**TALLINN UNIVERSITY OF TECHNOLOGY**

SCHOOL OF ENGINEERING

Department of Materials and Environmental Technology

# CARBON CAPTURE AND STORAGE FEASIBILITY IN AZERBAIJAN

MASTER THESIS

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**AUTHOR’S DECLARATION**

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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# THESIS TASK

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Study programme: Materials and Processes for Sustainable Energetics

Main speciality: Processes for Sustainable Energetics

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**Thesis topic**:

(in English) *Carbon Capture and Storage feasibility in Azerbaijan*

(in Estonian) Süsiniku kogumise ja säilitamise teostatavus Aserbaidžaanis

**Thesis main objectives**:

1. Technical analysis of possibility for integration of CCS into the already existing Oil and Gas industry of Azerbaijan

2. Calculate the investment needed for operation and introduction of CCS technology in Azerbaijan

3.Explain already existing main infrastructure advantages of Azerbaijan for integrating CCS into it's industries

**Thesis tasks and time schedule:**

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# PREFACE

It didn't take a long time for me to contemplate what sort of topic I should work on for my thesis project. Azerbaijan is the rich country in terms of cheap energy like Oil and Gas. The abundant and cheap source of fossil fuel generated energy like from Oil and Gas makes it difficult to consider renewable energy sources like Solar, Wind and Hydro. However, 36% of energy supply of Azerbaijan comes from renewable energy sources, mainly from hydro energy power plants, such as Mingachevir hydro energy power plant in southern Azerbaijan.

Since the beginning of my study in Tallinn University of Technology, mainly from second semester, I was interested in one topic, Carbon Capture and Storage. I saw huge potential for my country in this technology. Because of already available infrastructure of pipelines and pretty cheap well drilling technology for storage of it. I used to work for drilling companies for 6 years before the commencement of my master study in TalTech.

The reason for me to choose this topic is belief of mine that CCS technology can be easily applied to our already existing industry, without building any plants, because we already have pipelines, compressor stations and available reservoir for trapping GHG (greenhouse gases).

Writing this thesis wouldn't be possible without the knowledge and information which I have gained throughout my education in Tallinn University of Technology. That's why I would like to thank all of the management and professor staff for assisting me in gaining the deep knowledge in Renewable energy technology and the dean's office who arranged the scholarship for me for easing my student life. I would love to express my utmost gratitude to Associate Professor Eduard Latõšov for assisting me in my research for completion of my thesis. Additionally, I would love to thank my ex-colleagues in BP for their help in data collection phase of my thesis.

**Keywords**: Offshore injection, Greenhouse gases, Carbon capture and storage, Trapping

## List of Abbreviations and Symbols

CCS- Carbon capture and storage

GHG- Greenhouse gas

API- American Petroleum institute

EOR- Enhanced Oil Recovery

CRI- Cuttings re-injection

SOCAR- State Oil Company of Azerbaijan Republic

ACG- Azeri-Chirag-Guneshli

CAIT- Climate analysis indicator tool

PWI- Production water injection

SWI- Shallow water injection

DWI- Deep water injection

CAPEX- Capital expenditure

OPEX- Operational expenditure

CNPC- China National Petroleum Corporation

COE- Cost of electricity

INDC- Intended Nationally Determined Contribution

MTpa-Million ton per annum

HSE- Health safety environment

HPP-Hydro power plant

# INTRODUCTION

Many engineers disagree that Carbon Capture and Storage is not a new technology, because most of the CCS techniques have been around for many decades. Nevertheless, the potential of CCS for mitigating global warming has been discovered recently. CCS is the technology which can be used to reduce the GHG (greenhouse gas) emissions to the atmosphere, directly picking it up from the energy generation facilities such as coal power plants and etc. or from picking it up from the atmosphere itself using state-of-the-art technology.

It is mainly considered as the great tool for trapping the $CO_2$ from combustion of hydrocarbon fuels. However commercial deployment of CCS faces serious challenges. Another serious challenge is storing acid gases, because storing GHG is significantly related to geology and geology is the science full of uncertainties which could possible lead to risks for storing these acid gases.

However, having available pipeline networks, already drilled wells and depleted old gas reservoirs infrastructure could pave the way for deployment of CCS in Azerbaijan with relatively less CAPEX (capital expenditure), making it economically feasible. Apart from that I do believe that attractiveness of CCS for major oil and gas companies such as BP (British Petroleum) and SOCAR (State Oil Company of Azerbaijan Republic) is also quite big. That is to say these oil companies can use the CCS for demonstrating their care for climate change and environmental concerns and gain quite big public sympathy by investing relatively small amount of money.

The goals of this thesis are to examine the technical and economical possibility of integration of long established experience of oil and gas drilling, storage and transportation of oil and gas companies, which operates in Azerbaijan, with CCS systems and economic benefits of this integration.

# 1. LITERATURE REVIEW

## 1.1 Carbon Capture and Storage

CCS is a technology which is being used for trapping GHG (mainly $CO_2$) from big factories (such as cement producing facilities) and heat power plants and transferring it to a geological storage site where it could be stored for a quite long period of time. The goal behind this technology is to stop the large amount of $CO_2$ emissions entering into the atmosphere, which could possible limit the global temperature increase and decrease acidity level of oceans significantly.

CCS is not a new technology though. Oil and gas industry have used acid gases injection for recovering more hydrocarbons from the sub-seabed or from onshore geological formations. Apart from point sources such as cement facilities, GHG can be collected from the direct air as well. This carbon capture method is being called Direct-Air-Capture. A power plant equipped with CCS could reduce its carbon dioxide emission up to 90%**.**

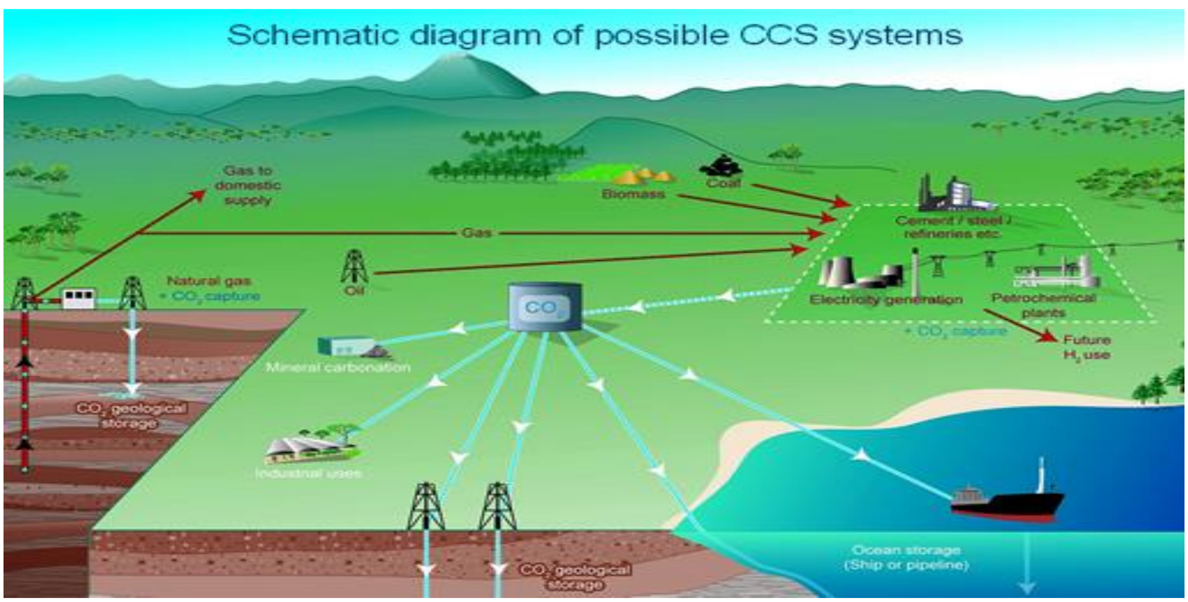


Figure 1.1 Schematic diagram of possible CC Systems [1]

Fortunately, CCS does not require too much of innovative research and knowledge in terms of geology, because the oil and gas industry experiences and know-hows in geology and already available subsurface expertise is quite satisfying for implementation of CCS technology, however, it has some specific differences and requirements, especially offshore storing of $CO_2$.

One of the other advantage of CCS technology is public support. Contribution of CCS into the global warming mitigation has significantly popularized the CCS systems. Deployment of CCS in commercial scale will slightly increase the utility cost and that's why the public consent in this matter is vital.

## 1.2 Types of CCS

There are three main types of systems for capturing $CO_2$: Post-combustion capture, Pre-combustion capture and combustion with oxygen fuel. The important factor for choosing which technique to use is concentration of $CO_2$ in flue gas flow, pressure of the flue gas flow and type of the fuel which is being used.

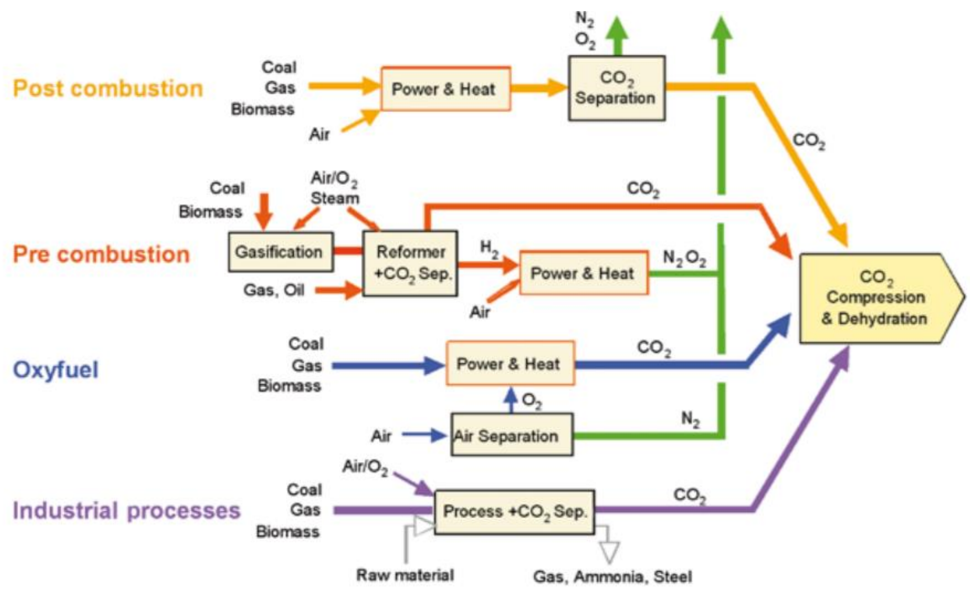



Figure 1.2 $CO_2$ capture systems [2]

**Post-Combustion Systems**. $CO_2$ capture after combustion is economically feasible at certain conditions. This method captures $CO_2$ from flue gases being bubbled through membrane with higher content of ammonia solvents, which is being placed in the flue gases chimney. When this membrane reaches its saturation with $CO_2$, the membrane is blowed with 120C° heated steam. This process releases $CO_2$ in membrane for containment and further transportation to storage site.

**Pre-Combustion Systems.** Capturing before combustion is being widely used in production of hydrogen and fertilizers. In pre-combustion technology, fuel (solid, liquid or gaseous fuels) is being converted to the mixture of hydrogen and $CO_2$ using technique of gasification. Gasification process is being used all over the globe.

**Oxy-Fuel Combustion.** This technology uses the pure oxygen for combusting the fuel instead of air, for obtaining flue gases which consists of mainly from water vapor and pure $CO_2$. Thanks to it the flue gas is characterized with high concentration of $CO_2$ (more than 80% per volume) [3]. Afterwards, water vapor is being removed with cooling effects and compression of the gas flow. Oxy-Fuel combustion systems requires separation of oxygen from air in the beginning of the process and oxygen with purity level 95%-99% is recommended.

## 1.3 Transportation of $CO_2$

Except the cases, in which the facilities are located on the geological storage site, the captured $CO_2$ have to be conveyed from the point of the capture to the storage location. The pipelines function as a commercial technology and today are the one of the main equipment for transportation of $CO_2$. Gaseous $CO_2$ is pressurized till 8 MPa, in order to prevent formation of two-phase substance while transportation and to increase the density, thanks to what it becomes less expensive for transportation [4]. $CO_2$ can also be transported with tankers and railways, in which the temperature of it is being kept significantly less than the room temperature and in a pressurized state.

The most important parameters of $CO_2$ for its transportation are water content, $CO_2$ purity degree and operation pressure limitation of pipeline network. Newly constructed pipeline operates within range of 40-130 bar, where compressed supercritical $CO_2$ transportation requires 70-80 bar [5].

**Water content** can pave the way for hydrate formation and corrosion within pipeline which can plug or hinder the flow rate, leading to operation failure and non-productive time for pipeline operator. [6]
Low **$CO_2$ purity**, which can possible contain $H_2S$ and $SO_2$ is responsible for high corrosion rate in the pipeline components which contains carbon steel in its make-up material. On top of that it could possible cause HSE (health, safety and environment) risk to operating personal in case of any leakages [6]. First this type of pipeline for transporting $CO_2$ has been constructed in USA in 1970x for transporting $CO_2$ from the anthropogenic sources. Through this pipeline (2400 km long) annually 44 $MtCO_2$ is being transported to Texas for EOR (enhanced oil recovery) applications. In pipelines the flow of liquified $CO_2$ is being organized by the compressor station which must be constructed on the upper end of the pipeline. However sometimes small compressor units are also present on some parts of pipeline network [7]. In some case it is economically profitable to transport $CO_2$ with tankers compared to pipelines. For example, when $CO_2$ has to be transported to the longer distance or through the sea.

At the same time, the pipeline for transporting the $CO_2$ through the inhabited areas might require less concentration of $H_2S$ in its content. Apart from that, delivery of $CO_2$ requires predetermined path of pipeline which can be scrutinized for any possible leakages and abnormal overpressure within the line.

The leakage of GHG to the atmosphere might happen during transportation phase, however during this period leakages are usually marginal. The $CO_2$ loss during transportation with sea tanker is 3-4% per 1000 km [8], taking into consideration the evaporation and the GHG emission of tankers themselves.

The accidents might happen as well, however the registered accidents regarding transportation with sea tanker didn’t happen yet.

## 1.4 Average cost of transportation

The approximate estimation of transportation has been conducted for both, transporting through pipelines and through sea path. In each cases the price depends on the distance and transporting amount. By pipelines, the price depends on the path of the pipeline: does it pass through the densely inhabited area or is there any mountainous area on the path. All these aspects influence the price of transportation by pipelines.

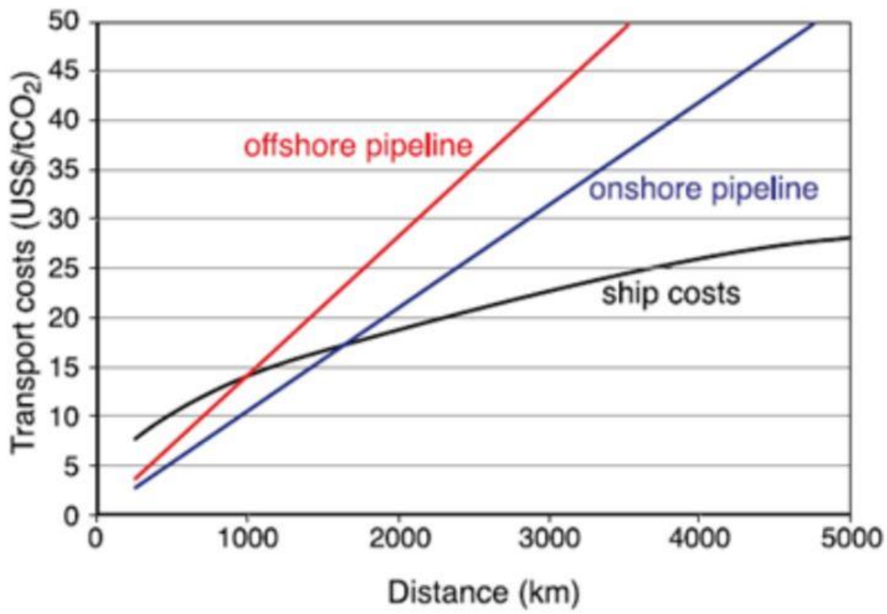



Figure 1.2 Approximate cost comparison of $CO_2$ transportation with offshore pipeline, onshore pipeline and ship [9]

By transportation with ships the key factor, determining the whole transportation expenses are the volume of the ship and characteristics of loading and unloading.

## 1.5 Subsurface storage

In any subsurface storage cases the formation which might be used has to have no commercial value. In other word it must have no carbohydrates within it. The possible formations for pumping $CO_2$ are those which has high porosity level, for containing $CO_2$ as they do contain water and carbohydrates. The potential storing formation can be located in coastal areas, as well as in offshore, such as in ACG (Azeri-Chirag-Guneshli) field.

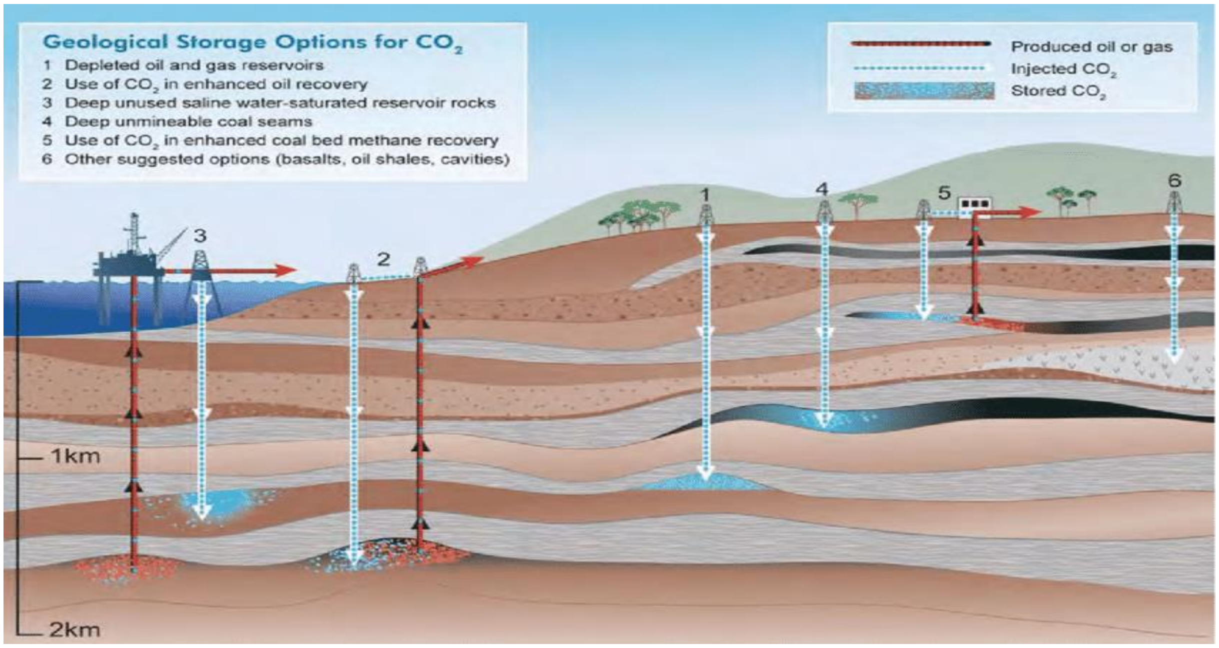



Figure 1.3 Geological storage options for $CO_2$ [10]

The technology for pumping $CO_2$ down to the porous formation is more or less the same as it is in oil and gas exploration and production processes. While projecting and implementation of geological storage techniques the developed technology of drilling, injecting and dynamical properties of porous formation were thoroughly used. In general, pumping of gas and other liquid waste into very deep reservoirs is being practiced throughout the world, mainly in America.

It's mainly accepted that the storage of $CO_2$ in the post-hydrocarbon formations is implemented in depth of 700-1000 m, where, because of the overburden pressure and temperature $CO_2$ remains in liquid form [11]. Because of the overburden pressure $CO_2$ in those reservoirs tends to move to upper formations. In order to isolate $CO_2$ migration it requires non-permeable upper formation, such as shale or chalk. This non-permeable formation is being called preventing layer.

The potential reservoir for storing $CO_2$ is available all around the world. CCS engineer mainly focus on depleted oil and gas reservoirs or the porous reservoir which has no commercial potential at all. That is to say all of the oil and gas producing countries can build their own application of CCS systems.

## 1.6 Risk analysis

There are risks of improper containment of $CO_2$ in subsurface formations as well. The catastrophic leakage, which might impact the environment seriously can happen only in the injecting phase of the process. As $CO_2$ being pumped to the chosen reservoir, the pressure within reservoir might reach its fracture gradient limit and it will activate or initiate formation faults or even sometimes can break up the impermeable top seal formation which prevents $CO_2$ from migrating to the surface. That's why reservoir calculation has to be conducted with an extreme care and accuracy.

Another risks regarding CCS are related to the monitoring after the injection and completion processes. Apart from the leakage monitoring, the monitoring of $CO_2$ underground migration might also be required. This monitoring is being conducted with seismic analysis and acoustic geophysical tools.

## 1.7 Greenhouse gas emission of Azerbaijan

Based on the CAIT (climate analysis indicator tool) Azerbaijan's greenhouse gases is mainly emitted by the energy sector, which is around 85%. 50% of it is caused by fugitive emission, which is leakage gases from industry activities, such as transportation or leakages from oil and gas producing installation. Apart from that flaring in Azerbaijan's oilfield installations is also main reason for fugitive emission. Because of the lack of infrastructure for storing gases, the flaring becomes inevitable. Otherwise the oil production has to be stopped. Electrical and heat generation power planst contribute around 25% to this amount, whereas agriculture accounts for only 10% [4].

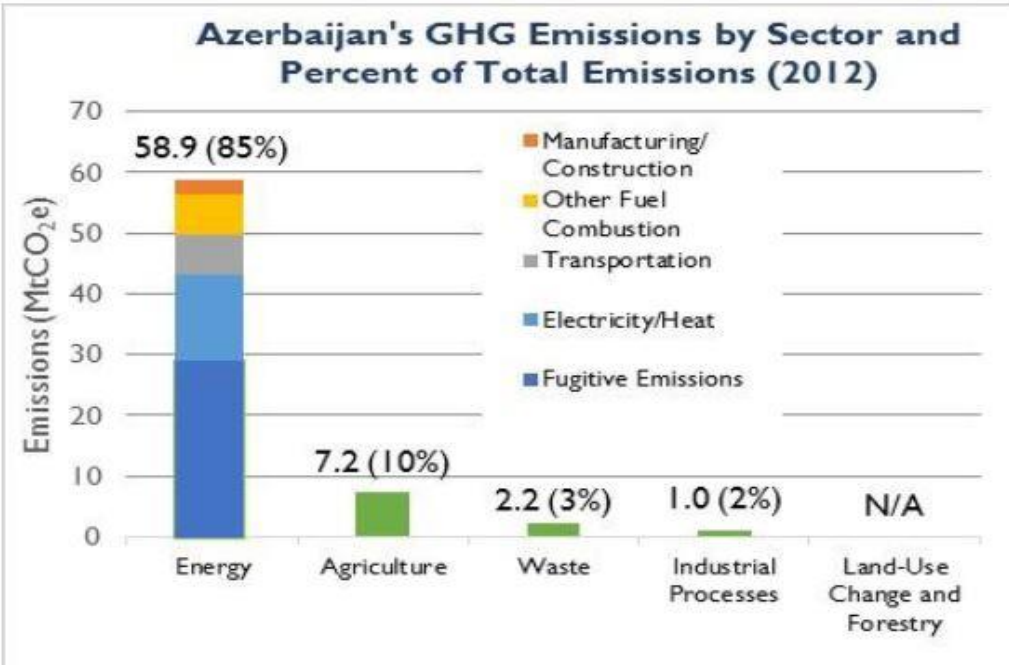



Figure 1.4 Azerbaijan's GHG emission by sector [12].

GHG emission in Azerbaijan increased around 8% between 1990-2018 [13]. The average increase per year was 0.7%. The main GHG emission increased was in energy sector, which amounted to 4% for this time interval. Azerbaijan took commitment to reduce fugitive emission by modernizing its pipelines systems for gas transportation and distribution systems and reducing flare gas.

Electricity generation installed capacity grew around 35% in Azerbaijan, however Azerbaijan succeeded to shift its electricity generation power plants from oil-based to natural gas fired power plants and thus achieved 40% decrease in GHG emission from electricity generation [14]. Nevertheless, the electricity generation is second main contributor of GHG emission after energy sector. Now 80% of all electricity in Azerbaijan is being generated by natural gas and 12% comes from 2 hydroelectric plants (Mingachevir HPP (hydro power plant) and Shamkir HPP), and the rest from other thermal, hydro and small hydro plants [15].

Azerbaijan's gross domestic product grew 215% between 1990-2018, whereas it's GHG emission increased approximately 8% at the same time interval [13].

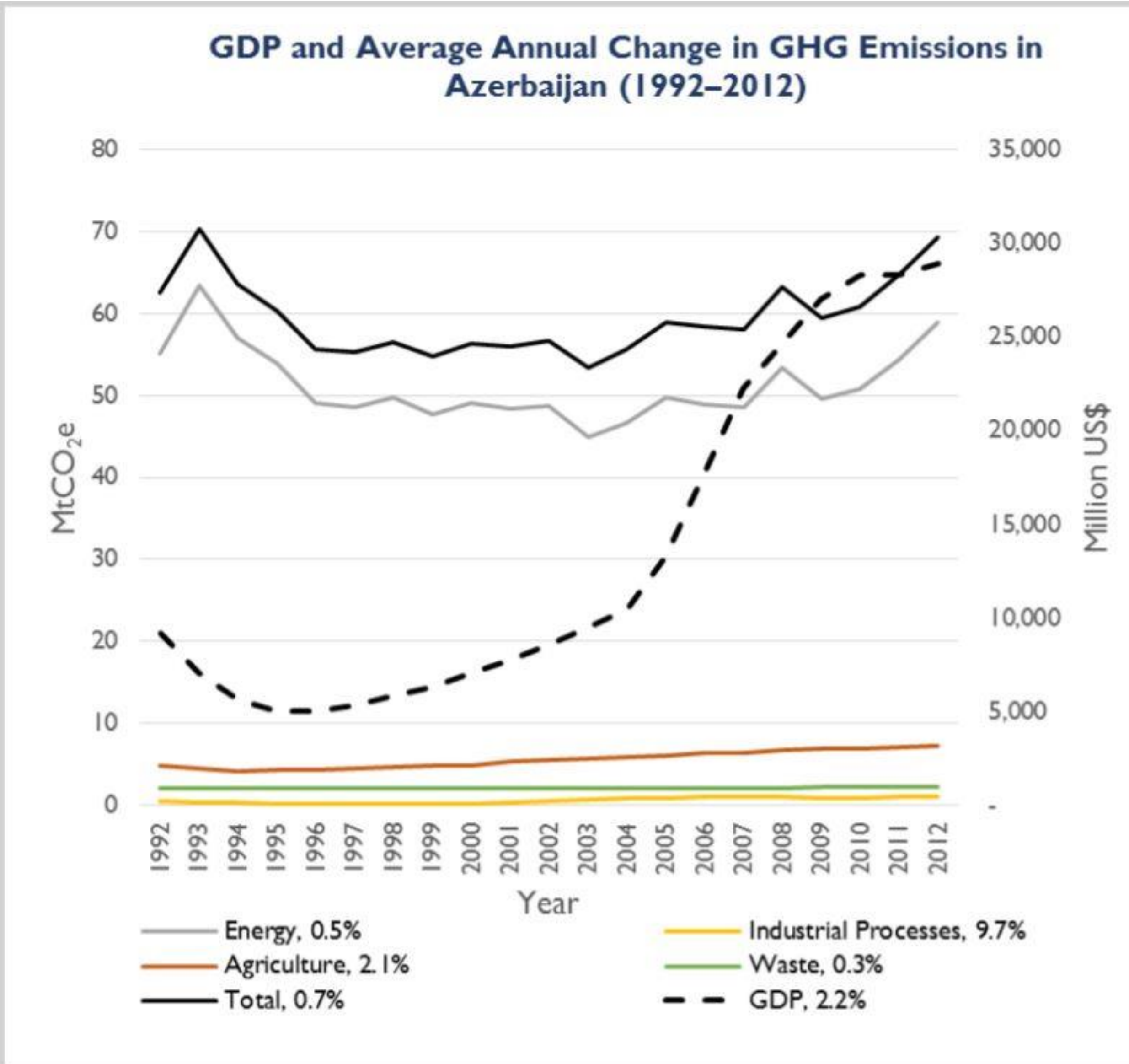



Figure 1.5 GDP and average annual change in GHG emissions in Azerbaijan (1992-2012) [14].

Still, Azerbaijan expressed its goal to decrease $CO_2$ emission around 40% by 2030 compared to the 1990 level, despite that fact that Azerbaijan's economy is predicted to grow at 8% annually till 2030. These goals are planned to achieve by modernizing flaring technology oilfield installations, pipelines for natural gas transportation, $CO_2$ capture from powerplants and development of sustainable energy technologies, as Azerbaijan has huge potential for it.

## 1.8 Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) is a technology which is being used to recover significantly more crude oil compared to primary technique. Up to 60% oil crude oil of reservoir might be produced by deploying this technology. There are 2 main method which EOR uses: thermal injection, gasification (gas injection and chemical treatment). In America, around 42% of EOR uses thermal injection technology. However, gas injection is the most common method for EOR in worldwide. Gas injection method pumps gases such as $CO_2$ and nitrogen down to the reservoir in order to reduce surface tension of oil and water. Water is present in oil bearing reservoirs and surface tension between two disable the chances of crude oil to migrate up to the wellbore and thus to be produced. Acid gases such as $CO_2$ are also main component of EOR. After being pumped down to the subsurface formation $CO_2$ reduced the viscosity of crude oil and enables it to freely move to wellbore. In America, there is quite big infrastructure for commercial use of $CO_2$ gases, mainly for EOR. For this application $CO_2$ have to be captured and liquified in order to be pumped to partially depleted oil-bearing reservoirs. This method is named $CO_2$-EOR and has been commercially profitable in all around the world. Even in Azerbaijan the subsea pipelines construction has been integrated with acid gases transportation lines for $CO_2$-EOR. Since the oil production in Azerbaijan are not in need for EOR these pipelines are currently not in operation. In Canada the operating oil and gas companies are buying $CO_2$ gases from CCS companies for its commercial use in theirs heavy crude oil-bearing formation. They have no intention of climate mitigation but rather profit driven motives for more production. One of the advantages of $CO_2$-EOR is that fact that used $CO_2$ remains safe under the ground after the oil recovery process and do not get re-introduced back to the atmosphere.

In some countries $CO_2$-EOR are being fostered with tax incentives so that the oil companies can produce more hydrocarbon for providing energy security of that country. Apart from that $CO_2$ based EOR is the good way for initiating the introduction of CCS systems into the public opinion and embracing it commercially.

## 1.9 Already operating CCS projects

The biggest number of operating CCS systems and projects is located in North America, mainly in United States of America. However, now Canada is home for biggest CCS project in the world.

**Boundary Dam** coal fired plant consist of 6 electricity producing units, with overall 824MW production capacity. Unit#3, which was commissioned on 2nd of October 2014, was integrated with worlds first commercial CCS system and costed around 770 million$. It is estimated that this CCS system captures 90% of all $CO_2$ emitted from 115 MW unit#3. CCS system will capture approximately 1 000 000 tons of $CO_2$ from electricity production in unit#3. Total $CO_2$ emission of the plant is 6.7 million tons. Trapped $CO_2$ is being used for EOR project in the nearby oilfield for obtaining maximum oil from the reservoir.[16]

**Sleipner $CO_2$ Injection-Norway** used to be the first commercial CCS project in the world. Instead of flaring, Statoil uses captured $CO_2$ from gas production and stores it in the saline underground formation. In 2008 the operating oil company succeed to capture and store around 10 million tons of $CO_2$ and approximately evaluated of possible volume of Sleipner reservoir is estimated around 600 billion tons. Sleipner project was the first one which used $CO_2$ for storing rather that for EOR. [17]

**Abu Dhabi- United Arab Emirates** CCS project was initiated in 2011, after successfully passing its pilot run. The systems were applied to iron and steel producing facility. As a consequence of steel production $CO_2$ is being produced and captured in the facility and later on being transported via 50 km long pipeline to the nearby oilfield for EOR application. This plant has a possibility of processing around 8 000 00 tons of $CO_2$ annually. [18]

**Petra Nova- US** is the plant which has been constructed in 1977. However, the post-combustion CCS System has been integrated to this plant only in 2017. 88% of $CO_2$ is being captured with CCS system and pumped to West Ranch oil field which 80 miles away for EOR application [19].

# 2. COST AND TECHNICAL FEASIBILITY ANALYSIS

Feasibility of CCS is highly dependent on the implementation and operation cost of CCS systems. In Azerbaijan, already available infrastructure such as drilled wells and constructed pipeline networks makes it very cheap for CCS compared to other countries to apply to our industry. The price of CCS is defined only in terms of commercial value. However, it doesn't include the damage price which GHG cause to environment.

## 2.1 Offshore subsurface storage and transportation infrastructure in Azerbaijan

ACG (Azeri-Chirag-Guneshli) oilfield is the largest oilfied in Caspian region, which lies 120 km off the coast of Azerbaijan. The ACG is mainly being operated by english energy giant BP (British Petroleum). 7 000 00 bbl (barrel) of oil being produced from this field daily and total available oil in this field is estimated to be around 5 000 000 bbl [20]. However, the production rate has started to decrease gradually since 2013 and experts relate it to partially depletion of the field.

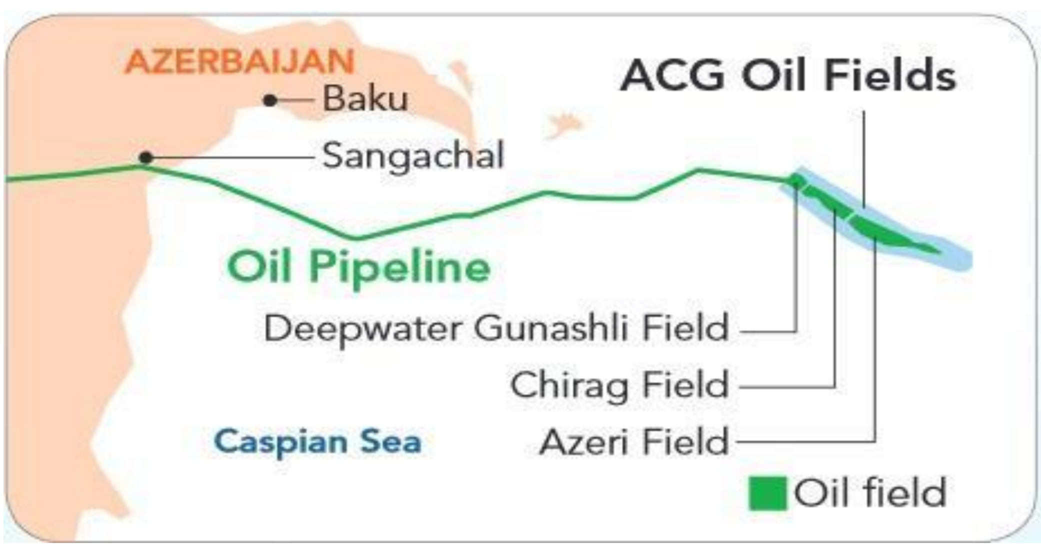



Figure 2.1 Azeri-Chirag-Guneshli oilfield [21]

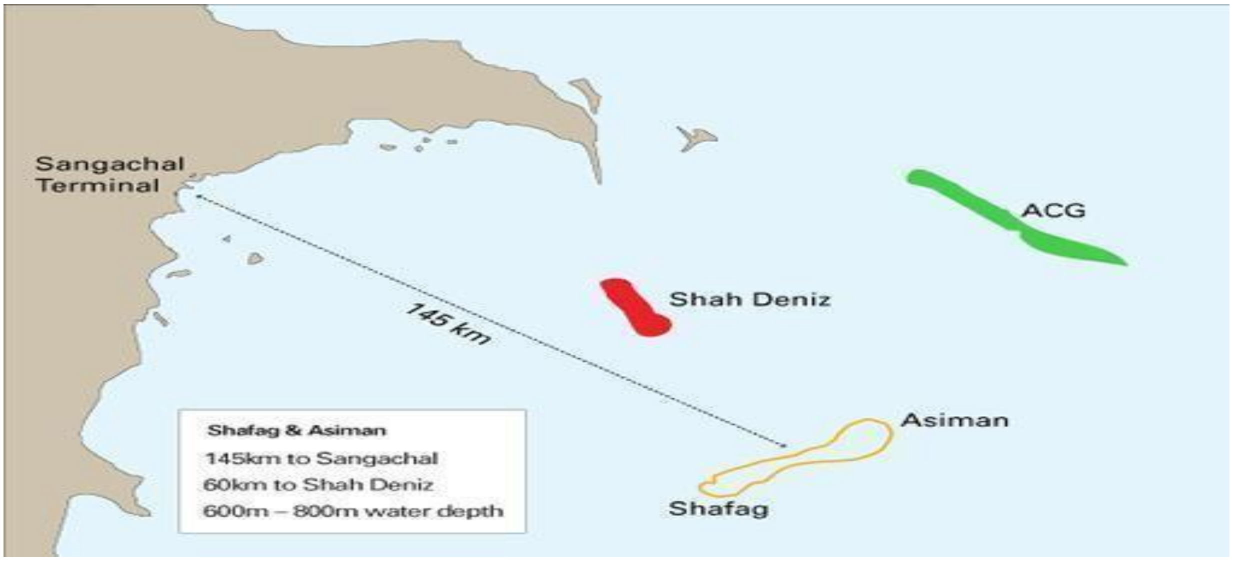



Figure 2.2 Location of ACG and Shafaq Asiman fields in Caspian Sea [21]

That is to say potential offshore geological storage site in ACG field is available for a massive amount of $CO_2$ trapping, which according to BP reservoir modeling team amounts to approximately 75 0000 $m^3$ in volume [21]. Since the transportation of drilling, completion and production generated wastes cost a lot to process and transport back to the onshore, the BP deploys the available CRI (cuttings re-injection) technology to pump all waste down to the subsurface formation for storing.

### 2.1.1 Onshore storage infrastructure and possibilities

Apart from offshore PWI (production water injection) of BP in its offshore installation, it also operates PWI sites in onshore. In 1999, BP geologist team has reviewed several subsurface fields close to Sangachal terminal for injecting waste water generated from oil and gas production from ACG field. 2 fields were chosen which were standing out for their depletion characteristics.

**Lokbatan field**- located 10 km southwest of Baku and 23 km northeast of Sangachal terminal. Lokbatan field under operation of SOCAR (State Oil Company of Azerbaijan Republic) was producing oil starting from 1920. BP has implemented SWI (shallow water injection) in deep reservoirs of this field was still producing oil and it could cause a risk for Azerbaijan to perform PWI into the deep, oil bearing reservoirs without significant amount of research. This field has relatively small capacity compared to Mishovdag field, with around 5 400 000 m³ [22]

**Mishovdag field**- This field is located southwest of Sangachal Terminal and is 242 km large. Mishovdag was producing hydrocarbons since 1956. Due to significant pressure drop in reservoir this field was deploying EOR systems with water for increasing its production. BP reservoir team analyzed the subsurface model of Mishovdag field for flow-back risks and suitability of the field for SWI and DWI (deep water injection) methods. The site was chosen for PWI and supplied with total storage capacity for waste water of 22 000 m³ tanks at water receiving site and additional 2800 m³ at injection site.

These fields have capacity of injecting 4200 m³ of waste liquid daily. Size of Mishovdag field is estimated to be around 12 750 000 m³ [23]


Figure 2.3 Location of Mishovdag and Lokbatan field in relation to Sangachal terminal [21]

## 2.2 Cuttings re-injection technology in ACG

CRI (cuttings re-injection) is a technology which has been deployed by BP in Azerbaijan for waste management purposes (figure 2.4). Without this technology transporting waste back to the surface for further processing would cost millions of euros in a long term, where the operating CRI system costs approximately 20 000 $, including engineering cost, for managing around 1500 barrel per day, depending on ongoing operation type [24]. This price also includes rent costs of equipment and electricity which is being used for operation of this system.

The drilling generated cuttings particles are usually 100-300 in micron size. Pumping these particles down to the wellbore would create artificial pressure increase in the wellbore which could cause formation fracture. When formation fractured, the hydrocarbons or $CO_2$ bearing storages can migrate up to the potable water resources and contaminate this potable water reservoir. That's why the grinding systems are also included in this system, which grind drilled particles for appropriate size for pumping.

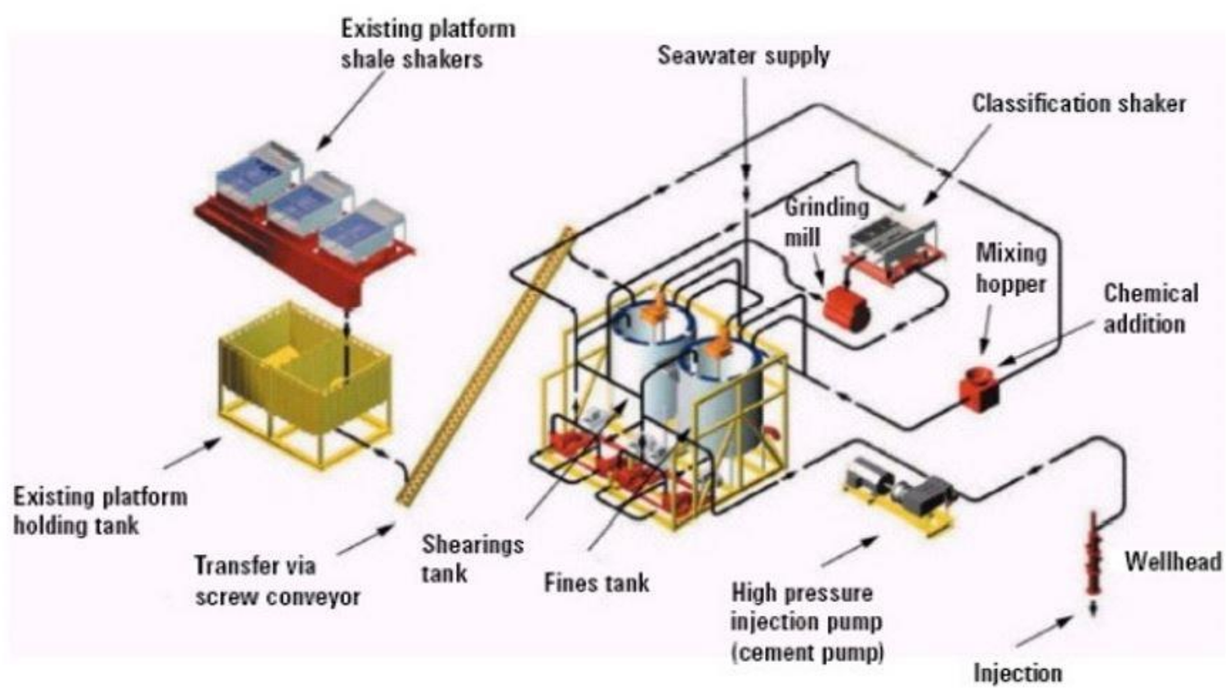



Figure 2.4 Schematic of cuttings re-injection system [25]

All types of wastes are suitable for CRI systems, that's why the waste water from process, waste oil, drilling generated solid particles and so forth. is being grinded and pumped down with this technology. After grinding the cuttings, they are being send to the slurrification unit. Without grinding and slurrification the waste would have pretty high viscosity, which would make it pretty hard for pumping.

Apart from the proper technology the suitable geological storage site also plays vital role in success of this operation, that's why site choice and site evaluation have to be given significant amount of consideration and engineering calculation. In waste management 100% containment is guaranteed, however, the $CO_2$ containment poses some risk because of the extremely low viscosity of liquified $CO_2$, which can lead to severe migration in case of improper trapping where top seal in subsurface site is permeable enough or in a presence of formation fault and fractures.

In ACG field during EOR with $CO_2$ no migration anomalies have ever been recorded. That is to say subsurface formations have no severe faults and anomalies for storage potential

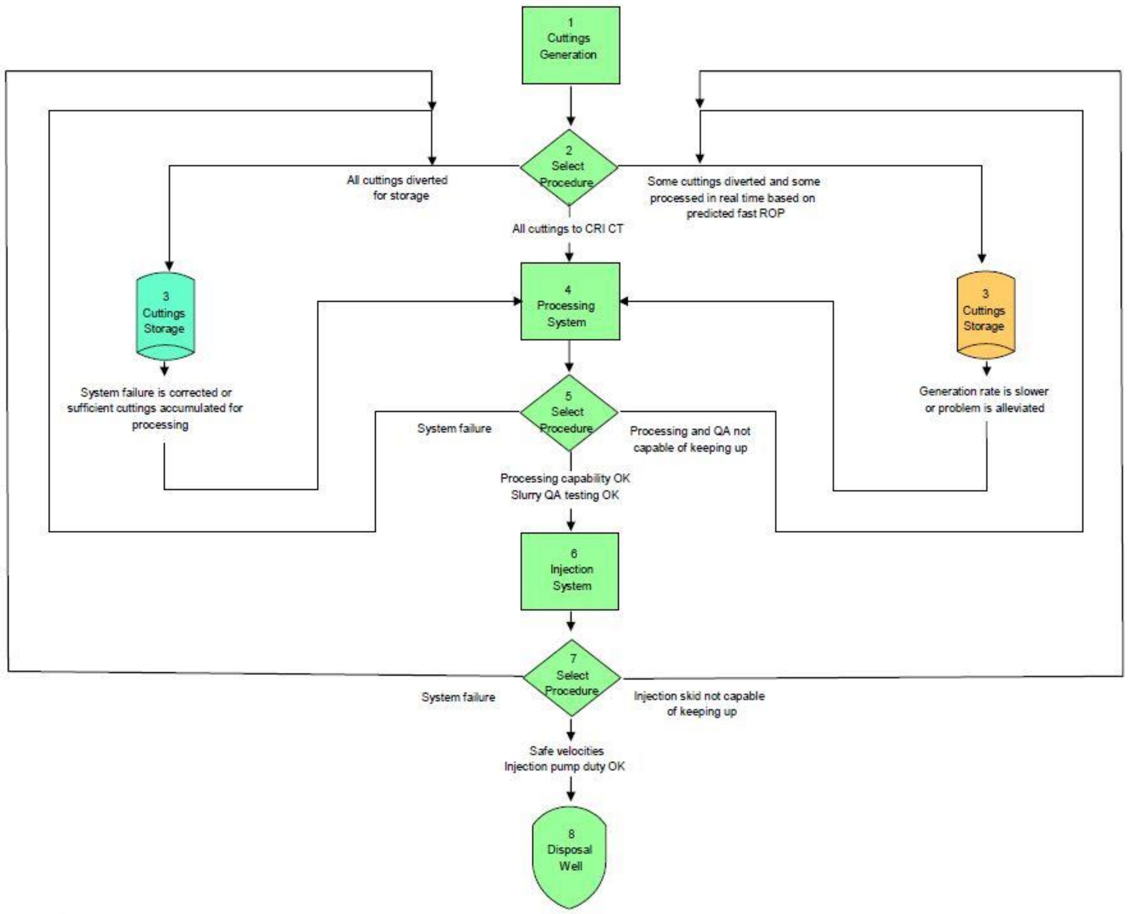
I myself have personally drilled several wells onshore for Methane containment for SOCAR. Even the onshore sites showed fantastic storage potential for natural gas with no leakages at all.

Acceptable waste/fluid type for CRI are those generated by drilling in forms of cuttings, excess drilling and completion fluids. The viscosity of these waste and process fluids are considerable high. That's why recommended pump rate for these types of fluids are 22.25 bbl/min. Liquified $CO_2$ has twice low viscosity compared to these wastes and fluids so pump rate for Liquified $CO_2$ will be 45 bbl/min, which would allow us shorter process time for $CO_2$ disposal.
There are two installed flow paths for CRI on ACG offshore platform:

- Ship to Shore
- Basic Flow Path

**Ship-to-Shore** flow path includes the facility which would process the injecting fluid to the shore for further processing as a waste material.

**Basic-Flow-Path** on the contrary is the technology which is being process and injected in offshore platform without being sent to the onshore.




CRI Process and Injection Systems are able to keep up with rate of cuttings generation and within safe injection parameters

CRI Process or Injection Systems cannot keep up with rate of cuttings generation or stay within safe injection parameters, therefore a percentage of the cuttings are buffered upstream of the process by diversion to the ISO Pumps. Should cuttings generation slow, or a problem be alleviated, cuttings may be introduced to the CRI system from the ISO Pumps while cuttings are being fed by gravity simultaneously.

CRI Process or Injection Systems develop problem, slow small hole drilling provides insufficient cuttings, or the disposal formation must rest to close the fracture, so all of the cuttings are buffered upstream of the process by diversion to the ISO-Pumps.

Figure 2.5 Basic-Flow-Path schematic diagram [24].

## 2.3 Pipeline networks of Azerbaijan

Azerbaijan is quite experienced and famous country with its Pipelines network such as Baku-Tbilisi-Ceyhan, Tanap and Tap and etc.

Significant share in its pipeline network are in subsea pipeline systems which connects all offshore platform with Sangachal oil and gas exporting terminal. Without these Subsea terminals oil and gas transportation would cost Azerbaijan billions of euros.

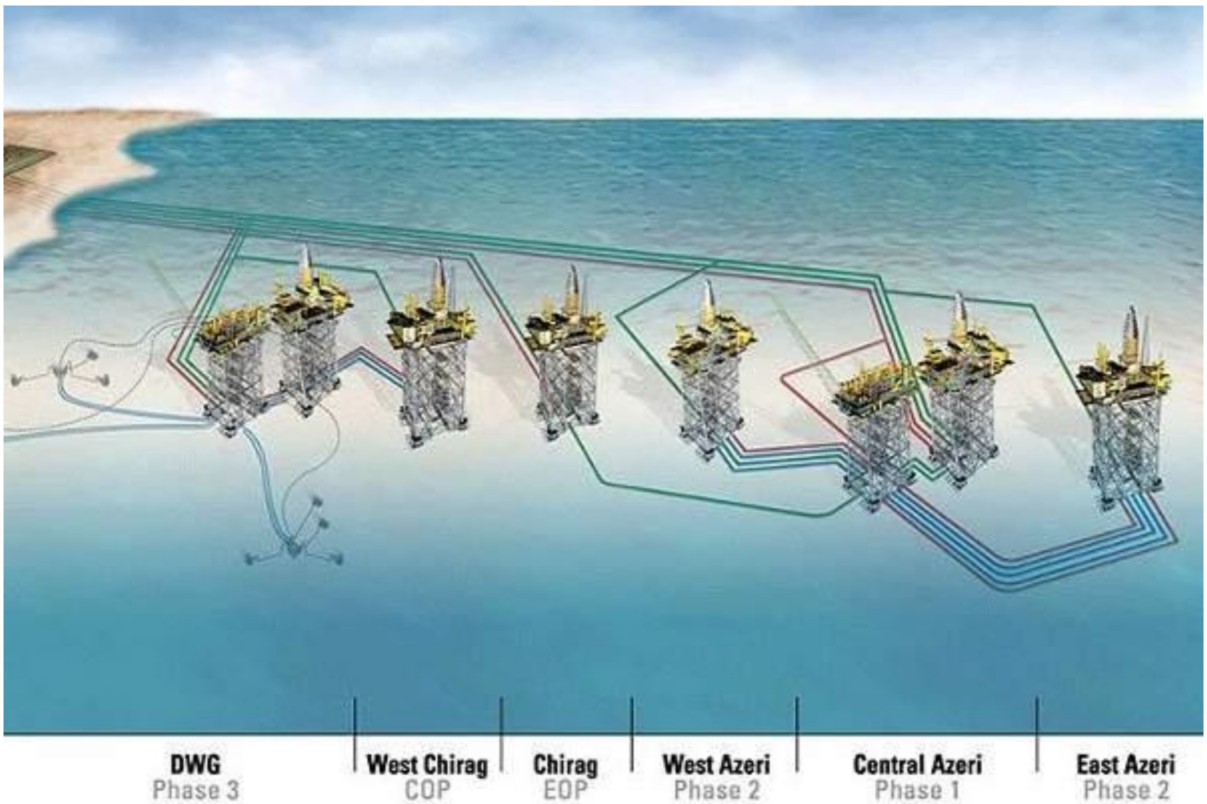



Figure 2.6 Schematics of subsea infrastructure and network [21]

As it's indicated in the figure 2.6 each platform is integrated with the subsea pipeline network which mainly operates for raw material transportation, including acid gases for EOR stage of oil and gas production.

Existing oil and gas projects' subsea pipelines in ACG can be reused for CCS projects in Azerbaijan, without additional cost for new midstream pipeline constructions [20]. Generally, this method is regarded safe for transporting big amount of $CO_2$ for offshore projects. The given amount of $CO_2$ gas has to be compressed in order to reduce the volume of it and for easy transportation. Almost 90% of existing pipelines are compatible for $CO_2$ transportation in terms acidity level and pressure limitation of compressed $CO_2$ [26].

Main power plants in Azerbaijan, such as in Shirvan power plant, (in proximity of Baku) have access to the existing pipelines network, which eliminates the need of commercial $CO_2$ transportation via truck or railway for EOR projects to the both, onshore and offshore oilfields [27]. However, $CO_2$ transportation from other, relatively small power plants will have to conduct transportation vie railway or trucks. Azerbaijan never had $CO_2$ trapping tradition in a commercial scale. Despite the fact that $CO_2$ injection is completely opposite process of natural gas production, they have lots of similarities. Mainly they are reverse operation of each other.

## 2.4 Cost of $CO_2$ transportation

More often than not the investment which is needed for CCS projects also includes the construction cost of pipelines for $CO_2$ transportation. The cost of construction is shown in table 2.1.

Table 2.1 Cost of pipeline construction [28]

| | €/"m | | |
|---|---|---|---|
| inch | Onshore | Offshore | Mountainous terrain |
| 12 | 49 | 74 | 98 |
| 16 | 40 | 60 | 80 |
| 24 | 35 | 52 | 74 |
| 32 | 35 | 52 | 69 |
| 40 | 37 | 56 | 75 |

However, the existing pipelines network in Azerbaijan is an extreme plus for implementation feasibility of commercial CCS projects in Azerbaijan and that's why we will exclude the pipeline construction cost out of CAPEX (Capital Expenditure). For the implementation of CCS in

Azerbaijan the around 80% [29] expenses will be required for the huge amount of $CO_2$ capture OPEX (operation expenditure) process, rather than pipeline construction phase of CCS project.

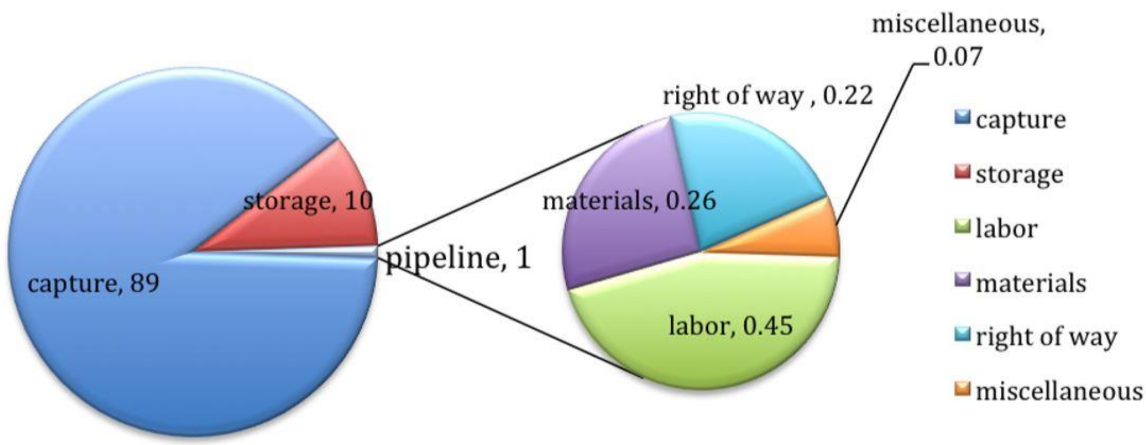



Figure 2.7 Breakdown of CCS project costs and $CO_2$ pipeline cost [26]

As it was mentioned previously the pipeline for PWI purposes of BP from ACG-to-Sangachal terminal and from Sangachal-to-Mishovdag-Lokbatan fields are perfectly suitable for $CO_2$ transportation. This pipelines from Sangachal terminal to ACG offshore is already transporting liquified $CO_2$ for EOR operations. One of the main factor influencing the cost of transportation via pipeline is the distance, in which how far the $CO_2$ is going to be transported [30]. In case of Azerbaijan, BP's expenditure for the unit transportation cost (€/ton) of $CO_2$ for EOR operations from Sangachal-Mishovdag, Sangachal-Lokbatan and Sangachal-ACG field is shown in table 2.2:

Table 2.2 Average low-end and high-end unit transportation cost of $CO_2$ from Sangachal-Mishovdag/Lokbatan and Sangachal-ACG in €/t$CO_2$:

| Distance km | 50 | 180 | 260 |
|---|---|---|---|
| Onshore | 0.4 -05 €/t$CO_2$ | 1.44 -1.67 €/t$CO_2$ | 2.08 -2.44 €/t$CO_2$ |
| Offshore | 0.72 -0.88 €/t$CO_2$ | 2.59 -2.97 €/t$CO_2$ | 3.74 -4.08 €/t$CO_2$ |

This price also includes the feeders and compressors operations and electricity costs which is required for feeding the pipeline with liquefied and gaseous $CO_2$ and compressing for its easier move in network. [31]

## 2.5 Injection and storage expenses

The preferable subsurface storage site for CCS projects are the ones which are located in proximity of $CO_2$ source (e.g from power plants), because in this case there will be no need for transportation expenses. For example: CNPC (China National Oil Corporation) Jilin oilfield CCS projects are among the most economically proven systems due to distance between storage site and $CO_2$ source.

The major cost element in subsurface storage operations is drilling the wells. CRI technology in ACG and depleted and abandoned wells in Mishovdag/Lokbatan fields combined with in-field pipeline feeders make the deployment of CCS systems in Azerbaijan attractive.

Geological $CO_2$ injection in ACG using CRI technology cost into depleted formation 1.2-1.4 €/t$CO_2$ (this price includes pre-injection, injection and post-injection monitoring and verification) for EOR operation [32]. CRI injection process is shown in appendix 1. $CO_2$ transportation to the offshore ACG platforms is not included in this price. The driving cost factors for injecting is the reservoir characteristics such as permeability and thickness of potential storage which would influence on the injection rate.

Worldwide $CO_2$ storage takes place in several types of reservoirs and storage cost differs from formation type. In Azerbaijan the main used types of reservoir are as follows [33]:

- Depleted and abandoned gas fields.
- Depleted and abandoned oil fields.
- Enhanced oil recovery fields.
- Enhanced gas recovery fields.
- Saline reservoirs.

In Lokbatan-Mishovdag fields most of the reservoir are depleted gas and oil fields, where in ACG, both depleted oil and gas, and EOR systems are suitable to be applied. These storage costs are considered for the depth of 1000-3000 m.

Table 2.3 Average injection price into various fields

| Formation type | Field | On or offshore | €/t$CO_2$ |
|---|---|---|---|
| Depleted Oil and Gas | Lokbatan | Onshore | 1.2€-1.3€ |
| Depleted Oil and Gas | Mishovdag | Onshore | 1.1€-1.2€ |
| Saline formation | ACG | Offshore | 4.50€-4.7€ |
| Depleted Oil and Gas | ACG | Offshore | 3.55€-3.75€ |
| EOR systems | ACG | Offshore | 2.2€-2.4€ |

The EOR systems are commercial solutions which are used for recovering oil. Different chemicals products can be used during EOR application for recovering oil. However, besides costly chemical compounds for recovering oil in EOR, $CO_2$ is also an alternative product. The product which is being produced during $CO_2$-EOR process is hydrocarbons which has commercial value in the market. Increase in oil production revenue related to $CO_2$-EOR will compensate the price of CCS injection cost. That's why the price of $CO_2$ injection to depleted reservoirs is going to be considerable cheaper in EOR CCS projects. Still, the transportation length to ACG field, which is around 120 km from Sangachal terminal and additional 60 km from $CO_2$ transportation Sangachal terminal, makes the price for ACG injection into the depleted reservoirs still more expensive compared to Lokbatan-Mishovdag fields [34].

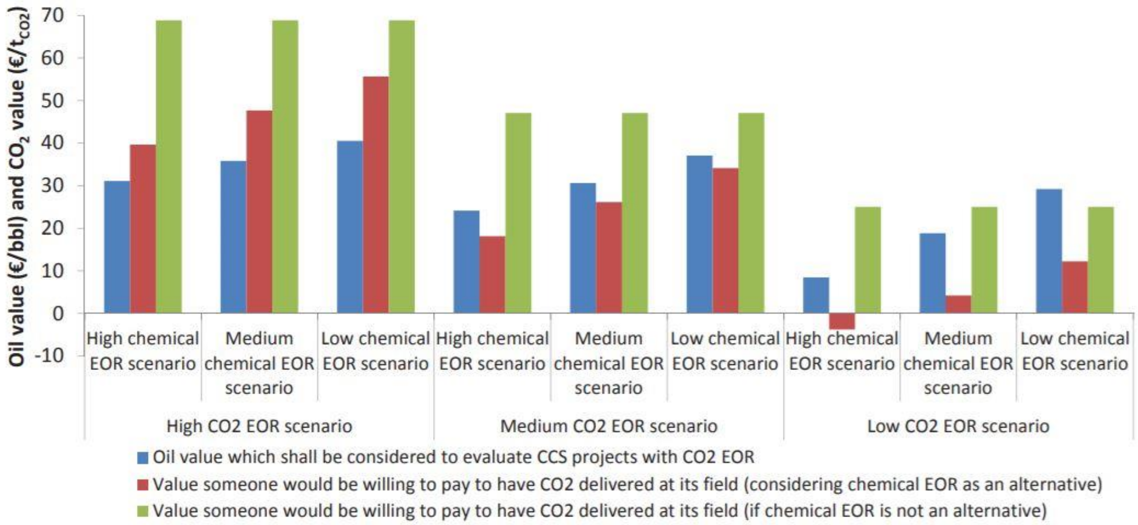



Figure 2.7 Oil value which will be considered in CCS project associated with $CO_2$-EOR (€/bbl) and values one would be willing to pay to have $CO_2$ to be delivered at its field (€/t$CO_2$) [35]

Saline formation, in comparison with depleted formation, has lower flow rate for injection due to lower permeability and reservoir resistivity. That's why it will consume more OPEX due to the higher energy consumption and more operating time which will lead to automatic increase in injection price. Mishovdag and Lokbatans fields on the other hand located in the proximity of Sangachal terminal, from where the compressor and high-pressure pumps will pump $CO_2$ and that's why the price of injection and operation will cost the least in these fields. Monitoring cost are also included into this price.

## 2.6 Capture cost of $CO_2$ in Azerbaijan

$CO_2$ capture process cost depends on the many factors, such as plant type, fuel type used, size of the plant and efficiency of the plant. The type of CCS systems also is a main determinant of the price for the $CO_2$ capture. $CO_2$ capture cost is determined by 4 main measures:

- Capital cost.
- Incremental product cost.
- $CO_2$ avoided cost.
- $CO_2$ captured cost.

All of them shows the added cost into the electricity cost of the particular CCS system.

**Capital cost** is used in order to describe the whole price of the system which is going to be applied and usually reported in €/kW. In other word the price difference between plant with CCS system and plant without it can be described as a capital cost.

**Incremental product** cost describes the impact of $CO_2$ capture process on the price of electricity which is being generated in power plant. The cost of electricity can be described using this formula:

$$COE = \frac{[(TCR)(FCF) + (FOM)]}{[(CF)(8760)(KW)]} + VOM + (HR)(FC) \quad (2.1)$$

Where

$COE$ - Cost of Levelized Electricity (€/kWh$^{-1}$)

$TCR$ –Total Capital Requirement (euro)

$FCF$–Fixed Charge Factor (fraction yr$^{-1}$)

$FOM$–Fixed Operating Cost (euro yr$^{-1}$)

$VOM$–Variable Operating Cost (euro kWh$^{-1}$)

$CF$–Net Plant Heat Rate (kJ kWh$^{-1}$)

$FC$–Unit Fuel Cost (euro kJ$^{-1}$)

$CF$–Capacity Factor (fraction)

$8760$–Total hours in typical year

$kW$– Net Plant Power

These parameters might change during the life of the operation that's why this price is approximate calculation.

**Cost of $CO_2$ avoided** can be defined as cost of prevention of releasing potential $CO_2$ to the atmosphere and can be calculated according to the formula:

$$Cost\ of\ CO_2 avoided = \frac{\left[(COE)_{captured} - (COE)_{ref}\right]}{\left[(CO_2 kWh^{-1})_{ref} - (CO_2\ kWh^{-1})_{cap}\right]} \quad (2.2)$$

Where $(COE)_{captured}$ –Cost of levelized electricity (€/kWh$^{-1}$)

$CO_2kWh^{-1}$-Mass emission degree (in tons) per kWh produced.

The cost of $CO_2$ avoided takes into consideration the transportation and injection avoidance as well, that's why the cost of $CO_2$ avoided is applied to whole system of CCS, including transportation and storage.

Another measure for calculating the cost of $CO_2$ capture is **mass of $CO_2$ captured** and it can be calculated according to the formula:

$$Cost\ of\ CO_2\ captured\ (\text{€/kg}) = \frac{\left[(COE)_{capture} - (COE)_{ref}\right]}{CO_2captured\ kWh^{-1}} \tag{2.3}$$

Where $CO_2captured\ kWh^{-1}$ –Total mass of captured $CO_2$/kWh [36].

There are lots of other factors which affect the price of carbon dioxide capture, mainly called fuel type, capture rate, power plant size and etc. The captured $CO_2$ have different price for each power plant because of the transportation distance and design of the plant. Sumgayit combined cycle power plant is a new power plant, which is located close to Baku. This plant has 3 electricity production units with overall 520 MW capacity. Unit#2 is integrated with CCS system for EOR application and has $COE_{captured}$ price around 0.064 €/kWh [37]. $COE_{ref}$ in Azerbaijan is around 0.037 €/kWh [38]. Using Sumgayit combined cycle power plant as reference plant, we can calculate the cost of $CO_2$ capture according to formula 2.3.

$$\frac{[0.064 - 0.037]}{0.9} = 0.03\ \text{€/kg}$$

Due to the relatively old design and lower total mass capture factor of other plants, the average cost of $CO_2$ capture in these plants is going to be relatively higher compared to new Sumgayit plant.

The essential fuel type which is being utilized in thermal power plants in Azerbaijan is natural gas. Due to abundancy of this resource in this country and lack of coal mines the thermal plants use only natural gas for their process. Natural gas releases almost twice less $CO_2$ emission to the atmosphere compared to coal.

Table 2.4 $CO_2$ emission according to fuel type [39]

| Fuel Type | $CO_2$, kg |
|---|---|
| Coal (anthracite) | 99 |
| Coal (bituminous) | 89 |
| Coal (lignite) | 93 |
| Coal (subbituminous) | 93 |
| Diesel fuel and heating oil | 70 |
| Gasoline | 68 |
| Propane | 60 |
| Natural gas | 51 |

The carbon content of fuel is responsible for emitted $CO_2$ concentration and amount of energy production. Coal has noncombustible elements such as sulfur and water within its content and thus making it relatively low energy content fuel compared with natural gas [39].

88% of electricity demand of Azerbaijan is mainly met by the thermal power plants which are spread all over the country [40]. The $CO_2$ removing process is achieved with ammonia membranes. Using these membranes 55-90% of $CO_2$ can be removed. The average COE price for natural gas fired power plants amounts to 64-85 €/$MWh^{-1}$ for EOR applications [37]. The cost for $CO_2$ captured is around 30-55 €/$tCO_2$. The figures are not absolute and can vary type, design and size of power plants. Remediation cost is not included in capture neither in transportation cost and regarded as a spontaneous cost.

# 3. CALCULATION RESULTS

The goal of this thesis is to analyze the cost needed for deployment CCS systems in commercial extend throughout Azerbaijan. Three main components of CCS: $CO_2$ capture, storage and transportation cost were analyzed for Azerbaijan’s scenario. In case of implemented the project will be 0.22 MTpa (million ton per annum) scale on first stages. Even if not implemented this thesis is going to serve as a good benchmark for possible deployment of CCS projects in Azerbaijan’s energy infrastructure.

## 3.1 Environmental impact

Azerbaijan produced 25 TWh of electricity mainly from natural gas (80%). According to World Bank data Azerbaijan has emitted 34 MT $CO_2$ in 2018 [22]. $CO_2$ emission per capita amounted 3.4 ton per person. Natural gas consumption as a fuel source in thermal power plants emitted 11300 kt of $CO_2$ [41].

According to Azerbaijan’s INDC (intended nationally determined contribution) Azerbaijan pledged to reduce its GHG emission by 35% till 2030 in comparison with 1990, despite the fact that Azerbaijan’s economy is predicted to grow 8% annually till 2025 [42]. In case of applied CCS systems will be able to contribute to Azerbaijan’s commitment for fulfilling its commitment of reducing GHG. That is to say approximately 25% of $CO_2$ emission of Azerbaijan can be reduced by using CCS systems in its heat power plants and extended EOR application in ACG field.

The only environmental risk which is related to CCS is the gradual or catastrophic leakage from storage site, which can severely damage the environment and initial purpose of CCS systems and even harm health of employees who will monitor and operate system.

## 3.2 Required investment

The deployment cost of CCS systems in Azerbaijan is mainly dominated by the cost of capture process, which would add 0.9-1.7 €/kWh$^{-1}$ to the process cost for natural gas power plants. That is to say carbon capture costs around 39-48 €/t$CO_2$ depending on the power plant size according to the paper of Azerbaijan Ministry of Ecology and Natural Resources and BP. [43] For existing natural gas power plants, $CO_2$ capture can be achieved by integrating an amine scrubber to the system. The ammine scrubbing process is shown in appendice 2.

The cost of CCS systems for Mishovdag and Lokbatan field is calculated within transportation distance of 50 km, as they are located close to Sangachal terminal, from where $CO_2$ will be compressed and pumped. When it comes to ACG field transportation cost has been calculated within 180 km distance as the distance between Sangachal terminal and ACG offshore installation is far out compared to Mishovdag and Lokbatan field.

Table 3.1 Cost summary for CCS application in Azerbaijan

| Performance and average cost measures` | Natural gas power plant | | | Cost of transportation, capture and injection combined |
|---|---|---|---|---|
| | Range | | Rep value | |
| | Low end | High end | | |
| Transportation (€/t$CO_2$) within 180km range offshore | 1.44€ | 1.67€ | 1.56€ | n/a |
| Transportation (€/t$CO_2$) within 50km range onshore | 0.4€ | 0.5€ | 0.45€ | n/a |
| Cost of $CO_2$ captured (€/t$CO_2$) | 30€ | 55€ | 42.5€ | n/a |
| Cost of CCS in Mishovdag (€/t$CO_2$) | 1.1€ | 1.2€ | 1.15€ | 44.1€ |
| Cost of CCS in Lokbatan (€/t$CO_2$) | 1.2€ | 1.3€ | 1.25€ | 44.2€ |
| Cost of CCS in ACG field (€/t$CO_2$) | 4.025€ | 4.5€ | 4.25€ | 47.2€ |

Range and representative data based on the table 2.2 and 2.3. Rep Value shows the closest to the real value of the said measurement. Whereas, low-end and high-end values show the minimum and maximum price estimation. Power plant sizes for this calculation is around 520-850 MW, where capacity factor of this power plants is around 55%-90% [44]. All costs include energy cost which is going to be used for operation and compression expenses, but not spontaneous remediation cost which might occur.

Initially, project will start as a demonstration project and will receive investment/grants/allocation step by step. In the beginning 20% $CO_2$ capture of total electricity generated emission in Azerbaijan will be targeted. If successful, capacity of project can be expanded by the further investment targeting 70% $CO_2$ capture from electricity generation. As it was already mentioned, Azerbaijan's $CO_2$ emission from electricity production amounts to approximately 11300 kt annually. In order to fulfill the 20% emission reduction within 2020-2024 using CCS technology in power plants, required initial investment will be approximately 105 000 000 €. The project is going to be a joint venture between BP, SOCAR and Azerbaijan Ministry of Ecology and Natural Resources.

# 4. CONCLUSION

According to the calculations the most expensive CCS systems are going to be in ACG field with 47.2 €/t$CO_2$ which is still 7.8 € cheaper compared to the CCS price in Boundary Dam coal fired plant in Canada (around 55 €/t$CO_2$) [45]. In case of approval of this project by 2022 it would be possible to initiate CCS demonstrative project as a start-up in 2024. In general, the project is technically feasible but is not promising in terms of return profit. Even in case of not implemented, this thesis research could be used as a good benchmark for future of CCS technology in Azerbaijan.

Technical feasibility and cost of the project is highly dependent on site-specific circumstances, including the size and type of plant, and the availability of space for accommodating a $CO_2$ capture system. The only disadvantage of power plants of Azerbaijan is their age. That is another factor which makes average carbon capture price in these power plants around 40-44 €/t$CO_2$, which is expensive compared to the power plant with new technology (such as in Sumgayit power plant), which doesn't require retrofitting new technology compatible with CCS systems.

Cost of CCS application is even cheaper in Mishovdag and Lokbatan field compared to ACG field because of the less transportation distance, which amounted to approximately 44-45 €/t$CO_2$. First stage/demonstration stage of the project will be implemented in these fields and later expanded to ACG field. As a result of 20% $CO_2$ emission reduction from electricity production, 2.26 MTpa (million ton per annum) reduction in GHG will be achieved. Azerbaijan pledged to reduce its GHG emission by 35% till 2030, which is reduction of 11.9 MTpa in $CO_2$ amount [42]. In case of fulfilled CCS systems will play a significant role in Azerbaijan's commitment to international environmental agreements.

# SUMMARY

In this research of mine I have aimed to shed the light on the gaps of information and possibility for Azerbaijan in $CO_2$ reduction technologies. This thesis claims that reduction of $CO_2$ with CCS systems, initially by 20%, compared with conventional power plants without CCS systems, will yield benefits for environment and climate related damage to human health. The deployment of CCS systems in Azerbaijan is technically feasible, even though economic sides of this technology is being questioned. This technology gives Azerbaijan a very good chance for combating GHG problems for cleaner environment with pretty good success chances, and relatively cheaper CCS system compared to systems in USA and in Canada. BP-Azerbaijan has already set a team of environmental engineers for $CO_2$ capture in its facilities for EOR and CCS applications, as they do have quite good knowledge of clean development mechanism and available infrastructure.

CCS project also should be supported from government side for development of cleaner environment for the generations to come. Tax credits and public subsidies from government could possible pave the way for broader deployment of CCS system throughout Azerbaijan. Credits will reduce operation and deployment expenses of CCS projects. With 0% tax incentives for CCS components and systems 10-18 €/t$CO_2$ price reduction can be achieved. For example, in USA tax incentives in 2011 has enabled CCS technology deployment in large scale coal fired power plants such as in Petro Nova [46]

Using carbon trading policy 105 000 000 € initial investment can be further reduced in future. In other word Azerbaijan's government/BP or another private investor will have the right to sell their carbon emission quote to the country with more $CO_2$ pollution, according to the clean mechanism development agreement under Kyoto protocol.

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# APPENDICES

**Appendice 1**

CRI step by step- includes grinding mill for bigger size of wastes, slurry tank, centrifugal pump and injection pump

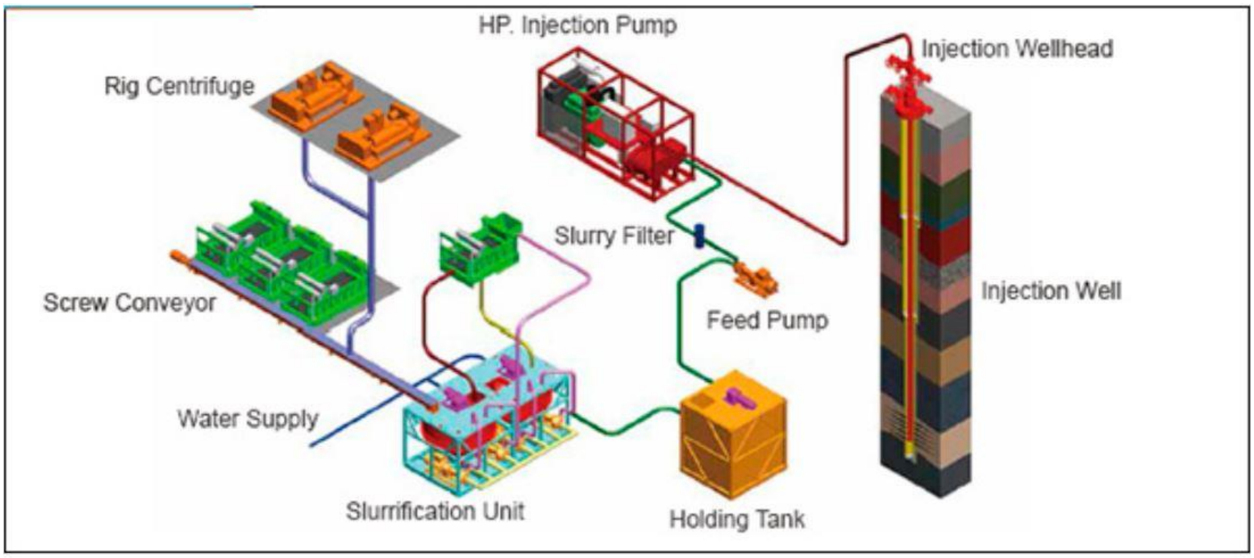


Figure A 1.1 CRI operation sequence and components. Source: http://go.jereh.com/Product/CRI-16S-Waste-Injection-Technology-And-Package-Unit-339.html

**Apendice 2**

Mono ethanolomine scrubbing process. $CO_2$ reacts with monoethanolomine to form water compound and then seperated by cooling

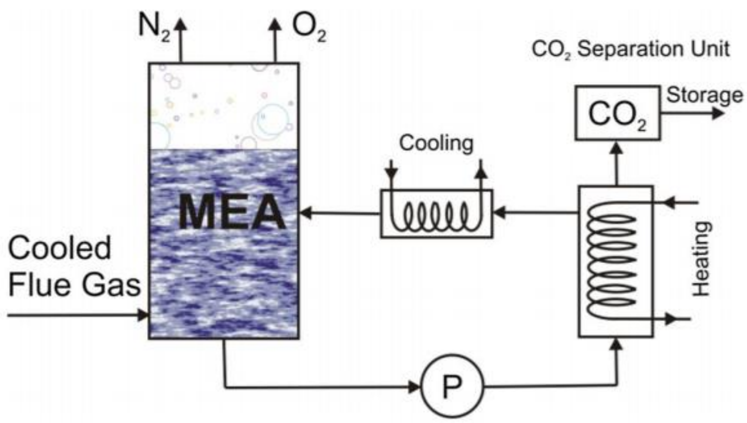


Figure A 2.1 Mono ethanolomine scrubbing process. Source: Advanced $CO_2$ Capture Process Using MEA Scrubbing: Configuration of a Split Flow and Phase Separation Heat Exchanger