



CCS Technology and Application of Geophysical Tools

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Abstract

Climate change has forced mankind to revisit the way humans are using energy today and consequently change and fill the energy basket with more and more renewables. To achieve the goals of energy security, affordability and sustainability for the nation, for short and medium terms, the necessity of the Oil and Gas business is a must. This did not discount the available global carbon budget and global yearly CO₂ emission of around 40 Gt per year. The only sustainable and feasible solution for mankind is to adopt negative carbon technology such as Carbon Capture and Storage (CCS). The Intergovernmental Panel on Climate Change (IPCC) has also emphasized the importance of CCS in restricting global warming to 1.5°C above the pre-industrial age. CCS is an offshoot of Oil and Gas production technology, used to Enhance Oil Recovery (EOR) in mature fields. Only difference between using CCS for CO₂ Storage to that of EOR is the understanding of the nature and composition of CO₂ and the reservoir required for CO₂ storage site. In the case of CCS, the storage integrity and the longer period of storage without any leakage is necessary to infuse confidence in the public and the regulator. The paper tries to understand the need for CCS, the physical and chemical properties of CO₂, and trapping mechanism within the geological reservoir. The understanding of Trap for long-term storage of CO₂ requires a different geological setting than usually found in Oil and Gas reservoirs. The use of 3D seismic for mapping the CO₂ reservoir, faults and seal is critical for the success of the CCS project. Post and Syn-injection monitoring of leakage is also vital aspect of CCS project. The paper takes an example from various active CCS site globally and identify the importance of Geophysical tool for the CCS Project.

Introduction

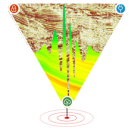
The world is in the process of moving towards low and zero carbon, in line with the Paris Agreement of

2015. To meet the goal of the Paris Agreement, decarbonization has become an imperative and priority for governments, industries, companies and society at large to become carbon neutral by 2050. Countries are using more and more renewable technologies in their energy mix towards their path to net zero.

Presently fossil fuel (Coal, Oil and Gas) accounts for more than 80% of the total energy needed globally. The global CO₂ emission is around 40 Gt per year. For 2°C of Global warming, the total carbon budget is estimated at around 2900 Gt of CO₂. Humans have already used around 73 % of this budget, that is 2100 Gt of CO₂. If the world is in a “business as usual scenario”, the global temperature will increase by more than 5°C by the end of this century. World had a pledge in Paris Agreement to hold the increase in global average temperature well below 2° C above the pre-industrial level.

To achieve the goal of Energy security in the near term, the only solution is fossil fuel. But to achieve the other goal of reducing global warming well below 2° C need to cut drastically the use of fossil fuel globally. For near-term planning to achieve two dichotomous goals depend on Carbon Capture Utilization and Storage (CCUS) or simply Carbon Capture and Storage (CCS). CCS is a bridge to achieve solutions for the two contrasting problems faced by mankind in the near future.

Carbon capture, utilization and storage (CCUS) have the potential to be a major contributor to our efforts to decarbonize the global energy system. CCUS covers various technologies which involve Capturing CO₂ from large industrial sources such as power plants, cement plants or sometimes directly from the atmosphere (Direct Air Capture DAC). Mostly CO₂ is captured from and near the large industrial hubs and is compressed and transported for injection in deep geological formations with the intention that this injected CO₂ remain there for much longer than a human lifetime. Presently CO₂ is mostly injected in depleted Oil and Gas reservoirs. But saline aquifers



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are also large and important reservoirs for CO₂ storage. Due care needs to be taken for the storage of CO₂ because of the chemical composition of CO₂.

There are presently many examples of CCS in a depleted Oil and Gas field for Enhanced Oil Recovery (EOR) purposes. This process is generally a boon for the E&P industry, depending on the nature of the reservoirs. But the process also has inherent risks associated with the nature and maturity of the Oil field. There is a risk of CO₂ leakage where the density of old wellbores is high. This is especially risky when the legacy well was plugged and abandoned before using these with the CCS project for CO₂ storage.

Properties of CO₂:

Carbon dioxide is gas at normal temperature and pressure and forms dry ice (Solid) when cooled and in pressurized condition. CO₂ behaves like a supercritical fluid at temperatures over 31^o C and at a pressure of 74 bar. In the supercritical phase, CO₂ behaves as both gas and liquid. This property of CO₂ allows it to be a highly compressed fluid ideal for storage in sedimentary basins with geothermal gradient and pressure profiles. The Phase Diagram of CO₂ is shown in **Fig-1**.

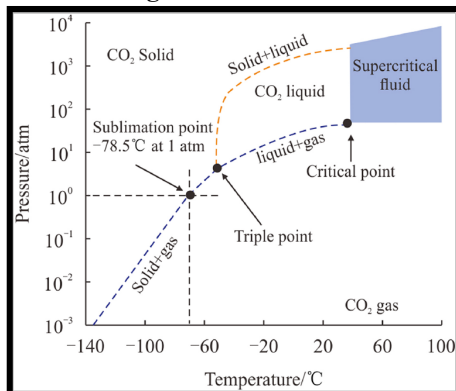


Fig-1 Phase Diagram of CO₂ Raza et. al, 2018

There are Fundamental differences in CO₂ molecules compared to CH₄ and other hydrocarbons. CO₂ is the smallest molecule and is 0.28nm wide compared to CH₄ with 0.38nm other Hydrocarbons are still larger in size. This makes the seal formation for CO₂ more challenging compared to other hydrocarbons for long-term storage of CO₂ in the geological formation. CO₂ in the presence of water reacts to form carbolic acid, which is highly corrosive. Carbolic acid reacts

with reservoir lithology and the fluid present in it and also sometimes with sealing rock. Carbolic acid reacts with rocks, especially those with significant carbonate components, it may also corrode infrastructure such as well casing and pipelines.

Trapping Mechanisms:

There are a number of different mechanisms available to store CO₂ in geological formations. These mechanisms can be classified as; structural and stratigraphic trapping, residual trapping, dissolution trapping and mineral trapping. Structural and stratigraphic storage is referred to as trapping CO₂ beneath a seal and requires structural or stratigraphic trap as is generally seen in the case of Hydrocarbon trapping in the geological formation. CO₂, once injected, moves in the subsurface and finds its way from the injector to trap. (Hermanrud et. al., 2019)

This happens because CO₂ is highly mobile due to its molecular composition. Residual trapping is referred to the CO₂, which remains in the porous rock after it has been flashed with CO₂. This residual CO₂ remains in porous rock due to the surface tension or wettability of the rock.

The other two classes of storage solubility/dissolution trapping and mineral trapping are slow processes, and they take time within the CO₂ reservoir. These processes are gradual in nature but provide more stable and permanent trapping. Mostly structural and stratigraphic trapping, residual trapping predates the next two trapping classes, i.e., solubility/dissolution trapping and mineral trapping. **Fig-2**.

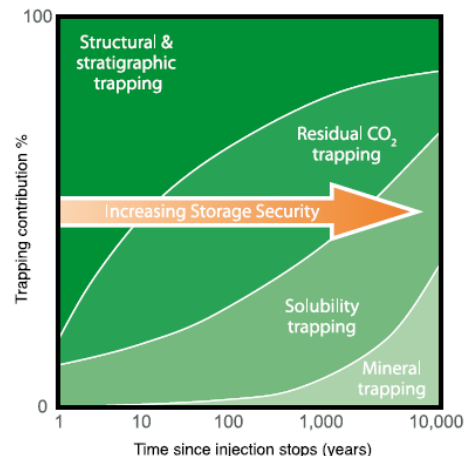


Fig-2: Mechanisms of trapping CO₂ showing time taken by various trapping classes. Hermanrud et. al., 2009

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The most efficient and secure way to store CO₂ in geological formations is to make CO₂ in its most dense state or solid. This is mostly achieved via solubility trapping and or mineral trapping. Intergovernmental Panel on Climate Change (IPCC) recommends trapping where CO₂ dissolves in formation water and is sometimes referred to as storage in Saline Aquifer. These processes are, however, time-dependent, and geochemical trapping, in particular, can take more than 1000 yr to achieve after injection because of the slow process of mineralization. The mineralization process may never occur, depending on the mineral and fluid content within the reservoir.

In the early years of injection, CO₂ exists in a separate phase, structural and stratigraphic trapping should be like that of Hydrocarbon trapping. That is why same geological and geophysical assessment of integrity of reservoir and seal that are conducted routinely for petroleum exploration and development projects must also be made for any potential CCS sites to ensure long-term security of storage. The potential leakage pathways through faults, fractures and seal failure must be identified and appraised. CO₂ escape through existing and planned wells infrastructure also needs appraisal and mitigation plans to be in place accordingly.

Selection of Geological storage site for CO₂.

The geological and geophysical aspect of the selection of CCS site is to identify the basin with reservoir and cap rock with certain concepts taking into consideration similar to that of E&P industry with the exception that to find out where we inject CO₂, and it migrates into the reservoir rock sealed with cap rock. Generally, a depleted hydrocarbon reservoir is a good enough reservoir for CO₂ with all aspects of reservoir and cap rocks present, but owing to other engineering issues, such as the presence of a large number of abandoned wells and the chemical composition of CO₂, might make their reservoir unsuitable for long term CO₂ storage in certain cases. A conceptual model developed by Deep Offshore Carbon Storage (DOCS) project by Vrije University Amsterdam for screening geology in western Dutch offshore. **Fig -3.**

It is imperative to inject CO₂ in the synclinal part of the Reservoir or, in some cases lower part of the reservoir to give time for CO₂ to migrate to the top of the reservoir and get trapped there. The time taken by

CO₂ to move up and get trapped will allow CO₂ to react with saline water and form CO₂-rich brine thus, all four trapping mechanisms will be in play in the reservoir. **(Fig-4)**

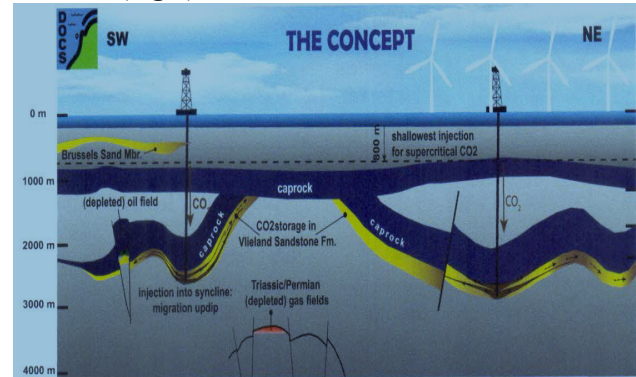


Fig:3 The concept of CO₂ injection in deep saline geometries as proposed by DOCS for Offshore Amsterdam.

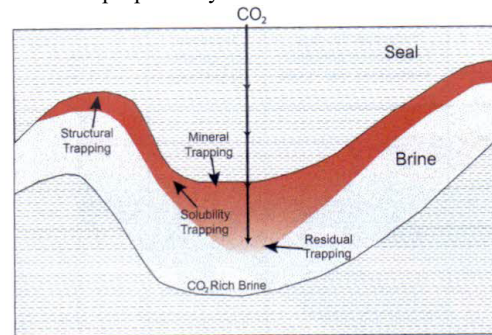
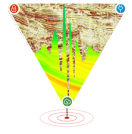


Fig-4: The interplay of four trapping mechanisms of CO₂ in the reservoir. Redrawn from *Emami-Meybodi. et al. 2015)*

Over time, the injected CO₂ plume will be trapped in storage by four different trapping mechanisms. Due to the natural buoyancy of CO₂ compared to formation brine, CO₂ will displace the water and migrate upward till it hit the seal where Capillary entry pressure \gg CO₂ buoyancy force and will be trapped there. Most of the petroleum system elements critical for the success of E&P business and exploration are also very critical for CO₂ storage, such as reservoir quality and seal integrity. A table of geological requirements for safe CO₂ storage is reproduced below (*Chadwick et al. 2008, Delpart-Jannaud et al.2013, Alexander Siebels et al.2022*).

	Positive Indicators	Cautionary Indicators
Storage Formation Properties		
Lithology	Sandstone	Limestone
Depth	>1000m, <2500	<800m, >2500



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	m	m
Reservoir thickness	>50 m	<20 m
Porosity	>20%	<10%
Permeability	>300 md	<10-100 md
Sealing Formation Properties		
Lateral continuity	Stratigraphically uniform, No Faults or maybe small faults	Lateral Variations Medium or Large Faults
Thickness	>100 m	<20 m
Capillary Entry Pressure	Capillary entry pressure >> CO ₂ buoyancy force	Capillary entry pressure ~ ~CO ₂ buoyancy force

CO₂ Storage Capacity Calculations:

Estimating accurate CO₂ storage capacity is an important factor for any CCS project. There are methods for calculating the theoretical capacity of CO₂ storage, but the effective capacity can only be a part of it and usually requires numerical simulation using site-specific reservoir and fluid properties, including the salinity of formation water, reservoir pressure and temperature. There are two approaches for determination of theoretical capacity based on the reservoir. Production based approach is used for producing or depleting fields (*Bachu et al.2007*). The theoretical storage capacity of CO₂ is:

$$M_{CO_2t_p} = RHO_{CO_2r} V_{pg} / FVF$$

Where RHO_{CO_2r} is the density of CO₂ at reservoir condition in Kg/cubic meter, and V_{pg} is the volume of produced gas in cubic meter, and FVF is the gas Formation Volume Factor. The calculation assumes natural pressure depletion of gas reservoir in which 100% of the pore space originally occupied by gas is available for CO₂.

Geoscience based approach for theoretical CO₂ capacity ($M_{CO_2t_p}$) determination is used for Saline Aquifer reservoir (*I.de Jonge-Anderson et al.2022*).

$$M_{CO_2t_p} = GRV * NTG * PHI_{eff} * (1-S_{Wirr}) * RHO_{CO_2r}$$

In this equation, GRV= Gross Rock Volume, NTG = Net to Gross is the fraction of the reservoir apportioned to reservoir sandstone, PHI_{eff} is the effective porosity of the reservoir, S_{Wirr} is the irreducible water saturation, and RHO_{CO_2r} is the density of CO₂ at reservoir condition.

The GRV is generally calculated after mapping and depth converting the top reservoir for each CO₂ storage site.

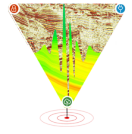
Use of seismic in CCS:

The geological criteria for successful CO₂ storage discussed above need seismic and petrophysical analysis in a way similar to Oil and gas exploration. The understanding of reservoirs and traps for CO₂ storage needs seismic and well-log analysis to link geological boundaries to seismic reflectors. An accurate definition of key geological events in the area from time domain seismic data is achieved by well-constrained velocity model, wherever data are available (*Anderson et al.2022*). In a new area where there are fewer numbers of well or no well, accurate depth interval velocity modelling will be required during pre-stack depth migration processing using tomography or more advance Full Wave Inversion (FWI) technique. Thickness and lateral extent, and porosity of the formation can be derived by multi-seismic attributes like amplitude and frequency, which are directly linked to physical properties of formations. A combination of Spectral decomposition studies and interval velocities derived from gather data can be used to know the reservoir extent and thickness.

Accurate fault mapping is another key aspect of successful CO₂ storage site. 3D fault framework (model) is critical to mitigating the risk of CO₂ leakages. 3D Seismic and its various structural attributes will be useful tool for accurate fault mapping. Attributes such as discontinuity, and coherency will be useful tools for understanding major and minor faults and other lateral features in the area. The depth surfaces and their associated faults will indicate the trap geometry, fault intensity, and gross rock volume for specific traps for CO₂ storage. The structural framework thus created will also be used for numerical reservoir modelling and future simulation for CO₂ storage operation.

Seismic amplitude and other attributes, including AVO and Pre stack inversion attributes, will be a useful and accurate tool along with well data for reservoir characterization for CO₂ storage as is being used for Oil and gas explorations. (*A D Hollinsworth et al. 2022*).

A typical workflow for CO₂ storage reservoir study using seismic and petrophysical data along with the core is reproduced below (**Fig-5**).



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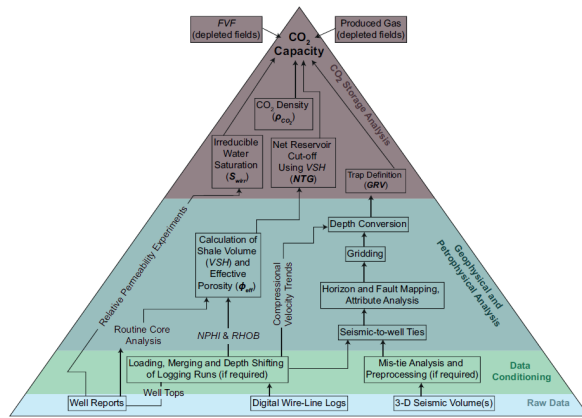


Fig-5: Flow Chart indicating the workflow to be followed for established Oil and Gas fields when used for CCS. (I.de Jonge-Anderson et al. 2022)

In case where there are no well and log and cores are nonexistent, 3D seismic with advanced processing will help in identifying CO₂ storage reservoirs. This situation may arise in case of the area not covered by exploration of oil and gas, especially when saline aquifer is being targeted for CO₂ storage in India near the source of CO₂ emitting industry.

The workflow in such a case will be slightly different because of less or no available well and log data. The geophysical process will be slightly different, emphasising advanced velocity modelling and Pre-Stack Depth Migrated images for subsurface mapping and depth conversion. As regards the calculation of shale volume and effective porosity and also to get information about permeability, we can use a combination of parametric wells and surface geological information within the basin.

Monitoring of CO₂ injection:

CO₂ molecules are toxic and are asphyxiated for human beings; moreover, the purpose of CCS is to reduce the amount of CO₂ from the atmosphere for a longer time compared to human life. It is generally assumed that the injected CO₂ will remain in geological formation for at least thousands of years after the injection without leaking back into the atmosphere. CCS is a nascent industry, and most of the projects at present are in the pilot stage or are in the conceptual stage, with very little CO₂ injected back into geological formation compared to the yearly CO₂ generated in the atmosphere globally.

There are very few regulations and guidelines for CCS projects worldwide. Due to the leakage risk and making CCS safe and leakproof through regulations and guidelines is must for its social acceptability. There are few regulations or guidelines for CCS in India. There is available European CO₂ storage directive, (CCS-Directive 2009/31/EC Guidance Document 2) under this directive, the CCS operator has to demonstrate “zero detectable leakage” in order to close a storage site and transfer the responsibility to the national authority. In this context, leakage is defined as the subsurface escape of CO₂ from the defined storage complex. With this definition in stricter senses, EOR using CO₂ is not a CCS project. There are few guidelines available for CCS specific to countries like Canada and USA. The European guideline starts with the sufficiency of 3D seismic data for static modelling and further for dynamic modelling to be carried out for risk assessment. The EC guidelines for complete sensitivity characterization and risk assessment cannot be carried out without extensive seismic and Geophysical analysis. The extensive list of items to be covered in each step cannot be completed without extensive study to be carried out on 3D seismic and also using 4D seismic of the CO₂ injection site.

One of the pilot projects taken up by erstwhile StratOil (Now Equinor) was the Sleipner project, and its data is being monitored from 1999 onward using 4D seismic. The change in amplitude and velocity profile of the CO₂ reservoir indicates the movement of CO₂ front within the reservoir and also proved 4D seismic as an effective tool for monitoring and risk assessment for CO₂ storage sites all over the world. (Chadwick et al., 2014)

The Sleipner injection is being performed in the Utsira Sand reservoir with the Top Utsira formation depth at about 800 mts. 4D seismic was carried out at different times, i.e., 1999 and 2010. The time-lapse seismic and its difference is shown in **fig 7 and 8**. Another repeat seismic was performed in 2010, and the difference from the baseline seismic of 1994 is shown in **Fig 8**.

In all, their seismic difference from the baseline survey does not indicate the movement of CO₂ beyond the top of Utsira formation. Thus, it can be said that the seal above reservoir is working well to contain the injected CO₂. The Sleipner seismic velocity models also indicate the change in velocity introduced due to the presence of CO₂ within the

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system. The layer-based velocity model change and corresponding seismic are shown in **Fig 9**.

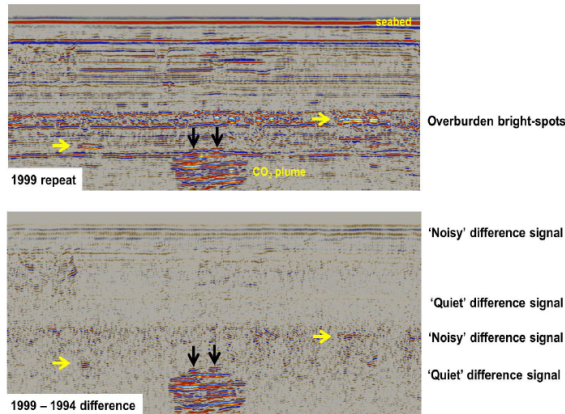


Fig 7: The top is the repeat survey of 1999 there is an overburden bright spot due to the presence of natural gas in the formation the top of the CO₂ reservoir is shown with a Black arrow at 900ms with a depth of 800m. The difference data is at the bottom, and it only indicates the presence of injected CO₂ in the reservoir. (Chadwick et al., 2008)

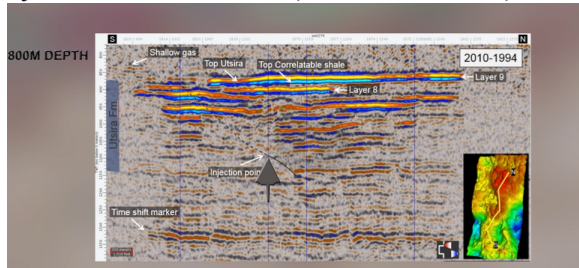


Fig-8: The seismic difference data from 2010 and 1994 with injection point is also shown. (Hermanrud et al., 2009)

The monitoring system discussed above is based on 3D and subsequent time-lapse seismic. Acquiring 3D seismic is a costly proposition for monitoring CO₂ injection in geological storage. There are other methods, one such method is the gravitational method, by monitoring the strength of Earth's gravitational field. The process will work based on relatively low-density CO₂ being injected and which displaced high-density water or hydrocarbon, there will be a tiny change in the local gravity measurements, which can be detected at the surface by a highly sensitive gravimeter. The change in the measurement can predict what has happened against what is predicted.

Another measurement and monitoring method is measuring the CO₂ and its concentration in the

underground water. It will be convenient when there is a water well in the vicinity and measurement of the concentration of CO₂ in the water any increase in the CO₂ concentration from the base data will indicate leakage. It is important to monitor the base data for at least two years in different seasons before injecting CO₂ into the subsurface. In case of any leakage, we have experience of Oil and Gas industry repairing the well plug the escape CO₂ from its reservoir.

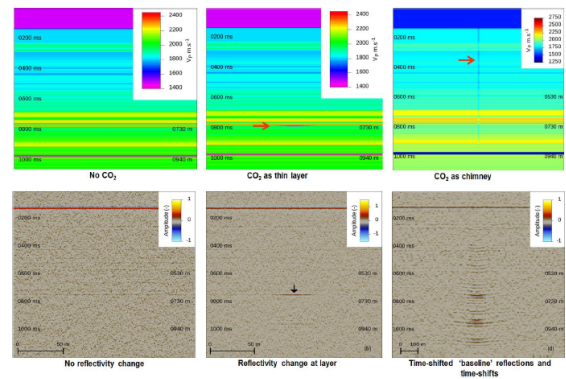


Fig-9: simplified Sleipner velocity models (top) with an arrow indicating the top of the reservoir. The model study was carried out by StratOil team to see the effect of CO₂ presence in the system. (Chadwick et al., 2008)

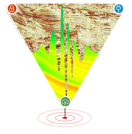
Another borehole measurement method that is also available to monitor CO₂ injection is pulsed neutron logging. This logging is used widely in cased holes and the measured macroscopic thermal absorption cross-section, which is sensitive to CO₂ saturation in high porosity saline water environments. The technology is demonstrated successfully to monitor the CO₂ plume moving through the two boreholes and the resulting saturation changes.

Conclusion:

CCS is one of the defining processes for negative carbon technology. Geophysical methods place a vital role in the characterization and evolution of potential subsurface reservoirs for the storage of CO₂ and also in the reservoir monitoring during the sequestration process and detection of possible leakage.

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