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Economic-mathematical modeling of costs for CO_2-enhanced oil recovery in Russia

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Abstract

The paper presents a method of cost assessment for CO_2-enhanced oil recovery (CO_2-EOR) projects in Russia. For a country with a strong dependence on the oil & gas sector, CO_2-EOR is a promising option to reduce greenhouse gas emissions and at the same time to increase oil recovery efficiency.

Through economic-mathematical modeling of separate stages of the project (capture, transport, injection), the author derives the dependency of economic costs on technological parameters of CO_2 sources and sinks, allowing to carry out a “rapid analysis” of CO_2-EOR projects and draw conclusions on their economic efficiency. The tool may be used for the selection of most promising options and creating efficient project portfolios on a scale of separate regions or the country as a whole.

Keywords: Carbon Capture and Storage, Enhanced oil Recovery, Russia, Cost Assessment, Express Analysis

Introduction

Today the world is facing the problem of global warming, which implies that emissions of greenhouse gases (primarily, CO_2) must be reduced without causing adverse effects to the energy and industry sectors. One of possible solutions is carbon capture and storage (CCS) – a technology to capture emitted CO_2 and inject it into geological formations for long-term storage. In certain cases, stored CO_2 can provide additional benefits, e.g. facilitate EOR when injected into depleted oil-fields.

CO_2-EOR technology appeared in the USA and has been actively developing there since 1970s. In 2014, nearly 60 Mt CO_2 have been injected into oil-fields, resulting in 37 Mt of additional oil extraction (Wallace&Kuuskraa, 2014).

In Russia the option is regarded as one of the most promising due to significant storage potential and possible economic benefits. A number of possible projects can be developed varying by CO_2 source characteristics, distance and other technological parameters. In order to assess the economic efficiency of these projects a method for a “rapid analysis” is needed to assess their feasibility. If applied, only relevant data on specific projects need to be inserted in the calculations to achieve the results.

1 CO_2 Capture

Coal-fired plants

According to estimates, CO_2 capture is the most expensive element of the CCS chain, being responsible for 60-70% of total costs (IPCC, 2005; Toth & Miketa, 2011).

In this paper only sources of CO_2 from the energy sector (namely, coal- and gas-fired power plants) are considered. Cost assessment is based on post-combustion amine capture technology as the most mature and relatively easy to implement at an already functioning plant. The costs of construction and maintenance were obtained from the Integrated Environmental Control Model (Carnegie Mellon University, 2015).

The main technological characteristic of a CO_2 source that has to be taken into account while assessing capture costs is its net output. Figure 1.1 demonstrates the relationship between total levelized annual capital and net output of the coal plant.

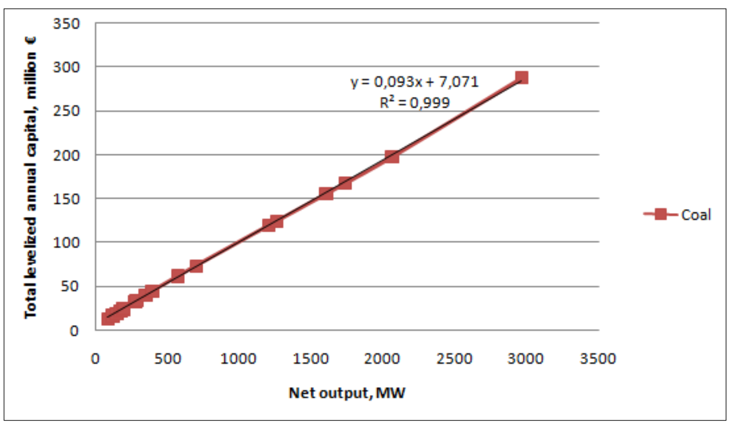

Figure 1.1: Relationship between total levelized annual capital and net output of the coal power plant
Source: Own calculations

In analytical form, discounted capture costs per tonne of CO_2can be presented in the following way:

$$Cost_{cap} = 0{,}703 \cdot \frac{(0{,}093 \cdot N + 7{,}071)}{0{,}091 \cdot {Q_{co_2}}^{e}}, \text{€/t} \quad (1.1)$$

N - net output of the power plant, MW;
${Q_{co_2}}^{e}$ – amount of CO_2 emitted by the source during the discount period, Mt.

Here and later discounted costs per tonne of CO_2 have been calculated for a lifespan of 25 years, at a discounting rate of 10%.

Obviously, the absolute value and structure of CO_2 capture costs differ in cases of retro-fitting and construction of a new plant (Figure 1.2). Yet in both cases the major costs are associated with the base plant equipment (steam generator, turbine island, coal handling) and CO_2 capture system (CO_2 absorber vessel, drying and compression unit).

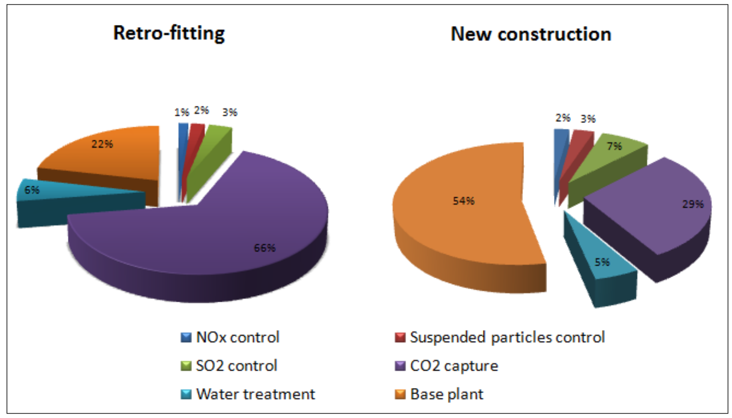

Figure 1.2: Structure of CO_2 capture costs for retro-fitting and new construction
Source: Own calculations

A comparison of construction costs for a 500-MW coal plant with and without CO_2 capture (Figure 1.3) demonstrates an increase in total costs by 48%, in specific costs – up to 86% in the former case.

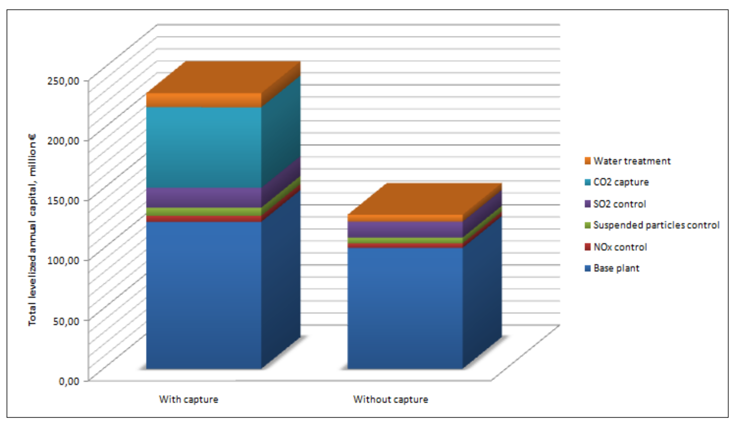

Figure 1.3: Comparison of construction costs for coal plants with and without CCS
Source: Own calculations

Despite such difference in costs, some countries manage to promote clean coal technologies – by either prohibiting construction of coal plants without CCS (Canada) or introducing a carbon tax (Norway, UK, Japan). One way or another, an increase in costs due to implementation of capture process has to be compensated by tax or penalty payments in case capture is not implemented.

Gas-fired plants

The methodology of capture cost assessment for gas plants is the same as the one applied for coal plants. Likewise, the main technological parameter of the CO_2 source is its net output. The established correlation between total levelized annual capital of the gas plant and its net output is presented in Figure 1.4

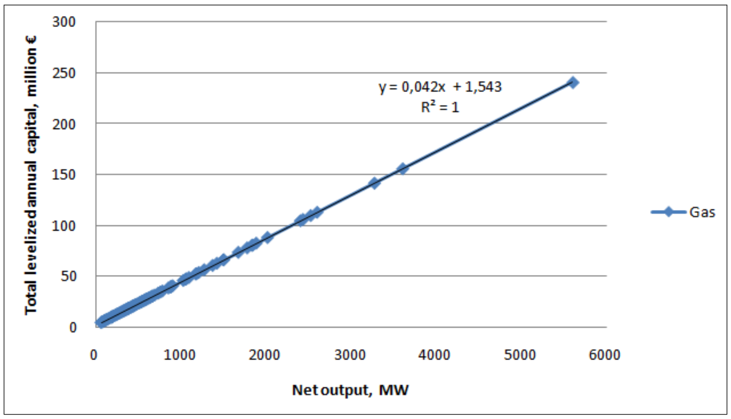

Figure 1.4: Relationship between total levelized annual capital and net output of the gas power plant
Source: Own calculations

Analytically, discounted capture costs per tonne of CO_2 can be presented as follows:

$$Cost_{cap} = 0{,}702 \cdot \frac{(0{,}042 \cdot N + 1{,}543)}{0{,}091 \cdot Q_{co_2}{}^{e}}, \text{€/t} \quad (1.2)$$

An analysis of this cost structure (Figure 1.5) demonstrates that apart from CO_2 capture itself, a significant share of costs falls on the process of natural gas combustion– acquisition or retrofitting of gas and steam turbines, steam generator, feed water system etc.

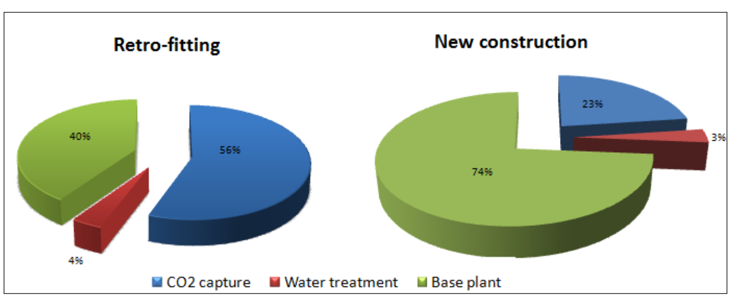

Figure 1.5: Structure of CO_2 capture costs for retro-fitting and new construction
Source: Own calculations

The implementation of CO_2 capture technology at a gas plant will result in a similar cost increase as in the case of a coal plant with the only difference in absolute values – the construction of a gas plant with the same net output is 2.5 times cheaper (Figure 1.6).

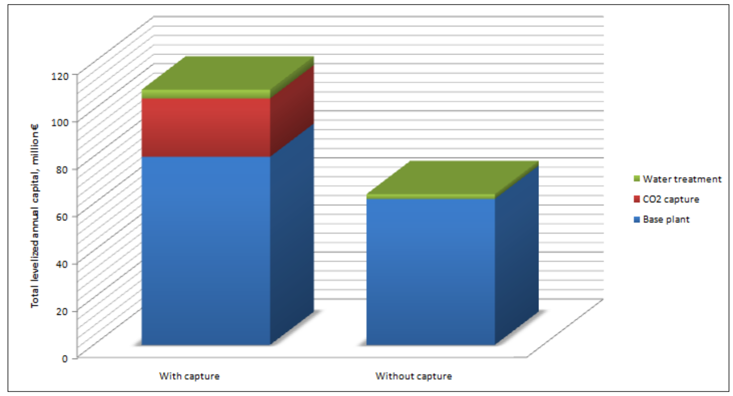

Figure 1.6: Comparison of construction costs for gas plants with and without CCS
Source: Own calculations

To sum up, currently in Russia prices for coal and natural gas are on the same level (on a TOE-basis), and the construction of power plants with CCS is much cheaper for gas than for coal, both in terms of capital costs and per kWh. However, specific costs for a tonne of CO_2 captured will follow an opposite trend due to greater bulk emission from coal plants.

2 CO_2 Transport

In the paper costs of CO_2 transport via pipeline were assessed. The economics of CO_2 transport largely depend on piping distance. Other factors of importance are the pipeline diameter and the CO_2 flow rate.

The longer the distance and the larger the amount of CO_2 transported annually, the larger the required diameter – it has to be taken into account, however, that the performance of the system has to be adjusted to a set of standard diameters, which makes the relationship rather stepped than linear (Figure 2.1).

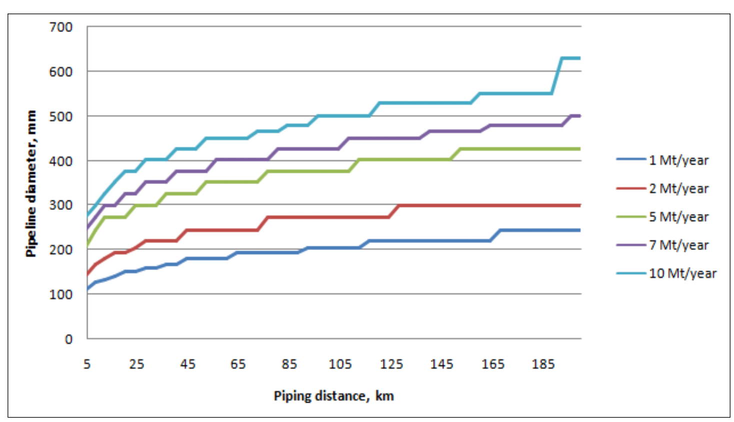

Figure2.1: Relationship between transportation distance, annual CO_2 flow and pipeline diameter
Source: Own calculations

Cost assessment for CO_2 transport was carried out on the basis of compression costs (Woodhill Engineering Consultants, 2002) and costs of pipeline construction (OZTI, 2010)adjusted to prices of 2015 (Inflation calculator, 2015).

Analysis of statistical data from aforementioned sources allowed to derive the following equations:

- For $L < 100\ km, Q < 1Mt$:

$$Cost_{tr} = \frac{0{,}005 \cdot L^{1{,}0264} + 0{,}579 \cdot L^{0{,}0264}}{0{,}091 \cdot Q_{co_2}{}^{tr}}, \text{€/t} \quad (2.1)$$

- For$L > 100\ km, Q < 1Mt\ or$ $L < 100\ km, Q > 1Mt$:

$$Cost_{tr} = \frac{0{,}005 \cdot L^{1{,}0298} + 0{,}578 \cdot L^{0{,}0298}}{0{,}091 \cdot Q_{co_2}{}^{tr}}, \text{€/t} \quad (2.2)$$

- For$L > 100\ km, Q > 1Mt$:

$$Cost_{tr} = \frac{0{,}008 \cdot L^{1{,}0198} + 0{,}626 \cdot L^{0{,}0198}}{0{,}091 \cdot Q_{co_2}{}^{tr}}, \text{€/t} \quad (2.3)$$

L - piping distance, km;
$Q_{co_2}{}^{tr}$ - amount of CO_2 transported during the discount period, Mt.

In general, transport costs per tonne of CO_2 range from 0.15 to 8.6 €/t and clearly demonstrate economy of scale – the more CO_2 is transported, the lower are transportation costs. However, capacity utilization is an important issue here – if a 414-mm pipeline, designed to transport 5-7 Mt/year, is working only at 20% capacity, the economic efficiency of such project raises doubts.

3 CO_2 Injection

Storage costs

The paper focuses on CO_2 storage in depleted oil-fields for the purpose of EOR. Estimates of injection costs are based on empirical data from US oil-fields (Lewin & Associates, 1981) adjusted to prices of 2015 (Inflation calculator, 2015).

Storage costs include:

- Costs of drilling and completion;
- Costs of production equipment;
- Costs of injection equipment;
- Costs of CO_2 processing facilities;
- Operation & maintenance costs.

The economics of CO_2 storage mainly depend on three parameters – well depth, number of wells (can be calculated as a function of oil productive area) and annual CO_2injection rate. Figure 3.1 demonstrates the effect of these factors on specific costs of injection. As the depth increases, the costs grow exponentially, whereas dependence on the number of wells is linear.

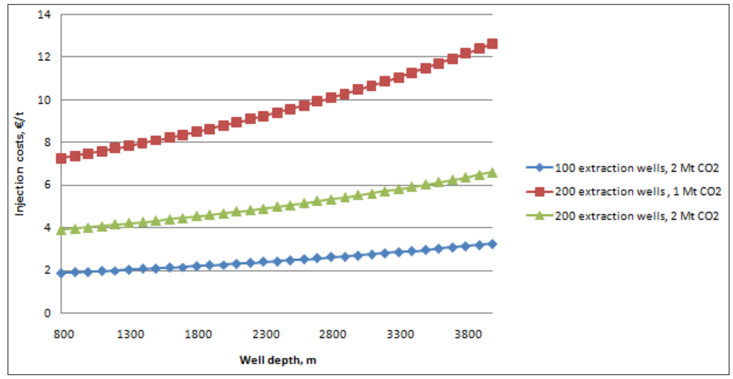

Figure3.1: Dependence of injection costs on well depth, well number and CO_2 injection rate
Source: Own calculations

The costs of monitoring also have to be taken into account at this stage – analysts estimate them in a range of 0.1-0.28 €/t (Toth & Miketa, 2011), which accounts only for a minor share in the overall costs of CO_2 injection and storage (1-2%).

The discounted injection costs can be calculated as follows:

$$Cost_{inj} = \frac{0{,}205 \cdot \frac{Spr}{230} \cdot e^{0{,}00019d} + 0{,}209 \cdot (\frac{Spr}{230})^{0{,}7519}}{Q_{co_2}{}^{inj}} + 0{,}172, \text{€/t} \quad (3.1)$$

S_{pr}–oil productive area, thousand m^2;
d–well depth, m;
$Q_{co_2}{}^{inj}$ - amount of CO_2 injected into the reservoir during the discount period, Mt.

It has to be noted that, if a project involves the injection of CO_2 from various power plants, the costs of the total injected amount, as a sum of individual amounts, is computed as a sum of the costs of each amount according to (3.1). In any case, $Q_{co_2}{}^{inj}$ should not exceed the maximum possible amount of CO_2 to be injected and has to be sufficient to facilitate EOR at one or more oil beds of the field.

EOR revenue

In case of EOR, the element of CO_2 storage holds a special place in the CCS chain due to the fact that it is through the injection of CO_2 that the revenue is generated and investment costs are partially or entirely compensated.

Some researchers hold an opinion that the storage potential of depleted oil-fields is so scarce that it can be of interest only at demonstration stage of CCS projects (Alvarado &Manrique, 2010). This is true only if CO_2 injection stops right after EOR operations are ended. In essence, during EOR, the limited CO_2 storage potential occurs because more than 70% of CO_2 mixes with the oil and eventually gets back to the surface. However, when the EOR stops, selected oil-fields have all the necessary infrastructure for further CO_2 injection just like saline aquifers or any other geological reservoir, and in the latter case their storage potential will be a lot more significant.

In the reservoir injected CO_2 mixes with oil and reduces its viscosity. Through a volumetric expansion of oil in place, CO_2 literally pushes it out of the pores to the productive wells. In the oil beds treated with CO_2, residual oil saturation decreases by a factor of 1.5 to 2, and sweep efficiency can reach 80%, which is 15 - 25% higher than the one achievable through water flooding (Surguchev, 1985).

From the viewpoint of technology, the main parameters defining efficiency of an CO_2-EOR operation are the following:

- Reservoir conditions (pressure, temperature);
- Water saturation and properties of water in place;
- Oil saturation;
- Oil density and viscosity;
- Chemical composition of oil in place;
- Effective porosity;
- Rock permeability;
- Presence of a gas cap.

A combination of listed parameters defines the amount of oil that can be additionally recovered from the field. Another important issue is the amount of CO_2 that has to be injected into the reservoir for this purpose. In the paper it was assumed that an average demand in CO_2 is 2.5-5.35 t/t of oil recovered (Surguchev, 1985).

As the recovery of oil is not uniform by year (Figure 3.2), the injection rates of CO_2 will also follow a decreasing trend.

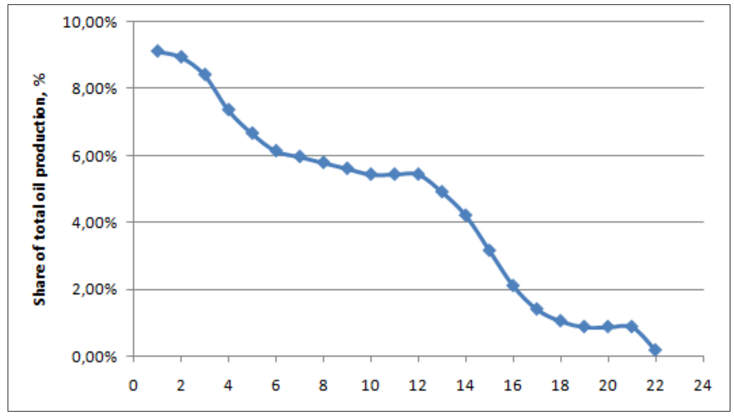

Figure3.2: Dynamics of oil production using tertiary recovery methods as an annual share of total oil production.
Source: Dooley et al., 2010

Part of injected CO_2 (15-25%) stays trapped in rock pores – so called reservoir losses. All the rest of CO_2 mixes with oil in the reservoir and gets to surface facilities, where it is separated from oil, processed and re-injected underground (Figure 3.3).

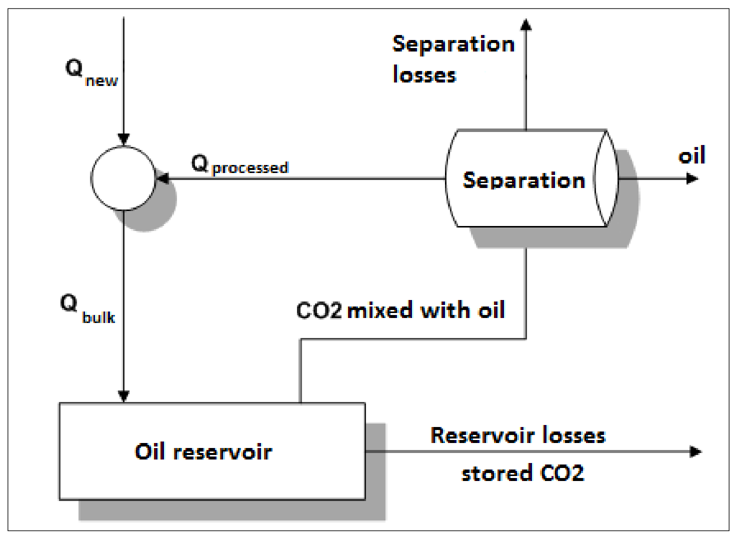

Figure3.3: Concept chart of CO_2 and oil flows during EOR operations
Source: Own construction

To calculate the economic efficiency of CO_2-EOR projects it is essential to understand the breakeven price of CO_2. In this paper approximately 2000 oil reservoirs of Russia have been assessed at an oil price of 48.79 \$/bbl, and the CO_2 breakeven price was found to be between 22.64 and 30.71 €/t with an average of 26.3-27 €/t (Figure 3.4).

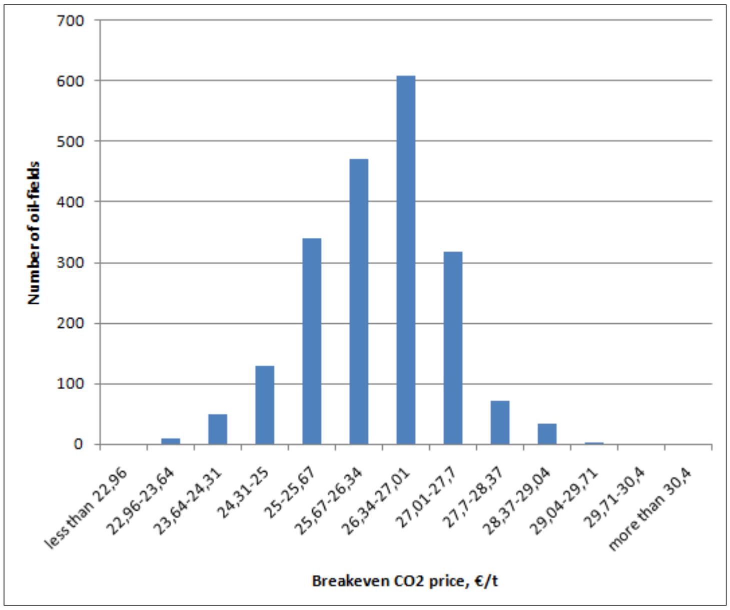

Figure3.4: Breakeven CO_2 price distribution at Russian oil-fields
Source: Own calculations

Assuming that the amount of CO_2 to produce 1 tonne of oil is constant, the breakeven CO_2 price depends neither on amounts of oil recovered nor on amounts of CO_2 injected. The empirical formula of the breakeven CO_2 price will be the following:

$$P_{co2}{}^{b/e} = \frac{21973{,}04}{\rho_{oil}}, \text{€/t} \qquad (3.2)$$

ρ_{oil} - oil density, kg/m^3.

4 Results & Discussion

From an economic viewpoint, the efficiency of CO_2-EOR projects can be assessed by comparing capture, transport and storage costs with a breakeven CO_2 price, which implies an inequality composed of aforementioned formulas (1.1- 1.2), (2.1-2.3), (3.1-3.2).

The high differentiation of the projects on each stage does not allow assessing their efficiency using only one formula, so the corresponding part of the inequality has to be chosen separately for each stage taking into account technological characteristics of the project (Table 4.1)

Table4.1: Composition of an inequity to assess economic efficiency of CO_2-EOR projects

Stage \Option	A	B	C
Capture	Coal (1.1)	Natural gas (1.2)	-
Transport	<100km, <1Mt (2.1)	<100 km, >1 Mt >100 km, <1 Mt (2.2)	>100km, >1Mt (2.3)
Storage	Depleted oil-fields (3.1)	-	-

Source: own construction

For example, the inequality for the project of capturing 2.5 Mt CO_2 from a gas power plant and transporting it to an oil-field 150 km away will be as follows: (B+C+A $\leq$P$^{b/e}$):

$$0{,}702 \cdot \frac{(0{,}042 \cdot N + 1{,}543)}{0{,}091 \cdot Q_{co_2}{}^{e}} + \frac{0{,}008 \cdot L^{1{,}0198} + 0{,}626 \cdot L^{0{,}0198}}{0{,}091 \cdot Q_{co_2}{}^{tr}} + \frac{0{,}205 \cdot \frac{Spr}{230} \cdot e^{0{,}00019d} + 0{,}209 \cdot (\frac{Spr}{230})^{0{,}7519}}{Q_{co_2}{}^{inj}} + 0{,}172 \leq \frac{21973{,}04}{\rho_{oil}} \qquad (4.1)$$

Assuming that the oil price and discount rate are constant, the main parameters defining the economic efficiency of the project are:

N – power plant net output, MW;
$Q_{co_2}{}^{e}$ – amount of CO_2 emitted by the plant during the discount period, Mt;
L–transportation distance, km;
$Q_{co_2}{}^{tr}$ - amount of CO_2 transported during the discount period, Mt;
S_{pr} - oil productive area, thousand m^2;
d - well depth, m;
$Q_{co_2}{}^{inj}$ - amount of CO_2injected into the reservoir during the discount period, Mt;
ρ_{oil} - oil density, kg/m^3.

The results obtained with formula (4.1) can now be compared with those generated by a detailed cost assessment to assess their accuracy.

The inequality can be used for a rapid analysis of CO_2-EOR projects at the initial stage of their economic efficiency assessment in order to decide whether a more detailed investment analysis is needed. The tool establishes a relationship between technological and economical parameters of the project and helps to sort out clearly inefficient projects, at the same time giving a rough estimation of probable profits.

5 Conclusion

Based upon cost estimation of separate stages of a CO_2-EOR project, a method for a rapid analysis has been developed that allows to assess the costs of CO_2 capture, transport and storage, to compare them with the breakeven CO_2 price and draw preliminary conclusions on the economic efficiency of the project judging by its technological parameters (net output of the power plant, piping distance, oil-field characteristics etc.).

Cost estimations have shown that the most expensive stage of CCS chain is the CO_2 capture. Capture costs depend on the net output of the power plant, type of fuel and capture technology. CO_2 capture increases price of electricity and according to calculations costs 14.3-20 €/tonne of CO_2 captured.

CO_2 transportation costs are defined by the transportation distance, the pipeline diameter the and annual CO_2 flow rate. Estimations vary from 0.15 to 8.6 €/t. At this stage there is an opportunity to reduce costs through economies of scale – in case of large-scale implementation of CCS and simultaneous functioning of several projects situated relatively close to one another, the construction of an extensive pipeline network of greater diameter will allow merging CO_2 flows from different projects.

While assessing storage costs, the focus was made on CO_2 injection into depleted oil fields in order to enhance oil recovery efficiency. In this way the costs associated with earlier stages of CCS – capture and transport – can be partially or entirely compensated. Injection costs vary greatly depending on depth of the oil bed and oil productivity area.

Revenues of CO_2-EOR projects are a function of recovery efficiency and oil market conditions. On average, breakeven CO_2 price varies between 22.64 and 30.71 €/t, but more accurate conclusions about the efficiency of the project can be made based on the detailed analysis of a “source-sink” couple.

Combining empirical cost functions for each element of the CCS chain with the value of a breakeven CO_2 price, an inequality was established which at the initial stage of the project assessment can replace a more labor-intensive investment analysis and give an initial estimation of the project’s economic efficiency.

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