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CO_2-EOR business opportunities in Romania and Turkey

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Abstract

To ultimately avoid CO_2 emissions into the atmosphere, the European research project "ECO-BASE" (Establishing CO_2 enhanced Oil recovery Business Advantages in South Eastern Europe, 2017-2020) has identified a number of candidate CO_2-EOR oil fields that could benefit economically from nearby industrial sources of CO_2, whilst permanently sequestering the captured CO_2 in the subsurface. On the near term, however, the objective of the ECO-BASE project was to raise sufficient interest among the emitters, oil field operators and national governments to develop a common understanding of the business opportunities and allow resources to be spent to further mature potential business cases along the various decision gates of their respective project maturation processes. To this end, two candidate oil fields have been investigated in-depth, i.e. the large Batı Raman heavy oil field in southeast Turkey, and the Brădești oil field in southwest Romania. Their business cases for CO_2-EOR combined with permanent CO_2 storage are discussed in this paper. It can be concluded that, in South Eastern Europe, CO_2-EOR has the potential to justify economically first-of-a-kind CO_2 infrastructure and sequestration projects that otherwise would not have been feasible.

Keywords: Batı Raman oil field; Brădești oil field; CO_2-EOR; CCS; CCUS; ECO-BASE; Romania; Turkey

1. Introduction

The Paris Agreement calls for greenhouse gas emission regulations consistent with keeping the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5 °C. Capturing CO_2 from industrial plants and permanently storing it in the subsurface (CCS) is an essential part of reaching this target, and commercial utilization of the captured CO_2 is one of the mechanisms to create revenues, and hence, support the business case for CO_2 storage. The objective of the ECO-BASE project was to investigate the potential of commercially deploying carbon capture, utilization and storage (CCUS) by screening available data, developing CCUS roadmaps and exploring for potential CO_2 Enhanced Oil Recovery (CO_2-EOR) pilots in South-East Europe (SEE). ECO-BASE has assessed the potential for CCUS (i.e. CO_2-EOR) through the following activities:

- Creating an inventory of CO_2 sources (potential capture projects) and sinks (potential sites for CO_2 usage through CO_2-EOR) in Romania and Turkey;
- Identifying possible source/sink clusters and performing case studies to evaluate the business potential of combining CO_2-EOR and permanent CO_2-storage;
- Setting up regional CCUS development plans through CO_2-EOR roadmaps;

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– Organizing knowledge transfer workshops for local CCUS stakeholders.

Through selected case studies in Romania and Turkey, the ECO-BASE project provided insight into prospective revenue streams and business models for CO_2-EOR in SE-Europe, with a long-term view to large-scale CCUS regional deployment. The project was financed in part by the EU ACT programme (see Acknowledgments), and carried out by organizations in Turkey, Romania, the Netherlands, and Norway. The case studies focused on the technical and business aspects of CO_2 emitters and oil field operators, potentially in demand for CO_2, to analyze the full value chain.

A prerequisite for realizing a CCUS/CO_2-EOR chain, i.e. with the CO_2 captured from industrial plants, is that all actors along the value chain have a positive business case. This includes the emitter capturing CO_2, the CO_2 transport operator that operates the pipeline, ship, or trucking facilities, and the operator of the oil reservoir where the CO_2 is utilized and stored. The business cases are typically assessed by defining a series of key performance indicators, with quantitative estimates of how the activity, as defined by a series of alternative decision pathways, may lead to positive future discounted cumulative net cash flows (NPV), including the associated uncertainties. The basic premise of a rational investment decision process is that the internal rate of return must exceed each company's weighted cost of capital, plus a risk and a profit margin. Business risks were identified and quantified, with due regard to the 'first of a kind' infrastructure nature and commercial complexity of these projects.

The remainder of this paper is organized as follows. In the next *Methodology* section, the workflow for the quantitative valuation of investment risks and rewards of both case studies is described. This is followed by a description of the *Cluster selection* process, including a brief description of the case studies. In the *Results* section, the decision pathways, KPIs and uncertainties modelled are explained. The paper ends by the *Conclusion* section.

Nomenclature

BAU	Business As Usual
bbl	Barrel, volumetric measure for oil (0.159 m3)
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage (in this case, utilisation means CO_2-EOR).
CO_2-EOR	Enhanced Oil Recovery by injecting CO_2 into the oil column of the reservoir.
ECCO (tool)	A CCS chain software analysis tool to compute the mass flows and cash flows resulting from investments in CO_2 capture from industrial plants, and investments in transport infrastructure and permanent subsurface storage.
ECO-BASE	Establishing CO_2 enhanced Oil recovery Business Advantages in South-eastern Europe, an ACT project to assess the potential of CO_2-EOR, combined with permanent CO_2 storage. The CO_2 is to be captured from industrial installations.
EMV	Expected Monetary Value, the average NPV from probabilistic processing of a technical/economic model.
EOR	Enhanced Oil Recovery
EORStore	CO_2-EOR, combined with permanent CO_2 storage in the oil reservoir
FID	Final Investment Decision
IRR	Internal Rate of Return, the discount rate at which NPV=0. The IRR is a measure for *capital efficiency*.
KPI	Key Performance Indicator, a decision-making criterion for an investment project
M€	Million Euro
Mt	Million ton (of CO_2)
NPV	Net Present Value, the cumulative discounted Net Cash Flow over the lifetime of a project
OIIP	Oil Initially In Place, the volume of oil in the subsurface reservoir rock formation prior to production
OPEX	Operating Expenditure
RF	Recovery Factor, the fraction of the Oil Initially In Place that will be produced to surface
TC	Type Curve, describing the relationship between Hydrocarbon Pore Volumes of CO_2 and water injected in an oil reservoir, and the Hydrocarbon Pore Volumes of oil, CO_2 and water produced from that oil reservoir. Steady-state conditions are assumed. Typically, this relationship is obtained from numerical reservoir simulation studies.
WTP	Willingness To Pay

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2. Methodology

In most commercial companies, the process of maturing investment projects is handled through a set of Decision Gate Reviews. At each decision gate, senior management decides to either cancel the project, or to move forward to the next phase, with or without special conditions. This process provides a controlled way of monetizing a business opportunity by moving along a series of well-defined project steps from first idea to technical and economic feasibility, concept selection, detailed design, Final Investment Decision (FID), development, operation and, finally, post implementation review and lessons learned.

As part of the technical and economic cluster analysis in Romania and Turkey, two detailed cases were selected as representing the 'low hanging fruit' and potentially providing the business incentive to initiate a 'first-of-a-kind' infrastructural project in their respective regions. A problem was however that only a limited amount of oil field data was publicly available, and that other field-specific data was not made available to ECO-BASE. To complete the case studies, the scarce published data from the actual sites were combined with publicly available correlations on how reservoir oil may benefit from CO_2-EOR. This was complemented by a detailed uncertainty analysis to compute ranges of possible outcomes (KPIs).

To explore and quantify the potential opportunities the following workflow was followed:

- First, frame the alternative decision pathways for each case study, describe the main uncertainties (physical and/or economical), establish the possible economic scenarios, and create the corresponding decision tree. Decision trees combined with probabilistic analysis represent a structured way of providing insight in how to address the risks and opportunities resulting from model input parameter uncertainties and from the selected series of (controllable) decisions.
- Second, evaluate the decision tree using an existing, analytical tool named ECCO-tool [2]. The ECCO-tool is an integrated technical/economic CCS multi-actor, multi-asset value chain assessment tool and was developed during the ECCO project [1]. It was made available to ECO-BASE project partners. When properly conducted, many possible scenarios (uncertainties) emerge during the framing process, including alternative decisions that can be made when monetizing a project. Also, decisions that respond to future information being revealed as time progresses can be included.
- The third step in the workflow is to collect the pertinent data and to estimate the uncertainties in the project. For example, the EOR reservoir performance of the Turkish case (i.e. historical CO_2-EOR data), but also analogue data, published correlations [3] etc. were used and combined with complementary reservoir numerical simulation modelling performed by the ECO-BASE team. This resulted in a series of EOR "Type Curves (TCs)", that link the cumulative hydrocarbon pore volume of CO_2-EOR oil, water and CO_2 produced, on the one hand, to the cumulative hydrocarbon pore volume of CO_2 injected, on the other hand (the latter was used in the Turkish case). In case of water-alternating-gas injection (WAG-injection), the combined impact of CO_2 and water injection can be related to produced volumes (this was used in the Romanian case). These type curves were supplied to the ECCO tool and used to estimate the EOR incremental oil as a function of time and as a result of the rate at which CO_2 (and water) is injected. The total field CO_2 storage capacity, extra oil produced by the EOR operation etc. was estimated using a combination of material balance and reservoir simulation modelling, where the fraction of back-produced CO_2 was used to estimate the CO_2 'lost' to the formation (i.e. assumed permanently stored).
- For the Romanian case, the mass balance of injected CO_2 and water, and produced CO_2, water and hydrocarbons, was used to evaluate under different injection and production rates the overall economy for the field operator. This was summarised in so called 'type curves'. To compute the economics, the field operator was assumed to purchase CO_2 at a wellhead price that meets the costs required for the capture and transport operators to have a positive business case. In addition to the CO_2 wellhead price, a series of other OPEX and CAPEX cost elements were included for the oil-field operator (related to well costs, various opex costs, separation and re-compression of back-produced CO_2 etc). The revenue consisted of the sales of the incremental oil production, i.e. the oil in addition to the production without CO_2-EOR. Cost elements for the handling of (back-)produced fluids, i.e. the separation, compression and re-injection of CO_2 were included in

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the analysis.

- Finally, uncertainty and sensitivity analyses were carried out using the Monte Carlo functionality of the XL statistical plug-in Crystal Ball. This was done to assess the impact of uncertainties in the physical reservoir properties (STOIIP), in reservoir performance (type curves), and in the planning and financial parameters (CAPEX, OPEX, revenues, timing) on the various Key Performance Indicators, such as net present value (NPV) and internal rate of return (IRR). For the global parameters (oil price, CO_2 price on the EU-ETS, inflation, CAPEX and OPEX escalators, etc.) time-series were taken from the publication 'Blue hydrogen as accelerator and pioneer for energy transition in the industry' [4].

3. Cluster selection

As a first Romanian CCS chain, the Brădești oil field in Oltenia-West, Romania, was selected as potential CO_2-storage, together with the nearby Işalniţa coal-fired power plant. This first CCS chain could at some later stage be extended to other oil fields and CO_2 emitting industries. The cluster of potential sources and sinks is located in a region producing over 30% of the national energy output and responsible for a significant share of the national industrial emissions (almost 35%). This initial CCS chain would capture the CO_2 at the powerplant, transport it by a 15 km pipeline to the Brădești oil field, where it would be used for CO_2-EOR, and eventually store the CO_2 permanently in the oil-bearing layers. The business case was evaluated from the perspective of the oil field operator: at which CO_2 wellhead price (as mutually agreed in a long-term contract between the emitter and the oil field operator) would he have a positive business case with an IRR that is commensurate with the investment risk incurred? In other words: what would be the oil field operator's 'Willingness To Pay' (WTP) for CO_2 delivered at the wellhead? The perspective for the power plant operator was: can this WTP wellhead price yield an IRR that is commensurate with the investment risk for a capture plant? For the pipeline operator, it was assumed that only his costs (discounted CAPEX + OPEX) needed to be recovered through a tariff per ton of CO_2 transported.

The 'Turkish case' consisted of analyzing whether one could economically prolong the ongoing CO_2-EOR operation in the Batı Raman oil field using captured anthropogenic CO_2 rather than the CO_2 from the depleting natural gas deposit in the Dodan natural CO_2 reservoir. The Dodan CO_2 reservoir will soon be unable to meet CO_2-demand from the Batı Raman oil field, and an alternative source is required to continue the CO_2-EOR operation. Dodan is connected to the Batı Raman field with an 82 km long pipeline. The Batı Raman oil field is a well-documented case, it is the largest oil deposit in Turkey with approximately 300 Million standard m^3 of oil in place and although the oil production has been going through phases of pressure decline, water injection and, since 1986, a combination of infill drilling and continuous CO_2 injection, the average recovery factor reached some 6% only in 2011 [5]. In our case study, two CO_2 sources were considered: the oil refinery in Batman and the cement factory in Kurtalan, both located in the vicinity of the existing CO_2 transport infrastructure between the Dodan field and the Batı Raman oil field.

4. Results

4.1. Romanian Case

Brădești is an oil field discovered in 1970 and that started production in 1971. It is currently approaching its end of life. Oil is produced from the Triassic, Sarmatian and Dogger formations. For the ECOBASE case study, only the Triassic formation was considered EORStore reservoir. The Işalniţa coal power plant is located only some 15 km away from the Brădești oil field and, consequently, the costs of connecting the two by a CO_2 pipeline, i.e. if the power plant were to be equipped with a CO_2 capture plant, would be relatively low. Nevertheless, the risk of developing this early infrastructure is considered high and no plans have been formulated to date.

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Due to the unavailability of field-specific data and the lack of production history, analogue data from selected CO_2-EOR projects in the United States was used in order to estimate the Brădești reservoir behaviour under CO_2 flooding conditions. The type curves were generated using an industry standard reservoir simulator (ECLIPSE300 by Schlumberger). To assess the uncertainty in CO_2-EOR reservoir performance, three different type curves were generated, i.e. for the low, medium, and high incremental oil recovery cases (Figure 1). These curves were used in all economic evaluations of the Romanian case and supplied to the ECCO tool according to the decision tree given in Figure 2.

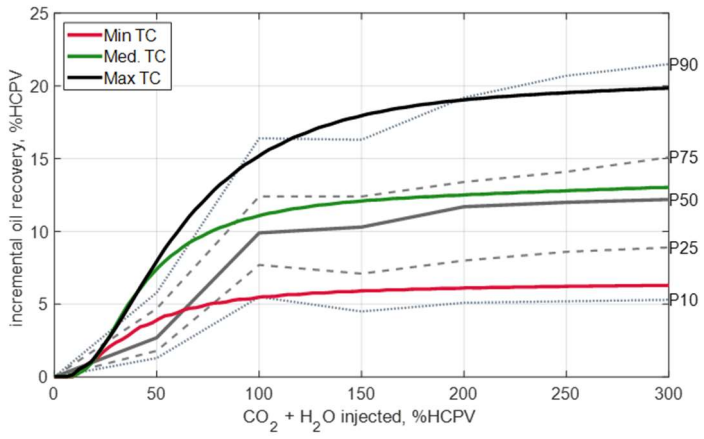


Figure 1. Minimum, median and maximal type curves of incremental oil recovery compared with percentiles for historical US projects used in ECOBASE simulations for the Romanian case.

To analyse the Romanian case of capturing CO_2 at the Işalniţa power plant and transporting the CO_2 to the Brădești oil field, the main alternative decisions, and main uncertainties (scenarios) were framed. This resulted in the decision tree displayed in Figure 2 below.

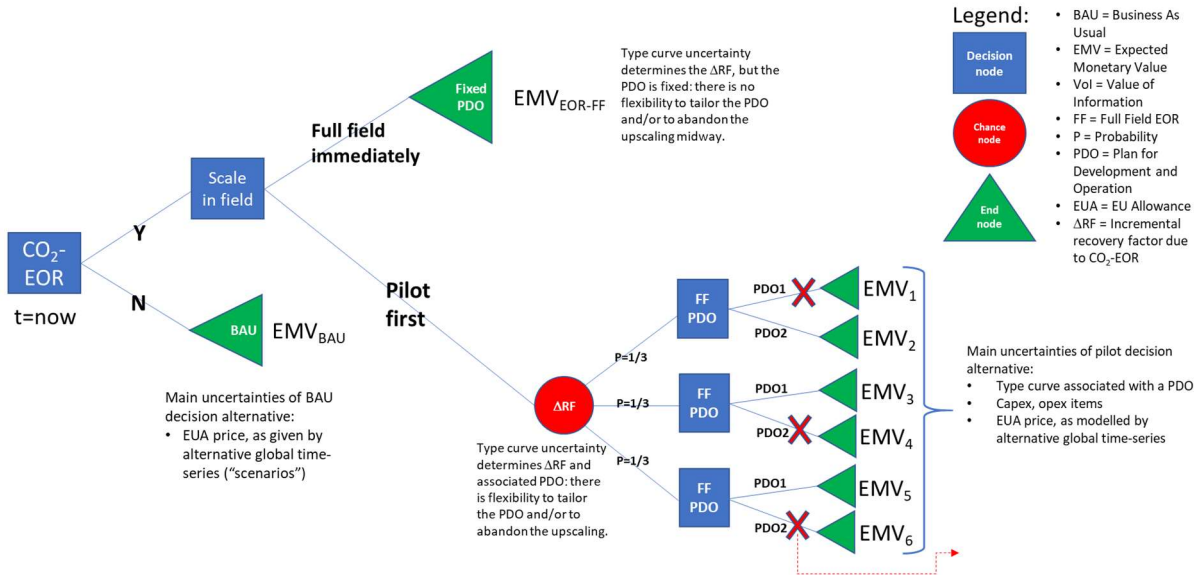


Figure 2. Decision tree for Romanian case with several scenarios defined: Business as usual, direct full field implementation of EORStore and application of EORStore after pilot test

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As can be seen from Figure 2, three options were identified from the perspective of the Brădești field operator: to continue with business as usual (BAU, i.e. continue water injection), to deploy CO_2-EOR over the full field from the onset of CO_2 injection operations, thereby assuming all risks deriving from this decision (mainly the uncertainties related to the reservoir performance), or to start with a 5-year pilot prior to full field deployment. Our simulations showed that in either case deploying CO_2-EOR is more profitable than the business as usual case. However, the NPV is quite sensitive to the unknown future oil price and to the poorly known characteristics of the reservoir. The reservoir characteristics used are merely educated guesses as we did not obtain access to the operator's (confidential) reservoir data and used analogue type curves. The KPIs assuming a 10% discount rate for the Romanian case are reported for the last year of economic production in Table 1 below.

Table 1. Overview of end results from the reference case simulations for BAU, pilot, full field EOR after pilot and full field EOR from start, respectively. These point estimates represent key performance indicators for the cases modelled with the ECCO tool.

	BAU	EOR full field from start 2025			EOR full field 2030			Pilot 2025-2029 (10% of the field)		
	Water inj.	Low TC	Med TC	High TC	Low TC	Med TC	High TC	Low TC	Med TC	High TC
Last year of production	2044	2037	2041	2045	2042	2046	2051	2029	2029	2029
NPV, M€	67.8	-29.6	269	423.8	-41.6	207.3	365.7	-23.4	-3.9	0.4
CAPEX, M€	n.a.	9.13			8.63			0.66		
Tot oil&gas sales (discounted), M€	258.3	463.5	846.8	1093.4	411.5	714.1	941.3	29.1	51.3	56.2
Tot Gov take (discounted), M€	44	83.3	173.2	227.9	81.3	164.2	213	3.5	7.9	9.1
Avg oil prod cost of proj. period, €/bbl	29.7	78.8	34.4	28.2	78.3	33	28	65.3	44.6	36.4
Tot cost of CO_2 (bought+recycled), M€	n.a.	285.6	372.4	467.2	286.9	361.5	474.9	28.5	25.6	24.5
Tot CO_2 bought from Işalniţa, Mt	n.a.	60.2	113.7	160.2	87.4	138.5	181.7	22	22	22
Oil produced by CO_2, MMbbl	n.a.	17.3	36.3	56.6	16.5	34.6	53.2	0.8	1.4	1.6
Additional recovery by CO_2, %	n.a.	5.90%	12.40%	19.30%	5.80%	12.20%	18.80%	5.30%	9.50%	10.70%
Total recovery, %	33.80%	36.50%	44.10%	51.40%	39.50%	47.30%	54.20%	35.80%	40.50%	41.50%

Obviously, the BAU case carries the lowest risk. However, BAU also implies the lowest average NPV ('expected monetary value' or EMV). To further assess the risk vs. reward relationship, the CO_2-EOR case was subjected to a sensitivity analysis offsetting the full field deployment from the onset vs. pilot testing first. Implementing full field CO_2-EOR from the onset is on average more profitable, however this comes at a larger risk than doing a pilot test first. Reservoir performance (as described by the type curves in our methodology) is the key factor influencing the economic performance of the operation (as can be seen in Table 1 by comparing the NPVs of the different type curves). Should the pilot test prove the low type curve to be applicable, then capex savings of 8.5 M€ (9.13-0.66) are possible by striking the 'exit option', i.e. not upscaling the CO_2-EOR operation to the full field. Starting with a pilot test comes at the cost of present value from the immediately upscaled project, but allows the risks related to reservoir behaviour to be managed. Moreover, a pilot may also yield additional information (on reservoir performance, practical operational issues, etc.) that allows the full-scale development to be optimized further. This trade-off between present value on the one hand, and risk mitigation + upside management on the other hand, generally is in favour of conducting a pilot test prior to full-scale development.

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4.2. Turkish Case

The Batı Raman heavy oil field commenced production in 1961 and due to its low gravity (12° API) and high viscosity (600 cP). Until 1986, only 1.7% of the OIIP (1850 million stock tank bbl) has been produced by primary recovery mechanisms related to pressure depletion [5]. As a result, enhanced recovery mechanisms had been investigated [5] and CO_2-EOR emerged as the most promising recovery mechanism (Figure 3). The CO_2 originated from a nearby natural CO_2 gas field, named Dodan, and transported to the oil field for injection into the oil column. Until 2011, the oil production increased to around 110 million bbl (around 6% of OIIP) as a result of immiscible CO_2 flooding [5], and the continued CO_2 injection increased the cumulative oil recovery to 130 million bbl in 2020. Since the early 2000s, the yearly oil production rate has been increased by an extensive infill drilling program. This increased demand for CO_2 from the natural deposit in Dodan will soon however not be sustainable as a result of pressure depletion in Dodan. To prolong the high oil recovery rates from Batı Raman, new sources of CO_2 are required (especially from 2024-2026). We analyzed the Turkish case under the assumption that CO_2 would either be captured from the refinery in Batman only, or from both the refinery and the cement plant in Kurtalan (note that the Kurtalan cement plant straddles the existing CO_2-pipeline from Dodan). The captured CO_2 is assumed to be piped to the Batı Raman oil field. After framing, the main alternative decisions and main uncertainties are represented in the decision tree of Figure 4.

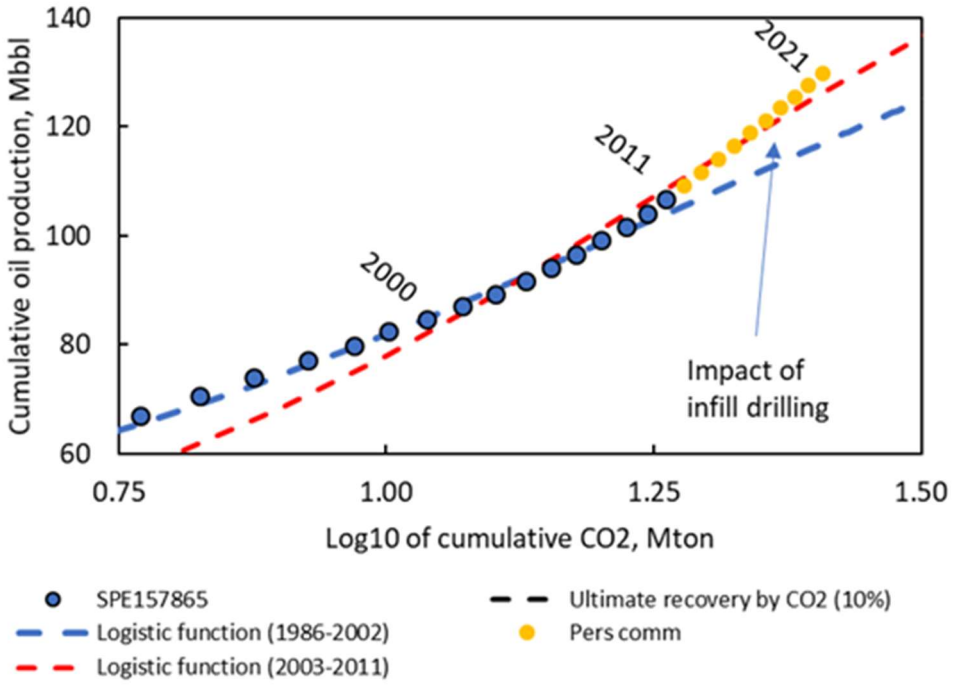


Figure 3. Historical oil production each year (blue circles) of cumulated oil production vs. cumulative CO_2 injection on a log-linear axis. The red dotted line was used for the future CO_2 driven oil recovery estimations. During 2005 to 2020 an infill drilling program has been active which is to be ceased in 2021.

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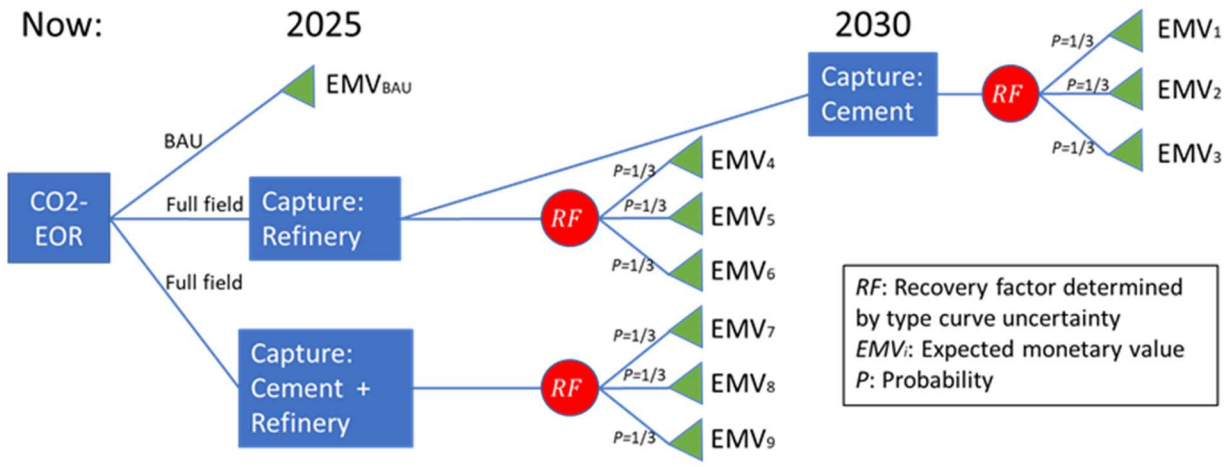


Figure 4. Decision tree for Turkish case with business as usual and two capture scenarios: from cement and refinery starting at 2025 and from refinery in 2025 and cement later in 2030.

Using the historical data provided by Sahin et al. (2012, ref. 5) in Figure 3, type curves were generated that relate cumulative oil production to the injected CO_2 (Figure 5). This was done by fitting a logistic (or analytical) function used as input to the ECCO tool. The ratio of the cumulative CO_2 stored to the cumulative CO_2 injected, i.e. the retention factor, was also calculated as 26.9% using the historical data. The back-produced CO_2 is separated, recompressed and re-injected into the oil reservoir in combination with the CO_2 delivered from the pipeline. Thus, the rate of CO_2 injected exceeds the CO_2 captured from the cement plant in Kurtalan and refinery in Batman. For the estimation of future oil, CO_2 and water production from the CO_2 injection rate these types curves were used by the ECCO tool.

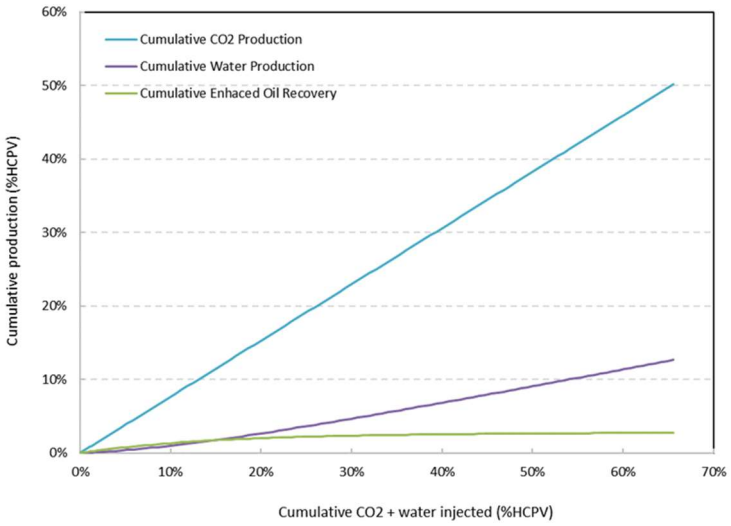


Figure 5. Type curves used in the ECCO Tool to calculate the production of oil, water, and CO_2 as function of cumulative CO_2 and water injection that is the base of economic cash flow calculations. These were based on historical CO_2-injection and oil-production data from the Batman field [5].

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The work proceeded to compute the decision paths and carry out the uncertainty analysis. When choosing for how to continue with CO_2 for EOR in the Batı Raman field, there are four decision paths that were simulated, namely the business as usual case (i.e., to deplete Dodan in 2026), source the CO_2 from the refinery in Batı Raman from 2025 with an option to source the CO_2 from the Kurtalan cement factory in 2030, or use both CO_2 sources immediately from 2025. For the base oil price scenario, the outcomes are almost the same, while when the oil price follows the high trend, the refinery capture from 2025 and simultaneous capture from the refinery and cement factory from 2025 are most profitable with the lowest financial risk. Overview of the KPIs for Turkish cases are presented in Table 2 with NPV and other parameters reported for the last year of production with a 10% discount rate. The total storage capacity at the field was estimated to be up to 16 Mt CO_2.

Table 2. Overview of the key performance indicators for Turkish cluster.

	BAU	Refinery 2025	Refinery 2025, cement 2030	Refinery and cement 2025
Last year of production	2026	2037	2040	2036
NPV, M€	116.6	197.7	287.0	410.4
Total oil sales, M€	322.8	663.8	930.3	1165.7
Total Govt. take, M€	74.1	132.6	189.0	249.4
Avg. oil prod cost, €/bbl	23.6	31.2	29.4	26.5
Total cost of CO_2, M€	6.0	57.5	112.8	151.1
Total CO_2 stored, Mt	0.6	2.1	5.5	5.38
Oil produced by CO_2, Mbbl	6.83	20.32	37.09	36.87
Total additional recovery	0.37 %	1.10 %	2.00 %	1.99 %

5. Conclusion

The main merit of the ECO-BASE project is that for the first time a methodology was developed and applied to actual case studies, despite the poor accessibility to field-specific data. This enabled the ECO-BASE team to assess the economic feasibility of CO_2 capture from industrial plants in Romania and Turkey, with CO_2 capture and transport to nearby producing oil fields. At the oil fields the CO_2 is injected both for Enhanced Oil Recovery purposes and for permanent sequestration of the CO_2 (the so called 'EORStore' concept). The methodology developed and presented to stakeholders in Romania and Turkey (i.e. government and industries) was aimed at initiating a discussion on possible next steps to further mature the concept of EORStore in Romania and Turkey.

Although actual available field data were limited, or even inaccessible due to their confidential nature, it can be argued that, potentially, significant amounts (up to tens of million tons) of CO_2 can be permanently stored in the oil reservoirs, and that this can be achieved under economically profitable conditions. This is because only a fraction of the injected CO_2 is back-produced, and then separated, compressed and re-injected. In the end, all the CO_2 transported to the field ends up in the ground, and significant value is generated to all stakeholders in the CCUS-chain by the incremental oil sales and, in case of Romania, the avoidance of having to purchase emission rights by the coal-fired power plant. Investments risks are manageable and seem commensurate with the reward, as given by the IRR metric. Stakeholders are encouraged to further investigate these possible business advantages and mature the concept to a next stage.

These 'first-of-a-kind' projects also address the role of the government to stimulate the development of an initial

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CO_2 infrastructure by providing guarantees and, if necessary, also subsidies. Follow-on projects in the designated potential regional CCS clusters, West-Oltenia in Romania and Batı Raman in SE Turkey, could profit from this initial infrastructure and would incur less risk.

It can be concluded that, in South Eastern Europe, CO_2-EOR has the potential to justify economically first-of-a-kind CO_2 infrastructure and sequestration projects that would not have been feasible without the CO_2 usage by producing oil fields.

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