in the working zone of the underground storage site (Equation (2)) and about 250 Mt of H_2, including cushion gas (Equation (1)).

If the facility were converted to pure CO_2 storage, the Bilche–Volytsko–Uherske site could potentially store almost 20 gigatonnes of CO_2 in an optimistic estimation, while a conservative option assumes a capacity of over 10 gigatonnes.

The CO_2 will be stored in the geological structure in a highly dense fluid state.

Although the Bilche–Volytsko–Uherske storage facility is considered the most promising, there is currently no public information regarding plans to repurpose it or other Ukrainian UGS facilities for H_2 or CO_2 storage. However, in June 2024, the Naftogaz Group, the subsidiary of which is Ukrtransgaz (a UGS operator), signed a memorandum of understanding with RAG Austria AG, Austria's largest gas storage operator, to collaborate on H_2 storage in gas reservoirs. This demonstrates intent not only to exchange expertise in H_2 storage in sandstone reservoirs but also to collaborate on the technical aspects of H_2 storage in gas facilities. This agreement showcases Ukraine's potential to become a key partner in the development of H_2 energy within the EU.

The optimistic CO_2 storage capacity of the 13 UGS facilities was estimated to be in the range of 0.4–19.9 Gt, and for all the analysed structures combined it was around 37.6 Gt. The "conservative" CO_2 storage capacity was in the range of 0.14–10.1 Gt, with a total capacity in all the structures of 18.8 Gt. The optimistic estimate represents the assumption that the full volume of working gas plus cushion gas can be replaced with CO_2 (see Equation (3)). The conservative estimate assumes that only the working volume of natural gas can be replaced with CO_2 for storage (see Equation (4)). The storage capacity of CO_2 cushion gas for H_2 storage is estimated to be in the range of 0.21–9.7 Gt, with a total of 18.8 Gt of CO_2.

The "total" H_2 storage volume of each of the 13 structures was estimated to be in the range of 3.2–250 Mt (average 35.4 Mt). The "total" H_2 storage volume of all the structures combined is approximately 459.6 Mt. The "working" H_2 storage volumes were estimated to be in the range of 1.7–127.4 Mt or 0.7–50.2 TWh (average 17.5 Mt or 7.4 TWh), and the total "working" capacity in all the structures combined was estimated to be 228.2 Mt or 89.8 TWh. The H_2 cushion gas was estimated for 13 UGS facilities to be in the range of 1.5–122.6 Mt (average 17.8 Mt), with a total of 231.27 Mt.

The H_2 and CO_2 storage capacities estimated here represent the first step in calculating the theoretical capacity that could be stored. It will not be possible to use the full volume since factors such as injectivity, irreducible water saturation, unrecoverable gas, and permeability variations will affect the amount of storage capacity that can be accessed at useful rates and within economic constraints (e.g., technically accessible CO_2 storage resource calculations in CO_2StoP for CO_2 storage) [44].

The accurate estimation of the H_2 storage capacity of a geological structure is a complex process that requires a multidisciplinary approach, specialised tools, and detailed site data to ensure safe and efficient operations. The presence of cushion gas in existing UGS facilities may affect the quality of the stored H_2.

H_2 has different physical and chemical properties than natural gas, and the cushion gas may mix with the stored H_2. This could lead to operational issues. Additionally, H_2 molecules can permeate materials more easily than natural gas and CO_2, which means that the integrity of the seal must be evaluated to confirm its effectiveness as a caprock for H_2 [44]. More detailed reservoir simulations and the pilot testing of this concept are required.

The issue of cushion gas in H_2 storage at UGS facilities necessitates a thorough approach that encompasses site integrity, compatibility, efficiency, and regulatory compliance to effectively transition from natural gas to H_2 storage.

5. Discussion

This study shows that the existing UGS facilities in Ukraine could play a crucial role in H_2 and CO_2 storage not only for Ukraine but also for Europe. Ukraine has a well-developed network of UGS facilities (13), with a working gas capacity of about 32 BCM, located in the oil–gas-rich western, central, eastern, and southern regions.

As part of the Hystories project, a detailed evaluation of the geology and petrophysical properties of UGS facilities was carried out, and their H_2 storage capacity was estimated in energy units. The Hystories database contains all the geological and petrophysical characteristics of the reservoirs and seals in the investigated UGS reservoirs, including thier age, formation, temperature, pressure, porosity, permeability, thickness, lithology, and depth. In this study, all the necessary parameters for calculating H_2 and CO_2 storage capacities were updated with the latest data, and the storage capacities for H_2 and CO_2 were estimated.

The total estimated H_2 storage capacity in all the studied UGS storage sites in energy units (maximum probability assessment) is about 98.8 TWh and 459.6 or around 228.2 Mt, considering the replacement of the total and working gas volumes, respectively. The total estimated CO_2 storage capacity in all the structures is approximately 37.6 Gt for optimistic scenarios and 18.8 Gt for conservative scenarios.

The significant capacities of existing onshore UGS reservoirs built on depleted gas/gas condensate fields and saline aquifers indicate that the UGS system could be the main potential location for H_2 and CO_2 storage in Ukraine and could make Ukraine a major player in the H_2 and CO_2 storage market. The depleted hydrocarbon traps are found in Palaeozoic (Carboniferous and Permian), Mesozoic (Triassic, Jurassic, and Cretaceous), and Cenozoic (Paleogene and Neogene) strata.

The UGS reservoirs, which comprise sandstones, limestones, and dolomites, have good reservoir properties: a porosity of 7 to 31% and a permeability of 8 up to 24 mD. The UGS seals consist of claystone, salt, siltstones, and anhydrites.

The geological features of the strata in Ukraine are promising for H_2 and CO_2 storage. These potential reservoirs have net thicknesses that range from 8 to 187 m and depths that range from 580 to 1210 m. It can be concluded that the existing UGS facilities in Ukraine are promising options for storing H_2 and CO_2.

Based on recently published techno-economic modelling of H_2 storage in European UGS facilities, several Ukrainian UGS facilities (Chervonopartyzanske, Dashavske, Oparske, and Bilche–Volytsko–Uherske) are considered the most favourable for H_2 storage in Europe [14]. However, it is also mentioned that UGS facilities could be repurposed in the future not only for H_2 or CO_2 storage but also for biomethane (CH_4) storage. There are several recent studies considering the use of CO_2 as a cushion gas and comparing this with CH_4 and Nitrogen (N_2) with different and sometimes contradictory results [45]. In addition to these studies, different gas mixtures have been modelled, with the authors concluding that the ideal cushion gas for H_2 storage is a mixture of H_2 (50%), CO_2 (40%), CH_4 (5%), and N_2 (5%) [46]. It was also reported [47] that the use of a high proportion of CO_2 in the cushion gas of sandstone reservoirs could minimise the risks associated with H_2 storage projects.

In our study, the amount of CO_2 that would replace the cushion gas for H_2 storage was calculated separately and, therefore, could be applied to the H_2 storage scenario we present, replacing the H_2 cushion gas with CO_2 cushion gas. The minimum depth required for H_2 storage is reported as 305 m [48,49]. The minimum depth required for CO_2 geological storage is usually reported as 800 m for dense phase CO_2 storage (>31.1 °C and >7.38 MPa) [50]. However, CO_2 could also potentially be stored in a liquid state at a lower temperature and at a shallower depth, although it would have a higher density and viscosity. In several of the investigated Ukrainian UGS reservoirs with a temperature range of 23–27 °C and a depth in the range of 660–770 m, the CO_2 could be stored in a liquid state (Table 4) with high-density efficiency for CO_2 storage. Considering the different depth requirements for CO_2 and H_2 storage, the shallower UGS facilities, such as Olyshivske, Chervonopartyzanske, and Krasnopopivske, are less favourable for CO_2 storage but could be suitable for H_2 or CH_4 storage.

6. Conclusions

The UGS facilities in Ukraine have the potential to serve as valuable assets for both H_2 and CO_2 storage (including using CO_2 as a cushion gas), contributing to various aspects of the energy transition and sustainability efforts. The repurposing of UGS facilities for H_2 and CO_2 storage requires careful planning, safety measures, and compliance with legal regulations. Additionally, fluid compatibility assessments and seal assessments are essential to ensure the safe containment of these fluids.

Underground H_2, biomethane, and CO_2 storage play important roles in transitioning to a low-carbon economy, reducing greenhouse gas emissions, and ensuring affordable, clean, and modern energy while enhancing energy security. Increasing the share of renewable energy and integrating sustainable development across various sectors of the economy is crucial for achieving climate goals. H_2 production will significantly promote the environmental, climate, and social dimensions of sustainable development by reducing CO_2 emissions, enhancing energy security, and creating new job opportunities.

Additionally, considering Ukraine's location and extensive experience in UGS, Ukraine could play a key role in developing a pan-European hydrogen economy.

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