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Assessment of safety of CO_2 storage in depleted oil and gas reservoirs

Abstract. Research relevance is determined by the need for safe geological storage of carbon dioxide as part of the implementation of carbon capture, transport and storage (CCS/CCUS) technologies. Study aimed to assess safety of CO_2 storage in depleted oil and gas reservoirs and to justify the feasibility of use of the natural pulsed Earth electromagnetic field (NPEMFE) method for real-time monitoring of reservoir pressure and the identification of potential fluid migration pathways. The research methodology was based on an analysis of the results of experimental geophysical studies conducted at the Dolynskyi oilfield research site in the western region of Ukraine, as well as on the application of spatial correlation analysis to establish relationships between NPEMFE parameters and reservoir pressure. Depleted hydrocarbon fields were considered as promising sites for long-term CO_2 sequestration due to their significant storage capacity, proven leak-tightness and existing production infrastructure. The study established a regular relationship between reservoir pressure and NPEMFE parameters. An inverse relationship was identified, whereby an increase in reservoir pressure is accompanied by a decrease in the intensity of the NPEMFE, whilst a decrease in reservoir pressure increases electromagnetic activity. Study demonstrated that changes in the intensity of the NPEMFE are associated with stress redistribution processes within the rock mass. The anisotropic nature of the spatial distribution of NPEMFE anomalies has been

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established, reflecting the directions of fluid flow and zones of increased permeability. Correlation analysis has confirmed the existence of a relationship between changes in the natural electric field and formation pressure. A conceptual approach has been developed for organisation of a geophysical monitoring system for CO_2 geological storage sites, based on regular observations of NPEMFE parameters, which can be used for early detection of potential hydrocarbon migration pathways and storage integrity breaches. The practical value of the results obtained is determined by their potential use by specialists in the oil and gas industry, geoecology and geophysical monitoring to monitor the condition of underground CO_2 storage sites, assess the risks of leaks and improve the environmental and technological safety of geological carbon storage

Keywords: geological CO_2 storage; depleted gas fields; formation pressure; the Earth's natural pulsed electromagnetic field; monitoring; storage site safety; fluid migration

Introduction

Global climate change and the need to achieve carbon neutrality targets cause rapid development of technologies for the capture, transport, utilisation and geological storage of carbon dioxide (CCUS). Geological storage of CO_2 is regarded as one of the most effective tools for reduction of anthropogenic greenhouse gas emissions and is a key component of decarbonisation strategies for the energy and industrial sectors in the European Union, the USA, Canada, China and other countries. Among the potential sites for geological storage, depleted oil and gas fields are of particular interest. Their advantages include the proven natural impermeability of the reservoirs, significant volumes of available pore space, well-developed well and transport infrastructure, as well as many years of experience in geological research and operation. According to existing estimates, the global potential for CO_2 storage in depleted oil and gas reservoirs amounts to hundreds of billions of tonnes, which exceeds annual global emissions.

One of the key factors in the successful implementation of geological storage projects is ensuring their safety. The main risks remain potential CO_2 leaks due to breaches in the integrity of the caprock, the activation of tectonic faults, the degradation of cement stone and well casings, and the formation of man-made fluid migration pathways. It is therefore necessary to establish effective monitoring systems capable of promptly tracking changes information pressure, the stress-strain state of the rock mass, and the development of potentially hazardous filtration zones. Traditional monitoring methods, based on the use of observation wells, repeat seismic surveys, and gravimetric and geodetic observations, are characterised by high costs and limited timeliness in obtaining information. In this regard, the search for alternative methods to monitor the state of the geological environment is substantial. The increase in global greenhouse gas emissions and the need to achieve climate neutrality are driving the active development of carbon capture, utilisation and storage (CCS/CCUS) technologies. One of the most promising areas for the implementation of these technologies is considered to be the geological storage of carbon dioxide in depleted oil and gas fields, which are characterised by significant storage capacity, the presence of natural isolating barriers and well-developed production infrastructure.

A comprehensive analysis of existing state of geological CO_2 storage in depleted hydrocarbon reservoirs is presented in the papers by B. Wei *et al.* (2023) and K.K. Nsiama *et al.* (2024). Authors noted that such sites are among the most well-prepared for the implementation of CCS technologies, as their geological structure, permeability and storage capacity, and the impermeability of the cap rocks have been studied in detail during many years of operation. At the same time, the effectiveness of long-term storage is determined by a combination of geological, geomechanical, hydrodynamic and technological factors. The prospects for use of existing underground gas storage facilities for the storage of CO_2 and hydrogen have been investigated by Y. Demchuk *et al.* (2025). The authors assessed the geological and petrophysical characteristics of Ukrainian underground gas storage facilities and established that a significant proportion of these sites offer favourable conditions for the implementation of geological carbon storage technologies. This creates the conditions for the development of a national CCS infrastructure and Ukraine's integration into European decarbonisation programmes. A substantial area of research is the use of CO_2 to improve oil recovery whilst ensuring its long-term sequestration in the reservoir. X. Zhou *et al.* (2024) summarised the results of existing research into CO_2-EOR technologies and demonstrated that, under optimal conditions, a significant proportion of the injected carbon dioxide may remain in the reservoir after the field has been depleted. Study also emphasised the need to address phase transitions, the interaction of CO_2 with formation fluids, and changes in the reservoir properties of the rocks.

A significant number of scientific papers have been devoted to the issues of long-term safety in the geological storage of carbon dioxide. According to the findings of A. Ahmed *et al.* (2025), the success of CCS projects depends to a large extent on integrity of the storage site over decades or even centuries. To achieve this, a comprehensive risk assessment must be conducted covering geological, geomechanical, economic and environmental aspects of the facility's operation. One of the most critical elements of a geological storage system is the wells. Research by V. Nguyen *et al.* (2023) has shown that prolonged contact between CO_2 and the metallic components of casing strings and the cement matrix can cause corrosion, cement degradation and the formation of potential leakage pathways. In this regard, monitoring the technical condition of wells at all stages of CCS project implementation is substantial. Monitoring systems minimise potential risks. According to M. Fawad & N.H. Mondol (2021), modern monitoring of geological CO_2 storage is based on the integrated use of geophysical, geochemical and hydrodynamic monitoring methods. Similar conclusions are presented in the work by W. Tang *et al.* (2025), which provides an overview of existing monitoring technologies and numerical modelling of carbon dioxide dispersion processes in the geological environment.

Study by V. Fedoriv *et al.* (2019) examined application of integrated interpretation of geophysical surveys to determine the petrophysical characteristics of reservoir rocks, in particular their clay content, porosity and structural features. Study demonstrated that the use of a combination of geophysical parameters improves the reliability of rock property estimates, which is substantial for prediction of storage and filtration characteristics of reservoirs. The approaches developed can be used in assessment of safety of geological CO_2 storage in depleted oil and gas reservoirs, as the accurate determination of the properties of reservoir rocks and cap rocks is essential for prediction CO_2 migration, assessment of integrity of the storage site and selection of an effective monitoring system. E.D. Kuzmenko *et al.* (2020) investigated the application of the NPEMFE method for prediction of deformation processes in rock masses. A correlation was established between electromagnetic anomalies and zones of instability in the rock mass, confirming potential for NPEMFE to monitor the safety of CO_2 storage in depleted oil and gas reservoirs.

Thus, an analysis of existing scientific publications indicates significant progress in the development of CO_2 geological storage technologies and methods for ensuring their safety. At the same time, issues relating to the operational monitoring of changes in reservoir pressure and the early detection of potential CO_2 migration pathways based on geophysical observations remain under-researched. Of particular relevance is the development of monitoring methods capable of ensuring continuous monitoring of the geological environment during the operation of storage facilities. The study aimed to assess the safety of CO_2 storage in depleted oil and gas reservoirs and to justify the feasibility of using the Earth's natural pulsed electromagnetic field to monitor reservoir pressure in real time and identify potential fluid migration pathways.

Materials and Methods

The test site is situated and operates within the Dolyna oilfield (wells No. 1-Smolianska, No. 61-Pivnichna Dolyna, No. 152-Pivnichna Dolyna, No. 81-Vygoda Vytvytsia, No. 64-Dolyna) and was established based on legacy oil wells following a special permit for subsoil use granted to the university by the State Service of Geology and Subsoil of Ukraine. To investigate the patterns of formation pressure variations within the Dolyna oilfield (well No. 152 "Pivnichna Dolyna"), the method of the Earth's natural pulsed electromagnetic field was employed. The natural Earth electromagnetic field method is one of the modern geoelectric techniques, which has become increasingly widespread for a wide range of geological and geophysical problems. Its principle is based on the detection of electromagnetic pulses generated by dielectric minerals under stress and strain. The Earth's natural pulsed electromagnetic field is understood to be the aggregate of electrical discharges that occur within the Earth's interior, particularly within rock masses. As rocks consist of heterogeneous mineral components containing impurities, pore spaces, charged dislocations and other structural defects, their internal structure is excited under the influence of external energy sources. This causes a disturbance of the equilibrium state and the accumulation of excess energy, which can be released in the form of electromagnetic pulses.

The main processes responsible for the generation of such pulses are the excitation of the crystal lattice in a field of alternating mechanical stresses, the intensive filtration of fluids through pores and capillaries, the relaxation of the excited medium, the formation of a double electric layer, and plasma formation processes. The combination of these physical phenomena causes Earth's natural pulsed electromagnetic field under various conditions of stress in rock formations. The study was conducted within the area surrounding Well No. 152 "Pivnichna Dolyna". The NPEMFE method was performed based on a radio-wave stress-strain indicator (RWSSI) and has the following characteristics (Table 1).

Table 1. *Technical specifications of the RWSSI device*

Parameter name	RWSSI
1. Number of registration channels	3(X,Y,Z)
2. Frequency range	2-50 kHz
3. Low-pass and high-pass filter	Discrete settings 2 kHz
4. Connecting external antennas	3 with a pre-amplifier, up to 10 metres
5. Measurement modes	Automatic, semi-automatic, manual
6. Measurement duration	1 s, 2 s, 10 s, 1 min
7. Pulse count scale	00000-131071
8. Scale for measurement of average pulse amplitude	0000-4095
9. Number of measurements at a single point	1-15
10. Time reference for measurements in semi-automatic and automatic modes	Present
11. Interface for connection of a removable memory module to a computer	Present
12. Power supply for the RWSSI indicator	12 V, 2.2 A rechargeable battery
13. Overall dimensions of registration unit	335×260×95 mm
14. Weight of registration unit	4.2 kg

Source: *compiled by the authors*

The RWSSI operated in the frequency range from 2 to 50 kHz and allowed the low-pass and high-pass filters to be adjusted in 2 kHz steps, which was used to isolate relevant signal and reduce the impact of external electromagnetic interference. The instrument supported the connection of three external antennas with pre-amplifiers and cable lengths of up to 10 m, providing flexibility for field measurements. Three operating modes were provided – automatic, semi-automatic and manual – adapting measurement process to specific research conditions. The recording duration could be 1 s, 2 s, 10 s or 1 min, depending on the tasks at hand and the required level of detail in the observations. The measurement range for the number of pulses was from 0 to 131,071, and for the average amplitude – from 0 to 4,095 conventional units. Furthermore, the instrument allowed for between 1 and 15 repeated measurements at a single observation point, which improves accuracy of the results and reduce random errors.

The procedure involved synchronising the two instruments before measurement (via a cable and by configuring same time), selecting the signal gain to ensure field differentiation and the correct detection of anomalies, as well as setting the frequency range to 2-50 kHz (or a narrower range, but not less than 5 kHz) with pulses recorded as an integral characteristic. In addition, a pulse accumulation mode was set (1-15 measurements of varying durations), which reduced random errors and can be used to calculate number of pulses per second. The frequency range of 2-50 kHz can be used to receive signals from the first few tens of metres up to a thousand metres, which is necessary for the set task.

The measurement time step is also set, which determines the intervals at which the signal is recorded simultaneously, covering the observation step and the movement between points. The X, Y, Z orientations of the antennas are set (X – north-south, Y – west-east, Z – vertical) is conducting, with the directions for both instruments aligned; the instruments are divided into variation and field units (the variation unit is set up in a homogeneous zone to negate external influences); and data is recorded for subsequent reading and processing using specialised software. The requirements for the NPEMFE observation grid are similar to the general requirements for geophysical profiling (electrical, magnetometric, gravimetric) in either profile or planar configurations. The layout of the profile lines within the study area is as follows: main lines – north-south and west-east; additional lines – north-west-south-east and north-east-south-west. This profile layout enables objective data to be obtained around the study area. The observation interval along the profiles for the NPEMFE is 10 metres. The observation scheme is shown in Figure 1.

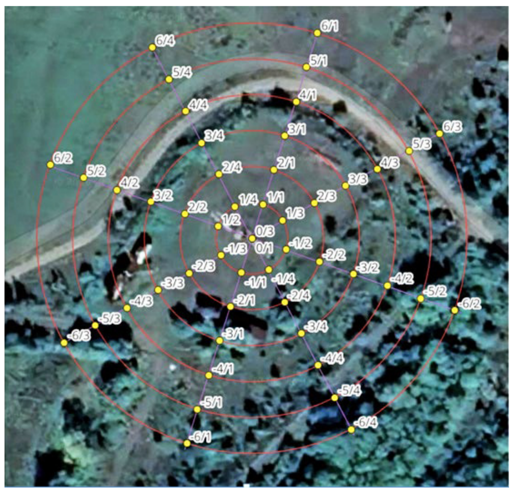


Figure 1. *Layout of observation profiles using the NPEMFE method at Well 152 "Pivnichna Dolyna"*

Source: *compiled by the authors*

The combination of mutually perpendicular and diagonal profiles ensures a more comprehensive detection of anomalous zones, regardless of their orientation, reduces probability of omitting local heterogeneities, and enhances the objectivity of the interpretation of results. This observation scheme is particularly effective during investigation of zones of faults, fracturing and other structural features of the geological environment. The observation spacing along the profiles was 10 m, which provides sufficient spatial resolution for detailed mapping of geoelectric heterogeneities and the identification of local anomalies in the Earth's natural pulsed electromagnetic field. The selected density of the observation network was optimal for detailed geophysical investigations, ensuring reliable information on the stress-strain state of the rocks within the study area.

Results and Discussion

Geological and man-made risks associated with CO_2 storage in depleted oil and gas reservoirs

The effectiveness of geological carbon dioxide storage is determined not only by the reservoir's capacity, but also by the geological system's ability to ensure the long-term integrity of the storage site (Benson & Cole, 2008; Bachu, 2015). When CO_2 is injected into a formation, this causes a change in formation pressure, a redistribution of stresses within the rock mass and a change in the filtration regime. If permissible pressure limits are exceeded, new fractures may form or existing ones may be activated, the integrity of the cap rock may be compromised, and fluid migration pathways may develop. The main potential pathways for CO_2 leakage are tectonic faults, naturally fractured zones, man-made disturbances in the near-wellbore zone of the formation, and abandoned wells (Bai *et al.*, 2016). Therefore, one of the key tasks of the monitoring system is the timely detection of zones of increased permeability and the monitoring of changes in formation pressure during the operation of the storage facility. Modern monitoring systems for geological CO_2 storage are based on the integrated use of seismic, geochemical, geodetic and geophysical methods. However, most of these systems are characterised by high costs and the discrete nature of the data collected. In this regard, a promising approach is the use of passive geophysical methods, in particular the Earth's natural pulsed electromagnetic field (EPEMF), which can be used to continuously monitor changes in the geological environment. The Natural Earth Pulse Electromagnetic Field (NEPEMF) method is an effective geophysical monitoring tool that can identify areas with elevated stress-strain states in rock formations and track changes in their physical and mechanical properties. The results obtained do not provide direct information on the technical condition of the underground repository; however, can be used for an indirect assessment of the geodynamic processes that may affect its geometric integrity and safe operation.

In particular, the NPEMFE method can be used to identify or indirectly assess the following potential risks:

- activation of faults and tectonic disruptions, which may form permeable channels for the vertical migration of gas;
- development of fractured zones in overlying strata, which reduces their insulating capacity;
- change in stress-strain state of rock mass associated with an increase in formation pressure during CO_2 injection;
- formation and development of local electromagnetic anomalies, which may indicate increased activity in deformation zones or filtration processes.

Assessment of the safety of geological CO_2 storage in depleted oil and gas reservoirs emphasises control of reservoir pressure and its impact on the stress-strain state of the reservoir and overlying rocks. During CO_2 injection, the increase in reservoir pressure may impose additional mechanical loads on the rock mass, whilst its redistribution may alter the stability conditions of existing geological structures (Rutqvist, 2012). If these changes exceed the rocks' adaptive capacity, tectonic faults may be activated, existing fractures may open, or new microfractures may form. Such processes are accompanied by the generation of electromagnetic pulses, which can be recorded using the natural pulsed Earth electromagnetic field (PEMEF) method. Thus, changes in the parameters of the natural electromagnetic field can be used as an indicator of the development of deformation processes associated with changes in formation pressure during CO_2 storage.

The formation of zones of fracturing or increased permeability is one of the key risk factors for the long-term safety of CO_2 storage, as such areas may create potential pathways for the migration of carbon dioxide outsode the target formation. Fractures and weakened zones within the rock mass are characterised by elevated concentrations of mechanical stresses and may act as channels for more intense filtration of formation fluids. Under these conditions, physical processes are activated, accompanied by the generation of electromagnetic pulses, as a result of which local anomalies in the NPEMFE may be recorded above such areas. Analysis of the spatial distribution, intensity and configuration of these anomalies can identify potentially weakened zones, assess their orientation and determine areas requiring further geophysical, geomechanical or engineering-geological investigations. It is worth noting that results of the NPEMFE are interpretative and do not constitute direct evidence of a breach in the integrity of the geological repository or of CO_2 leaking outside the reservoir. To draw reliable conclusions regarding storage safety, a comprehensive analysis of the NPEMFE results must be conducted in conjunction with geological, geomechanical, hydrodynamic and industrial geophysical data, as well as information on CO_2 injection regimes, changes in formation pressure and the operational parameters of the storage facility.

The relationship between formation pressure and the intensity of NPEMFE

The results of experimental studies at the Dolinsky oilfield research site indicate a regular relationship between formation pressure and the parameters of the Earth's natural pulsed electromagnetic field. The experiment involved measuring the Earth's natural pulsed electromagnetic field under three specified operating conditions: 1) formation pressure of 72; 2) formation pressure is falling; 3) formation pressure is reduced and equal to zero. The distribution of the pulsed field corresponding to the specified formation pressure levels is shown in Figure 2. The borehole for all conditions was located at the centre of the site at the intersection of four profiles defined at the surface, with a distance of 10 metres between points along the profiles. At an initial stable maximum pressure of 72 atm, the distribution of the NPEMFE intensity is not isometric but is elongated into a band-shaped anomaly (a), which corresponds to a decrease in field intensity. As the pressure decreases (drops), the anomaly of reduced intensity extends from the north to the south-east (b), and subsequently the reduction in intensity extends to the eastern and southern parts of the study area. In other words, a pronounced anisotropy of formation pressure has been observed. An explanation for the observed distribution of the anomaly at this stage should be sought in the correlation between changes in formation pressure and the intensity of natural radiation. In particular, the direction of oil inflow varies over time, as demonstrated in Figure 2. The natural pulsed electromagnetic field measured at the earth's surface is variable in nature and depends on the formation pressure at the wellbore. At the same time, its isotropic nature is confirmed.

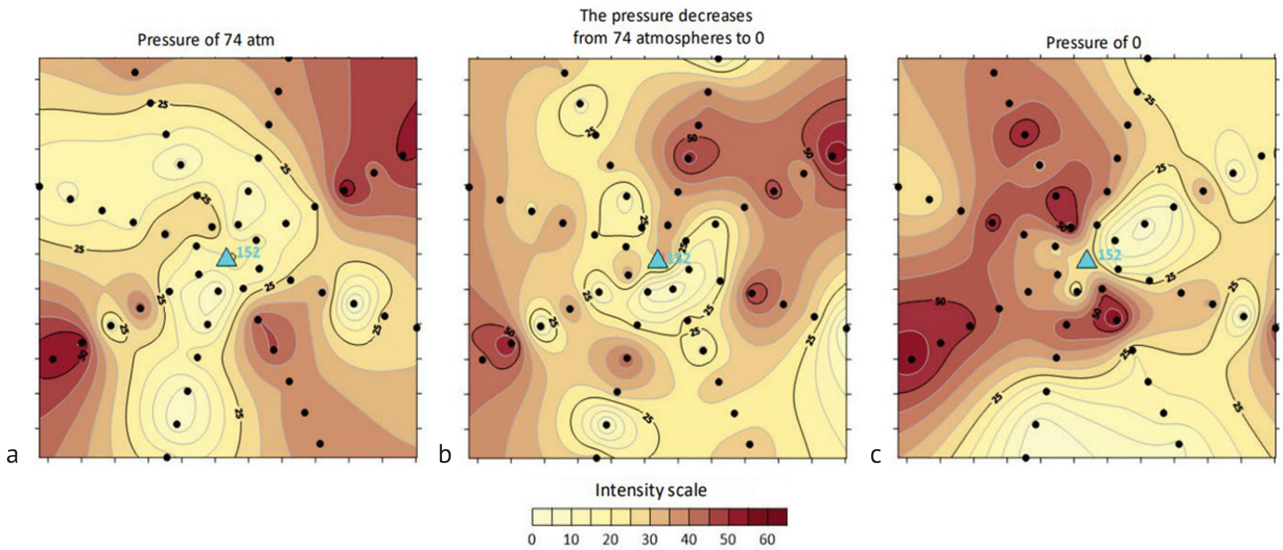


Figure 2. *Variation in the intensity of NPEMFE radiation at different formation pressures in Well No. 152, "Pivnichna Dolyna"*

Notes: *a) pressure is stable at 74 atm; b) pressure decrease from 74 to 0 atm; c) pressure is 0 atm*

Source: *compiled by the authors*

The observations showed that, at maximum formation pressure values in the well, the lowest values of NPEMFE intensity were observed. As the pressure decreases, the intensity of electromagnetic radiation gradually increases. The established relationship is of an inverse nature and reflects the response of the geological environment to changes in the stress-strain state and filtration processes within the formation. Physically, this pattern is determined by changes in the flow conditions of formation fluids within the porous medium. An increase in formation pressure contributes to the stabilisation of the hydrodynamic regime and a reduction in local deformations of the pore space. When the pressure decreases, processes such as stress redistribution, the opening of microcracks and local changes in the direction of filtration flows are activated, accompanied by the generation of additional electromagnetic pulses (Fig. 3).

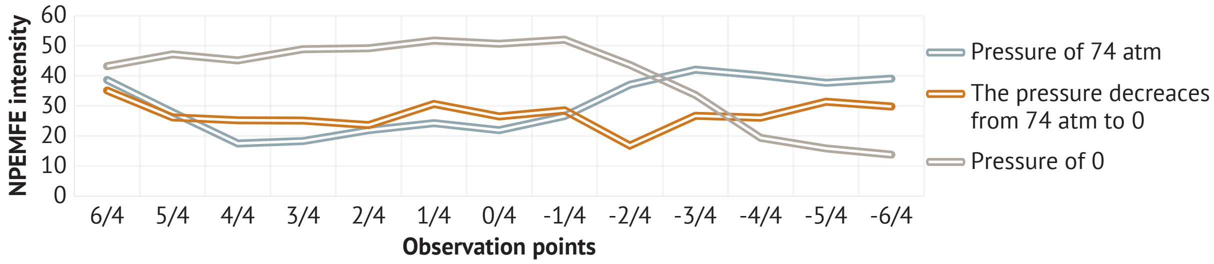


***Figure 3.** Graphs depicting intensity of electromagnetic field radiation at different formation pressures*

***Notes:** formation pressure 72 atm; formation pressure decreases from 74 to 0; formation pressure is reduced and equals zero*

***Source:** compiled by the authors*

For CO_2 geological storage projects, this is substantial, as introduces use of NPEMFE parameters as an indicator of changes in formation pressure without the need to drill additional monitoring wells.

Identification of areas of increased permeability and potential CO_2 migration pathways

The observed anisotropy in the distribution of electromagnetic anomalies is of particular interest for assessing the safety of storage facilities. When formation pressure changes, the anomalous zones of the NPEMFE form an elongated shape and exhibit a defined orientation in specific directions (Fig. 4).

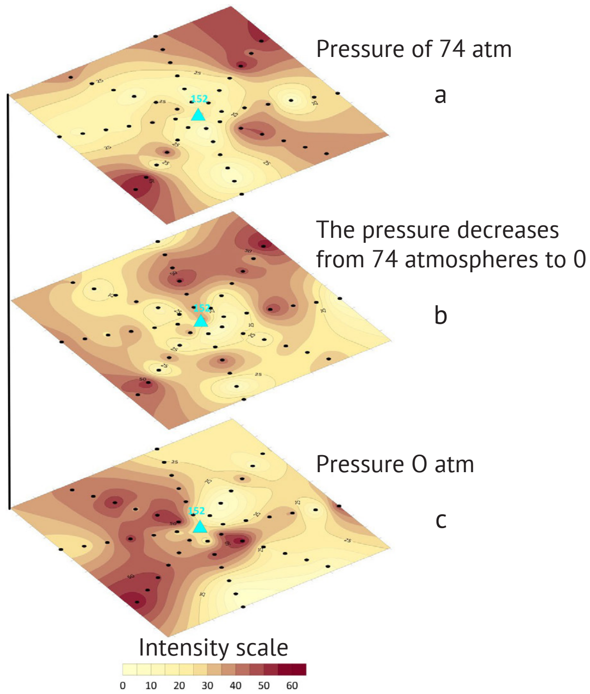


***Figure 4.** Distribution of the pulsed electromagnetic field according to the specified formation pressure levels*

***Notes:** a) formation pressure of 72 atm; b) formation pressure decreases from 74 to 0; c) formation pressure is reduced and equals zero*

***Source:** compiled by the authors*

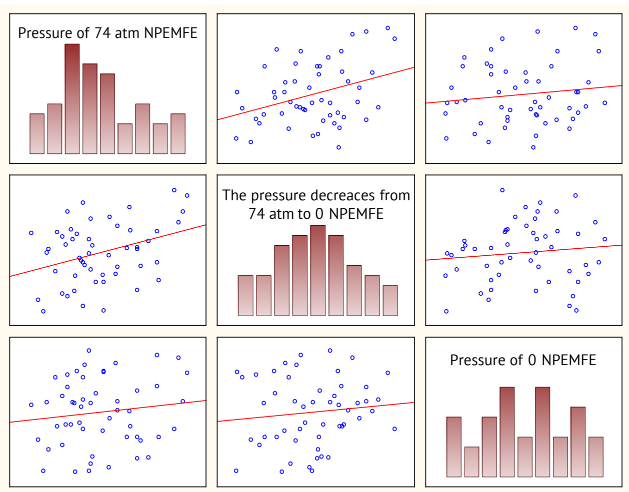
Spatial organisation of the electromagnetic field indicates the existence of zones of increased permeability, which are controlled by fracture systems or local tectonic disturbances. These areas may act as natural channels for fluid migration during CO_2 injection. Analysis of the NPEMFE distribution maps shows that the directions in which the anomalies develop change in tandem with changes in formation pressure. This indicates the presence of active filtration processes and confirms the method's high sensitivity to changes in the formation's hydrodynamic regime. For CO_2 geological storage sites, the identification of such zones is substantial, as it can be used for localisation of potentially hazardous areas even before the start of commercial injection or during the early stages of storage operation.

The most relevant factors for interpretation are the differences in intensity, extent, shape and spatial location of the NPEMFE anomalies. Comparison of individual parts of the figure can be used to assess how the distribution of electromagnetic pulses changes under different reservoir operating conditions. Appearance of new anomalous zones, displacement of existing anomalies, and changes in their size or intensity should be emphasised. If the anomalies retain their position but change in amplitude, this may indicate a redistribution of stresses within existing geological structures. If, however, their spatial position or configuration changes, this may be a sign of the activation of new deformation zones or a change in filtration conditions. Changes in formation pressure during CO_2 injection into depleted oil and gas reservoirs are accompanied by a transformation of the stress-strain state of the reservoir and surrounding rocks, which may affect the characteristics of the Earth's natural pulsed electromagnetic field. An increase in reservoir pressure during CO_2 storage can lead to the concentration of mechanical stresses in localised areas of the geological environment, particularly near zones of faults, fractures and rock heterogeneities. Such changes may manifest as an increase in intensity, an expansion in area or a change in the spatial position of individual NPEMFE anomalies.

When the storage facility's operating conditions change – in particular, when formation pressure decreases, or pressure redistribution occurs as a result of fluid migration – further changes occur in the stress state of the rock mass. This may form new local electromagnetic anomalies or changes in the configuration of existing ones. Analysis of the dynamics of the spatial distribution of NPEMFE can be used to assess geological environment's response to changes in CO_2 storage conditions and identify areas of potential geomechanical instability. Thus, spatio-temporal changes in NPEMFE parameters can be used as an additional indicator of processes associated with stress redistribution within the formation during CO_2 storage. However, the method fails at direct determination of formation pressure or confirmation of CO_2 migration; therefore, the results obtained must be analysed in conjunction with hydrodynamic modelling, well logging, seismic monitoring and other methods of storage site monitoring (Ajayi *et al.*, 2019; Massarweh & Abushaikha, 2024).

Anisotropy is manifested in the uneven distribution of electromagnetic anomalies in different directions. On NPEMFE maps, this is reflected in the fact that anomalous areas have an elongated shape, a predominant orientation, or varying intensity along different profiles. Such features may be associated with the direction of tectonic faults, the system of natural fracturing, the layering of rocks, or the orientation of principal mechanical stresses. The detection of anisotropy can form conclusions regarding presence of structural heterogeneity in the geological environment and determine predominant directions of deformation processes. Under natural conditions, the filtration of liquids and gases predominantly occurs not uniformly, but along fractures, faults and other weakened structural elements characterised by increased permeability. These elements are often linear or elongated in nature, which is why NPEMFE anomalies form a similar shape. If elongated anomalies extend over a considerable distance and are consistent with known geological structures or the results of other geophysical surveys, they can be interpreted as potential zones of increased permeability or the predominant directions of formation fluid flow. However, such an interpretation must be corroborated by a suite of independent data, as the NPEMFE method is indirect and does not independently determine the presence of flow pathways.

Further confirmation of the relationship between formation pressure and geodynamic processes was obtained through a correlation analysis of NPEMFE data at different formation pressures. The correlation coefficients obtained demonstrate consistency in the spatial structures of the anomalies under different well operating conditions (Fig. 5). The greatest changes in the structure of the correlation functions are observed during periods of active change in formation pressure, confirming the sensitivity of electromagnetic methods to stress redistribution processes within the rock mass.



	NPEMFE (Pressure 74 atm)	NPEMFE (Pressure decreases from 74 to 0 atm)	NPEMFE (Pressure 0 atm)
NPEMFE (Pressure 74 atm)	1.000	***0.348***	0.131
NPEMFE (Pressure decreases from 74 to 0 atm)	***0.348***	1.000	0.113
NPEMFE (Pressure 0 atm)	0.131	0.113	1.000

Figure 5. *Pairwise correlation matrix*

Notes: *values marked in red are statistically significant at $p < 0.05000$*

Source: *compiled by the authors*

Figure 5 shows the correlation coefficients between the spatial distributions of the Earth's natural pulsed electromagnetic field (NPEMFE), obtained under three formation pressure regimes: at a pressure of 74 atm, during its decrease from 74 to 0 atm, and after it has fully decreased to 0 atm. Values of 1.000 are shown on the main diagonal, as each dataset is fully correlated with itself. The highest correlation coefficient between different regimes is observed between the state at a formation pressure of 74 atm and the process of its reduction to 0 atm (r = 0.348). This indicates a moderate similarity in the spatial distribution of NPEMFE anomalies, which is to be expected, as some structural features and stress concentration zones are still preserved during the process of reservoir depressurisation.

By contrast, the correlation between the distributions obtained at a pressure of 74 atm and after the pressure had been fully reduced to 0 atm is only 0.131. Similarly, the correlation coefficient between the gradual pressure reduction regime and the final state at 0 atm is 0.113. Such low values indicate a significant change in the spatial structure of the electromagnetic field following the completion of the reservoir depressurisation process. The results obtained demonstrate that a change in formation pressure is accompanied by a noticeable reorganisation of the spatial distribution of NPEMFE anomalies. The greatest similarity is observed between the initial state and the transient regime, whilst after zero formation pressure is reached, the nature of the electromagnetic pulse distribution differs significantly from the previous states. This may be associated with a redistribution of the stress-strain state of the rock, a change in the activity of existing fracture zones, and the weakening or emergence of new sources of electromagnetic pulse generation. It should be noted that the correlation coefficients presented characterise only the degree of statistical similarity between the NPEMFE maps. They fail to establish causes of the changes and must be analysed in conjunction with geological, geomechanical and industrial geophysical data. The identified patterns can be used to predict the directions of propagation of the injected CO_2 front and to assess the risks of it extending outside design boundaries of the storage site.

A methodology for monitoring the safety of geological CO_2 storage based on NPEMFE

Based on the results, a methodological approach to monitoring the safety of geological CO_2 storage using the NPEMFE has been proposed. In the first stage, a baseline map of the natural electromagnetic field is generated prior to the start of CO_2 injection. Subsequently, during operation, regular observations are conducted along a network of profiles located above the reservoir and within the predicted fluid migration zones. Comparison of existing data with baseline can be used for rapid detection of: changes in formation pressure; activation of fractured zones; emergence of new filtration channels; directions of movement of the CO_2 front; potential areas where the storage facility may leak. In the event of local anomalies detected by the NPEMFE, the relevant areas may be further investigated using seismic, geochemical or borehole methods. Thus, NPEMFE can be used to create an early warning system for potential leaks from geological storage sites and significantly enhances the safety of long-term carbon dioxide storage in depleted oil and gas reservoirs.

The proposed methodological approach is based on research findings which have shown that the spatial distribution of NPEMFE varies depending on the formation pressure regime. Analysis of the NPEMFE maps and correlation relationships demonstrated that a significant restructuring of the electromagnetic anomaly pattern occurs during the transition from a pressure of 74 atm to 0 atm. The low correlation coefficients between the states at 74 atm and 0 atm (r = 0.131), as well as between the process of reservoir depressurisation and the final state (r = 0.113), indicate the method's high sensitivity to changes in the stress-strain state of rocks. This confirms the suitability of using NPEMFE as one of the tools for geophysical monitoring of underground and geological CO_2 storage sites.

NPEMFE baseline map depicts the natural state of the geological environment before the onset of anthropogenic influence. It serves as the reference against which all subsequent changes in the electromagnetic field are assessed. Without such a map, it is impossible to determine whether the detected anomalies are the result of CO_2 injection or whether they existed previously as natural features of the geological structure. Furthermore, the baseline map can be used to identify background anomalies associated with faults, zones of natural fracturing and lithological heterogeneities.

Existing measurements must be conducted following the same observation scheme, using identical profiles, measurement intervals, recording parameters and data processing conditions. The comparison should include an analysis of the spatial location of anomalies, their intensity, extent, configuration and orientation. It is also advisable to use statistical indicators, in particular correlation coefficients, difference maps and other methods of spatial analysis, which can be used for a quantitative assessment of the degree of deviation from the baseline. The emergence of new local anomalies, a significant increase or decrease in the intensity of already known anomalous zones, or a change in their geometric dimensions, orientation or spatial location may provide grounds for conducting further investigations. Anomalies that recur systematically over several observation cycles, or that spatially coincide with known tectonic faults, boreholes or other potentially hazardous areas, should be emphasised. Such changes do not constitute direct evidence of a breach in the storage facility's integrity; however, they may indicate a change in the stress-strain state of the rock and require verification using other methods.

The NPEMFE method is best used as part of a comprehensive monitoring system. NPEMFE data can be correlated with the results of 3D seismic surveys or repeat seismic surveys to refine the location of faults and zones of disturbance. Geochemical studies of soil gases or groundwater can accompany verification of whether electromagnetic anomalies by the migration of CO_2 or other fluids. Well-based methods (monitoring of formation pressure and temperature, well logging and geophysical surveys) provide information on the condition of the reservoir directly within the wellbore. Consistent results from several independent methods significantly improve reliability of the interpretation (White, 2009; Michael *et al.*, 2010).

The integrated use of NPEMFE alongside traditional methods provides a more comprehensive picture of the state of the geological environment. In contrast to borehole measurements, which characterise individual points, NPEMFE can be used for areal mapping of the study area and rapid detection of local changes in the stress-strain state. The method is non-invasive, relatively quick to conduct and can be applied repeatedly without interfering with the operation of the storage facility. Its main advantage lies in the early detection of areas where changes in the geomechanical state are occurring, after which these specific areas can be investigated in detail using more expensive or localised methods. Thus, NPEMFE should be regarded as a tool for initial screening and spatial monitoring, rather than as a standalone method for confirming leaks or breaches in the integrity of a geological repository.

Comparison of the results obtained with data from existing studies

B. Wei *et al.* (2023) investigated the prospects for using depleted oil and gas fields for the long-term storage of carbon dioxide. Study found that the safe operation of such facilities is determined not only by the geological characteristics of the reservoir, but also by the ability to continuously monitor CO_2 migration processes and changes in reservoir pressure (Albertz *et al.*, 2023). This conclusion is fully consistent with the results of presented study, as the identified relationship between formation pressure and NPEMFE parameters can be used as an additional tool for such monitoring. Similar conclusions were reached by K.K. Nsiama *et al.* (2024), who conducted a comprehensive analysis of modern technologies for the geological storage of CO_2 in depleted hydrocarbon reservoirs. The researchers noted that one of the key factors for long-term safety is the ability of monitoring systems to detect changes in the physical state of the reservoir in a timely manner. The results obtained in presented study confirm the validity of this approach and demonstrate the potential for use of geophysical parameters as indicators of changes in the geological environment.

Y. Demchuk *et al.* (2025) investigated geological and petrophysical characteristics of Ukrainian underground gas storage facilities concerning their suitability for storage of hydrogen and CO_2. The authors found that most of the sites studied have sufficient capacity and favourable geological conditions for the implementation of CCS projects. Presented study correlates with these conclusions; however, the assessment of storage site suitability must necessarily be accompanied by the development of systems for the continuous monitoring of the reservoir's geomechanical state. This aspect is insufficiently addressed in study of mentioned authors. A. Ahmed *et al.* (2025) is noteworthy for interpretation of the results obtained. It addressed integrity and safety of underground CO_2 storage sites. The researchers concluded that the main risks remain breaches in the integrity of the caprock and wells, which can form gas migration pathways. The results obtained in this study do not contradict these conclusions. On the contrary, the ability to record changes in the stress state of the rock mass using the NPEMFE method could serve as an additional tool for the early detection of potentially hazardous zones.

X. Zhou *et al.* (2024) analysed the effectiveness of CO_2-EOR technologies and the behaviour of carbon dioxide in oil reservoirs. The authors found that changes in reservoir pressure significantly influence CO_2 migration processes, the degree to which it is retained in the reservoir, and the ultimate effectiveness of sequestration. These results are consistent with presented observations, as reservoir pressure is one of the main factors determining changes in the parameters of the NPEMFE model.

M.S. Shah *et al.* (2026) examined geological and technical aspects of the safe storage of CO_2 in depleted oil and gas reservoirs. Study emphasised significance of comprehensive monitoring of the condition of storage sites, control of formation pressure, assessment of cap rock integrity and identification of potential CO_2 migration pathways. The findings confirm the suitability of the NPEMFE method as an additional geophysical tool for assessing changes in the stress-strain state of rocks during CO_2 injection. When combined with seismic, well logging and geochemical methods, NPEMFE can improve effectiveness of the monitoring system and ensure early detection of potentially hazardous areas where storage integrity is compromised.

P.A. Eigbe *et al.* (2023) examined the prospects for using depleted oil and gas fields for the geological storage of CO_2, emphasising the need to assess reservoir capacity, cap rock integrity, injection parameters and the geomechanical stability of the system. Study noted that the safe storage of CO_2 requires comprehensive monitoring of changes within the reservoir, as the increase in pressure during injection may affect the stress-strain state of the rocks and the activation of permeability zones. The findings confirm benefits of the NPEMFE method as an additional tool for monitoring the geomechanical state of the reservoir, as it can detect changes associated with stress redistribution and the development of fracturing. When used in conjunction with seismic, well logging and geochemical methods, NPEMFE can improve the reliability of safety assessments for the long-term storage of CO_2 in depleted hydrocarbon reservoirs. J.-P. Deflandre *et al.* (2011) investigated the modelling of CO_2 injection processes at the In Salah industrial site (Algeria), emphasising the relationship between CO_2 flow, changes in reservoir pressure and the geomechanical response of the reservoir. The authors demonstrate that a reliable assessment of the storage site's behaviour requires a combination of hydrodynamic modelling, geomechanical calculations and monitoring results, in particular satellite observations of surface deformation. The results obtained confirm that pressure changes during injection can cause a redistribution of stresses in the rock and manifest as deformation anomalies. This approach is relevant for assessment of safety of CO_2 storage in depleted oil and gas reservoirs and justifies the use of NPEMFE as an additional method for monitoring changes in the stress-strain state of the rock mass.

This approach is supported by W. Tang *et al.* (2025), who conducted a review of current geophysical monitoring technologies for geological CO_2 storage. Study noted the great potential of electromagnetic methods due to their sensitivity to changes in rock fluid saturation and alterations in the medium's electrophysical properties. The current results confirm this conclusion and demonstrate that electromagnetic parameters can also reflect changes in the stress-strain state of the reservoir. The proposed approach involves creation of a baseline map of the distribution of NPEMFE parameters before the start of CO_2 injection, which characterises the natural state of the geological environment and serves as a reference for subsequent comparisons. During subsequent stages of storage operation, periodic measurements are conducted on a network of observation profiles located above the reservoir and within zones of potential fluid migration. Comparison of existing data with the baseline state can identify changes in the geodynamic state of the rock mass and processes associated with storage operation. In particular, analysis of the spatio-temporal variations in NPEMFE parameters can assess changes in formation pressure, identify the activation of zones of increased fracturing, record the formation of potential filtration channels, and determine the directions of possible propagation of the injected carbon dioxide front. Furthermore, local anomalies in the electromagnetic field may indicate the presence of areas with an increased risk of leakage from the geological storage facility.

Should anomalous zones be detected, the monitoring results can be used to plan further detailed investigations using seismic, geochemical or borehole monitoring methods. This approach enables multi-level verification of the data obtained and enhances the reliability of assessments of the geological environment. The results obtained demonstrate that the use of the NPEMFE method has the potential to create an early-warning system for detection of hazardous changes within geological CO_2 storage sites. The advantages of the proposed approach include the ability to rapidly obtain information on changes in the stress-strain state of rock masses, the relatively low cost of fieldwork, and the possibility of integration with other monitoring methods. This defines NPEMFE as a promising tool for improvement of safety of long-term geological storage of carbon dioxide in depleted oil and gas fields. Analysis of results of this study in the context of scientific publications, it is possible to state no contradiction of existing interpretaion of the mechanisms governing the operation of CO_2 geological storage sites. On the contrary, the data obtained expand current approaches to monitoring underground reservoirs using the Earth's natural pulsed electromagnetic field as an indicator of changes in formation pressure and the stress-strain state of rocks. However, further research is required at other underground gas storage facilities and potential geological carbon dioxide storage sites to definitively confirm the identified patterns. This can be used for an assessment of the universality of the proposed approach and determine the limits of its practical application in CCS monitoring systems.

Conclusions

An analysis of existing scientific research has shown that depleted oil and gas fields are promising sites for the long-term geological storage of carbon dioxide due to their significant pore volume, proven natural impermeability and the presence of a well-developed production infrastructure. At the same time, it has been established that the main risk factors during the implementation of CO_2 geological storage projects remain breaches in the integrity of the cap rocks, the activation of tectonic faults, well degradation and the formation of man-made fluid migration pathways. The research established the existence of a regular relationship between changes in formation pressure and the parameters of the Earth's natural NPEMFE. A consistent inverse relationship has been identified: an increase in formation pressure is accompanied by a decrease in the intensity of the Earth's natural NPEMFE, whilst a decrease in formation pressure increases electromagnetic radiation. This pattern is determined by changes in the stress-strain state of the rocks and the intensification of filtration processes in the geological environment. An investigation of the spatial distribution of the NPEMFE anomalies revealed their pronounced anisotropy and dependence on the formation pressure regime. It has been established that elongated anomalous zones reflect the directions of fracture development and the movement of formation fluids, which defines them as indicators of zones of increased permeability and potential migration pathways for carbon dioxide. The results of the spatial correlation analysis confirmed the existence of a genetic correlation between the Earth's atural electric field and its natural pulsed electromagnetic field. It was established that changes in the structure of the correlation functions are most manifested during the redistribution of formation pressure and reflect changes in the stress-permeability state of the geological environment.

Based on the results obtained, the feasibility of use of NPEMFE method as a tool for real-time monitoring of the safety of geological CO_2 storage was demonstrated. It has been demonstrated that the method can be used for remote monitoring of changes in formation pressure, the identification of active filtration zones, the localisation of potential leakage pathways, and the assessment of the condition of the geological environment without the need to drill additional observation wells. A conceptual approach is proposed for establishment of a system of continuous geophysical monitoring of CO_2 storage sites based on regular NPEMFE observations. Implementing this approach can be used for early detection of reservoir integrity breaches, the prediction of carbon dioxide migration pathways, and an improvement in the environmental and operational safety of geological storage. The results obtained indicate the potential for further research aimed at quantitatively establishing the relationships between NPEMFE parameters, formation pressure, rock permeability and the volumes of injected CO_2. Development in this area lays the scientific foundations for the design of automated monitoring systems and risk-based management of geological carbon dioxide storage sites.

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Conflict of Interest

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Оцінка безпеки зберігання CO_2 у виснажених нафтових та газових пластах

Анотація. Актуальність дослідження зумовлена необхідністю безпечного геологічного зберігання вуглекислого газу в межах реалізації технологій уловлювання, транспортування та зберігання вуглецю (CCS/CCUS). Метою дослідження була оцінка безпеки зберігання CO_2 у виснажених нафтових та газових пластах і обґрунтування можливості використання методу природного імпульсного електромагнітного поля Землі (ПІЕМПЗ) для оперативного контролю пластового тиску та виявлення потенційних каналів міграції флюїдів. Методологія дослідження базувалася на аналізі результатів експериментальних геофізичних досліджень, виконаних на науковому полігоні Долинського нафтопромислового району західного регіону України, а також на застосуванні просторово-кореляційного аналізу для встановлення взаємозв’язків між параметрами ПІЕМПЗ та пластовим тиском. Виснажені родовища вуглеводнів розглядалися як перспективні об’єкти для довготривалої ізоляції CO_2 завдяки значній ємності, підтвердженій герметичності та наявній виробничій інфраструктурі. У результаті дослідження встановлено закономірний зв’язок між пластовим тиском і параметрами ПІЕМПЗ. Виявлено інверсійний характер залежності, за якого підвищення пластового тиску супроводжується зменшенням інтенсивності ПІЕМПЗ, тоді як його зниження призводить до зростання електромагнітної активності. Показано, що зміни інтенсивності ПІЕМПЗ пов’язані з процесами перерозподілу напружень у породному масиві. Встановлено анізотропний характер просторового розподілу аномалій ПІЕМПЗ, який відображає напрямки руху флюїдів і зони підвищеної проникності. Кореляційний аналіз підтвердив наявність взаємозв’язку між змінами природного електричного поля та пластовим тиском. Розроблено концептуальний підхід до організації системи геофізичного моніторингу об’єктів геологічного зберігання CO_2 на основі регулярних спостережень параметрів ПІЕМПЗ, що забезпечує раннє виявлення потенційних каналів міграції вуглеводнів та порушень герметичності сховища. Практична цінність отриманих результатів полягає у можливості їх використання фахівцями нафтогазової галузі, геоекології та геофізичного моніторингу для контролю стану підземних сховищ CO_2, оцінювання ризиків витоків і підвищення рівня екологічної та технологічної безпеки геологічного зберігання вуглецю

Ключові слова: геологічне зберігання CO_2; виснажені газові родовища; пластовий тиск; природне імпульсне електромагнітне поле Землі; моніторинг; безпека сховищ; міграція флюїдів