REPORT

UNDERGROUND GAS STORAGE FACILITIES IN UKRAINE:

"GAS SHIELD" FOR EUROPE

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INTRODUCTION

Underground gas storage facilities in Ukraine: "gas shield" for Europe

This report include information about existing underground gas storage facilities and pipeline network in Ukraine for future underground hydrogen transport and storage facilities.

Underground gas storage facilities enable efficient and reliable supply of natural gas, ensuring uninterrupted transit of gas through Ukraine to Europe and the creation of gas reserves to boost energy security. In today's unstable energy world situation, Ukraine, as the second country in terms of active gas storage in Europe, acts as a powerful "gas shield" for European countries and individual companies.

Ukraine's underground storage facilities are in favorable geological setting, which makes the system strategically important, reliable and competitive, and their use by European countries can balance gas supplies in the event of fluctuations in supply and demand.

Purpose of the report:

- Assess the possibilities of using UGS facilities in Ukraine in order to create a strategic gas reserve for European countries.
- Determine the potential of using UGS facilities and GTS of Ukraine for storage and transportation of hydrogen in the perspective of decorbanization.

Scope:

- Characteristics of UGS facilities and existing pipeline transport system.
- Efficiency of operation of UGS infrastructure and GTS main networks
- Determining the reserve of active UGS capacities for European partners.
- Potential of using UGS and GTS of Ukraine for hydrogen storage and transportation.

Abbreviation

UGS	underground gas storage
MCM	million cubic meters
BCM	billion cubic meters
GTS	gas transmission system
UKRGTS	Ukrainian gas transportation system
GW	gigawatts
RES	renewable energy sources

1. General underground gas storages characteristics

Underground gas storage (UGS) responds to the need of storing large amounts of natural gas and it is therefore used for strategic purposes. Underground storages can be natural structures (depleted gas reservoirs, aquifers, or salt caverns) or hand-made. They are pressurized natural gas containers: pressure builds up the more gas is added. The higher the pressure, the more readily can the gas be extracted, while as the pressure falls below that of the wellhead, the resource cannot be pushed out of the facility [1].

Underground natural gas storage facilities in Ukraine are a complex of underground gas storage facilities on the territory of Ukraine, consisting of **13** storages (**12** storages are located on Ukraine territory, **1** storage is located in the Crimea occupied territory and is not considered in the report as therer is no data).

1.1. Key figures

- Total active capacity of Ukrainian UGS facilities – **30.95 BCM**.
- Total capacity of exit points to the gas transmission system from gas storage facilities (withdrawal) – **260.1 MCM/day**.
- Total capacity of entry points (injection) – **252.37 MCM/day**.
- The level of UGS filling at the end of the 2021 injection season – **18.6 BCM** (the highest over the past 10 years in 2020 – **28.3 BCM**) .
- The average level of UGS filling of Ukraine at the beginning of the 2012-2021 injection season – **18.8 BCM**.
- Volume of UGS of Ukraine in total volume of UGS of Europe – **21 %**.

1.2. Location

In terms of storage of active gas, Ukraine ranks third in the world (after the United States and Russia) and second in Europe.

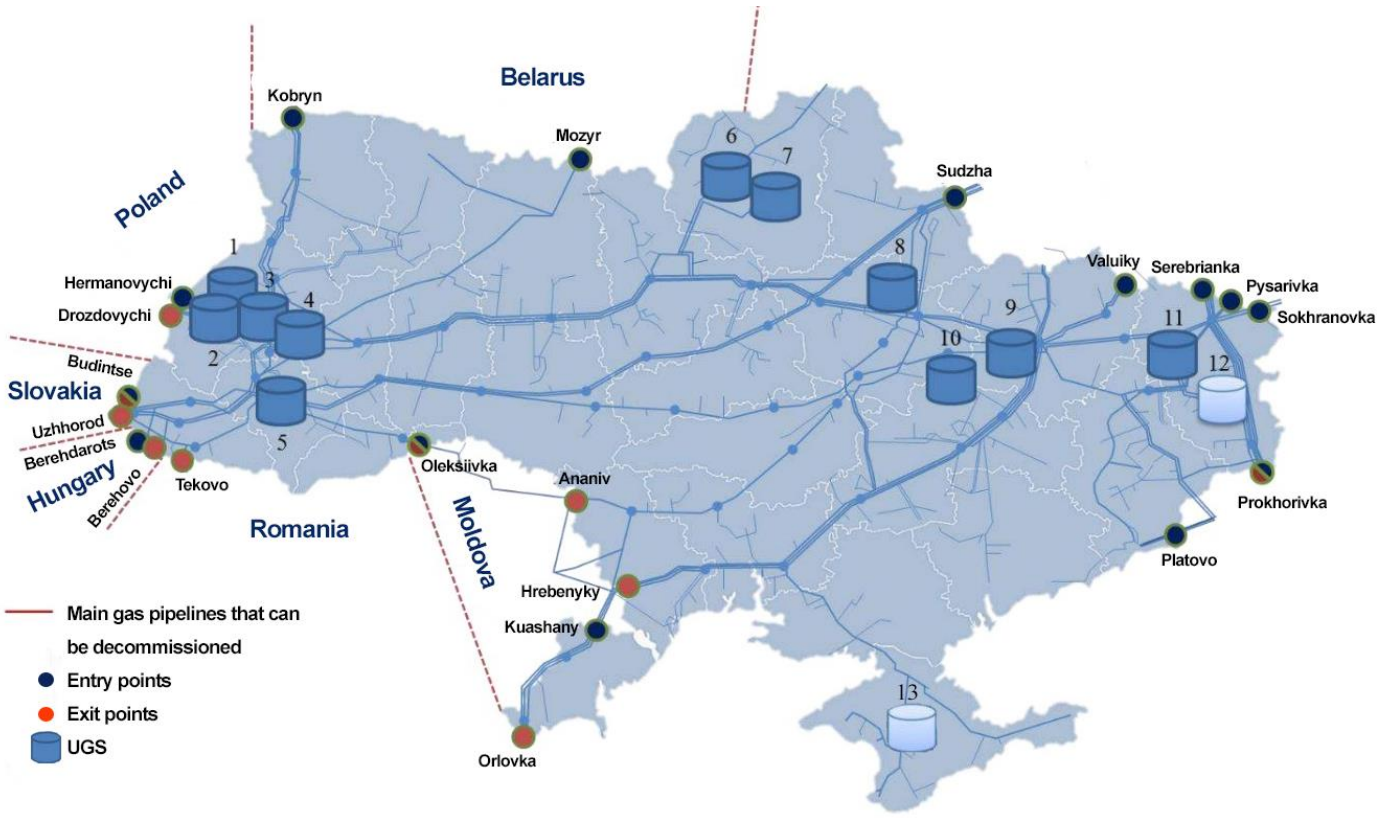


Fig. 1. Map of UGS location in Ukraine [2].

1.3. Geological setting and capacities

Ukraine has a developed network of underground natural gas storage facilities with a significant potential (Table 1).

Table 1. Ukraine's underground natural gas storage system [2].

#	UGS name	Year	Design indicators of storage capacity, MCM		Production wells stock		Type	Complex
			Total gas volume (including buffer)	Active gas volume	plan	fact		
1	Uherske	1969	3 850	1 900	88	88	Depleted deposit	Western
2	Bilche-Volytske-Uherske	1983	33 450	17 050	341	341	Depleted deposit	Western
3	Oparske	1979	4 570	1 920	75	76	Depleted deposit	Western
4	Dashavske	1973	5 265	2 150	99	100	Depleted deposit	Western
5	Bohorodchanske	1979	3 420	2 300	156	156	Depleted deposit	Western
6	Olyshivske	1964	660	310	40	40	Aqueous layers	Central
7	Chervonopartyzanske	1968	2 973.8	1 500	69	67	Aqueous layers	Central
8	Solokhivske	1987	2 100	1 300	81	81	Depleted deposit	Central
9	Kehychivske	1986	1 300	700	53	53	Depleted deposit	Central
10	Proletarske	1986	2 980.3	1000	99	251	Depleted deposit	Southern
11	Krasnopopivske	1973	800	420	43	40	Depleted deposit	Eastern
12	Verhunske	1975	951	400	73	73	Depleted deposit	Eastern (is in the temporarily occupied territory of Luhansk region)
13	Hlibivske		-	-	-	-	Depleted deposit	Southern (is in the occupied territory of Crimea)
			62 320,1	**30 950**	**1 217**	**1 366**		

The vast majority of UGS facilities are established on the sites of depleted gas and gas condensate deposits. UGS are located in all oil and gas provinces of Ukraine at a depth of 400 to 2000 m.

Two of them – Chervonopartyzanske and Olyshivske (the oldest in Ukraine, founded in 1964) - are based on aqueous layers. Bilche-Volytsko – Uherske UGS is the largest not only in Ukraine, but in the whole Europe and can hold more than 17 BCM of natural gas.

The total wells stock as of 01.01.2020 is 1679 wells, of which 1366 are production wells, including 134 wells pending connection, and 313 - observation and special wells.

1.4. UGS complexes: Western, Central, Eastern and Southern

According to the location and connection to the system of main gas pipelines in Ukraine, there are four underground gas storage complexes:

1. Western,
2. Central,
3. Eastern,
4. Southern.

The **Western complex of underground gas storage** was created in the Carpathian region in the system of transcontinental, interstate and intrastate gas pipelines and contains 5 gas storage facilities:

1) Uherske,
2) Bilche-Volytske-Uherske

3) Oparske,
4) Dashavske,
5) Bohorodchanske.

The UGS facilities of the complex are connected by a system of gas pipelines, which creates favorable setting for the redistribution of gas flows, meeting the needs of local and remote consumers. It is also possible to accumulate the necessary gas reserves to solve operational and strategic tasks.

The achieved capacity of the complex in terms of active gas volume is about 81% of the total amount of active gas in the country's gas storage facilities.

According to the production wells stock – 53% of the total number of production wells drilled in underground gas storage facilities in Ukraine.

The Western Ukrainian UGS complex is the most powerful storage complex in Ukraine, which meets the needs of the Western region of the country both in the required volumes of gas storage and in productivity. It ensures the security of gas supply not only in the western region, but also in transit supplies of export gas to Western and Eastern Europe. At the same time, in other regions of Ukraine (Northern, Central, Eastern and Southern) there is a significant shortage of underground gas storage facilities. This is especially true in the Eastern region and the Dnieper region, where the country's greatest industrial potential is concentrated.

The Central complex of UGS includes:

1) Olyshivske (injection has not been carried out since 2012),
2) Chervonopartyzanske,
3) Solokhivske,
4) Kehychivske,

The Central complex was created in the Kyiv system of main gas pipelines and is designed to ensure reliable gas supply to consumers in Kyiv, Khmelnytsky, Vinnytsia, Zhytomyr, Kirovohrad, Cherkasy, Chernihiv, Poltava, Sumy and Kharkiv regions. Gas storage facilities are interconnected by a system of gas pipelines, which allows, if necessary, to regulate the volume of injection and selection within the complex.

The achieved amount of active gas within the complex is 11.5% of the total amount of active gas in the country's gas storage facilities.

Production wells stock – 16% of the total number of production wells drilled in underground gas storage facilities.

The **Eastern complex of underground gas storage** consisting of:

1) Krasnopopivske,
2) Verhunske gas storage facilities (injection has not been carried out since 2012, is located in the territory of Luhansk region not controlled by the Ukrainian government).

The Eastern complex was created in the Donetsk gas pipeline system and is designed to ensure reliable gas supply to Donbass consumers.

The achieved amount of active gas within the complex is 2.5% of the total in the country's underground gas storage facilities.

The stock of production wells is 8% of the total number of production wells drilled on the underground storage.

The **Southern complex of underground gas storage** is being created in the Dnieper region and the Autonomous Republic of Crimea in the system of gas pipelines of the Balkan direction and includes two UGS facilities:

1) Proletarske,
2) Hlibivske (located in the Crimea occupied territory).

The complex is designed to ensure the reliability of gas supply to domestic consumers and transit gas supplies through the southern regions of Ukraine to Moldova, the Balkan Peninsula and Turkey.

The achieved value of active gas within the complex is 5% of the total value.

Stock of production wells - 23% of the total number of production wells drilled at UGS of Ukraine.

Each of Ukraine's underground storage facilities has a unique location, at a distance of 3–3.5 thousand km from the main fields of natural gas production, and is in favorable geological setting, which makes the UGS system strategically important, reliable, competitive against the background of growing demand for UGS in neighboring countries [3].

From a technical point of view, the underground storage is an extremely complex system, the main elements of which are the reservoir connected to the surface equipment of wells. The modes of operation of these facilities, in contrast to gas fields, are unstable over time, which complicates their reliable operation.

Therefore, scientific studies of the peculiarities of the operation of UGS facilities in the conditions of elastic-water-pressure regime are urgent problems of increasing the reliability of gas supply. These researches are directed on studying of formation of gas-saturated volume of a deposit, revealing of features of display of an elastic-water-pressure mode during cyclic operation of storage, definition of influence of a deposit on an aquifer zone of a formation.

1.5. UGS volumes in Ukraine for the period 2013-2022 and max productivity

As of September 1, 2021, 18.6 BCM of gas were stored in UGS facilities (Fig. 2) - this is almost 60% of the total capacity of Ukrainian UGS, which corresponds to the average level of gas storage facilities in Europe.

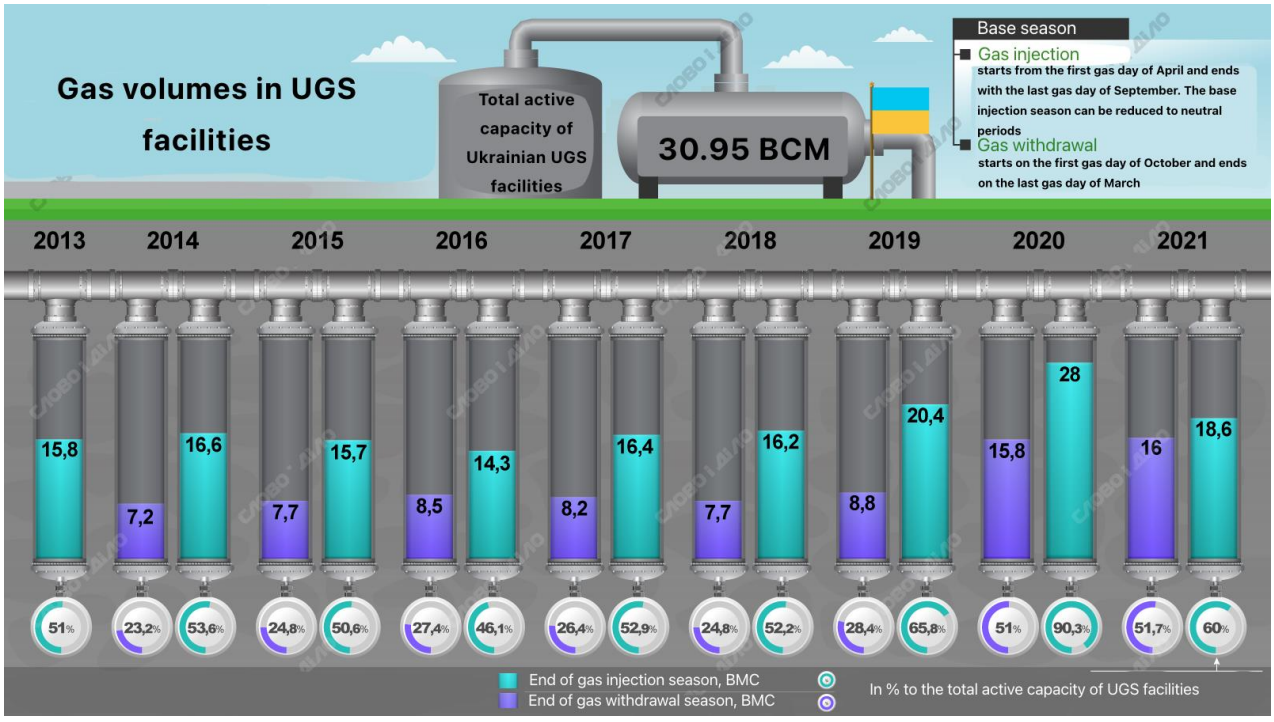


Fig. 2. UGS volumes in Ukraine for the period 2013-2021 [Source - 4].

As of the end of the gas injection season in 2014, there were 16.6 BCM, and storage facilities were 53.6% full [4].

In September 2015, there were 15.7 BMCof natural gas in storage facilities in Ukraine (50.6%). Almost the same figures were recorded in 2013.

The lowest volume of gas in underground storage facilities was in 2016 - 46.1% of the total active capacity.

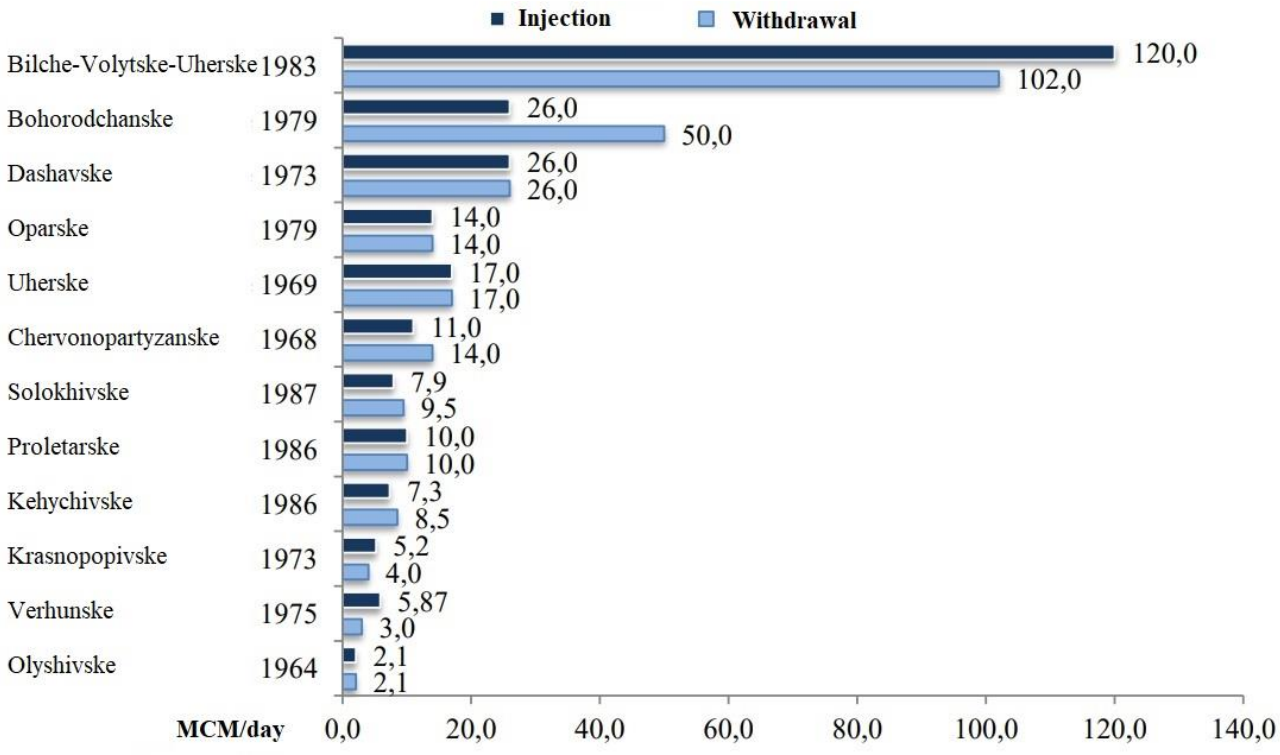
In September 2017-2018, gas volumes amounted to 16.2-16.4 BCM, and storage facilities were filled by about 52%.

In 2019, at the end of the season, gas injection was 8 BCM less than natural gas, and storage facilities were 65.8% full.

The largest amount of gas in storage was in 2020 - then they were filled by 90% (28 BCM). First of all, because of foreign customers who actively used gas storage facilities to store their own reserves.

As of 01.01.2022, gas reserves in UGS facilities amounted to 13.5 BCM (excluding reserves of Vergunsky underground storage facility located in the temporarily uncontrolled territory of Donetsk region). These volumes of gas are enough for the sustainable heating season in Ukraine [5].

Characteristics of the maximum productivityof Ukrainian UGS facilities during injection/withdrawal.



1.6. UGS Operator

Ukrtransgaz JSC (hereinafter - the Operator, the Company, https://utg.ua/en/)) provides operation of Ukrainian UGS facilities as well as upgrade and construct gas pipelines and its objects. Ukrtransgaz JSC is the state owned company, a part of Naftogaz Group.

Fig.3. UGS Operator Logo.

The goal of the Operator of Ukraine to become a customer-oriented operator on the European market by 2025. Accordingly, the Operator pay much attention to improving customer service system [6].

At present, the Company operates 11 underground storage facilities and has 1 more underground storage facilities on its balance sheet in the temporarily uncontrolled territory (Luhansk region, Vergunske underground storage facility).

Ukraine's gas storage Company operates an underground gas storage system. Today, the gas storage Operator of Ukraine is a full participant in the international gas market and an important component of the energy systems of Ukraine and Europe in general. Customers from Europe, Asia and North America keep their gas reserves, and the list of companies and countries that use gas storage services in Ukraine is constantly growing.

80% of the UGS facilities are concentrated on the western border of Ukraine. The proximity of UGS facilities to Europe and the convenience of logistics make underground gas storage advantageous for both foreign traders and Ukrainian companies working with cross-border natural gas transmission and storage.

2. Current utilisation of UGS in Ukraine and existing pipeline transport system

2.1. Current utilisation of UGS in Ukraine

Underground gas storage is usually used to regulate the unevenness of gas supply in seasonal periods that depend on the environment, ie temperature. They allow gas transmission companies to increase the utilization rate of gas pipelines, which allows to reduce the specific costs of gas delivery to consumers, as well as increase its reliability and continuity.

In addition to improving the reliability of gas supply, underground gas storage also plays a significant role as a means of optimizing the load of pipelines and, consequently, reducing the specific operating costs of the gas transmission complex, especially in conditions of fierce competition from alternative energy sources.

UGS facilities in Ukraine are designed for:

- regulation of seasonal uneven gas consumption;
- additional gas supply to consumers during extreme temperature drops both on certain days and during abnormally cold winters;
- creation of long-term gas reserves in the event of unforeseen emergencies, such as long-term cessation of gas supplies due to major accidents, natural disasters, supplier failures, etc .;
- gas reservation in case of short-term emergencies in the gas supply system;
- ensuring reliable transit of gas through the territory of Ukraine to European countries;
- hydrogen storage (in the future).

2.2. Gas Transmission System of Ukraine

Underground natural gas storage is one of the most important technological elements of the gas transmission system of Ukraine, which ensures its reliable and uninterrupted operation.

Ukraine's gas transportation system is the second largest in Europe, one of the most powerful and largest networks of main gas pipelines in the world. It is closely connected with the gas transmission systems of neighboring European countries - Belarus, Poland, Slovakia, Hungary, Romania, Moldova, through them integrated into the European gas network, and is a bridge between major gas producing regions and consumers in Europe (Fig. 4) [7].

Ground-based Gas Transmission System (GTS) is extensive and easy to maintain. In the event of an accident, gas volumes can be quickly redirected to other pipelines, thus not stopping transit during repairs.

In addition to the transit and import of natural gas, the GTS of Ukraine performs another important function - the transportation of gas to domestic consumers.

The GTS of Ukraine includes:

- **6** cross-border connection points with operators of six neighboring countries with which cooperation agreements have been signed;
- **65** active industrial sites in all regions of Ukraine;
- **33 079** km of main gas pipelines,
- **57** compressor stations,
- **33** gas measuring stations
- **1389** gas distribution stations.

GTS capacity [9]:

- At the entry to the GTS – **281 BCM**
- At the exit from the GTS – **146 BCM**

Table 2. The main gas pipelines of Ukraine (Fig.4).

Name of the main gas pipeline	Total length, km	Capacity, BMC/ year	Diameter of pipes, mm	Length in Ukraine, km
Torzhok-Dolyna	-	1,5-2,7	1420	529
Urenhoi-Pomary-Uzhhorod	4 451	32	1420	1 160
Kursk-Kyiv	434	-	1220	-
Ananiv-Chernivtsi-Bohorodchany	-	17,52	-	-
Kremenchuk-Ananiv	532	1,3	1020	-
Dzhankoi-Feodosiia-Kerch	235	-	500	235
Donetsk-Mariupol	102,9	-	-	-
Ostrozhsk-Shebelynka	236	-	1020	131
Ivatsevychi-Dolyna	400	29	1220	
“Soiuz”		26	1400	1567,3
Tula –Shostka- Kyiv	490	-	1220	-
“Prohres”	3743	26	1400	1160
Kyiv -Western border of Ukraine 1	367	19,3	1020	367
Kyiv -Western border of Ukraine 2	506		1220	506
Shebelynka-Dnipropetrovsk	197,5	12,6	700	197,5
Shebelynka – Dnipropetrovsk- Odesa (1)	-	-	700	-
Shebelynka – Dnipropetrovsk- Odesa (2)	-	-	1000	-
Shebelynka - Dnipropetrovsk - Kryvyi Rih - Izmail	-	15	1000	-

Diameters of main gas pipelines vary from 500 to 1400 mm, operating pressure - from 45-55 to 75 atm.

Fig. 4. Gas Transmission System of Ukraine [9].

2.3. GTS Operator

LLC Gas Transmission System Operator (https://tsoua.com/en/) provides transportation of natural gas to consumers of Ukraine and its transit to the countries of the European Union.

The natural gas transport sector reform was completed in 2019.

The UKRGTS operator has earmarked $1.5 billion in its ten-year development plan, to futureproof Ukraine's pipeline transportation industry. This will largely be spent on the maintenance of critical infrastructure, such as compressors.

Simultaneously, Ukraine is devising several new opportunities for UKRGTS.

UKRGTS operator became a member of the European Clean Hydrogen Alliance and now looks into opportunities connected with hydrogen transportation, which is particularly important in the context of the EU Green Deal and Europe's carbon reduction endeavours [12].

3. Prospects for European clients to utilise the Ukrainian UGS facilities for buffer storage of natural gas. Possibilities to convert some of these facilities into hydrogen transport and storage sites.

3.1. Prospects for European clients to utilise the Ukrainian UGS facilities

Underground gas storage plays a significant role in the international arena. For many years, their main task was only to ensure the uninterrupted transit of gas from Russia to Western Europe. But today more and more European gas companies are choosing Ukrainian storage facilities for storing blue fuel. This outlines a new strategic role and provides new profits.

Today the services of the UGS Operator are used by about 1000 clients, over 100 of them are foreign companies from 27 countries of the world. hese are the EU, the USA, Canada, the United Arab Emirates, Singapore and Hong Kong (Fig. 5).

Fig. 5. Geography of Ukrainian UGS clients [5].

European companies use underground storage facilities for seasonal storage of fuel and its subsequent supply to the EU, as well as transit gas through Ukraine at favorable rates.The first foreign customer of Ukrainian UGS facilities was a company from France in 2016.

Favorable gas storage tariffs, “Customs Warehouse” services (duty-free for 1,095 days) and “short haul” services (special tariff for gas transportation from the border to UGS), clear and transparent cooperation in the provision of services have become key factors in attracting foreigners to gas storage in Ukrainian UGS facilities. In 2020, more than 40% of all imports were made using the “short-haul” service.

Ukraine continues to successfully integrate into Europe's energy system.

Ukraine ranks first in Europe in terms of active gas volume (Fig. 6) and dynamic performance indicators of underground storage, with the exception of Germany, which has a significant amount of underground storage in salt caverns (Fig. 7).

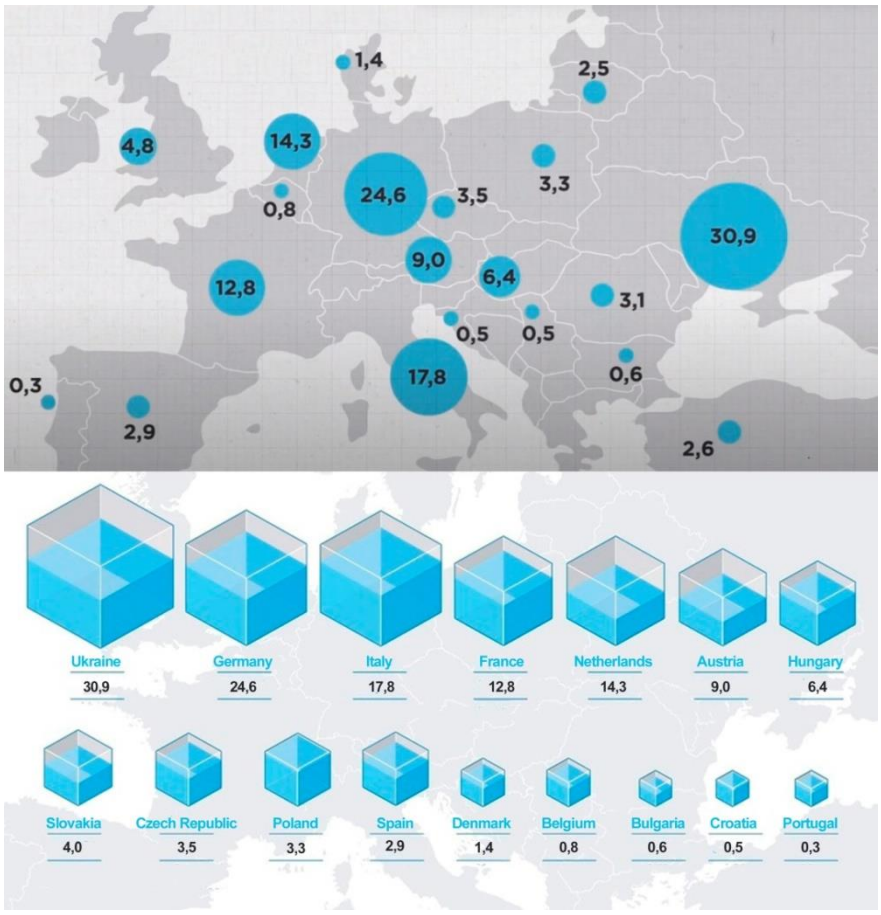


Fig. 6. Total active capacity of UGS facilities of Ukraine and other European countries [7].

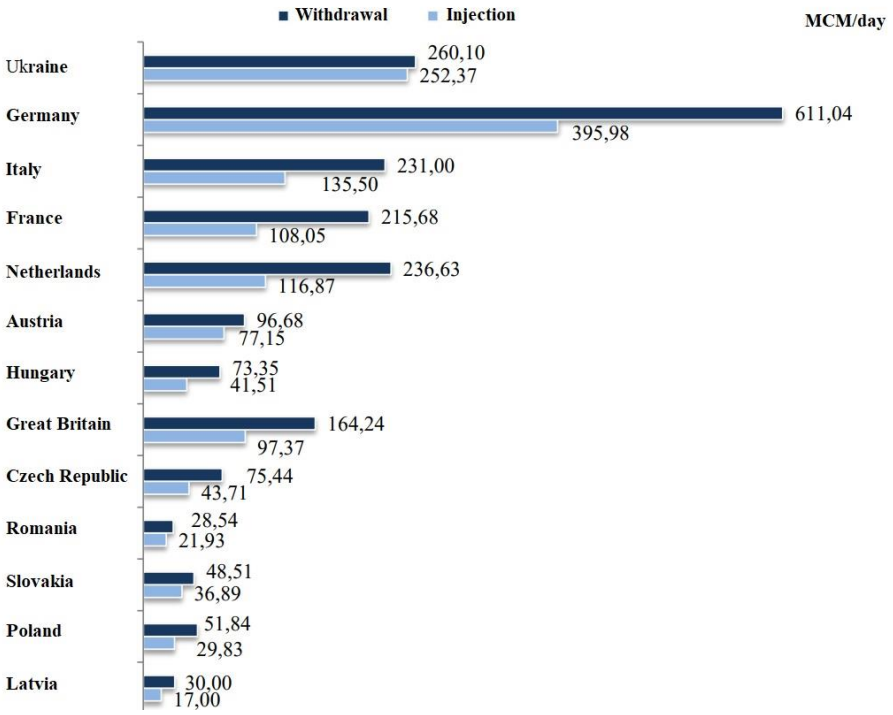


Fig. 7. Total dynamic indicators of UGS of individual European countries.

Significant active UGS volume in the Western region of Ukraine, capacity to inject and a wide range of natural gas withdrawal from UGS provide extraordinary maneuverability of gas flows, optimization of operating modes, the ability to create the necessary operational and strategic gas reserves, which is important in market relations.

The potential of UGS is assessed as significant, which allows to attract new partners, increase their efficiency, technical parameters and attract the best world experience in managing them. As a result of recent years, Ukraine has used up to 60% of total underground storage capacity for its own needs (approximately 15 BCM of active gas), which confirms the presence of a significant reserve of active underground storage capacity of about **8-15 BCM** of free storage that can be rented to European partners.

Ukraine could help make the gas situation more stable for Europe by providing some underground storage facilities that could become a "gas shield" for European countries and individual companies. This would guarantee the use of the transit component of Ukrainian underground storage facilities in case of Europe's refusal of Russian gas and Russia. A detailed comparison of UGS of Ukraine (Table 1) and other countries (Fig.6) shows their clear advantage: large volume and opportunities for further modernization.

In the Regional energy security partnership (RESP) initiative, Ukraine proposes to use these underground storage facilities to create a strategic gas supply for European countries [11].

According to the Association Agreement between Ukraine and the European Union, Ukraine is actively implementing measures aimed at further integration into the European gas market. EU key and regulatory provisions and codes have been implemented that could not be adapted for ten years.

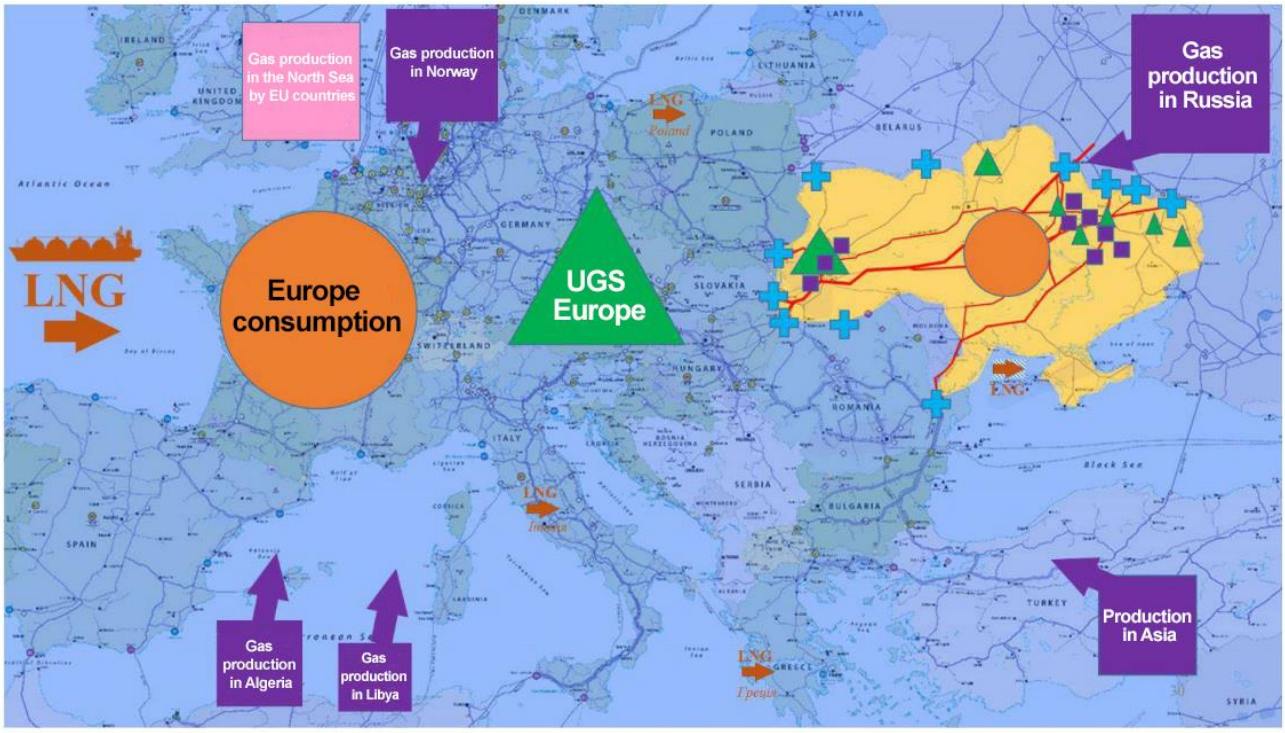


Fig. 8. The role of Ukraine in the European gas market.

3.2. Focus on hydrogen

In the context of decarbonisation of the economy, hydrogen energy has become one of the trends in the world today.

Therefore, the hydrogen trend fits perfectly into the concept of the European Green Deal (2019). Thus, in July 2021, the European Commission approved the "EU Hydrogen Strategy", which provides for the widespread use of hydrogen as an energy source for those industries that cannot be electrified, and aims to reduce carbon emissions to zero by industrial facilities, transport, energy, construction, etc.

At the same time, the European Clean Hydrogen Alliance was established, comprising public agencies, research centers, financial institutions, and the EU's leading energy and industrial companies.

The EU's priority is green hydrogen, which is produced from renewable energy sources (mainly solar and wind energy) and nuclear energy.

The European Union - in the context of the development of hydrogen energy - has high hopes for Ukraine. Moreover, the European Commission has identified Ukraine as a priority partner in the "2x40 GW Green Hydrogen Initiative" and will encourage the country's participation in the European Clean Hydrogen Alliance. The EU expects that 10 GW of clean hydrogen production capacity could be set up in Ukraine. It is planned that 75% of Ukraine's fuel will be exported to the European Union, and the rest will be used for its own needs.

Today, Ukraine is allegedly showing positive "feedback". Thus, in 2021 the Ministry of Energy and Coal Industry of Ukraine, together with international partners, developed projects "Hydrogen Strategy of Ukraine" [24] (three-level process until 2035+) and "Roadmap for production and use of hydrogen in Ukraine" [22] . The main directions and prospects of green hydrogen use in Ukraine are presented: in electric and heat power industry, industry, transport, autonomous energy supply systems, as well as opportunities for hydrogen integration in gas networks and Ukraine's advantages as an exporter of green hydrogen.

The most compelling argument in favor of hydrogen energy is the possibility of using hydrogen produced from RES for long-term balancing of the energy system. The function of hydrogen is to accumulate energy from unstable energy sources - the sun and wind - in chemical form. In practice, this means that during periods of maximum solar insolation or strong winds, excess electricity, not currently in demand, is sent to the cell and converted into chemical energy H2. This can be a good solution for dealing with unstable and volatile solar and wind energy. In the peak hours of generation, its excess can be converted into hydrogen by electrolysis, and in periods of greatest need - to generate electricity from it [14].

Under this scheme there is a need for daily and seasonal storage of large volumes of hydrogen in the gaseous state. The largest volumes of hydrogen storage can be provided by UGS facilities in Ukraine on the basis of depleted gas fields or aqueous layers.

Storing hydrogen in them is as safe as natural gas. In addition, once gas resources are depleted, they can be converted into hydrogen storage facilities.

The main method of hydrogen transportation in Ukraine is pipelines [19].

There are two possible hydrogen delivery ways for pipeline transport:

- adding hydrogen to existing gas pipelines to specified concentrations;
- transportation of 100% hydrogen through new or existing pipelines.

In addition to its main purpose as a mechanism for transporting hydrogen, the use of pipelines can provide a number of additional benefits:

1. Improving gas supply: with uncertainty surrounding natural gas supply constraints, hydrogen substitution could provide a shorter-term opportunity to offset growing gas demand.
2. Convergence of electricity and gas network: with increasing share of RES in the electricity network and reliability / stability requirements, hydrogen provides a new direction for optimizing electricity production: converting excess renewable energy into hydrogen gas using electrolysis technology with proto-exchange membrane (“power-to-gas ”). Hydrogen can be pumped into the natural gas supply network. Thus, hydrogen can replace natural gas by reducing greenhouse gas emissions and dependence on high-carbon fuels.
3. Energy storage: gas pipelines provide an additional option for storing hydrogen through a packaging pipeline or "energy transfer over time".
4. Decarbonization of the gas network: the injection of hydrogen into natural gas pipelines increases the opportunities for decarbonization in the energy sector.

Hydrogen can be transported not in its clean form, as it can quickly damage the pipes, but mixed with natural gas. Hydrogen concentration up to 10-20% by volume is considered acceptable. The main limitation is the ability of end-use devices to meet higher hydrogen concentrations. Due to its volatility and low atomic mass, hydrogen escapes through the smallest cracks and is explosive. As shown by a few static tests conducted by one of the gas operators, even at low hydrogen concentrations, typical leaks were threaded and coupling connections, connection points for pressure sensors and regulators, and welds [25].

In Ukraine, the level of use of natural gas pumped by pipelines is 30-35 BCM per year, so the capacity of this segment of the economy may be 6-7 BCM of hydrogen per year.

The existing network of gas pipelines laid on the territory of Ukraine may be used for hydrogen transportation. These are the main gas pipelines (Torzhok-Dolyna, Urengoy-Pomary-Uzhhorod, Kursk-Kyiv, Ananyiv-Chernivtsi- Bohorodchany, Kremenchuk-Ananiv, Dzhankoi-Feodosiia-Kerch, Donetsk-Mariupol, Ostrozhsk-Shebelynka, Ivatsevychi-Dolyna), gas pipelines-branches, gas distribution stations, compressor stations, underground gas storage facilities, gas metering stations and gas consumption measuring points. Diameters of main gas pipelines vary from 500 to 1400 mm, operating pressure - from 45-55 to 75 atm.

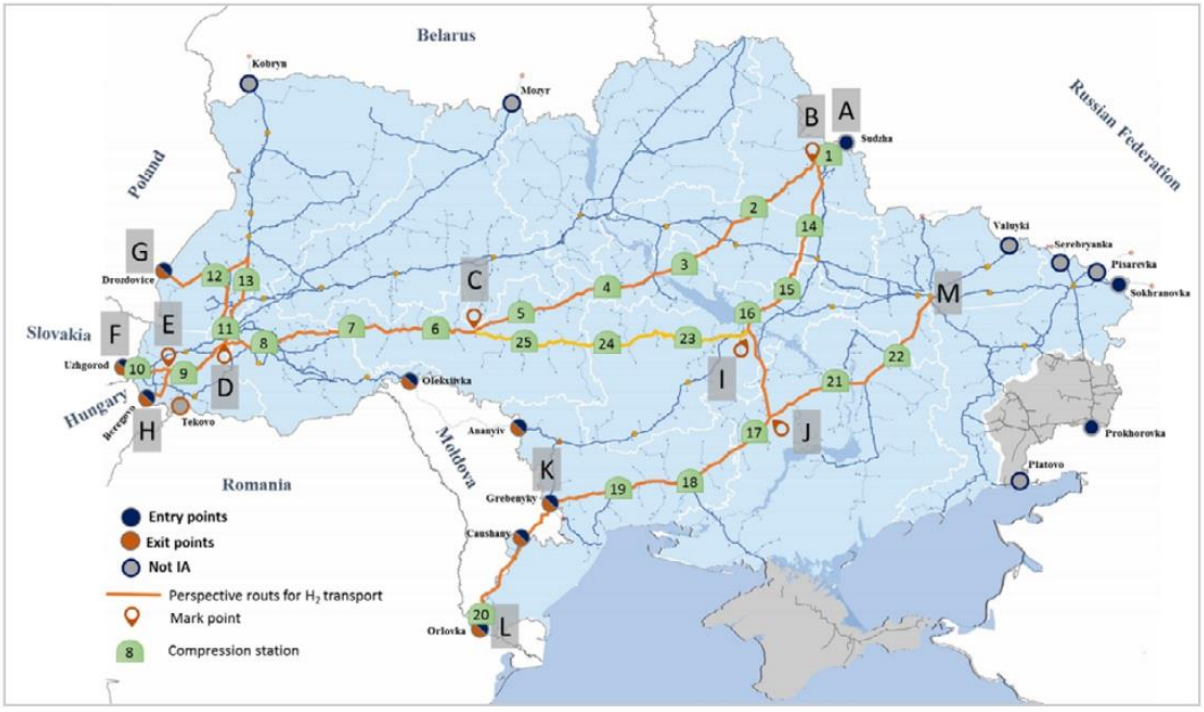


Fig. 9. Promising routes for hydrogen transportation.

One of the notable problems with the inclusion of hydrogen in the natural gas network is the impact it has on measurements. Transporting 100% hydrogen through the pipeline can cause problems with the fragility of the pipes depending on the operating pressure and the material of the pipeline. Despite the fact that this risk increases with increasing operating pressure, the use of steel, plastic-reinforced pipes, able to transport hydrogen at pressures of 70-105 bar. In the internal gas distribution network, where the pressure varies between 1-7 bar, the risk of loss of strength will be significantly reduced. High density polyethylene is considered the best material for such a pipeline [19].

Pipeline hydrogen transportation also has an advantage over electricity transmission, where hydrogen is relatively easy to store in underground and above-ground storage facilities under pressure and delivered through pipelines to consumers at their discretion at predetermined times and in controlled quantities. In this regard, the construction of hydrogen pipelines is promising. Protecting such transport routes from the hostile environment requires significant investment, but a ready-made hydrogen pipeline is the cheapest way to deliver large volumes of hydrogen. The development of a network of specialized pipelines can also make hydrogen the cheapest way to transmit electricity over long distances.

The most significant obstacle to the development of hydrogen energy in Ukraine is the critical condition of gas transport infrastructure. Thus, even model projects for the transportation of hydrogen as an energy carrier are impossible without a "global" redesign of the main and gas distribution networks.

3.3. Hydrogen experience in Ukraine

In 2019, the Regional Gas Company (RGC, https://rgc.ua/en/) for the first time in Ukraine began a test transportation of a mixture of hydrogen and natural gas in closed areas of the gas distribution system in five regions of the country. Experimental landfills are located in Volyn, Dnipropetrovsk, Zhytomyr, Ivano-Frankivsk and Kharkiv regions. These are closed areas of networks that are not connected to external consumers - businesses or individuals. They correspond to the actual condition of real gas distribution networks - there are metal and polyethylene 28 pipes of different diameters, with different service life and different sealing materials. Also used a variety of pressure control technologies, several types of gas control points. It is now important to understand how the existing gas delivery system will behave using hydrogen. Initially, mixtures of natural gas with hydrogen in concentrations from 2% to 100% are used to test the networks.

It is planned to build a hydrogen production plant at one of the landfills. Scientific support of the project allows to obtain detailed and comprehensive information about all the nuances of using new, environmentally friendly energy sources. The project is not limited to testing the hydrogen mixture, and is preparing work with other synthetic gases, such as biogas. And the priority over hydrogen is because hydrogen has the smallest gas molecule and relatively low density. Foreign experience is used, but there is a point that makes the RGC project unique compared to all foreign ones. In Europe, gradually increase the concentration of hydrogen in the mixture, starting with 1-3%, and now in some places increased to 20%. The RGC plans to immediately conduct tests with the transportation of 100% hydrogen, which will give an idea of the compliance of networks with the new energy source.

In August 2020, the practical part of the test program for the use of hydrogen in existing gas distribution networks began to operate. The first experiment was conducted at the landfill in Chernyakhiv, Zhytomyr region, taking into account the prospects of the EU Hydrogen Strategy, with which RGC interacts. For hydrogen testing, the gas system of the Chernyakhiv landfill was reconstructed by Zhytomyrgaz JSC specialists in such a way that it became a model of the existing gas distribution system in terms of equipment composition, selection of materials and degree of wear. During the experiment, the landfill systems were pumped with inert gas and then filled with hydrogen, the concentration of which was increased to 99%. The

high concentration of hydrogen in the system allows to obtain unique information about the behavior of different materials of gas pipelines and equipment. The next stages of RGK's research program include static and dynamic tests of hydrogen and its mixtures with natural gas at four more specially prepared landfills in the Volyn region.

During 2020, the GTS Operator of Ukraine became part of the European Clean Hydrogen Alliance, EU industry associations - European Gas Research Group (GERG), Marcogaz, Gas Infrastructure Europe (GIE), to coordinate development strategies, prepare domestic regulatory and technological framework for the transition to renewable gas transportation, implement pilot projects to promote GTS decarbonisation, reduce the environmental impact of Ukraine's energy sector [13].

On November 26, 2021, the UGS Operator joined the H2EU + Store initiative, which envisages the production of "green hydrogen" from renewable energy sources in western Ukraine with the possibility of storage in Ukrainian gas storage facilities, with its further export by gas pipelines to the EU, pumping to underground storage facilities in Austria sales to consumers in Central Europe [16].

3.4. Risks and restrictions of hydrogen transportation in Ukraine

The European Clean Hydrogen Alliance has classified the challenges and risks associated with the development of hydrogen energy, among which the following are important for the functioning of the GTS Operator of Ukraine:

- lack of a functioning hydrogen market, the level of supply and demand is insufficient for the emergence of the need for transport services within the existing business model of the GTS Operator of Ukraine;
- uncertainty about the ability of operators to continue their hydrogen-related activities - regulatory recognition of costs for the reconstruction and adaptation of gas infrastructure to hydrogen is not provided for in the EU regulatory framework. Incomprehensibility for gas network operators regarding property rights, modes of operation and financing of hydrogen infrastructure within the existing regulatory framework;
- lack of appropriate standards for testing the readiness of existing pipelines for hydrogen transportation, which requires a separate internal approach, laboratory testing and communication with manufacturers;
- unlike main gas pipelines, compressor units are much more difficult to adapt to work with hydrogen and, most likely, this component will require additional investment;
- there is a shortage of experienced suppliers of engineering services and hydrogen-tolerant equipment with real experience and great potential for scaling production. There is no mechanism for training in the field of hydrogen technology;
- Ukraine does not provide instruments for financial support for the development of hydrogen projects and does not provide access to EU funding.

CONCLUSIONS

- The complex of underground natural gas storage facilities in Ukraine consists of **13** facilities (12 facilities are located on the territory of Ukraine, 1 facility is located in the occupied Crimea territory and currently no data about it).
- Total design capacity for active gas **30.95 BCM**.
- In terms of storage of active gas, Ukraine ranks third in the world (after the United States and Russia) and second in Europe.
- UGS facilities are created on the basis of depleted gas and gas condensate fields. Two of them are Chervonopartizanske and Olyshivske on the basis of aquifers.
- UGS belong to four underground gas storage complexes according to their location and connection to the main gas pipeline system in Ukraine: West, Central, East, South.
- UGS are located in all oil and gas provinces of Ukraine at a depth of **400** to **2000** m.
- The level of UGS filling at the end of the 2021 injection season – **18.6 BCM** (the highest over the past 10 years in 2020 – **28.3 BCM**).
- JSC Ukrtransgaz provides the activities of Ukrainian UGS facilities, as well as works on modernization and construction of main gas pipelines and facilities on them.
- Ukraine's UGS facilities are usually used to regulate seasonal uneven gas consumption, create long-term gas reserves, and ensure reliable gas transit through Ukraine to European countries.
- Ukraine's GTS is the second largest in Europe. Today, it is an integral part of the European energy system, and its integration will only deepen in the future.
- The total length of the main gas pipelines is 33 079 km, with entry capacity of 281 BCM and exit of 146 BCM.
- GTS Ukraine Operator LLC provides transportation of natural gas to Ukrainian consumers and its transit to the European Union.
- Today UGS of Ukraine is used by about 1000 clients, more than 100 of them are foreign companies from 27 countries. These are the EU, the United States, Canada, the United Arab Emirates, Singapore and Hong Kong.
- Favorable gas storage tariffs, “Customs Warehouse” services (duty-free for 1 095 days) and “short haul” services (special tariff for gas transportation from the border to UGS), clear and transparent cooperation in the provision of services have become key factors in attracting foreigners to gas storage in Ukrainian UGS facilities.
- Ukraine has used up to 60% of total underground storage capacity for its own needs (approximately 15 BCM of active gas), which confirms the presence of a significant reserve of active underground storage capacity of about **8-15 BCM** of free storage that can be rented to European partners.
- Ukraine is implementing key and regulatory provisions and EU codes for further integration into the European gas market.
- Hydrogen energy has become one of the trends in the world today.
- In its long-term plans, Ukraine is considering the use of regional and transport infrastructure of gas pipelines for local transportation of hydrogen in large quantities and for export.
- Pipelines are the main method of hydrogen transportation in Ukraine, and UGS facilities can serve as storage tanks.

- Hydrogen can be transported not in its clean form, as it can quickly damage the pipes, but mixed with natural gas. Hydrogen concentration up to 10-20% by volume is considered acceptable.
- In Ukraine, the level of use of natural gas pumped by pipelines is 30-35 BCM per year, so the capacity of this segment of the economy may be 6-7 BCM of hydrogen per year.
- **The synchronization of the energy system and gas infrastructure will take place in accordance with the** 2x40 GW Green Hydrogen Initiative
- Ukraine, as the largest participant among all member countries of the Energy Community, is allocated the creation of 10 GW of new capacity for the production of "green" hydrogen, most of which is intended for export to the European Union.
- Excess energy from renewable sources is planned to be converted into synthetic gas and pumped into the pipeline.
- The main problem in the development of hydrogen energy in Ukraine is the critical condition of gas transport infrastructure.
- The process of Ukraine's transition to hydrogen energy requires legislative and organizational changes. The process of attracting hydrogen to Ukraine's underground storage and utilities will be time-consuming, technically complex and costly.
- In August 2020, the Regional Gas Company, in cooperation with a number of Ukrainian institutes, launched a large-scale study on the prospects for the use of hydrogen and its mixtures in low and medium pressure networks.
- Favorable geographical location, availability of gas transport infrastructure and potential opportunities for "green" generation make Ukraine attractive for future European hydrogen projects.

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EU Hydrogen Strategy	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
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