Mestrado Integrado em Engenharia Química

Preliminary Economic Analysis of Carbon Dioxide Transportation for Microalgae Production

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Abstract

Increasing emissions of greenhouse gases, particularly anthropogenic carbon dioxide, CO_2, arising mainly from fossil fuel combustion, are thought to be contributing to global warming. In order to avoid severe consequences to mankind, immediate action has to take place in developing new technologies and solutions.

Carbon Capture and Storage, CCS, has emerged as a suitable method in preventing CO_2 emissions to reach the atmosphere, essentially by capturing it from large sources and storing it. Options for long-term isolation of CO_2 include ocean storage, which may encompass adversities such as water acidification, or geological storage.

Biological fixation of CO_2 can be seen as a different approach to CCS, in which instead of storing the previously captured CO_2, it would be used as a reactant in the photosynthetic process, much as in the case of a natural sink. Since microalgae have extraordinary properties, such as high proliferation rates, tolerance to extreme environments, among others, they are preferred as the biological fixation medium.

Carbon dioxide emissions derived from large stationary sources, such as power stations, cement production and refineries, require large areas for the implementation of reactors. Such areas may not be available in the immediacy of the industrial complex and therefore require the transportation of the gas until its biofixation location.

Three distinct scenarios for CO_2 transportation in the specific case of microalgae production were proposed.

Case A, supposes the transportation of a highly concentrated stream of CO_2, whereas in **Case B** the gas transported is the one directly collected from flue gas stacks. The separation process inherent to Case A for the treatment of the flue gas involves higher energy consumption and also higher costs, when compared to Case B, in which the gas is simply fed to the reactors without the separation. Despite that fact and since Case B involves a stream of around 12% of CO_2, a larger volume of gas has to be transported, and so, costs are increased for the same quantity of CO_2. **Case C** assumes the transportation of CO_2 dissolved in water, which would work as a part of the culture medium and therefore would not require the transportation of an extra stream of water. Therefore, an analysis is necessary for comparing the costs of transportation of these three scenarios, so as to decide which would represent the best option.

For the cases present previously a general optimization of design parameters was performed and a preliminary economic evaluation of the three different scenarios for the transportation of CO_2 from critical emission sources until the reactor's location was prepared.

The results of the evaluation show that the lowest cost transportation is attained by the transmission of a relatively pure stream of CO_2.

Key words: CO_2, pipeline, microalgae, economic analysis

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Notation and Glossary

Symbol	Description	Units
C	pipe material cost	€/ton
C (eq.8)	overall design coefficient, minimum 1.25 for PE	
Cost	compression costs	€/year
D	inside diameter	m
$D_{i,opt}$	optimum diameter	m
Energy price	energy price (0,0903)	€/kw.h
f	friction factor	dimensionless
G	mass flux	$kg.m^{-2}.s^{-1}$
Hours	working hours per year	h/y
L	length of the pipe	m
L (eq.3)	length	km
M	molecular weight	$kg.mol^{-1}$
m_{CO2}	mass flow rate of CO_2	kg/s
p_1	upstream pressure of gas	Pa
p_2	downstream pressure of gas	Pa
P_d	discharge pressure	atm
Power	compressor power	watt
Power (eq. 6)	compressor power	kw
P_s	suction pressure	atm
Q	volume flow rate of the gas	m^3/s
Q (eq. 9)	volumetric flow	m^3/s
Q_{H2O}	volume flow rate of water	m^3_{H2O}/s
R	universal gas constant (8,314)	$Pa.m^3.mol^{-1}.K^{-1}$
r	compression ratio	dimensionless
Re	Reynolds number	dimensionless
s	CO_2 solubility in water at PTN	
T	gas flowing temperature	K
T (eq.3)	pipe wall thickness	mm
ΔP_f	pressure drop due to friction	Pa
ε/D	relative roughness	

Greek Letters

η	compressor performance	
ρ	fluid density	kg/m^3

Chemical structure

$CaCO_3$	calcium carbonate
CaO	calcium oxide
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
H_2CO_3	carbonic acid
$MgCO_3$	magnesium carbonate
MgO	magnesium oxide
NO_x	nitrogen oxides
SO2	sulphur oxide

List of Abbreviations

GHG	Greenhouse gas	
CCS	Carbon Capture and Storage	
EOR	Enhance Oil Recovery	
ECBM	Enhance Coal Bed Methane	
MOP	Maximum Operating Pressure	
DN	Diameter Nominal	
NPS	Nominal Pipe Size	
SCH	Schedule	
MOP	maximum operating pressure	bar
MRS	minimum required strength	MPa
OD	pipe outside diameter	mm
PMC	pipe material cost	€
SDR	standard dimension ratio	
PE	Polyethylene	

1 Introduction

1.1 The Challenges of Carbon Dioxide

Carbon dioxide, CO_2, is a colourless and odourless gas present in the atmosphere at low concentration values. Volcanic eruptions, respiration performed by animals and plants as well as the decay of organic materials are examples of natural sources releasing CO_2 to the atmosphere. This is counterbalanced to a certain extent by physical and biological processes, called natural sinks. Photosynthesis and dissolution in sea water are examples of such natural sinks.

Only slight changes in atmospheric CO_2 values would have been observed if this natural balance was to carry on. However, the industrial revolution led to the escalating of anthropogenic CO_2 emissions, mainly from the burning of fossil fuels (for power generation, industry, transportation and residential purposes) but also from other activities such as deforestation. In fact, measurements show that since 1750 there has been an increase in the amount of CO_2 present in the atmosphere, from around 280 ppm (parts per million) to 382 ppm.[1,2]

Carbon dioxide plays an important role in the greenhouse effect, warming the Earth's surface and lower atmosphere. The increasing concentration of anthropogenic CO_2, as well as other greenhouse gases (GHGs), intensifies the greenhouse effect and is believed to be the fundamental feature causing global warming.

The impact of global warming is still not entirely understood, but it is predicted to lead to increasing threats to human life. In order to avoid consequences of climate change, it is essential to stabilise the concentration of GHGs to safe values as soon as possible, i.e. the rate of addition of these gases to the atmosphere must equal the rate at which they are removed by natural systems. [3]

Several mitigation options may include improvements in energy efficiency, which consequently reduces fossil fuel consumption, the switch to less carbon-intensive fuels, the use of renewable energy sources, like wind, solar, biomass, hydro, geothermal and tidal power. The enhancement of natural sinks would also play an important role in reducing GHGs emissions, but may be limited by land use practice.

It has been predicted that between 2004 and 2030 the demand of electricity will increase approximately 50 % and for that reason reducing CO_2 emissions in the energy sector has become a major priority. Carbon dioxide Capture and Storage (CCS) appears in this context as one promising technology with the capacity to reduce CO_2 emissions in a short timescale. [4]

1.2 Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage, aims to capture CO_2 from large stationary sources, such as fossil fuel power plants or large industrial processes, and store it underground or below sea floor, where it would be trapped indefinitely. CCS involves three main components: capture, transport and storage, as illustrated by figure 1.

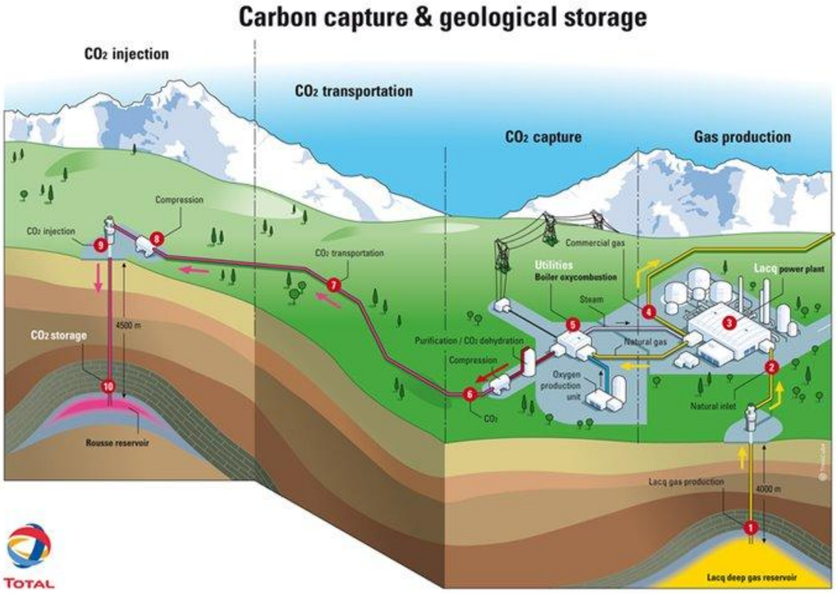


Figure 1. Carbon capture and geological storage. [11]

1.2.1 Carbon Dioxide Capture Systems

The capture step involves the separation of CO_2 from other gaseous products in order to produce a concentrated stream of CO_2 that can be compressed and transported to the storage site. Roughly, three different approaches for capturing CO_2 from the combustion of fossil fuels exist: pre-combustion, post-combustion and oxyfuel combustion (fig. 2).

Pre-combustion capture systems involve removing the CO_2 stream prior to combustion. *Steam reforming* or *partial oxidation* (also called *gasification)* are two processes by which a mixture of carbon monoxide, CO, and hydrogen, H_2, (the syngas) can be produced. This is followed by a *shift reaction* in which the addition of steam converts CO into CO_2.[3]

Post-combustion capture systems separate CO_2 from the flue gases produced by combustion of the fossil fuels in air. Flue gases resulting from combustion of fossil fuels typically contain between 3 to 15% of CO_2, which must be separated through absorption, cryogenics or membrane technologies.[3]

Oxyfuel combustion systems use a stream of oxygen, with a purity of 95-99%, instead of air for the combustion of the fuel. This produces a flue gas with high CO_2 concentrations, greater than 80%.[3] The water vapour can then be removed by cooling and the CO_2 stream can be compressed and transported. Up to now, this capture system exists only on pilot scale. [5]

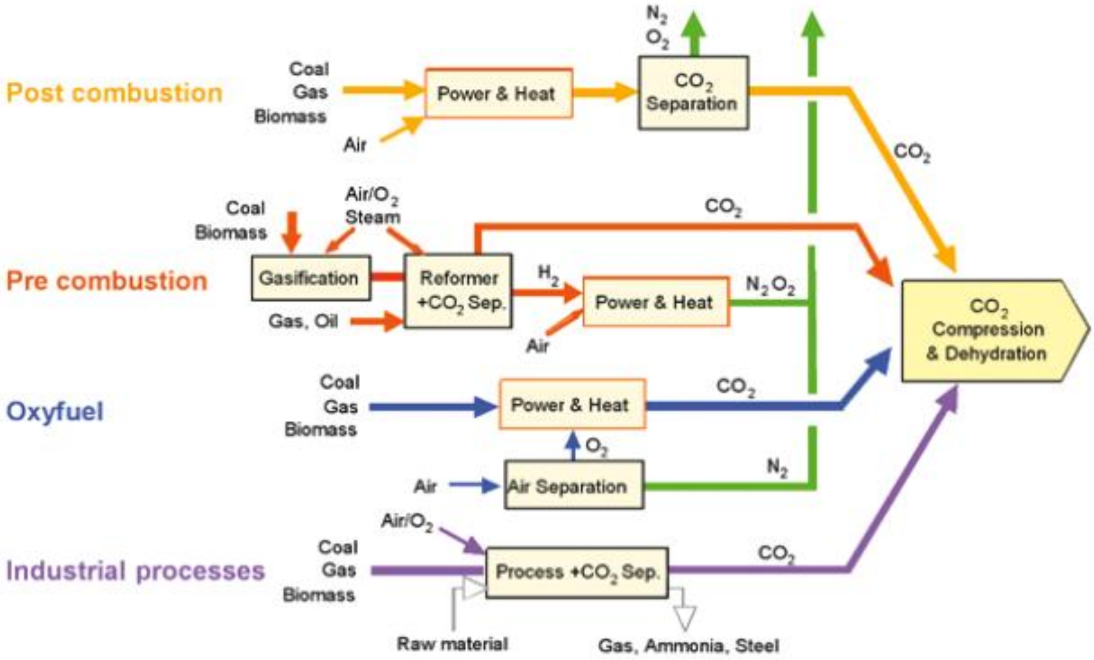


Figure 2. Carbon dioxide capture systems. [3]

1.2.2 Carbon Dioxide Transportation Systems

The CO_2 previously captured has to be transported from its capture site until an appropriate storage location. This transportation can be either made by ships, road and rail tankers in the liquid phase, or by pipeline in the gas or liquid phase.

Studies report that transportation of CO_2 by ships becomes cost-competitive with pipelines only in the case of large distances or overseas.[3] For CCS applications a large network of transportation from numerous anthropogenic sources to limited storage locations is predicted, so as a result pipeline systems are presented as the most feasible solution.

Transportation of CO_2 by means of pipeline usually involves a dry and pure stream of CO_2, to reduce the risk of pipeline corrosion. The high compression of the gas encompasses some risks, especially when its route goes through populated areas, requiring an over-pressure protection, leak detection and other design factors. Even though CO_2 is considered relatively harmless, as it is neither flammable nor explosive, in case of leakage it presents threat to human health if it reaches concentration levels greater than 3 % by volume.

CO_2 is injected into mature oil fields to enhance oil production, the so called Enhance Oil Recovery (EOR). Currently, over 2500 km of CO_2 pipelines are used in the United States for EOR purposes. [3]

1.2.3 Carbon Dioxide Storage

Options for long-term isolation of CO_2 from the atmosphere are still under research and development for insuring the integrity of storage sites. Below is presented an explanation on ocean and geological storage.

Ocean storage consists in the injection of CO_2 into the water column of the ocean or at the sea floor. Several obstacles including the direct adverse impacts, such as acidification of the water, makes this approach somewhat discredited.

Another option is the **geological storage**, which involves the injection of CO_2 into a rock formation bellow the Earth's surface. Deep saline aquifers, depleted oil and gas reservoirs, and unminable coal beds are some of the most important types of geological sinks. The biggest concern of geological storage is the ability of the structures to retain or not the CO_2 without leaking.

EOR or coal beds associated with enhance methane production (ECBM) have the potential to offset the costs of CCS.

Geological storage is already taking place on industrial-scale in the North Sea (Sleipner project), in Canada (Weyburn project) and in Algeria (In Salah project). Also numerous projects of EOR exists for several years, particularly in Texas, USA. [8]

1.3 Carbon Dioxide Reuse

Carbon Dioxide can be used in the natural process of mineral carbonation. In this process CO_2 reacts with oxides, such as magnesium oxide (MgO) and calcium oxide (CaO), to produce carbonate compounds, such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$). The stability of these components over large periods of time makes them suitable for disposal or re-use in construction, although this last one in a smaller scale. A drawback of mineral carbonation is that reaction occurs slowly, making it impracticable for large scale carbon capture applications.

Several industries use CO_2, either as a reactant, as in the methanol and urea production, or applied directly, such as in beverages, fire extinguishers or food packaging. A disadvantage of these processes is that the CO_2 is kept from the atmosphere only in a short time scale creating a small contribution to the net reduction of atmospheric CO_2.

Box 1. Storage approaches

- **Ocean Storage** – encompasses a high risk of water acidification and impact on the ecosystems.

- **Geological Storage** – main concern is the ability to retain the CO_2 without leakage.

- **Mineral Carbonation** – some development is still required for attainment of a technology which has the ability efficiently work on a scale large enough to impact global warming.

1.4 Biological Fixation of Carbon Dioxide using Microalgae

Photosynthesis is a natural process of CO_2 fixation by capturing and converting it into carbohydrates and oxygen, which makes it a potential solution for reducing atmospheric carbon emission. However, the use of terrestrial plants for capturing CO_2 directly from flue gas is not an economically feasible option.

Microalgae have been identified as fast growing species and whose carbon fixation rates are higher than terrestrial plants, granting them high potential in large scale carbon capture applications. Other advantages of microalgae include its wide tolerance for extreme environments which allows them to proliferate even in the presence of many of the components which make up flue gases, such as nitrogen oxides (NO_x) and sulphur dioxide (SO_2), as well as in a broad range of temperatures and pH values.

Also, microalgae production cost can be offset by using it as a raw material in, for example, biofuel production, human nutrition, livestock feed and cosmetics.

One of the most relevant problems of CCS relates to the energy efficiency reduction related essentially with the application of the capture system. Since microalgae have the ability to proliferate even in flue gas conditions, such a capture system may not be required.

A sophisticated transportation system would be of great value for the construction of a large scale CO_2 biofixation industry. Due to the diversity of microalgae growth conditions, different solutions are purposed in this study and its costs are evaluated.

1.5 Contributions from this Work

Biological fixation of CO_2 from large point sources requires large areas for the implementation of reactors. Such areas may not be available in the immediacy of the industrial complex and therefore require the transportation of the gas until its biofixation location.

In this work, a preliminary economic evaluation of three different options for the transportation of CO_2 from critical emission sources until the reactor's location was prepared. The results of this evaluation will help further understanding the costs of CO_2 transportation for the specific case of microalgae production.

2 State of the Art

A pipeline represents all parts of the facility through which fluids are transported. This includes the pipe, valves, compressor units, pump stations, metering stations, regulator stations, delivery stations, holders and fabricated assemblies.

Pipelines are mainly used for the transportation of petroleum, natural gas and water (including sewage).

A wrought iron pipe constructed in the 1860s in Pennsylvania is said to have been the first oil transportation pipeline. Increasing demand of oil stimulated improvements in pipelines for longer and safer transportations. Quality control regulations led to the development of new materials, such as steel. Nowadays, technology allows for enhancements in all sectors of the pipelines.

In 1972, the first large scale CO_2 pipeline in the USA, consisting of 354 km, was built in Scurry County, Texas, for EOR. The CO_2 transported by this pipeline was originated from gas wells in the Val Verde Basin, which produced natural gas with a CO_2 contamination of 18 to 53%.[6]

The preliminary study for the design of the mentioned pipeline was described by West, in which he compares the transportation of CO_2 at different states: low pressure (in the gas phase); high pressure (in the supercritical phase) and as a refrigerated liquid. The evaluation determined that supercritical transportation was the most feasible option for this project. Therefore the minimum operation pressure was set to 95 atm, which allows the fluid to maintain a single phase flow for a wide range of temperatures. [6]

Recently, a publication by Zhang (2005) compared the energy efficiency and costs of transportation of supercritical fluid and subcooled liquid of CO_2 pipelines for sequestration. According to this report subcooled liquid transportation maximizes the energy efficiency and minimizes the cost of CO_2 transportation, which is quite unexpected and goes in opposition to the generally supercritical EOR projects.[7]

CO_2 pipelines are already in commercial use, transporting CO_2 from natural reservoirs for injection into oil fields so as to enhance oil production (fig. 3).

Figure 3. CO2 pipelines in the USA.[17]

Several other EOR projects emerged not only in the US but also in other parts of the world, as for example, Turkey and Canada.

For more than 30 years, the US has been transporting CO_2 from naturally-occurring reservoirs, usually presenting a relatively concentrated stream of CO_2, for EOR projects. For that reason, moderately pure CO_2 streams have been used for injection in wells. Future projects for CCS or microalgae production may not require such demands, and therefore other studies have to be done analyzing the effects of impurities arising from fossil fuel burning in the transportation of CO_2.

3 Technical Description and Discussion of Results

Biofixation of CO_2 from large stationary sources in a scale large enough to impact atmospheric GHGs values might involve a pipeline distribution network. The core of this system would be an arrangement of microalgae reactors, capturing the GHGs gases. Therefore, there is an increasing need for understanding the impact of transportation in the total cost of such a system, which requires careful analysis.

3.1 Identification of alternatives

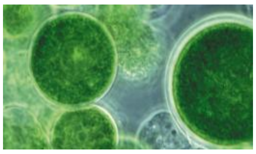
Three scenarios for the transportation of CO_2 from flue gas stacks until the reactor's location are schematically represented below. For each case, there is a brief description of the required essential processing steps. In order to compare the three different scenarios, it is assumed a CO_2 mass flow rate of **60 000 tones per year**.

Case A – Transportation of a **pure stream of CO_2**

- Separation from other components
- Dehydration of the stream

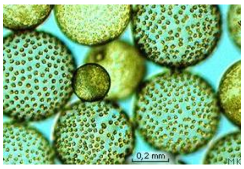
Case B – Transportation of the **flue gas**

- Dehydration of the stream



Case C – Transportation of **CO_2 dissolved in water**

- Dissolution of the gases in water



Case A

Case A represents the transportation of a highly concentrated stream of CO_2 to be fed to the reactor. In terms of transportation efficacy this is the best solution, given that one can transport the greatest amount of CO_2. However, the treatment required for attaining such a pureness is expensive and may counterbalance the advantages.

Case B

Case B involves the transportation of flue gases instead of CO_2. The concentration of CO_2 in the flue gas essentially depends on the emission sources. For example, in the case of coal combustion, the CO_2 present in the dry gas stream is around 15 % (volume). Consequently, the efficacy of CO_2 transportation is reduced. However, fewer costs are associated with the gas treatment, since the separation of CO_2 is no longer necessary.

Case C

In the last case, the transportation is done by dissolving the gases in water. No dehydration would be necessary, and so, the costs would be reduced. As in case B, from the point of view of CO_2 transportation efficacy, this scenario would not be very appealing. Nevertheless, one should keep in mind the aim is to produce microalgae, and this requires the transportation of water to the reactor’s site as well.

3.2 Economic Evaluation

3.2.1 Case A - Transportation of CO_2

3.2.1.1 **Parameter Determination**

In order to perform an economic evaluation, some parameters, such as the length of the pipeline and the downstream pressure, had to be estimated.

The length of the pipeline was set to 50 km, according to the estimation for a possible project implementation.

At the downstream end of the pipeline, the discharge pressure, p_2, was estimated as 1,5 atmosphere. Such pressure is calculated on the hypothesis of a reactor with a maximum height of 5 m, which equals an extra 0,5 atm to the atmospheric pressure. Below a tentative illustration is presented.

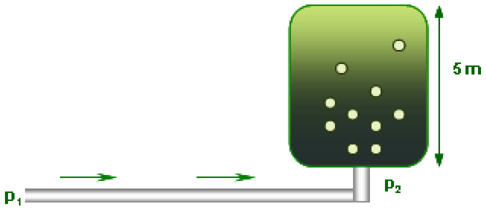


Figure 4. Schematic representation of CO_2 transportation.

Pipeline Material - Carbon Steel

Carbon steel is the material typically used not only for CO_2 transportation, but also for most pipeline installations. This is an inexpensive material with excellent properties in non corrosive environments and is available in a wide variety of sizes.

Nevertheless, in corrosive environments, a serious control has to be kept in order to maintain the integrity of the pipeline and insure a long lifetime.
Dissolved CO_2 reacts with water to form carbonic acid (H_2CO_3), which can cause the so called “sweet corrosion” of carbon steel.

$$CO_2(aq) + H_2O(l) \leftrightarrow H_2CO_3(aq)$$

For this reason, the transportation of CO_2 requires a dry stream and therefore a dehydration processing unit should be included in case A and B.

Maximum Operating Pressure – 20 atm

The choice for the maximum operating pressure (MOP) was based on the properties of CO_2. As it was decided to transport the CO_2 in the gas phase, lower pressures have to be maintained for a wide range of temperatures, including winter temperatures. It is safe to assume that the CO_2 will be in the gas phase as long as the pressure is below **20 atm**, as demonstrated by the temperature-pressure diagram in figure 5.

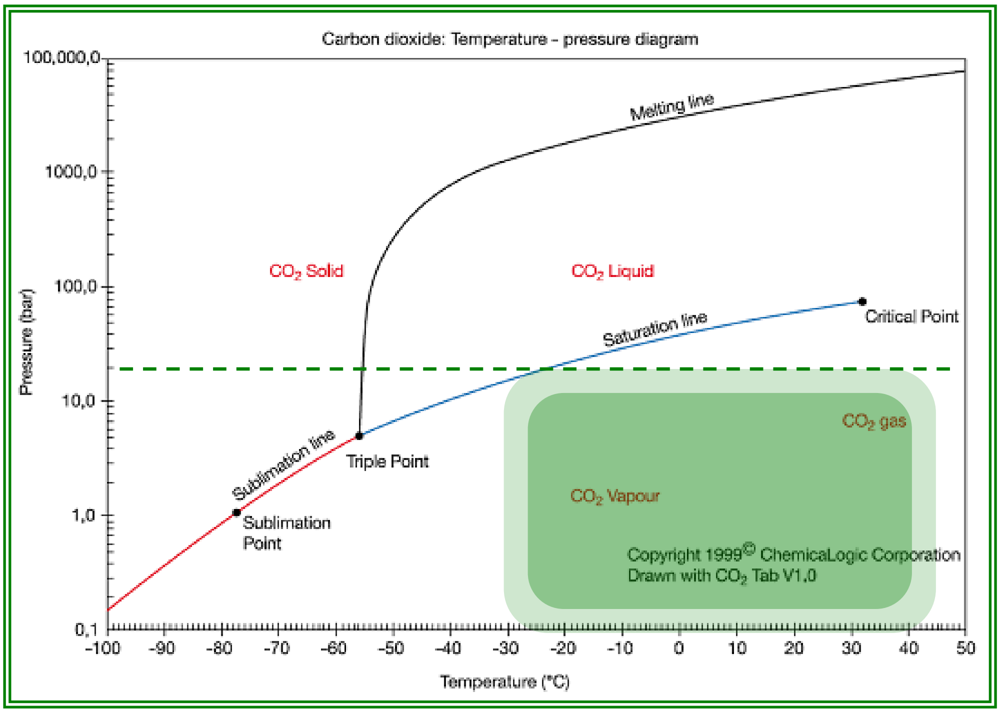


Figure 5. Temperature-pressure diagram for carbon dioxide. [3]

Pressure drop for compressible flow - Isothermal analysis

Compressible flow analysis is usually done by either considering isothermal or adiabatic behaviour. However, real situations behave somewhere in the middle of these models and therefore, choosing one that better adjusts our situation is of rather importance.

Due to the fact that the pipeline is quite long and no special isolation exists, it is considered to be closer to an isothermal behaviour.

Therefore the model for isothermal flow was chosen, eq. (1), deduced in Annex 1.

$$\left(p_1^2 - p_2^2\right) = G^2 \frac{RT}{M}\left[\frac{4fL}{D} + 2\ln\left(\frac{p_1}{p_2}\right)\right] \tag{1}$$

where

p_1 = upstream pressure of gas, Pa

p_2 = downstream pressure of gas, Pa

G = mass flux, kg.m^{-2}.s^{-1}

R = universal gas constant, (8,314) Pa.m^{3}.mol^{-1}.K^{-1}

M = molecular weight, kg.mol^{-1}

T = gas flowing temperature, K

f = friction factor, dimensionless

L = length of the pipe, m

D = inside diameter, m

The friction factor, f, was calculated using an approximation of Colebrook-White equation, deduced by Haaland, eq. (2).

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{6{,}9}{\mathrm{Re}} + \left(\frac{\varepsilon/D}{3{,}7}\right)^{1{,}11}\right] \tag{2}$$

where

Re = Reynolds number, dimensionless

ε/D = Relative roughness

By means of an iterative process, the calculation of the pressure drop due to friction was performed using equation (1). Represented in figure 6 is the pressure drop profile for the Nominal Diameter (DN) 300 and schedule (SCH) 40 pipeline. Refer to Annex II for detailed clarification on pipeline standard sizes.

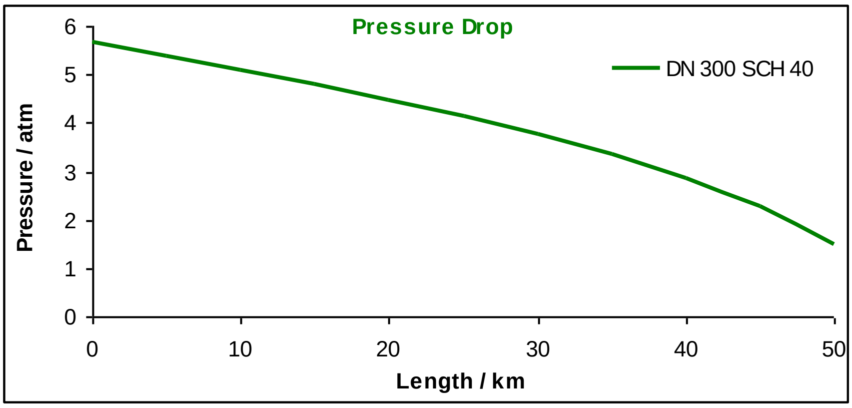


Figure 6. Pressure drop for carbon steel pipeline DN 300 Sch 40.

Table 1. Summary of the parameters previously described.

Summary of defined parameters	
Length, L	50 km
Discharge pressure, p_2	1,5 atm
Maximum operating pressure, MOP	20 atm
Pipe Material	Carbon Steel
Mass flow rate	60 000 ton/year

3.2.1.2 **Economic Pipe Diameter**

The economic pipe diameter or optimum diameter is the one which results in the minimum costs. Increasing the diameter will cause a decrease in the pressure drop, and therefore less power is required for compressing the gas. However, bigger sizes imply higher pipe material costs. Accordingly, smaller sizes result in higher pressure drop and lower material costs.

In case A, an analysis was performed accounting for the material and compression costs, supposing 20 years of useful life. Such analysis returned ambiguous results and therefore a different strategy was attempted.

Instead of only accounting for the material and compression energy costs, an extra parameter was also taken into consideration: the compressor station investment costs. Below, a description of each calculation is presented.

Pipe Material Cost [9]

The pipe material cost was calculated according to equation (3), which essentially calculates the weight of the pipe and multiplies it by its cost per tonne.

$$PMC = 0{,}0246 \times (OD - T) \times T \times L \times C \tag{3}$$

where

PMC = pipe material cost, €

L = length, km

OD = pipe outside diameter, mm

T = pipe wall thickness, mm

C = pipe material cost, €/ton

Installation Costs [9]

Installation costs should take into consideration the characteristics of the terrain in which the pipeline is to be established. However, since there is no such indication, an estimation of the order of magnitude of costs was performed by means of typical pipeline costs based on those presented in table 2.

Table 2. Typical pipeline installation costs. [9]

DN , mm	NPS , in	Avg cost, $/in/mile	Avg cost, €/in/km
200	8	18000	7059
250	10	20000	7843
300	12	22000	8628
400	16	14900	5843
500	20	20100	7883
600	24	33950	13314
750	30	34600	13569
900	36	40750	15981

The currency exchange used for the calculations was 0,63 € per $.

Compressor Stations

Compressors are necessary for compensating the pressure loss, due to friction, throughout the pipeline. Therefore, the cost estimation of compressors is based on the horsepower required for overcoming pressure losses.

The number of compressor stations is calculated taking into consideration the MOP. For example, in the evaluation of Case A with a pipeline DN 150 Sch 40, we achieve the following pressure drop (fig.7).

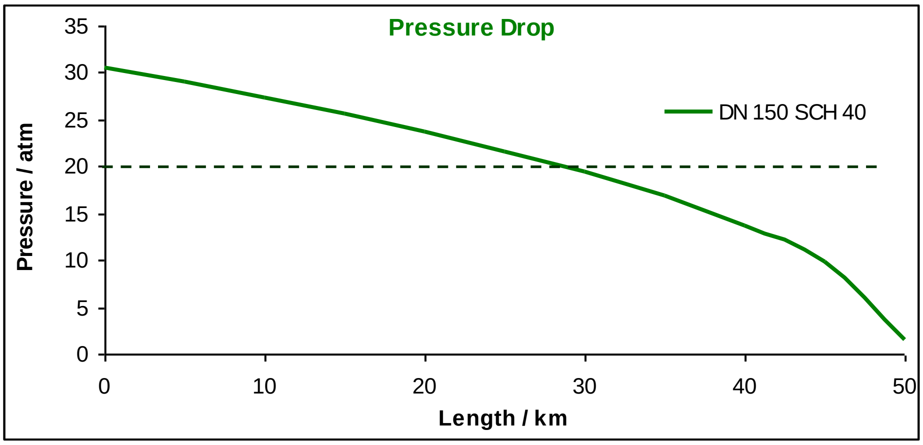


Figure 7. Pressure drop for DN 150 Sch 40 carbon steel pipeline.

The calculated pressure at the upstream end of the pipeline was approximately 31 atm, exceeding the MOP by 11 atm.

In order to estimate the number of compressor stations required for this case, a compression ratio, r, was set to 1,5 . Supposing a maximum discharge pressure, P_d, of 20 atm, the suction pressure, P_s, should be around 13,3 atm.

$$r = \frac{P_d}{P_s} = 1{,}5 \tag{4}$$

where

r = compression ratio, dimensionless

P_d = discharge pressure, atm

P_s = suction pressure, atm

In isothermal conditions, the pressure drops from 20 atm to 13,3 atm in approximately 12 km. This being the case, the system requires three similar compressor stations along the pipeline and another one with higher compression rate at the upstream end.

The capital cost calculation of each compressor was performed using an available estimator. The lifetime of each compressor was set to 10 years. [10]

Compression Energy Cost

The energy required to be input to the system is estimated by the pressure loss, supposing a 70 % efficiency of the compressors.

$$Power = \int_0^L \frac{Q}{\eta}\left(\frac{\Delta P_f}{L}\right) \times dL \tag{5}$$

where

Power = compressor power, watt

Q = volume flow rate of the gas, m^3/s

ΔP_f = pressure drop due to friction, Pa

η = compressor performance

The energy costs associated to the compression of the gas are calculated according to equation (6).

$$Cost = Power \times Energy \quad price \times hours \tag{6}$$

where

Cost = compression costs, €/year

Power = compressor power, kw

Energy price = 0,0903 €/kw.h [12]

Hours = working hours per year, h/y

The result of this evaluation is schematically represented in fig. 8.

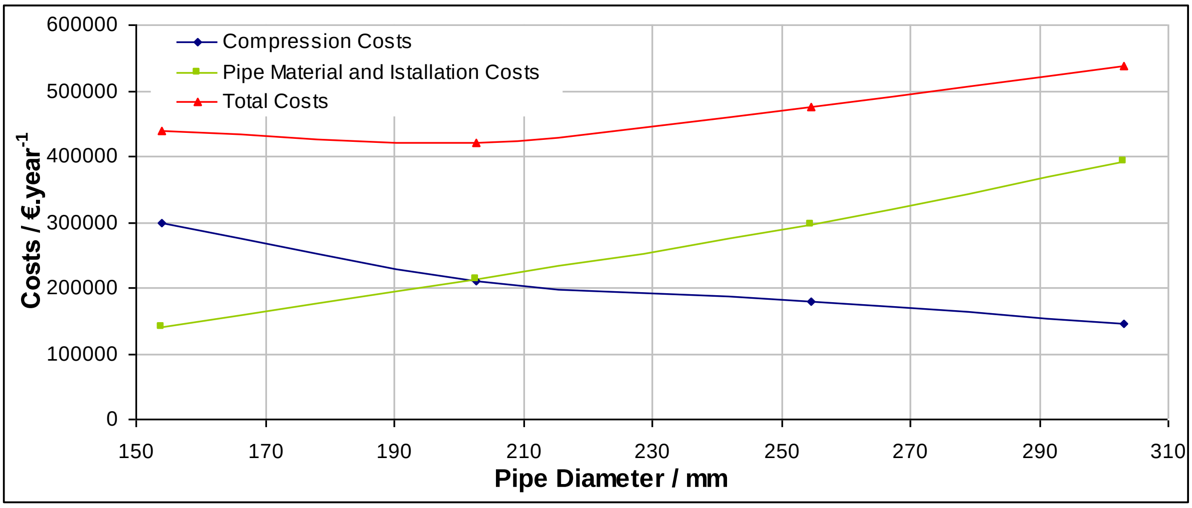


Figure 8. Material and energetic costs as a function of the pipeline diameter.

Therefore, according to this evaluation, the optimum diameter is **200 mm**. The pressure and velocity profile for the selected diameter is represented in fig. 9.

The difference in cost between the DN 200 and the closest lowest cost diameter, DN 150, is of only 4 %. Such difference would increase significantly if the maintenance costs would be added, since DN 150 requires several compressor stations, and therefore greater maintenance costs.

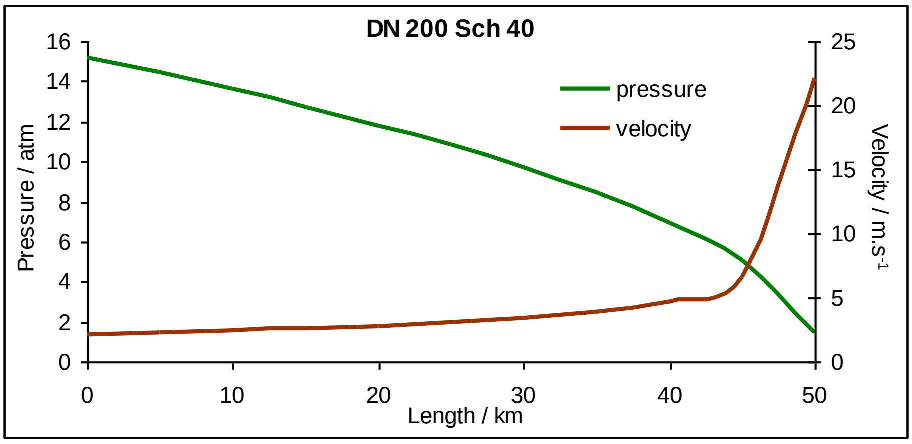


Figure 9. Pressure and velocity profile for DN 200 Sch 40.

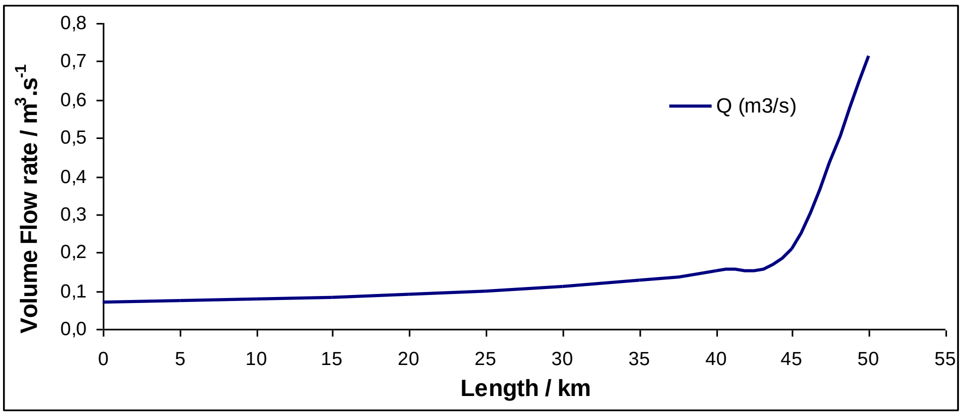


Figure 10. Volume flow rate throughout the pipeline.

3.2.1.3 **Capital Costs**

Selection of compressor

Taking into consideration the flow rate at the inlet and the discharge pressure, which can be seen in figures 9 and 10, a reciprocating positive displacement compressor was selected.

Cost of Compressor

The cost estimation for the compressor was based on an exponential method. This method makes use of existing cost data, C1, on a certain equipment of size (capacity), q1, to determine the cost of similar equipment of size (capacity) q2. [13]

$$C_2 = C_1 \left(\frac{q_2}{q_1} \right)^n \tag{7}$$

where

C_i = cost of equipment *i*

q_i = size (capacity) of equipment *i*

n = exponent factor, function of type of equipment or plant

A reciprocating compressor of size 224 kW costs 133 000 $ for Marshal and Swift (M&S) index of 1000; n is 0,84. Therefore we obtain an estimation of 148 655 $ for our 256 kW pump. [13]

$$present \quad \cos t = original \quad \cos t \left(\frac{index \quad value \quad at \quad present}{index \quad value \quad at \quad time \quad original \quad \cos ts \quad were \quad obtained} \right) \tag{8}$$

At 2004 the M&S Equipment Cost index was 1194.00, therefore, for a currency exchange rate of 0,63 €/$, the present value is **111 822 €**.

Table 3. Capital Costs for the case of transportation of a pure stream of CO_2.

Capital Costs	
Pipeline (material and installation)	4,235 M€
Compressor Station	0,112 M€
Miscellaneous costs	1,729 M€

Other capital costs such as valves, engineering and construction management are accounted in the miscellaneous cost. It was estimated as approximately 40 % of the pipeline and compressor costs, according to the references.[9]

3.2.1.4 Operating Costs

Table 4. Operating Costs for the case of transportation of a pure stream of CO_2.

Operating Costs	
Energy for compression	0,202 M€ /y
Capture of CO_2	1,096 M€ /y

The capture of CO_2 was calculated according to data published by IPCC, which refers the costs of capturing CO_2 as being around 29 US$/ton CO_2. Considering the flow rate of 60 000 ton /year, and a currency rate of 0,63 €/$, one can obtain the value in table 4. [3]

3.2.2 Case B - Transportation of flue gas

3.2.2.1 Parameter Determination

Case B involves the transportation of flue gas instead of a pure stream of CO_2. The flue gas usually refers to the gas arising from the combustion of fossil fuels. The composition varies significantly, particularly with the type of fuel used for burning, and the oxygen percentage in excess which is fed to the furnace. A typical flue gas composition presented in table 5 was used as a base for the calculation of the mass flow rate in Case B.

Table 5. Typical flue gas composition in the dry stream.

Typical Flue Gas composition	
CO_2	12%
O_2	5,5%
SO_2	400 ppm
NO_x	120 ppm
N_2	82%

The flow rate of flue gas required for the transportation of 60 000 ton/year of CO_2 is therefore **500 000 ton/year.**

Table 6. Summary of the parameters previously described.

Defined Parameters	
Length, L	50 km
Discharge pressure, p_2	1,5 atm
Maximum operating pressure, MOP	20 atm
Pipe Material	Carbon Steel
Mass Flow Rate	500 000 ton / year
Number of pipelines	2

3.2.2.2 Economic Pipe Diameter

Performing an analysis of the economic pipe size, using the previously described method, results in extremely large diameter pipelines. Such diameters are not frequently manufactured, and therefore construction costs would escalate relatively to those estimated.

For this reason, the transportation is considered to take place in two pipelines instead of one. An analysis of the economic pipe diameter results in an optimum diameter of **DN 1100 Sch 20**. In figure 11 is represented the material and compression costs for each diameter.

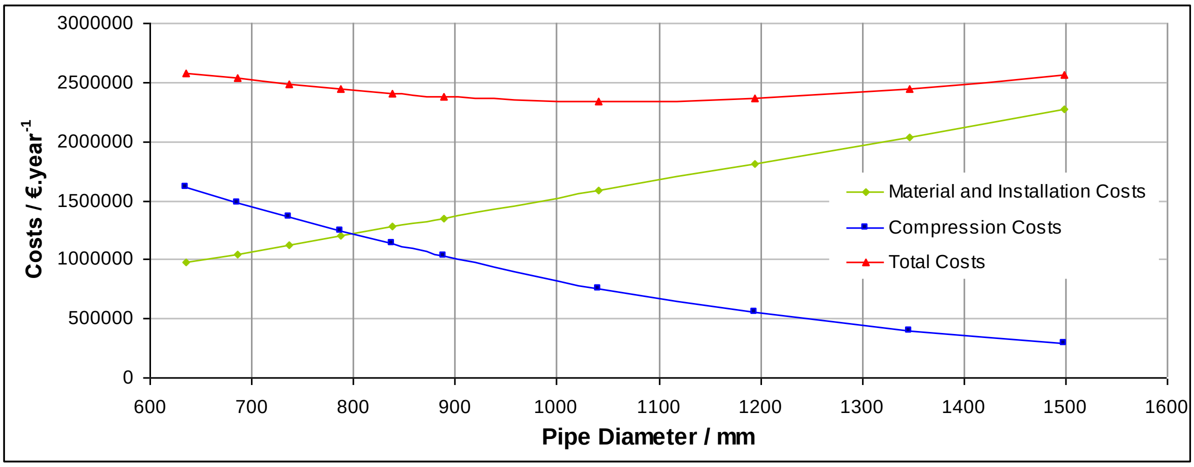


Figure 11. Material and energetic costs as a function of the pipeline diameter.

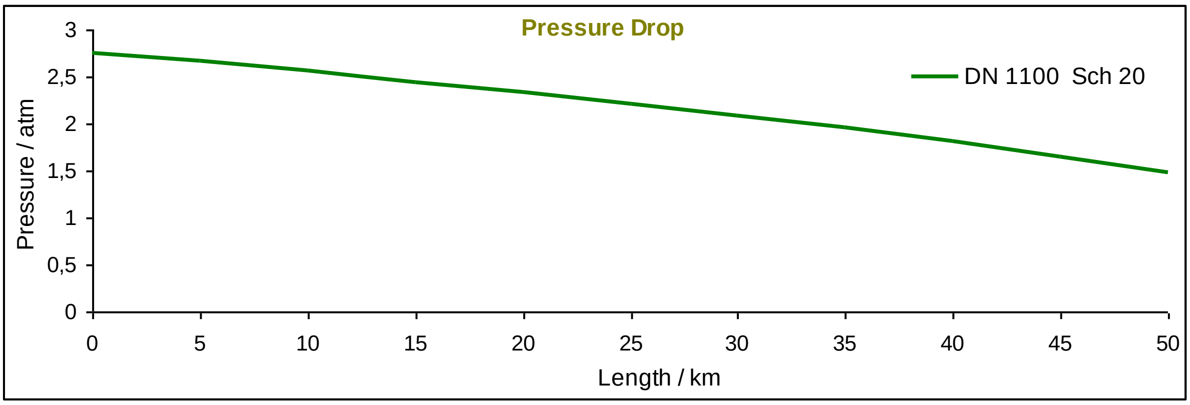


Figure 12. Pressure profile for DN 200 Sch 40.

3.2.2.3 Capital Costs

Selection of compressor

Considering the flow rate at the inlet, of 7,4 m^3/s, and the discharge pressure, which can be seen in figure 12, a blower was selected for promoting the movement of the fluid.

Cost of Blower

The cost estimation for the blower was based on the exponential method, previously presented for case A.

A blower of size 4,72 m^3/s costs 67 000 \$ for Marshal and Swift (M&S) index of 1000; n is 0,6. Therefore, according to eq. (7), we obtain an estimation of 87 909 \$ for our blower with volume flow of 7,42 m^3/s. [13]

At 2004 the M&S Equipment Cost index was 1194.00, therefore, by eq. (8) and for a currency exchange rate of 0,63 €/\$, the present value is **66 127€**. Since we have two pipelines, we have also two blowers and therefore the total cost for case B is **132 254 €**.

Table 7. Capital costs for the case of transportation of flue gases.

Capital Costs	
Pipeline (material and installation)	63,290 M€
Compressor Station	0,132 M€
Miscellaneous costs	25,369 M€

3.2.2.4 Operating Costs

Table 8. Operating Costs for the case of transportation of flue gases.

Operating Costs	
Energy for compression	0,756 M€ / y

3.2.3 Case C - Transportation of CO_2 dissolved in water

3.2.3.1 Parameter Determination

In case C, CO_2 transportation is done by dissolving it into an aqueous solution that will later be used as the cultivation medium for microalgae.

The quantity of water required to transport the CO_2 was calculated considering the solubility of CO_2 in water at normal temperature and pressure (NTP, 20 °C and 1 atm), which is approximately 0,1688 grams of CO_2 per 100 cm^3 of solution. [13]

$$Q_{H_2O} = \frac{\dot{m}_{CO_2}}{s} \tag{9}$$

where

Q_{H2O} = volume flow rate of water, m^3_{H2O}/s

m_{CO2} = mass flow rate of CO_2, kg/s

s = CO_2 solubility in water at PTN

The solubility of CO_2 changes considerably with pressure and temperature, increasing with increasing pressure and / or decreasing temperature. The solubility was calculated at NTP, because if we saturate the water with CO_2 at the upstream pressure, due to the pressure drop along the pipeline, CO_2 might be released forming a two-phase flow.

The interference of other gases in the solubility of CO_2 was not accounted for in the calculations, for simplicity's sake.

Pressure Drop for uncompressible flow

The pressure drop due to friction for uncompressible flow is calculated according to equation (10).

$$\frac{\Delta P_f}{\rho g} = h = f\,\frac{L}{D}\frac{v^2}{2g} \tag{10}$$

The variables have been previously identified.

Pipeline Material – Polyethylene (PE)

In this case the transportation should not be done by carbon steel, since the corrosion effects would harm the material and significantly reduce its lifetime. Therefore, the material proposed for water transportation is polyethylene, PE.

PE pipes present several advantages, such as resistance to corrosion, low friction coefficient, and lower costs. Also, the introduction of PE 100 allows for even greater operating pressures, up to 10 bar.

Maximum Operating Pressure (MOP)

The maximum operating pressure is defined by the material properties. The two types of PE pipes analysed were the PE 80 and PE 100. For the calculation of the MOP, equation (11) is used.

$$MOP = \frac{20 \times MRS}{C \times (SDR - 1)} \tag{11}$$

where

MOP = maximum operating pressure, bar

MRS = minimum required strength, MPa

$MRS_{(PE\ 80)}$ = 8 MPa; $MRS_{(PE\ 100)}$ = 10 MPa

C = overall design coefficient, minimum 1.25 for PE

SDR = standard dimension ratio

Table 9. Summary of the parameters previously described.

Defined Parameters	
Length, L	50 km
Discharge pressure, p_2	1 atm
Maximum operating pressure, MOP	Defined by material
Pipe Material	Polyethylene (PE)
Mass Flow Rate	17 Mton / year
Number of pipelines	2

3.2.3.2 Economic pipe diameter

Eq. (12), valid for turbulent flow, was used to determine the economic pipe diameter, in order to select the best pipe size.[14]

$$D_{i,opt} = 0{,}363 \times Q^{0,45} \rho^{0,13} = 0{,}363 \times 0{,}564^{0,45} \times 998^{0,13} = 0{,}688 \quad m \tag{12}$$

where

$D_{i,opt}$ = optimum diameter, m

Q = volumetric flow, m^3/s

ρ = fluid density, kg/m^3

The volumetric flow rate in eq. (12) is half of that calculated previously in eq. (10) because instead of having a single pipeline, a two pipeline system for transporting the solution was considered. Such supposition was made due to the high value of the calculated mass flow rate of 17 Mton of water per year.

Pipe Material Cost

The pipe material costs are estimated according to the supplier's information.[15] In table 10 and table 11 are represented the costs for pipeline PE 80 and PE 100 for sizes close to that estimated by equation (12). The difference between these two types of PE, is that PE 100 enables a higher maximum operating pressure.

Table 10. PE 80 costs per meter for several dimension ratios. [15]

	PE 80		
	DN	**e**	**€/m**
SDR 33	630	19,3	205,68
	710	21,8	261,40
	800	24,5	331,13
SDR 21	630	30,0	313,04
	710	33,9	398,58
	800	38,1	505,21
SDR 17	630	37,4	385,31
	710	42,1	488,97
	800	47,4	620,03
SDR 13,6	630	46,3	469,43
	710	52,2	569,43
	800	58,8	759,00

Table 11. PE 100 costs per meter for several dimension ratios. [15]

	PE 100		
	DN	**e**	**€/m**
SDR 26	630	24,1	255,40
	710	27,2	324,64
	800	30,6	411,16
SDR 21	630	30,0	314,03
	710	33,9	399,83
	800	38,1	506,79
SDR 17	630	37,4	386,58
	710	42,1	490,51
	800	47,4	621,97
SDR 11	630	57,2	572,00

The choice of the best diameter for the economic analysis was based on two critical hypotheses. The first, as referred previously, supposed that the transportation should be done in two pipelines instead of one. This is justified by the high flow rates. The second assumption lies in the fact that we are supposing the need for two pumps in each line, which otherwise would result in higher pressures and larger diameters.

Performing the hydrodynamic calculations of the referred PE sizes results, in most cases, in pressures above the MOP. From those in which the operating pressure was in agreement with the MOP the diameter with the lowest cost was **PE 100 SDR 21** with **DN 710**.

Therefore, simply multiplying the price given in table 11 by the total length of the pipeline, considering the two pipelines, results in a total cost of **39,883 M€.**

Pumping Cost

The energetic costs associated with pumping the fluid are calculated in a similar way as it was done for case A and B, by equation (6). The analysis of the power consumption, however, differs significantly. While in the other cases, due to the compressibility of the gas, the volume flow rate changed throughout the pipeline, in the case of water the pumping is simply calculated from equation (13), in which the volume flow rate is considered constant.

$$Power = \frac{Q \Delta P_f}{\eta} \qquad (13)$$

The power determined by equation (13) was approximately 399 kW. The annual energetic costs are 315 493 €/year for each pump. Since we would have four pumps, two in each line, the total energetic cost would be approximately **1,262 M€/year**.

3.2.3.3 Capital Costs

Selection of Pump

After some careful examination on the pumps available in the market, a centrifugal pump with axial flow was selected for performance analysis. For the operating conditions a performance of approximately 80 % is estimated.

Cost of Pump

The estimation of the pumps cost was based on exponential method.

A centrifugal pump of size 74,6 kW costs 4 400 $ for Marshal and Swift (M&S) index of 1000; n is 0,67. Therefore we obtain an estimation of 13 532 $ for our 399 kW pump. [13]

At 2004 the M&S Equipment Cost index was 1194.00, therefore, for a currency exchange rate of 0,63 €/$, the present value is **10 179 €**. Since the system contains 4 pumps, the total capital cost is **40 717 €.**

Installation Costs

It was assumed a 45 % of pipe material cost, resulting in **17,992 M€.**

Table 12. Capital costs for the case of transportation of CO2 dissolved in water.

Capital Costs	
Pipeline (material and installation)	57,975 M€
Pumps	0,041 M€
Miscellaneous costs	23,206 M€

3.2.3.4 Operating Costs

Table 13. Operating costs for the case of transportation of CO2 dissolved in water.

Operating Costs	
Energy for pumping	1,262 M€ / year

3.3 Scenario’s evaluation

Considering an interest rate of 8 % for 20 years we can annualize the capital costs, according to equation (14).[9]

$$PV = \frac{R}{i}\left(1 - \frac{1}{(1+i)^n}\right) \tag{14}$$

Where

PV = present value, €

R = series of cash flows, €

i = interest rate

n = number of year

The calculation performed by equation (14) results in a cash flow value, R, of **0,618 M€/year**. For the other cases the results are shown in detail in table 14.

Table 14. Summary of transportation costs for all cases.

	Case A		**Case B**		**Case C**	
Capital Cost	Pipeline	4,235	Pipeline	63,29	Pipeline	57,975
	Compressor Station	0,112	Compressor Station	0,132	Pumps	0,041
	Miscellaneous costs	1,729	Miscellaneous costs	25,369	Miscellaneous costs	23,206
R	Annualised Capital Cost	**0,618**	Annualised Capital Cost	**9,044**	Annualised Capital Cost	**8,273**
Operating Costs	Energy for compression	**0,202**	Energy for compression	**0,756**	Energy for pumping	**1,262**
	Capture of CO_2	**1,096**				
Total (M€/year)		**1,92**		**9,80**		**9,53**

The total annual costs of transportation can be calculated per tonne of CO_2. This is done by dividing the sum of the annualized costs and the operational costs by the total amount of CO_2 transported per year.

$$Annual \quad Cost \quad per \quad ton \quad of \quad CO_2 = \frac{(0{,}618 + 0{,}202 + 1{,}096)x10^6}{60 \quad 000} = 32 \quad €/ton \tag{15}$$

Equation (15) exemplifies the calculation for case A, which results in 32 €/ton of CO_2.

The results performed for the remaining cases are schematically represented in table 15.

Table 15. Summary of transportation cost related to the quantity transported.

Transportation Scenario	Cost of transportation, €/ton
Case A	32
Case B	163
Case C	159

In order to allow for an accurate evaluation of the transportation costs, the water fed to the reactors should be taken into account in Case A and B. This is required because the culture medium for microalgae production is mainly composed of water, which has to be transported until the reactor's location.

Since Case C represents the transportation of water, it is used as a base for calculation of the costs of water transportation. The cost previously calculated was 9,53 M€/year for a distance of 50 km. By adding this value to the other case's yearly costs we obtain the values represented in table 16.

Table 16. Summary of transportation cost related to the quantity transported.

Transportation Scenario	Cost of transportation, €/ton CO_2
Case A	191
Case B	322
Case C	159

Being this the case, the conclusions would be different from the ones taken from the values at table 15 and Case C would be the cheapest option. Nonetheless, the total costs of the 50 km water pipeline were considered for the calculation, which is clearly oversized and overestimated. Most possibly, water could be reached in a closer location to the reactors and not necessarily from the same location as the emission source, and therefore the construction of a 50 km pipeline would not be necessary. It was calculated that for length values up to 40 km the transportation cost per tonne of CO_2 is lower for case A.

4 Conclusions

A preliminary economic analysis of CO_2 transportation for microalgae was performed in this study. From the three purposed scenarios, the one which resulted in lower costs was case A, consisting on the transportation of a pure stream of CO_2.

Case B had lower operating cost than case A. However, the initial capital cost of case B was around 15 times higher than the initial capital cost of case A. This is why, even on a 20 year period, transportation of a pure stream of CO_2 (case A) is the best economical option.

The capital cost due to the installation of a dehydration unit, needed in cases A and B, was not taken into account. This is due to the impossibility to find a good price reference for such a unit. However, the same unit would be needed in cases A and B, so this would not change the fact that case A is more economical than case B.

Also, case C has the same operational costs as case A, and much higher capital costs (81 M€ for case C versus 6M€ for case A). It is assumed that a dehydration unit would not cost so much as the difference between these two values, so case A is also more economic than case C even if we take into account a dehydration unit.

Nonetheless, if we account the fact that water has to be transported to the reactor's location, and if there is no close water supply in a 40 km area, conclusions could be different.

Therefore, decisions based on the results from this study are valid only for the set parameters and conditions, and extrapolating these results to other conditions could lead to bad decision making.

An analysis on how each of the most important parameters affects the final cost is essential for being able to apply the results for a wide range of conditions. Also, an evaluation of the transportation of CO_2 in phases other than the gas phase would give a better idea of the total options available and possibly an optimum option might surge from that assessment.

I believe this study lays a good base for a future analysis, having already defined a good evaluation methodology for a given set of parameters.

5 Performance Evaluation

5.1 Accomplished targets

The aim of this work was a preliminary economic evaluation on the transportation of CO_2 for the specific case of microalgae production.

Three different scenarios were proposed and an optimization design for each case was performed for calculation of parameters.

Afterwards, an economic analysis for the set or calculated parameters was carried through.

5.2 Restrictions and Future Work

The economic analysis was performed for a set of calculated or estimated parameters, and changing these has a great impact on the final costs. For this reason, I believe it would be important to study the influence of the most important parameters on the costs. If such is accomplished, the results could be useful for a wide range of conditions.

I also consider that a study of the effects of the different constituents of flue gas would be of great relevance in the pipeline design.

5.3 Final Evaluation

It was with great satisfaction that I have accomplished this work, which allowed me to learn so many things and deal with so many subjects of interest.

This study is important in many senses, providing an estimation of pipeline systems costs on the order-of-magnitude. It also allows decision making when choosing the most viable project for CO_2 transportation.

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Annex I

Deduction of Compressible Flow Equation in Isothermal Conditions

Mass Balance

$$\dot{m} = \rho v A = const \tag{1}$$

If the Diameter of the pipe is considered constant, A is constant, therefore equation (1) results:

$$\rho v = \frac{\dot{m}}{A} = const = G \tag{2}$$

In the differential form:

$$v \cdot d\rho + \rho \cdot dv = o \tag{3}$$

or

$$\frac{1}{\rho} d\rho + \frac{1}{v} dv = o \tag{4}$$

Energetic Balance

$$\underbrace{\cancel{\alpha}}_{\alpha\ \sim\ 1\ \text{Turbulent regime}} \cdot v \cdot \left(\frac{dv}{dx}\right) + g\underbrace{\cancel{\left(\frac{dz}{dx}\right)}}_{\sim\ 0\ \text{no elevation}} + \frac{1}{\rho}\left(\frac{dp}{dx}\right) + \left(\frac{dh_f}{dx}\right) = \underbrace{\cancel{\hat{W}}}_{\text{No work}} \tag{5}$$

So,

$$v \cdot \left(\frac{dv}{dx}\right) + \frac{1}{\rho}\left(\frac{dp}{dx}\right) + \left(\frac{dh_f}{dx}\right) = 0$$

$$v \cdot \left(\frac{dv}{dx}\right) + \frac{1}{\rho}\left(\frac{dp}{dx}\right) + \frac{4f}{D}\frac{v^2}{2} = 0 \tag{6}$$

Equations of State

$$pV = ZRT \tag{7}$$

$$\rho = \frac{PM}{zRT} \tag{8}$$

If the compressibility facto, Z, is constant:

$$\frac{dp}{p}+\frac{dV}{V}-\frac{dT}{T}=0 \tag{9}$$

or

$$\frac{dp}{p}-\frac{d\rho}{\rho}-\frac{dT}{T}=0 \tag{10}$$

From equation 10,

$$\frac{1}{p}\left(\frac{dp}{dx}\right)-\frac{1}{\rho}\left(\frac{d\rho}{dx}\right)-\frac{1}{T}\left(\cancel{\frac{dT}{dx}}\right)=0$$

~ 0 isothermal flow

$$\frac{1}{p}\left(\frac{dp}{dx}\right)=\frac{1}{\rho}\left(\frac{d\rho}{dx}\right)$$

Dividing eq. (6) by v^2, results

$$\frac{1}{v}\cdot\left(\frac{dv}{dx}\right)+\frac{1}{v^2\rho}\left(\frac{dp}{dx}\right)+\frac{2f}{D}=0 \tag{11}$$

According to equation (4) and (9)

$$\frac{1}{\rho}d\rho=-\frac{1}{v}dv \tag{12}$$

$$\frac{1}{p}\left(\frac{dp}{dx}\right)=\frac{1}{\rho}\left(\frac{d\rho}{dx}\right) \tag{13}$$

Introducing these last equation into equation (11),

$$-\frac{1}{p}\cdot\left(\frac{dp}{dx}\right)+\frac{1}{v^2\rho}\left(\frac{dp}{dx}\right)+\frac{2f}{D}=0$$

As,

$$v^2\rho=\frac{G^2}{\rho} \tag{14}$$

We obtain,

$$-\frac{1}{p}\cdot\left(\frac{dp}{dx}\right)+\frac{\rho}{G^2}\left(\frac{dp}{dx}\right)+\frac{2f}{D}=0 \tag{15}$$

The density, ρ, for isothermal flow can be calculated as:

$$\rho=\frac{\rho_1}{p_1}p \tag{16}$$

Introducing into equation (15), results:

$$-\frac{1}{p}\cdot\left(\frac{dp}{dx}\right)+\frac{\rho_1}{p_1G^2}p\left(\frac{dp}{dx}\right)+\frac{2f}{D}=0$$

$$-\int\frac{dp}{p}+\frac{\rho_1}{p_1G^2}\int p\cdot dp+\frac{2f}{D}\int dx=0$$

$$-\ln\left(\frac{p_2}{p_1}\right)+\frac{\rho_1}{2p_1G^2}\left(p_2^2-p_1^2\right)+\frac{2f}{D}L=0$$

$$\boxed{\ln\left(\frac{p_2}{p_1}\right)^2+\frac{\rho_1}{p_1G^2}\left(p_1^2-p_2^2\right)=\frac{4f}{D}L}$$

ISO-T ; A = const; Z = const

Annex II

Pipelines are manufactured according to standard sizes, usually designated by two numbers, the nominal pipe size (NPS) and the schedule number (SCH), according to American standards. NPS relates to the diameter size in inches, although not always the value indicated is the corresponding value of the outside diameter. SCH refers to the thickness of the pipe. Usually SCH 40 is used, depending, of course, on the application and operating pressure. These should follow ASME/ANSI B 36.10 *Welded and Seamless Wrought Steel Pipe* regulations.

The metric designation that is in conformity to International Standards Organization (ISO) is called "diametre nominel", DN.

Table 1. Standard pipe sizes. [16]

DN / mm	NPS, in	OD, mm	Schedule	Wall Thikness, mm	Inside Diameter, mm
25	1	33	40	3,4	26,6
			80	4,5	24,3
			160	6,4	20,7
40	1,5	48	40	3,7	40,9
			80	5,1	38,1
			160	7,1	34,0
50	2	60	40	3,9	52,5
			80	5,5	49,3
			160	8,7	42,9
80	3	89	40	5,5	77,9
			80	7,6	73,7
			160	11,1	66,7
100	4	114	40	6,0	102,3
			80	8,6	97,2
			120	11,1	92,1
			160	13,5	92,1
150	6	168	40	7,1	154,1
			80	11,0	146,3
			120	14,3	139,7
			160	18,2	139,7
200	8	219	20	6,4	206,4
			30	7,0	205,0
			40	8,2	202,7
			60	10,3	198,5
			80	12,7	193,7
			100	15,1	189,0
			120	18,2	182,6
			140	20,6	177,8
			160	23,0	174,6

DN / mm	NPS, in	OD, mm	Schedule	Wall Thikness, mm	Inside Diameter, mm
250	10	273	20	6,4	260,4
			30	7,8	257,5
			40	9,3	254,5
			60	12,7	247,7
			80	15,1	242,9
			100	18,2	236,6
			120	21,4	230,2
			140	25,4	222,3
			160	28,6	215,9
300	12	324	20	6,4	311,2
			30	8,4	307,1
			40	10,3	303,2
			60	14,3	295,3
			80	17,4	289,0
			100	21,4	281,0
			120	25,4	273,1
			140	28,6	266,7
			160	33,6	256,7
350	14	356	10	6,4	342,9
			20	7,9	339,8
			30	9,5	336,6
			40	11,1	333,4
			60	15,1	325,5
			80	19,1	317,5
			100	23,8	308,0
			120	27,8	300,1
			140	31,8	292,1
			160	35,7	284,2
400	16	406	10	6,4	393,7
			20	7,9	390,6
			30	9,5	387,4
			40	12,7	381,0
			60	16,7	373,1
			80	21,4	363,6
			100	26,2	354,0
			120	30,9	344,5
			140	36,5	333,4
			160	40,5	325,5
450	18	457	10	6,4	444,5
			20	7,9	441,4
			30	11,1	435,0
			40	14,3	428,7
			60	19,1	419,1
			80	23,8	409,6
			100	29,4	398,5
			120	34,9	387,4
			140	39,7	377,9
			160	45,2	366,7
500	20	508	10	6,4	495,3
			20	9,5	489,0
			30	12,7	482,6
			40	15,1	477,9
			60	20,6	466,8
			80	26,2	455,6
			100	32,5	442,9
			120	38,1	431,8
			140	44,5	419,1
			160	50,0	408,0