ADVANCED OPTIMIZATION OF MULTI-SINK CO_2-EOR OPERATIONS IN THE CONTEXT OF LONG-TERM CCUS SUPPLY CHAIN DESIGN

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Abstract

This work describes a novel MILP formulation for the advanced optimization of CO_2 Enhanced Oil Recovery (EOR) tactical planning. The goal is to address the long-term design of supply chain network (SCN) for the carbon capture, utilization and storage (CCUS) management, developing a decision support system for the CO_2 management considering strategic and tactical decisions such as (1) the selection of carbon capture technologies, (2) the development of multi-modal transport infrastructure to match CO_2 sources with potential storage and carbon utilization nodes, and (3) the tactical planning of EOR operations with CO_2 injection. Even though many works in the literature address the CCUS problem, there is a lack of integration between all the decisions, both from the capture and the utilization side. The novelty of this paper relies on the integration of the CCUS supply chain design decisions considering a long-term planning horizon, with a particular focus in a comprehensive modelling of the CO_2-EOR operations, which are one of the most important utilization options in order to mitigate and reduce CO_2 emissions. The model maximizes the net present value considering capital and operational costs, as well as the revenues from the additional oil produced by CO_2-EOR operations and the carbon credits associated with the CO_2 sequestrated. The formulation is tested in a large case study, obtaining near optimal results in reasonable CPU times, showing the integration of capture facilities, pipelines network and the optimal allocation of captured CO_2 in several fields over a large planning horizon.

Keywords

CO_2 Enhanced Oil Recovery, Carbon Capture Utilization and Storage, Optimization, Supply Chain Design

Introduction

Reducing carbon dioxide emissions is a global challenge in all type of organizations, mainly to fulfill the objectives of the Paris Climate Accords (2016), which seeks to establish actions to avoid future climate crisis. Particularly, the long-term temperature goal is to keep the rise below 2 °C above pre-industrial levels, and preferably limit the increase to 1.5 °C, recognizing that this would substantially reduce the effects of climate change. To that end, emissions should be reduced as soon as possible and reach net-zero by the middle of the 21st century. To stay

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below 1.5 °C of global warming, emissions need to be cut by roughly 50% by 2030 (UNFCCC, 2021). Therefore, every country and organization must commit to this agreement. Meeting these goals entails great challenges involving the use of renewable energy, promoting the efficient use of energy, and facilitating the deployment of CCUS supply chains.

Mathematical optimization models can be a powerful tool when trying to make decisions on how to plan the CO_2 capture, storage and utilization infrastructure. When considering many CO_2 sources, utilization options and transport modes, as well as numerous technical, financial and business constraints, jointly with a long-term planning horizon, the complexity of the decisions is enormous. As stated in the review by Tapia et al. (2018), one of the main issues when using mathematical optimization models for CCUS planning, is the lack of efficient integrations between the different echelons of the supply chain.

The main objective of this work is to present an optimization framework for the CCUS supply chain design, with specific focus on the multi-sink CO_2-EOR tactical planning for the long-term decisions. References for the supply chain design model are the work of Han et al. (2012), Montagna & Cafaro (2019) towards the design of efficient networks with no predetermined echelons in the superstructure, and the recent work of Duarte et al. (2022). Surrogate models proposed by Hasan et al. (2015) and commercial data is considered for the capture technologies alternatives.

Enhanced Oil Recovery with the injection of CO_2 is one of the most important operations to reduce the CO_2 emissions at the same time incremental oil production is obtained. Also, it is a well known operation for oil and gas companies, which makes its deployment easier. Regarding CO_2-EOR operations modelling, works of Calderon & Pekney (2020) and Tapia et al. (2016) were used as reference. EOR tactical decisions consider crude oil and CO_2 production curves, operational conditions and CO_2 injection rates, as well as the monitoring, workover, replacement and abandonment of injection wells. In many EOR works, significant detail is incorporated, like injection-production wells schemas, operations scheduling, reservoir modelling, among other. However, when integrating EOR decisions with the long-term CCUS supply chain network design, the complexity of combining operational with strategic decisions is very challenging. Therefore, some tactical CO_2-EOR decisions are prioritized and integrated with the CCUS supply chain network, whose mathematical formulation is presented next.

The relevance and novelty of this work is the efficient integration of all the decisions over a complete CCUS supply chain network long-term design, allowing to obtain comprehensive solutions to help decision makers assess alternative configurations. Particularly, significant advances are shown on how to integrate tactical CO_2-EOR decisions in the context of a CCUS supply chain design.

Problem Statement

Next, the main assumptions of the problem are stated:

1. Time horizon discretized in years (multiperiod model).
2. Pipeline installation costs vary with the pipeline diameter (economies of scale), and with the total length.
3. Pipeline transportation capacity depends on the diameter.
4. CO_2 sources and the emissions over the planning horizon are given data. We also know the CO_2 streams composition.
5. Three specific alternative sizes are stated for each capture technology, with the corresponding min/max capacity.
6. Capex and Opex parameters for pipelines and facilities are given in terms of the capacity and total flows managed.
7. A piecewise linear segmentation is applied on the CO_2 and oil production curves (*Figure 1*).
8. CO_2-EOR operations have a minimum and maximum duration, while the operations cannot be interrupted.
9. All terms are discounted back to present time in the objective function.

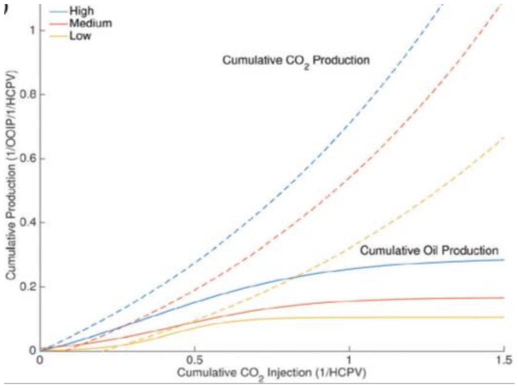

Figure 1. CO_2 and Oil cumulative production curves from Kolster et al. 2017.

The model must determine the:

1. Selection of the CO_2 capture technologies, location and sizing. Also determine the period of installation.
2. Transport network decisions. Linking nodes, sizing and period of installation of the transport mode selected.
3. Utilization and storage technologies selection and sizing.
4. Flow balances over the network
5. For every available reservoir (sink), decide the number of injection wells to drill per year. Also, determine the number of workovers, abandonment and replacement tasks over the existing injection wells.
6. Determine the scheduling of the CO_2- EOR operations among the available fields.
7. Determine CO_2 injectivity levels to produce incremental crude oil from the reservoir.
8. Compute the Oil and CO_2 production (which is recycled).
9. Determine all economic terms and objective function.

Mathematical Formulation

The main equations of the MILP formulation are presented, focusing on those that are key constraints of the problem. Many secondary constraints are not presented to comply with space constraints.

Supply Chain Design, Flow and Transport Equations

Equation (1) shows the generalized flow balances for every node *g*, which allows the design of a supply chain network with no predetermined number of echelons. The positive variable $X_{C_{ct,j,g,t}}$ [Mt/y] is the amount of CO_2 captured by technology *ct* of size *j* in node *g* during period *t*, while Pnc_{ct} is a parameter, which represents the capture efficiency. Also, $X_{Q_{l,g,g',t}}$ [Mt/y] is the amount of CO_2 transported by mode *l* from region *g* to region *g'* during *t*, while $X_{CO2INPUT_{c,t}}$ [Mt/y] is the amount of CO_2 to be injected in field *c* (located in *g*) during *t.* Equation (2) establishes minimum and maximum capture capacities, linking the positive CO_2 capture variable with the corresponding binary variable $BV_{IC_{ct,j,g,t}}$, which is 1 if a capture facility *ct* of size *j* is installed in node *g* during period *t.* Equation (3) fixes the upper bound of CO_2 captures to the annual emissions $P_{Eg,t}$, and Eq. (4) forces a minimum annual capture target in line with the company objectives.

$$\textstyle\sum_{g'} X_{Q_{l,g',g,t}} + \sum_{ct,j} Pnc_{ct}\, X_{C_{ct,j,g,t}} = \sum_{g} X_{Q_{l,g,g',t}} + X_{CO2INPUT_{c,t}} \quad \forall\, g,\, t \tag{1}$$

$$BV_{IC_{ct,j,g,t}} MinCap_{ct} \le X_{C_{ct,j,g,t}} \le BV_{IC_{ct,j,g,t}} MaxCap_{ct} \tag{2}$$

$$\textstyle\sum_{ct,j} X_{C_{ct,j,g,t}} \le P_{E_{g,t}} \quad \forall\, g,\, t \tag{3}$$

$$\textstyle\sum_{g,\,ct,j} X_{C_{ct,j,g,t}} \ge \sum_{g} Target\, P_{E_{g,t}} \quad \forall\, t \tag{4}$$

Regarding transportation constraints, Eq. (5) computes the number of transport units $Y_{NTU_{l,t}}$ required per mode different than pipelines, while Eq. (6) controls the capacity of the installed pipelines, with $BV_{IP_{l,d,g,g',t}}$ being equal to 1 if a diameter *d* pipe is installed between *g* and *g'* during *t*. Equation (7) establishes that between two nodes, only one pipe in one direction can be installed.

$$Y_{NTU_{l,t}} \ge \frac{\sum_{g,g'} X_{Q_{l,g,g',t}}}{CapTrans_l} \quad \forall l \ne pipes,\ c,t \tag{5}$$

$$X_{Q_{l,g,g',t}} \le \textstyle\sum_d Cap_d\, BV_{IP_{l,d,g,g',t}} \quad \forall l = pipe, g < g', t \tag{6}$$

$$BV_{IP_{l,d,g,g',t}} + BV_{IP_{l,d,g',g,t}} \le 1 \quad \forall l = pipe, g < g', t \tag{7}$$

CO_2-EOR Equations

The CO_2-EOR process has been modeled considering the typical petrophysical properties of oil reservoirs and the dynamic oil and CO_2 production profiles. The oil and CO_2 production rates depend on the CO_2 injection rate, where the CO_2 injection and production rates are normalized by hydrocarbon pore volume ($HCPV_c$, [m^3]) of each reservoir c. According to Eq. (8), $HCPV_c$ is a function of reservoir properties such as area (A_c, [m^2]), net pay thickness (h_c, [m]), average porosity (ϕ_c), and the initial water saturation ($S_{wi,c}$). The oil production is normalized by the original oil in place ($OOIP_c$, [m^3]), which is defined in the Eq. (9).

$$HCPV_c = A_c h_c \phi_c (1 - S_{wi,c}) \quad \forall\, c \tag{8}$$

$$OOIP_c = HCPV_c / \beta_{oi,c} \quad \forall\, c \tag{9}$$

where $\beta_{oi,c}$ represents the initial oil formation volume factor. Each field is characterized by a unique $HCPVc$, and it determines the oil and CO_2 production rates of the field.

The rate of CO_2 injected at each period of time *t* per field ($X_{CINJ_{c,t}}$, [Mt/y]) is limited in Eq. (10) by both the max CO_2 injection rate per well ($qCO2_c^{max}$, [Mt/(y·well)]) and the number of injection wells available in the field ($Y_{WI_{c,t}}$, [well]). The number of injection wells (integer variable) is limited to the drilling campaign of the company in Eq. (11).

$$X_{CO2INJ_{c,t}} \le \textstyle\sum_{t' \le t} qCO2_c^{max} \cdot Y_{WI_{c,t'}} \quad \forall\, c, t \tag{10}$$

$$\textstyle\sum_{t' \le t} Y_{WI_{c,t'}} \le wt_{c,t}^{max} \quad \forall\, c, t \tag{11}$$

The oil and CO_2 production variables are calculated using a piecewise linearization of the dimensionless curve representing the incremental recovery factor for oil and the cumulative CO_2 production (both as a function of cumulative CO_2 injection as described in previous sections). According to the work of Misener et al. (2009), four alternative piecewise linearization techniques were explored: (1) the classic method, (2) linear segmentation method, (2) convex hull method, and (4) special structure method, each one with different computational impacts. All of them were tested: the most efficient was found to be the fourth alternative. In that technique the key is the definition of two special ordered sets namely *k1* and *k2*, for CO_2 and Oil production curves, respectively, covering the segments in which each curve is divided. Then, two Type 2 Special Ordered Set variables are introduced (SOS2, according with GAMS (2022)): (1) $\lambda_{c,t,k1}^{1}$ and (2) $\lambda_{c,t,k2}^{2}$, which are the weights applied to each segment extreme point to make the convex combination to represent any point in a linear segment (Figure 2). Recall that SOS2 variables are those of which at most 2 can be non-zero and they must be adjacent in terms of the set *k1* or *k2*.

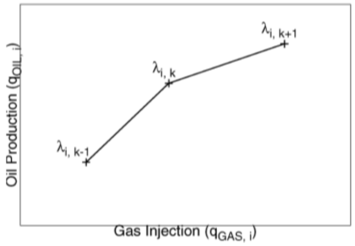

Figure 2. Illustrative piecewise linear segmentation using SOS2 variables from Misener et.al (2009).

Equation (12) establishes the convex combination of the nodes weights, while Eq. (13) and (14) determines the position in the x-axis of each curve, depending on the cumulative injection of CO_2 variables $X_{CO2_{INJCUM_{c,t}}}$.

$$\textstyle\sum_{k1} \lambda_{c,t,k1}^{1} = 1 \quad \sum_{k2} \lambda_{c,t,k2}^{2} = 1 \quad \forall c, t \tag{12}$$

$$X_{CO2_{INJCUM-CO2_{c,t}}} = \textstyle\sum_{k1} \lambda_{c,t,k1}^{1} * QCO2x_{co2_{c,t}} \tag{13}$$

$$X_{CO2_{INJCUM-OIL_{c,t}}} = \textstyle\sum_{k2} \lambda_{c,t,k2}^{2} * QCO2x_{oil_{c,t}} \tag{14}$$

Equation (15) forces identical x-axis positions for each field *c* and period *t*. Then, Eq. (16) and (17) determine the corresponding CO_2 and Oil cumulative production as the convex combination of the active points in each curve. *QCO2x* and *QCO2y* represent the extreme points values for each segment of the linearization applied (given data).

$$X_{CO2_{INJCUM-CO2_{c,t}}} = X_{CO2_{INJCUM-OIL_{c,t}}} \tag{15}$$

$$X_{CO2_{PROD_{c,t}}} = \sum_{k1} \lambda^1_{c,t,k1} * QCO2y_{co2_{c,t}} \tag{16}$$

$$X_{OIL_{PROD_{c,t}}} = \sum_{k2} \lambda^2_{c,t,k2} * QCO2y_{oil_{c,t}} \tag{17}$$

Finally, the annually produced CO_2 is considered to be completely recycled, which is added to the fresh CO_2 for EOR ($X_{CO2INPUT_{c,t}}$) that is obtained from the capture processes in the sources. The mass balances at the reservoirs injection wells is given at Eq. (18) and Eq. (19)

$$X_{CO2RECY_{c,t}} = X_{CO2_{PROD_{c,t}}} - X_{CO2_{PROD_{c,t-1}}} \quad \forall\, c,t \tag{18}$$

$$X_{CO2INPUT_{c,t}} + X_{CO2RECY_{c,t}} = X_{CO2INJ_{c,t}} \quad \forall\, c,t \tag{19}$$

No Interruption of CO_2-EOR Operations

The next equations aim to avoid the interruptions of the EOR operations in a field, which is a potential behavior of the solution that must be mathematically prevented. Equation (20) defines that the operations in any field c starts only in one period of the planning horizon, using the binary variable $BV_{START_{c,t}}$. Then, Eq. (21) establishes that the EOR activity binary variable $BV_{ACT_{c,t}}$ can be equal to 1 only if it is the starting period, or if in the previous period there were operations. Once the activity is stopped, it is impossible to reactivate them. Equation (22) determines min and max injection rates related with the activity binary variable, and Eq. (23) limits the operations duration.

$$\sum_t BV_{START_{c,t}} \leq 1 \quad \forall c \tag{20}$$

$$BV_{ACT_{c,t}} \leq BV_{ACT_{c,t-1}} + BV_{START_{c,t}} \quad \forall c, t \geq 2 \tag{21}$$

$$MinInj BV_{ACT_{c,t}} \leq X_{CO2INPUT_{c,t}} \leq MaxInj\ BV_{ACT_{c,t}} \ \forall c,t \tag{22}$$

$$MinDuration_c \leq \sum_t BV_{ACT_{c,t}} \leq MaxDuration_c \ \forall c \tag{23}$$

Economic Equations and Objective Function

Economic equations determine all the operation and capital cost of the model decisions, including both the corresponding to the CO_2 capture and transport operations, and those related with the CO_2 injection in EOR operations. Also, the corresponding incomes from oil selling are considered. The objective function in the MILP is to maximize the net present value NPV [MUSD], which is a function of the CCUS supply chain incomes, the total operation and capital costs, which are all discounted to the present time using an interest rate r, as shown in Eq. (24).

$$Max\ NPV = \sum_t (Oil_{Price} . X_{OILP_{c,t}} - \sum_{j,ct,g} BV_{IC_{ct,j,g,t}} Cost_{ct,j} - \sum_{l,d,g,g'} BV_{IP_{l,d,g,g',t}} Cost_{ct,j} - Opex_t) /(1+r)^{t-1} \tag{24}$$

Case Study Description

The superstructure comprises 3 hubs with CO_2 emissions and 5 potential fields where it is possible to perform CO_2-EOR operations, as observed in Figure 3, where also a connection node is introduced in the superstructure. The global emission profile ranges between 1.092 Mt/y (from year 3 to 6) and 4.124 $MtCO_2$/y since year 7. Particularly, for Hub 2 the emissions are constant and equal to 0.198 $MtCO_2$/y, while for Hub 1 are equal to 0.848 until year 7 and 3.647 afterwards, both in $MtCO_2$/y. Finally, for Hub 3 the emissions are equal to 0.046 until year 7 and 0.279 until the last period.

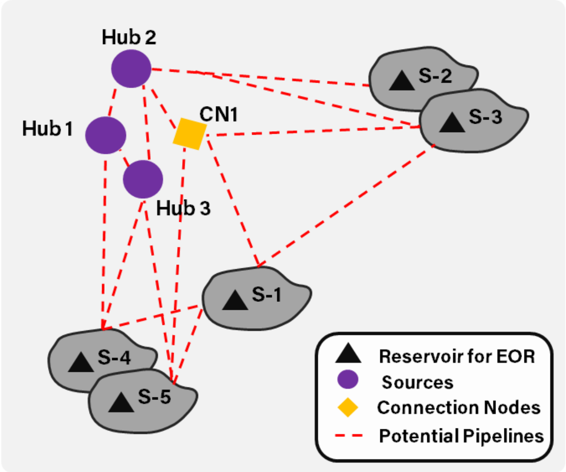

Figure 3. Case Study Superstructure

A long-term planning horizon of 42 discrete annual periods is considered. Alternative commercial CO_2 capture technologies can be selected by the formulation, like those based in amines and super-amines, or emerging technologies from surrogate models proposed by Hasan et al. (2012) and Zhang et al. (2020). Likewise, a capture efficiency of 95% was assumed for a Tech1, 90% for Tech2 and emerging technologies, while a 100% for sources only requiring compression due to their high purity (>92%). Also, 3 different plant sizes (small, medium, and large) are considered, each one with a minimum and maximum capture capacity. From the economic side, the interest rate is 10%, the oil price is assumed to be 50 USD/bbl, while carbon credits are equal to 35 USD/tCO_2.

Regarding transportation modes, only pipelines have been considered. The optional diameters are of 6, 8, 10, 12, 16, 18 and 20 inches.

In the case of the CO_2-EOR operations, 5 potential fields are considered, each one with their corresponding data such as the hydrocarbon pore volume (HCPV) and the original oil in place (OOIP), among others. The following data was assumed as economic parameters: (1) Opex of production wells 18 [USD/bbl], (2) capex of drilling and completion of injection wells 2.3 [MUSD/well], (3) Opex of injection wells workover [0.51 MUSD/well], and (4) fraction of injection wells for annual workover 0.19.

Results

The final net present value of the optimal solution is 345.77 MM USD (see the next sub-section for more computational results). First of all, observe in Figure 4 the general solution, where the pipeline network is displayed. The CO_2 captured in Hub 2 is transported towards Hub 1, where it is mixed with additional CO_2 and sent to Hub 3. All the CO_2 is merged in Hub 3 to be sent to S-1 field through a 16 in pipeline. Then, the CO_2 stream is split between the amount that is used in S-1 for injection, and two additional parts that are sent to S-3 and S-4 fields. Once in S-3 and S-4, a final echelon is incorporated to reach close fields S-2 and S-5 respectively, which is made through smaller pipelines. Observe how the model decides to collect all the CO_2 into a master 16” pipeline, taking advantage of the associated economies of scale, to then split to particular fields.

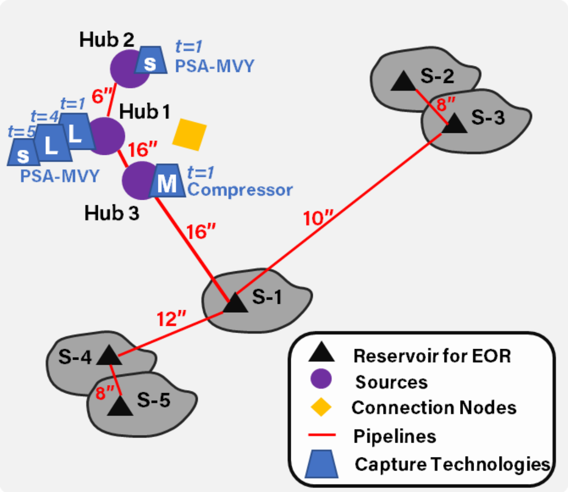

Figure 4. General solution for the case study, showing pipeline network and capture technologies installed.

Regarding capture technologies, a medium-size compressor is installed in Hub 3, due to its high purity source of CO_2. In Hub 2, a small PSA-MVY technology (Zeolite-based physical adsorption of CO_2 for Pressure Swing Adsorption) is selected, while in Hub 1, the node with largest emissions, 3 facilities are installed, two of large sizes, in period 1 and 4, and one of small size in period 5. Observe how the installation periods coordinate the increase in the emission profile.

The net present value of the capital costs for capture facilities is 168.4 MUSD, while for the transport network is 18.2 MUSD and in turn is 188 MUSD the total Capex for EOR activities. Moreover, the net present cost of capture facilities and pipeline network operations is equal to 347 MUSD. All the costs are clearly outweighed by the corresponding incomes.

Figure 5 shows the capture level of CO_2 and its comparison with the emission level for the Hub 1. For Hub 2 and Hub 3 the capture level is almost 100% during the initial 27 years, decreasing to zero for Hub 3 in the final periods. In Hub 1, clearly the region with largest emissions, the capture is near 50% all over the planning horizon. One of the reasons is that there is no more capacity to store or inject CO_2 in the fields, as observed next.

Figure 6 shows the cumulative evolution of the net injected CO_2 in every field. We can observe that for almost all the fields the maximum level is reached. Then, no more capacity is available for CO_2, and no more CO_2 can be practically captured.

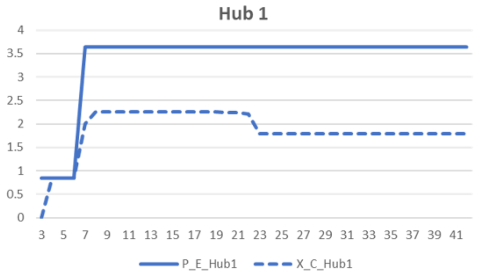

Figure 5. Emissions and capture level of CO_2 for the Hub 1

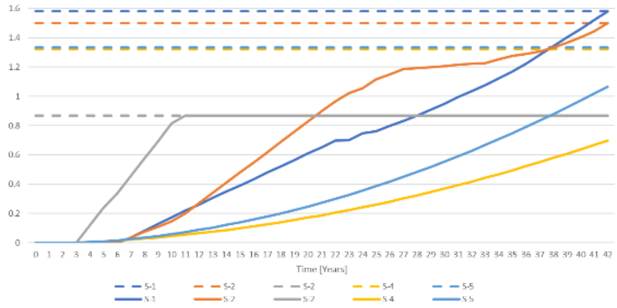

Figure 6. Cumulative CO_2 injection and max. injection level.

Observe in Figure 7 the evolution of the net oil production, and notice the shape of each curve, showing the operations intensity. Figure 6 and 7 show that EOR operations start in S-3 field, continuing intensively with S-1 and S-2 once the emissions level grow in period 7. Likewise, the development of S-4 and S-5 fields is with a slower peace. One of the reasons behind this behavior is that those fields have a very small injectivity level, requiring a very large number of injection wells to be fully developed.

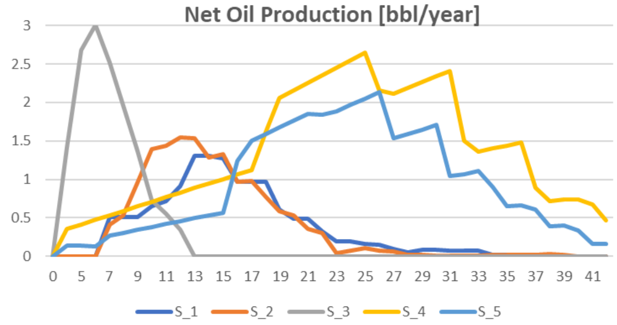

Figure 7. Net oil production for each reservoir.

Observe in Figure 8 that the number of new wells in S-4 and S-5 is the maximum, being impossible to accelerate the oil production with more injection wells; while after the period 12 no more wells are drilled.

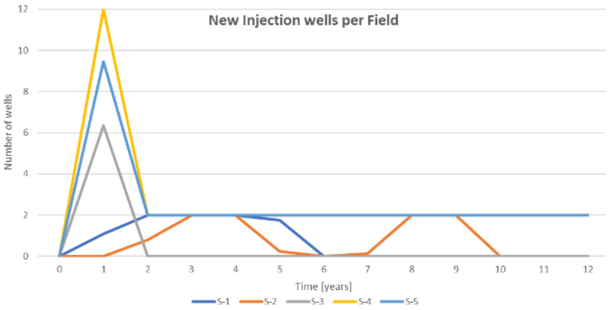

Figure 8. New injection wells annually drilled in every field.

Computational Performance and Model Statistics

The final model size, after preprocessing, has 17004 positive variables and 10785 integer variables, with a total of 15468 constraints. The reported solution was obtained after 2300 CPU seconds, while after 42500 seconds the optimization gap was closed to a 0.7%. Gurobi 9.0 was used as solver and an Intel Core i7-10510U processor with 16 GB RAM.

Conclusions

This study presents a comprehensive MILP optimization framework to support the efficient coupling of supply chain network design with EOR operations. The proposed formulation effectively integrates an advanced optimization of the tactical decisions related with the CO_2-EOR operation of several sinks, with the CCUS supply chain optimal design in the long term. Besides, specific constraints are introduced, taking into account the petrophysical properties, oil and CO_2 production profiles and operating conditions. A generalized supply chain network design is proposed, with no predetermined number of echelons in the network to transport the CO_2 from sources to sinks. Additionally, specific sizes of capture plants and alternative technologies were also considered.

The solutions show an optimal allocation and assignment of the CO_2 captured in EOR fields, maximizing the profits from selling oil while selecting the most appropriate capture technologies and transportation modes.

Future research will be focused on the integration of additional alternatives for the CO_2 utilization, such as sequestration in depleted fields or saline aquifers, nature-based solutions and obtaining added-value products.

Additionally, future work will also involve new solutions strategies, effective binary cuts, identification of symmetries, building valid relaxations and temporal or spatial decompositions to improve the computational performance for even larger cases of study.

It is important to emphasize that the final MILP model yields a framework notably close to the actual infrastructure planning process for CO_2-EOR operations, even more in the context of a long term CCUS supply chain design optimization problem. Therefore, the capacity of estimating realistic economic indicators for the whole project is highly valued, mainly due to the large investments and costs involved. All of this is a direct consequence of the improved components and features of the proposed MILP formulation.

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