ECCIS, a generic Model of Carbon Capture and Sequestration System for Enhance Oil Recovery Operations

Master Thesis

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“…yo cada día he recordado

que si un árbol está florido, pues

algo tiene sepultado…”

-Sepultado. I.R.A (Punk).

…in memoriam of Sebastian Henao, -**el trenzax**.

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Was worth it just to have known all of you!!

Content

List of Tables

List of Figures

List of Graphs

INTRODUCTION

Capture and Storage (CCS) is one of the main technologies called to mitigate the release of greenhouse gases (GHG) due electricity production as a transitional measure whist Energetic Transition is a fact. The components of this technology (Capture, Compression, Transport and Injection) are very well deployed in isolation; nonetheless there is lack of holistic approaches. This study aims to explain a generic System Dynamics (SD) model which simulates the CCS production chain, as well as the oil field development and the basic reservoir dynamics involved. The CO_2 captured out of combustion processes or oil refinement operations by means of CCS can replace water as an injection fluid, enhancing oil production. The deployment of an oil field goes throughout several stages: Primary (natural flux), Secondary (pressure increase and maintenance) and Tertiary (EOR operations). The differentiation, analysis and management of each stage depends on the reservoir conditions. The model developed here is a tool for policy design on CCS-EOR system optimization.

PROBLEM STATEMENT

There are four main issues motivating the development of this study: (i) greenhouse gas emission mitigation, (ii) guarantee maintenance of domestic oil production, (iii) enhancing oil reservoir performance assessment and (iv) solving the lack of holistic approaches to analyze CCS-EOR matters.

In the last decade about 60% of electricity production has been based on fossil fuel and this level is expected to remain almost stable [1].

Currently there is consensus on the fact that the burning of these fuels is causing the so-called 'Global Warming' with deleterious consequences for life on earth [2]. Aiming for a viable future in concordance with planetary boundaries and the comfort that modern society demands; science and industry have developed systems for electricity generation which are friendly for the environment (Renewable Energy) [3]. However, this increase in efficiency (also called Energy Transition [4]) is a tortuous process that requires huge investments and political will. Therefore it is surrounded by uncertainty resulting in unavoidable delays against the total abandonment of the reliance on fossil fuels.

As fossil fuels and CO2-intensive industries play a dominant role in our economies. The CO2 Capture and Sequestration will remain as a feasible solution in order to reduce greenhouse gas emissions. With coal and other fossil fuels remained dominant in the energy matrix; there is not an environmentally friendly scenario in the long-run without CCS [5].

CO2 sequestration is a process by which this gas, after being separated before or after burning the hydrocarbon fuel; it is injected into the ground through wells in porous and permeable geological formations where it is trapped forever in depths ranging from 800 to 5000m [6].

The oil industry has used CO_2 in enhanced oil recovery process for several decades therefore CO_2 usage in oil fields is a known process [7] (so far this CO_2 comes from natural deposits, also located underground [8] and valuable as this compound provides advantages (due to its affinity with oil [9]) that water injection (or waterflooding) does not provide. However, the supply of CO_2 from natural deposits is low and this makes attractive the option of capture it from fixed points (like power plants, oil downstream operations, cement industries and such) although some component of the CCS chain are costly in the current state of research and development.

This combination of high cost CCS projects combined to significant benefits of increasing domestic oil production and therefore the demand for CO_2 for Enhance Oil Recovery (EOR), plus the potential CO_2 sequestration of oil fields in the next two or three decades, deserves a serious look to increase the number of CCS-EOR projects [10].

In [11] a virtual tool is described to evaluate the performance in environmental terms of different arrangements of the CCS production chain. However, for stakeholders involved in development of these CCS systems, there is still default on integrating tools of the elements to consider in a CCS system.

This master thesis reports the development of a generic System Dynamics called ECCIS (Emisión, Captura, Compresión y Secuestro, in spanish) which it is accessible and innovative model as it includes not only the production of CCS but also the deployment of an oil field as well as the main oil reservoir dynamics wherein CO_2 is injected. The thesis goes as follows:

Initially a overview of the main dynamics modeled simulated by ECCIS and their related substructure. Afterwards it is offered a detailed explanation of the main issues addressed by ECCIS. Later on it is shown how the validation was made and at the end, it is possible to find details of all the flows, stocks and variables of every sector.

WHAT THE MODEL CAN DO

Although the model itself does not offer a greenhouse gas emission mitigation tool, it assess pivotal questions regarding the four motivations in this study. For instance, how long does it takes to reach total development (it means the efficacy of the process is near 100% thereby no CO2 is released to atmosphere) of capture, compression and injection technologies? The former based on the feedback between two variables (i) level of investment (for each technology) and total amount of CO2 captured, compressed and injected, respectively. For so doing, the model contains the next structure:

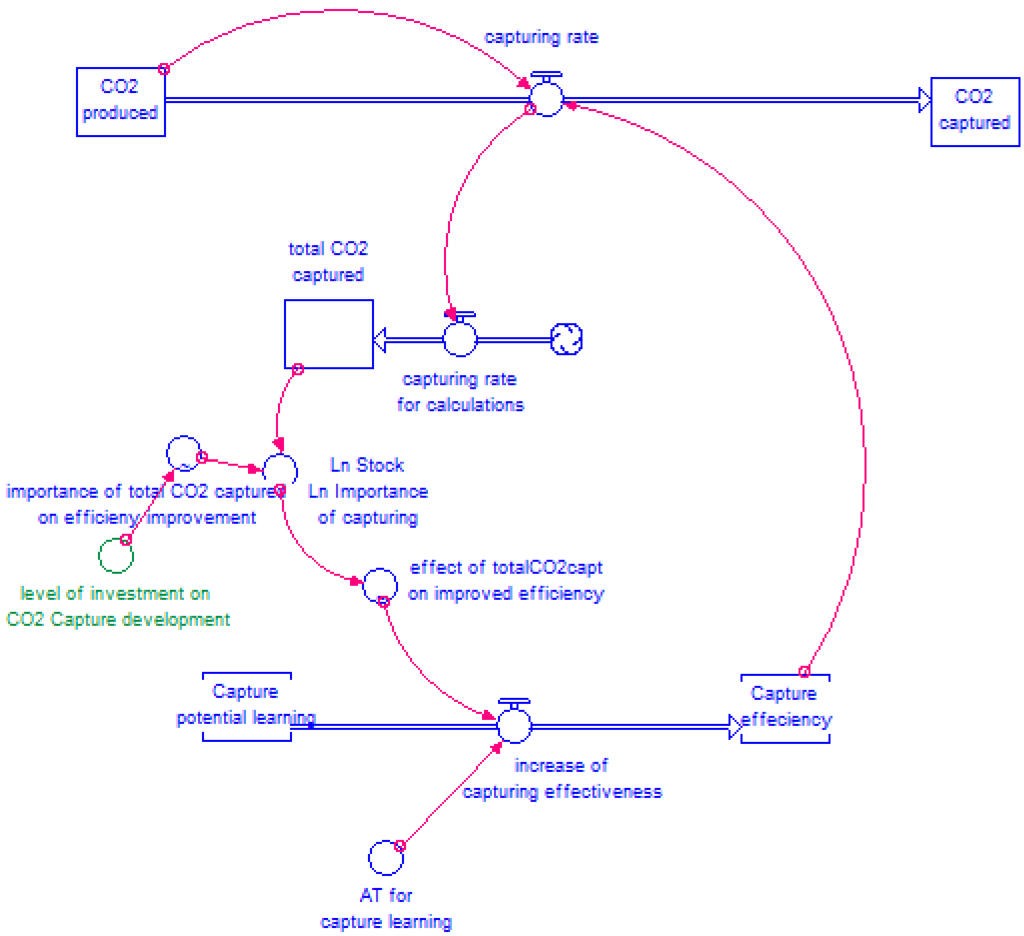


Figure 1. Structure of the learning process

The stock *CO2_produced* is changed but the rate of CO_2 produced by electricity production and from oil refining operations (see below Figure 3 and Figure 4). This stock stores all the potential CO_2 out of these two processes and it's measured in [tonsCO2]. Once in there CO_2 is ready to be captured however this is not a linear process. Instead CO_2 capture is not a mature technology [12] thereby *Capturing rate* flow varies upon certain level of expertise here named *Capture efficiency*.

The theory under this structure and the usage of the logarithmic function [13] in it argues that the inflow *Increase of capturing effectiveness* depends on two variables: one is the policy design variable: *level of investment on CO2 capture development* (in green) which allows testing different scenarios of investment (from 1.0 to 9.9). The other variable is *total CO2 captured*. Although this theory is far from certainty, it definitely takes into account the learning process based in how much matter has been already captured (or compressed or injected) and the undeniable propelling effect of investment in how rapidly that technology reaches total efficacy. Thus, closing the loop.

As it was mentioned earlier, the logarithmic function plays a starring role as it allows relating: a physical quantity, a policy variable and the joined effect of both variables on efficiency improvement:

$\text{Log}_{\text{investment}}$ (total_CO2_captured) = X, wherein 'X' is a number related with an effect on *Increase of capturing effectiveness.* 'X' can also be calculated using natural logarithmic function (as iThink doesn't have Log function) like this: LN(total_CO2_captured)/LN(importance_of_total_CO2_captured_on_efficieny_improvement) = X

Regarding the maintenance of domestic oil production, the model shows the effect of oil price on the development of an oil field [15]. The structure that reproduces this dynamic is the next:

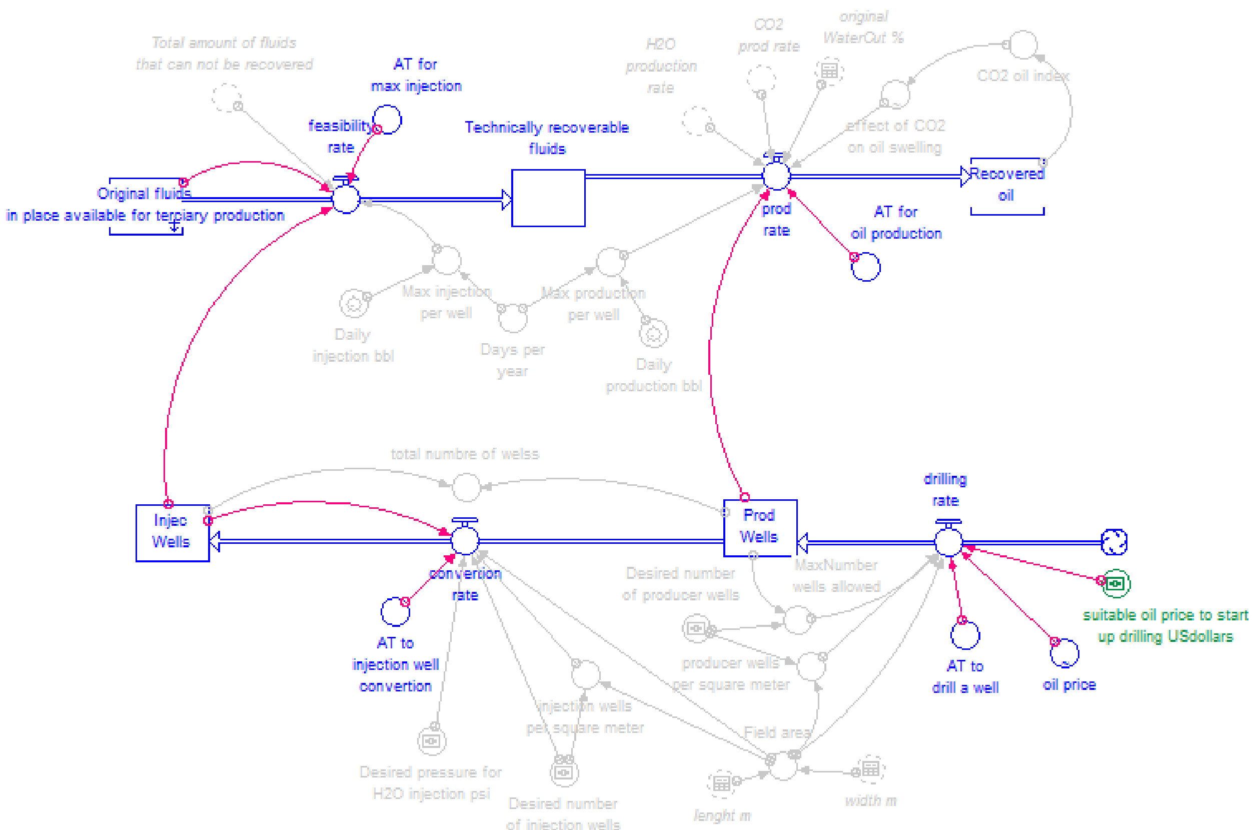


Figure 2. Structure of an oil field develpment.

The exogenous variable *oil_price* incorporates the yearly price per barrel of oil [15]. The policy design variable *suitable_oil_pric_to_start_up_drilling_USdollars* triggers the *drilling_rate* which accumulates production wells inside *Prod_Wells* stock, and according to the time needed to construct an oil well.

As these wells are the only ways that oil is produced from the reservoir rock, the more production wells the larger the *prod_rate* of oil. Once the oil production causes the *Reservoir_pressure* (explained later) to reach a policy designed point (*Desired_pressure_for_H2O_injection_psi*), will start up a conversion of *Prod_Wells* into *Injec_Wells* (injection wells). This is due depletion of the oil reservoir pressure because of fluid production. In other words, the available energy of the fluids-reservoir rock system that enables to get the fluids up in surface is going to exhaustion. This stage is called

‘Primary Production’ or ‘Production per natural flux’. Once the reservoir is depleted, there is no way how to increase oil production unless a direct intervention to the reservoir-fluids system is made. This stage is called ‘Secondary Production’.

Although there are several techniques of ‘Secondary production’ [16,] the most used one is water flooding because of water’s easiness to deal with and availability in the places where this operation is run.

As this is inherently a physical model, it takes into account the mass balance resulting of water injection and fluid production. In the structure above this dynamic is captured when more *Injec_Wells* triggers the *feasibility rate* (because more water is injected) which means that fluids which weren’t up to production are now available in *Technically_recoverable_fluids* stock.

Originally_fluids_in_place_available_for_terciary_production plus *Technically_recoverable_fluids* are the total amount of fluids (oil & connate water [17]) present inside the reservoir.

This model considers two types of CO2 sources. One is CO2e out of oil refining activities and, added to it, the model also traces CO2 from coal and gas base power plants. Figure3 and Figure4 show the structures of both sources.

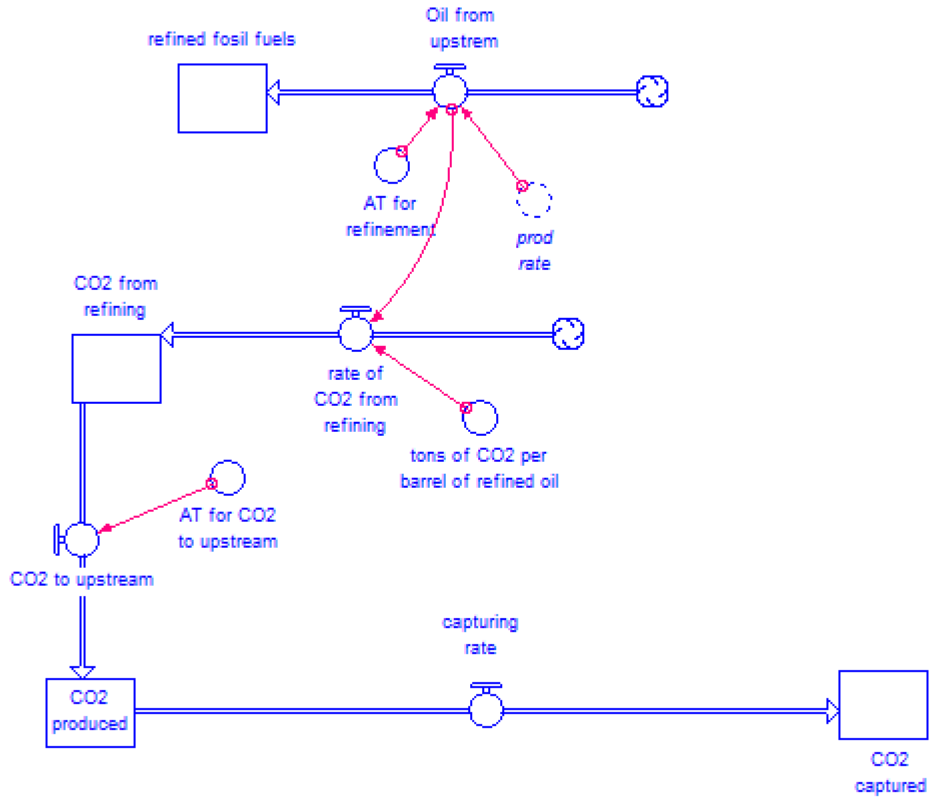


Figure 3. Structure of CO2 production due oil refinement

This structure traces the CO2 from refining activities of the *Recovered_oil*. It is important to clarify the terms 'upstream' and 'downstream'. The oil industry refers -upstream as the operations made until the oil produced is on surface (drilling, completion, well testing and such) and –downstream to the operations onwards (including for instance, transport and refining).

As this model simulates the all CCS-EOR chain, it is possible to find out what would be the impact of a waste material from energy exploitation on the energy exploitation itself (CO2, in this case).

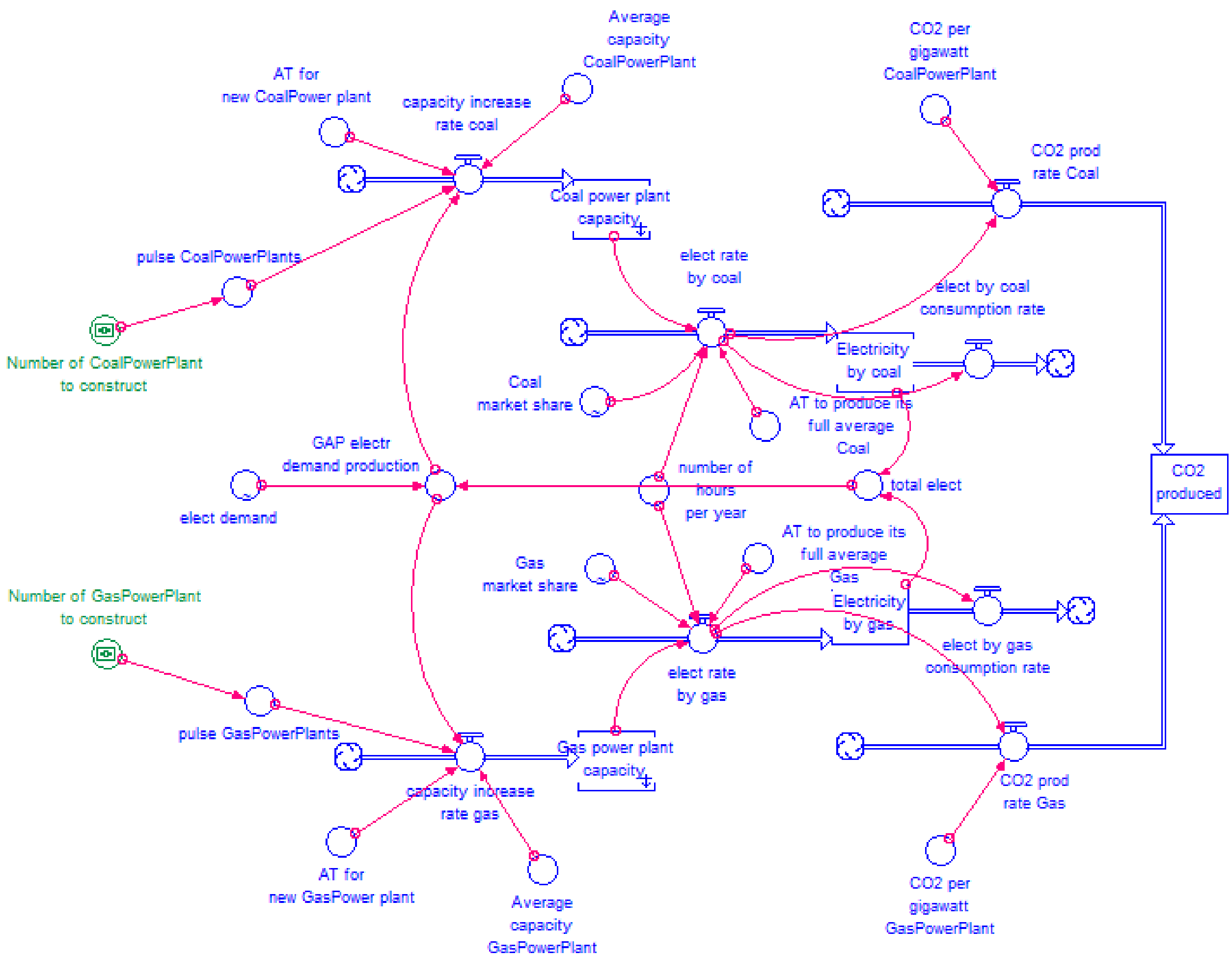


Figure 4. Structure of CO2 production due electricity generation and evolution.

This structure frames in the history and development of electricity production taking into account the two main pollutants used as energy sources, coal and gas. Their pollution related is basically CO2 from burning processes. The stock *CO2_produced* then takes into account the inflow of both: coal and gas burning operations.

The symmetry of the structure above suggests that CO2 from gas burning shares the same structure as CO2 from coal burning (though both use different inputs).

The policy design variable *Number_of_CoalPowerPlant_to_construct* triggers the capacity increase of coal base electricity production and alongside its related CO2 production. As expected due structure's symmetry, there is also *Number_of_GasPowerPlant_to_construct*.

There are three exogenous variables in this structure and in this case it is used data from USA:

- *elect_demand* (electricity demand) [18]: is the total electricity demand from 1990 to 2040. This means it takes into account not only the electricity produced by coal & gas but also different sources like nuclear, renewable or hydro.
- *Coal_market_share* [19]: is the total electricity production from coal since 1990 until 2040 forecast.
- *Gas_market_share* [20]: is the total electricity production from gas since 1990 until 2040 forecast.

This means that the variable *GAP_electr_demand_production* (gap of electricity demand) will be always >0 unless either more coal or gas power plants are constructed. To wit, the theory behind the structure claims that the more hydrocarbon base capacity the less non-hydrocarbon base capacity is needed.

Else, another two issues related the reservoir itself (wherein CO2 and water are injected) that can be addressed through the model structure are: which is the behavior of the injected water in terms of importance as a decision making index? Also, as the intern pressure of the reservoir rock plays a crucial role as indicator of the likelihood to obtain further oil production, this model allows understanding which of the flowing substances (oil, water or CO2) has higher incidence in reservoir performance. For doing so, the Figures 5 and Figure 10 show the structure of the model on these regards.

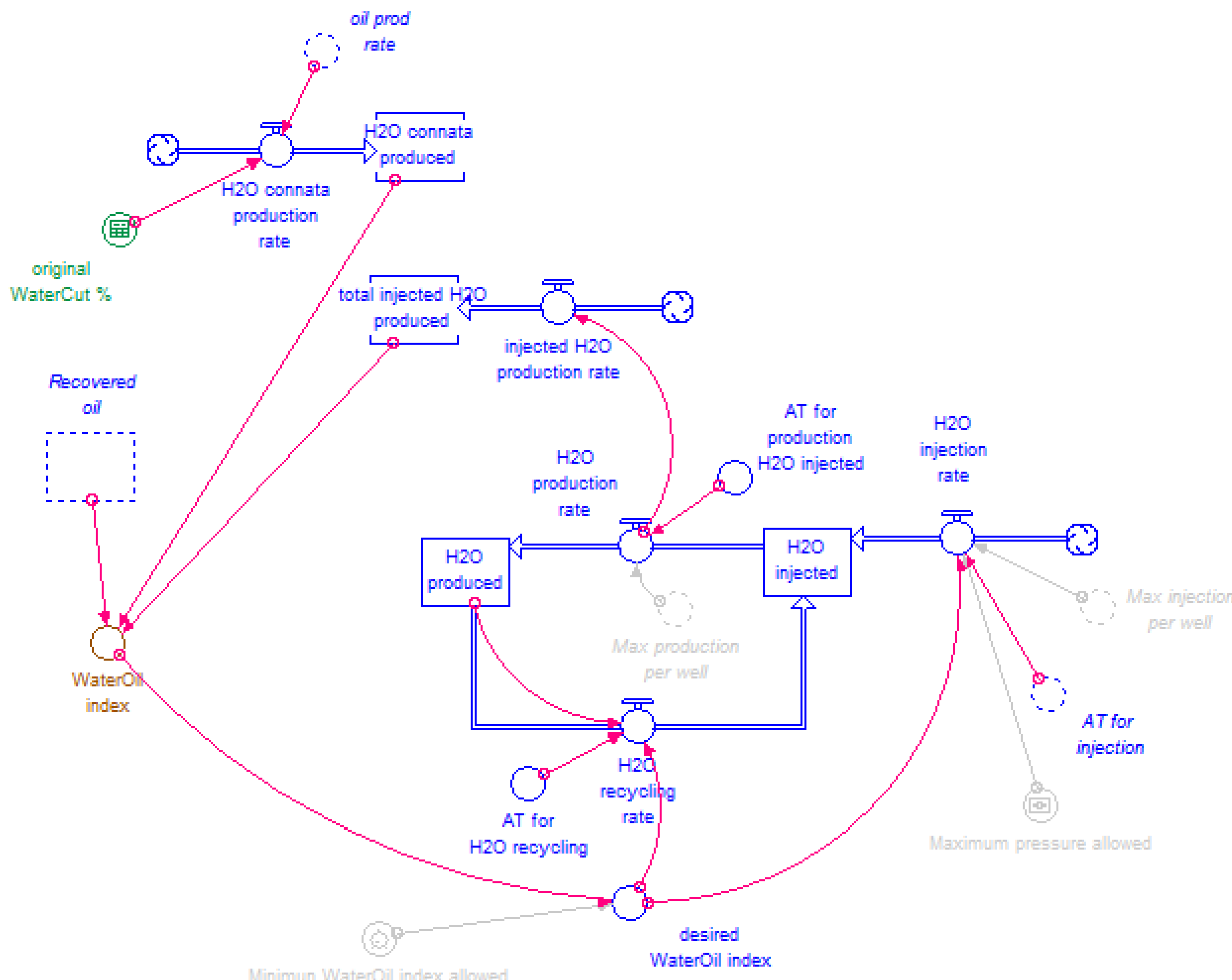


Figure 5. Structure of Water's dynamics.

Once 'production per natural flux' stage is ended, it's time for 'waterflooding'.

Water injection is done in order to displace residual oil from pores and channels within the reservoir rock. As mentioned earlier, water offers advantages that other fluid does not offer (fluids like steam, natural gas, CO2, etc). Specifically, an ample availability which means pretty much no constrains for use it.

The water is inherently involved in the oil exploitation as this substance is found alongside oil in the pores at ranges between 1 to 99% [21]. This water is called: 'connate water'. Usually connate water must be cleaned off in order to be suitable for reinjection into the reservoir or released on surface water streams.

It is expected then that whereas 'Primary production' the *WaterOil_index* remains constant because the mix of produced fluids has not been intervened anyhow.

As explained before, a couple of policy design variables: *Reservoi_pressure* and *WaterOil_index* dictate the suitability for starting up waterflooding. The consequences of this intervention are seen in both policy design variables. On the one hand *Reservoir_pressure* rises because matter in is filling up the voids let by prior and constant fluid production, and on the other hand, as additional water is coming into the oil-connate water system then the index *WaterOil_index* rises.

An oil reservoir is an underground rock which posses a set of properties that allows to contain migrant fluids within its matrix. The reservoir rock must be porous, permeable, and surrounded by impermeable rocks at first. There is ample variation among reservoirs concerning particularities [22]. Nonetheless, this model runs a –usual case.

In this case the oil reservoir contains oil & water mixture under certain pressure that is the result of overburden weight and fluids (hydrocarbons) maturation. When a well is drilled until the reservoir rock and oil production begins, there will be a pressure gradient towards the wellbore and consequently a special type of flux emerges. This flux is called 'Transient flux regime' and is intimate related with the reservoir pressure [23]. In few words, the de-pressurization causes fluid flow but this action happens gradually from wellbore until reservoir edges, therefore this is a non-linear process that oil industry manage it using the 'Diffusivity equation' [24]

$$\frac{\partial^2 p}{\partial^2 r} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\emptyset \mu c_t}{0.000264k}\frac{\partial p}{\partial t} \qquad (1)$$

(1) (p= pressure
r= ratio
$\emptyset$= porosity
μ= viscosity
c_t= total compresibility
k= permeability)

This equation allows the characterization of pressure drop in porous systems accordingly to two principles and one law. Both principles are obviated whereas the law 'isolated' determines the model's dynamic in this regard. To wit:

- Principle of continuity [25]: this model utilizes an average pressure and assumes this value to the all reservoir,
- Mass balance: Stock and Flow diagram permit to trace down all the matter (stocked and flowing) of the system,
- Darcy's law [26]: this model uses the next equation to model and simulate the reservoir pressure. The Darcy's law claims that the pressure change depend on fluid properties (viscosity and caudal) and particularities of the medium (permeability, area, length) accordingly to the next equation:

$$Q = -\frac{kA}{\mu}\frac{\Delta p}{\Delta L} \qquad (2)$$

-
- (Q= caudal
- k= permeability
- A= flux area
- μ= viscosity
- Δp= Pressure diferential
- ΔL= distance between producer and injection well)

The next structure represents the net flow through the reservoir in terms of fluid production and injection. Here is where Darcy's law is used to analyze this process in terms of pressure drop, increase or maintenance:

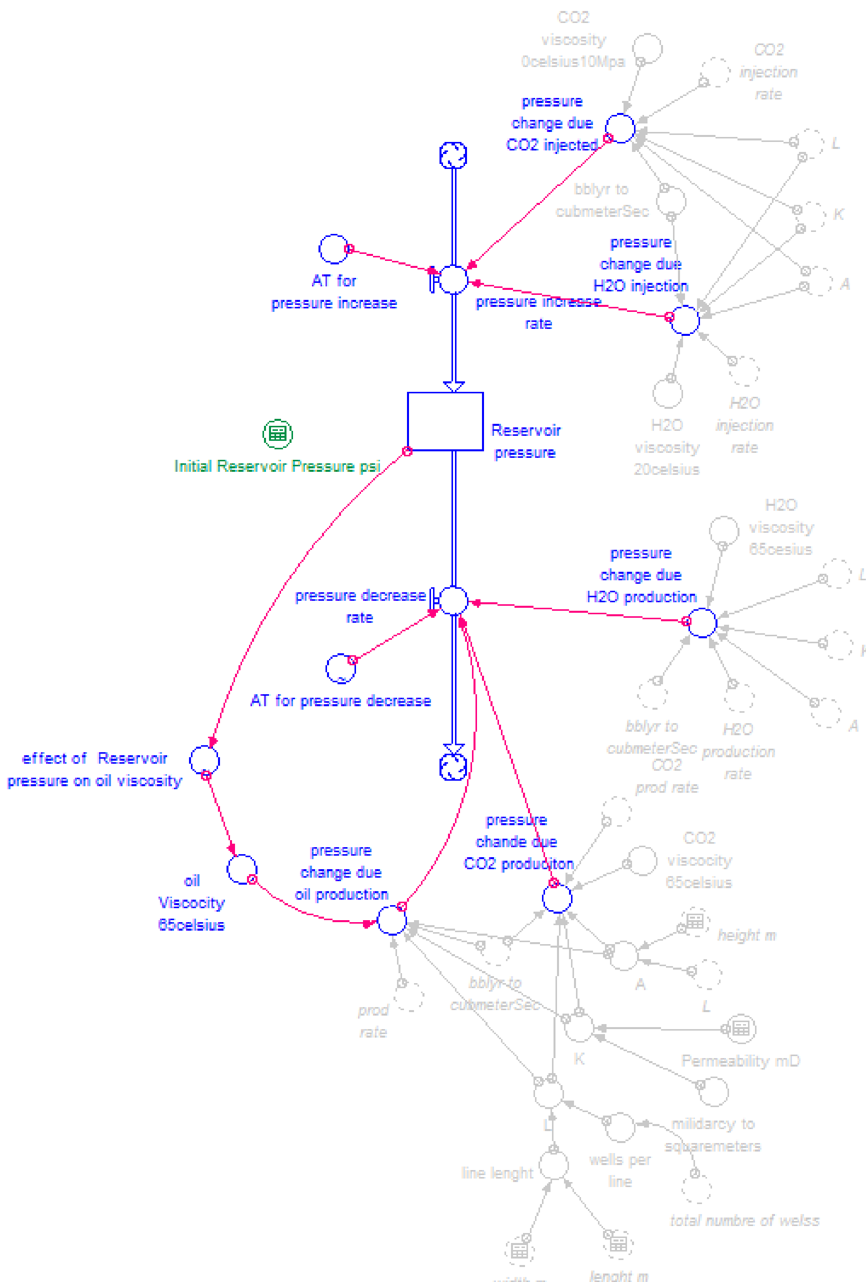


Figure 6. Structure of pressure dynamics.

The inflow corresponding to *Reservoir_pressure* stock traces the injection fluids whereas taking into account some of their properties like temperature and pressure. Water's in standar conditions[1] and CO2's is expressed as it is usually used in EOR operations (liquid state)[27].

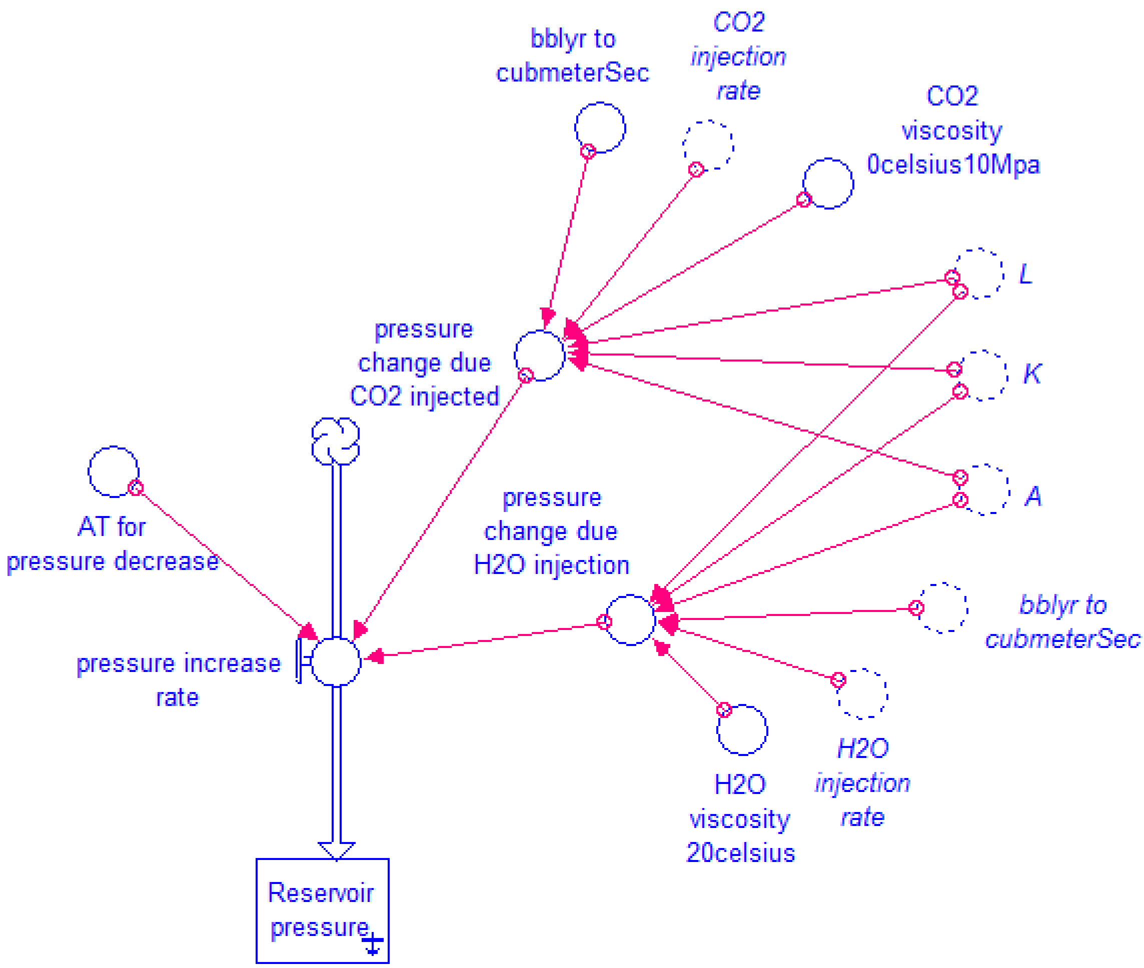


Figure 7. Structure of pressure increase.

The values L, K, and A are length (L) between injection and producing wells, thus is related to the reservoir's size and the amount of wells (this matter will be explained later on); permeability (K),

[1] 14.7psi and 25ºCelsius

which is defined as the easiness of a fluid to break through certain material (in this case a reservoir rock) and the area (A) where this displacement takes place.

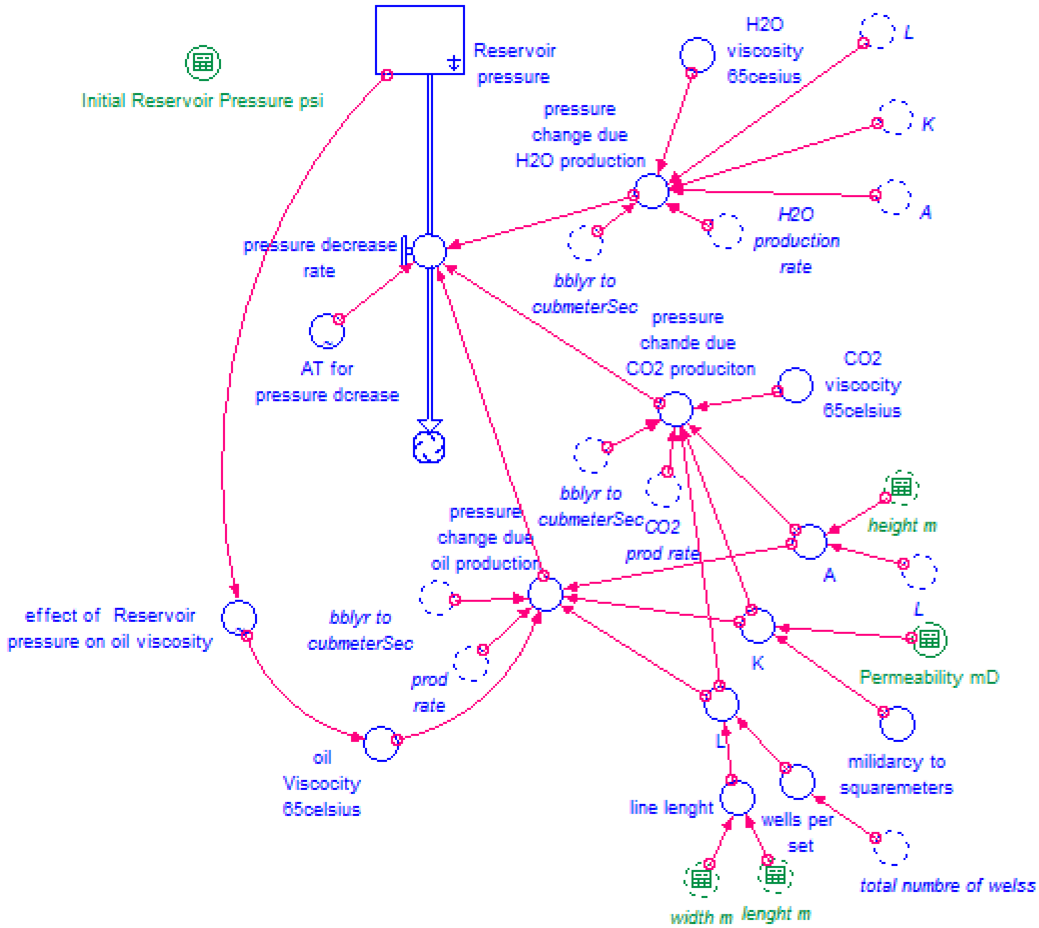


Figure 8. Structure of pressure decrease.

As shown in figure (up), outflow of *Reservoir_pressure* stock is made of those fluids that leave the reservoir pursuant to the Darcy's law. Those variables in green are 'policy design variables' and must be declared prior running the model in order to determine the reservoir size, initial conditions and reserves. The variable *effect_of_Reservoir_pressure_on_oil_viscosity* (down-left) is one of the advantages of CO2 over water as a working fluid in EOR operations. This effect is called 'Oil Viscosity reduction' due mixing with CO_2 molecules that diminish friction among oil molecules thereby inducing further fluid displacement through pores and channels. There are two more advantageous effect, besides 'Oil Viscosity reduction' that CO_2 posses as EOR agent comparing water: (i) one is related with the size increment of oil molecules when those interact with CO_2 molecules at certain pressure (minimum miscibility pressure) which causes the union or mixing of both and thereby propelling energy for fluids displacement. This effect is known as 'swelling effect' [28]:

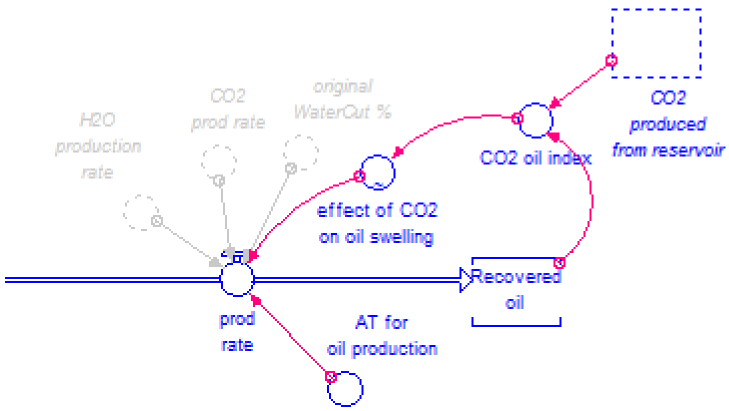


Figure 9. Structure of CO's 'swelling effect' on oil.

The structure of the 'swelling effect' places the total amount of CO_2 injected over the total amount of oil produced as the index that triggers further oil production.

The other known effect is (ii) 'Solubility increase', this property is related to the gas within oil solution [28] and is not included in this model since it contains no dynamics associated with gas production.

CO_2 injection is a 'Tertiary recovery techniques' [28] and alike waterflooding, CO_2-flooding uses the same structure outside (injection and producer wells) as well as inside (porous system, flow channels) than water injection. The piece of structure of the model on this regard is:

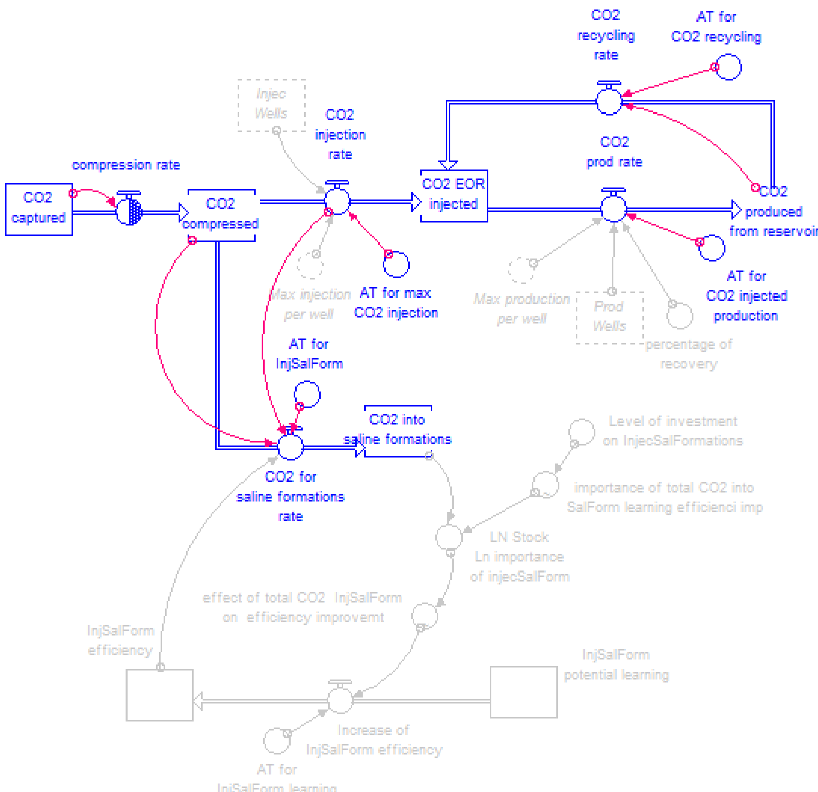


Figure 10. Structure of CO2 conduced for sequestration and/or for EOR.

Once CO2 is captured, it flows out of *CO2_captured* stock towards compression because CO2 have to in supercritical phase (liquid) to be ready for injection. The white-blue *compression_rate* faucet indicates that there is a unit conversion in there. So, units of *CO2_captured* are [tonnsCO2] whereas units of *CO2_compressed* and onwards are [bbl] (barrels).

Another important aspect of this structure of Figure 10 is that it traces not only the CO2 up to EOR operations but also the CO2 conduced to sequestration into saline formations [29]. Recalling the prior two production stages of the reservoir (primary and secondary), it is deductible that meanwhile those stages, CO2 production still vivid. As this is true, the CO2 compressed (unneeded for oil exploitation yet) is conducted to underground deposits. This operation still not mature technology [30], so it can be treated with the learning theory- explained before.

Regarding the last and four motivation of this study, this model asses holistically whether the energetic balance of CCS-EOR system is enough to consider it as a proper technology to overcome greenhouse gas emissions. As 'holistically' must be understood the fact that this energetic balance is based on energy consumption of every step of the chain as well as on the energy associated to the produced oil. So, this analysis includes: Energetic balance = energy associated with oil – (energy consumption of capture + energy consumption of compression + energy consumption of injection + energy consumption of oil refining). The structure in this regard is:

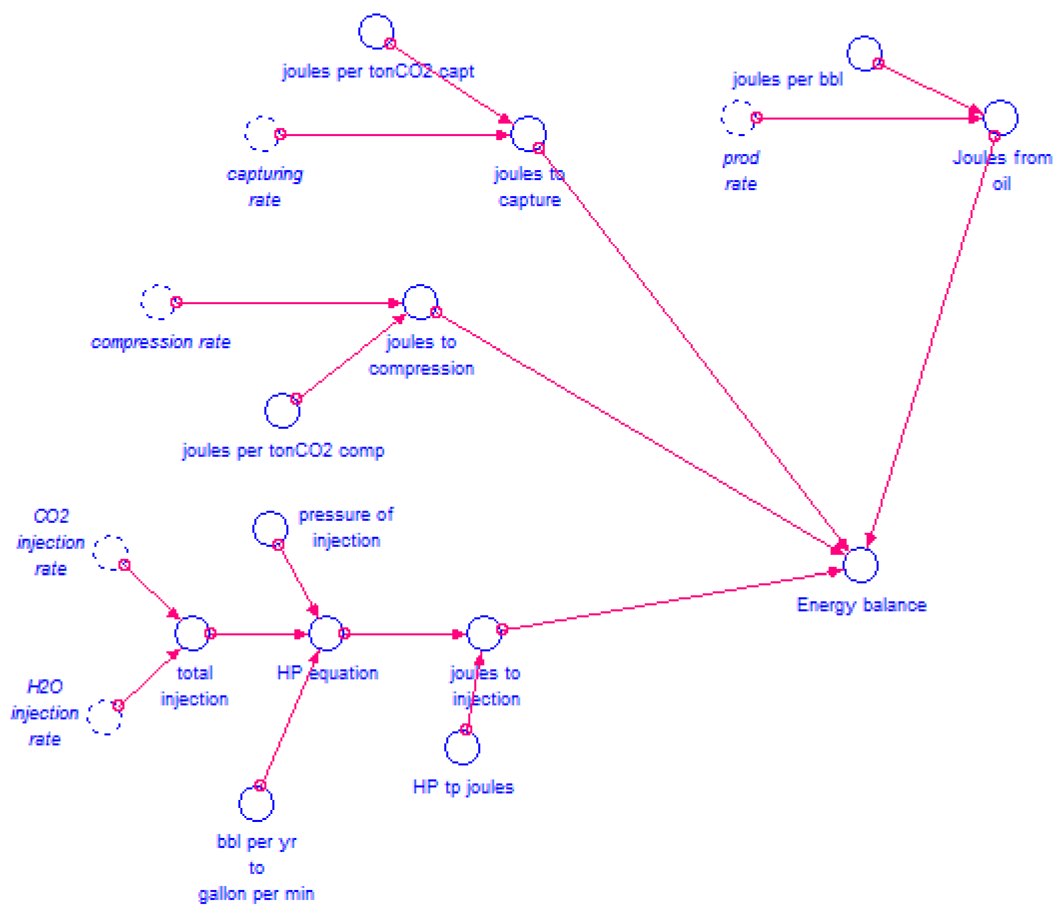


Figure 11. Structure of *Energy_balance* calculations.

ADDRESSING THE REALITIES

As explained so far, this model simulates a CCS-EOR chain within a timeframe of 5 decades, starting in 1990 and until 2040. To do so, the model comprises 30 stocks, 35 flows and 144 variables.

The model can be divided into six basic structures, several of which were explained in the previous section. (see -Model documentation and validation documentation- section for details about every single variable of the model. See also Annex 1 for details of the equations that compose the model)

System dynamics is suitable for addressing the system that studied in this thesis for several reasons. Among them, the possibility of simulating scenarios based on any set of policies designed and, more important, the need to analyze the impact of these policies on system's behavior and the change that its variables experience under any particular set of policies. This is inherently an innovative approach on CCS-EOR topic as some of those variables are used outside this –virtual world- to monitor, control and intervene in the –real- system.

Another reason to consider System Dynamics as appropriate is because t allows representing the passage of matter and its transformations with the information it generates and its feedback on the dynamics of matter itself.

It can also be mentioned the suitability of System Dynamics to cope with non-linearities involved on pressure drop, as well as the effects of CO_2 on oil viscosity reduction and swelling effect.

THE MODEL SECTOR BY SECTOR

Before explaining the operation of the model by sectors, it is worthwhile to catch a glimpse of the complete structure of the model and thus have a general idea about the role of each sector in the aggregate behavior of the entire model. For it the following causal diagram is shown below:

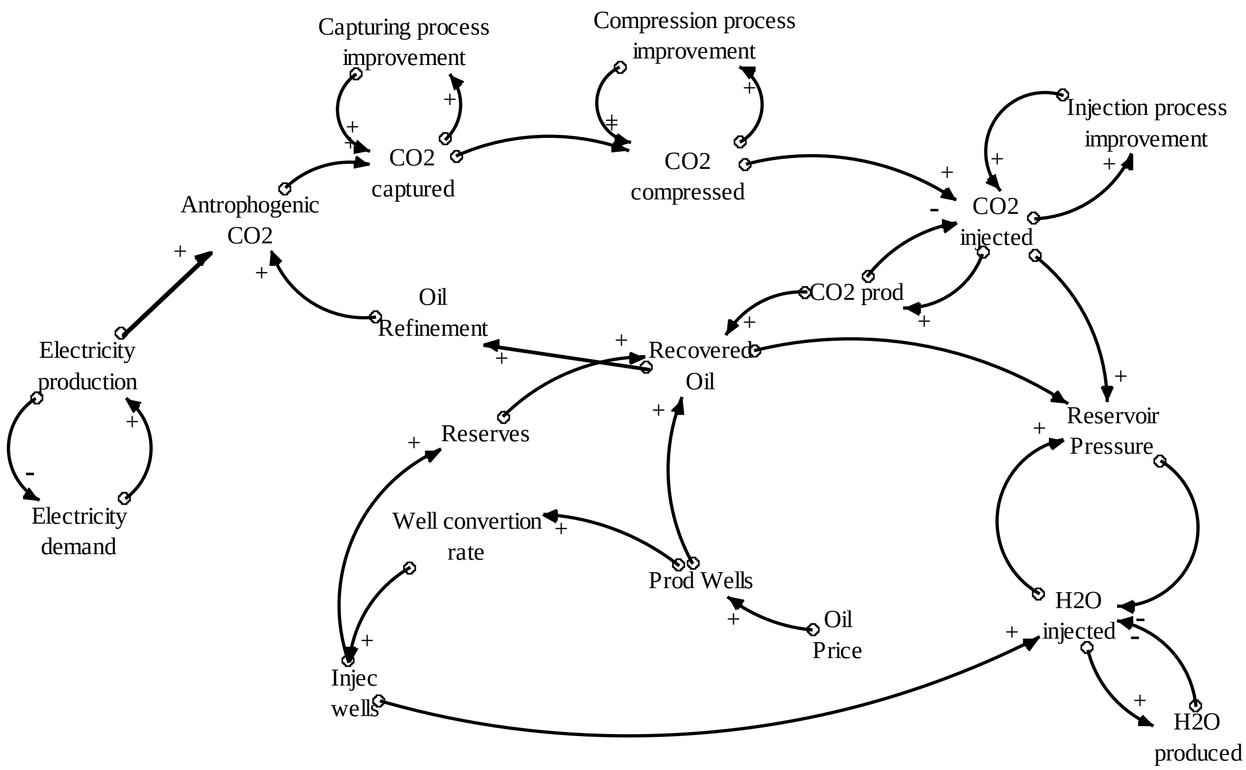


Figure 12. CLD of ECCIS structure.

Now considering the structure above; details of the structure and behavior of each of the six sectors are displayed:

- Oil Field:

The Figure 2 shows the structure related with this sector. Called ‘Oil field’ because it accounts for the initiation and development of an oil field in terms of the appropriateness of drilling and wells transformation (from producer into injector) as well as estimating reserves and oil production.

First, the following Figure 13 shows the model’s interface.

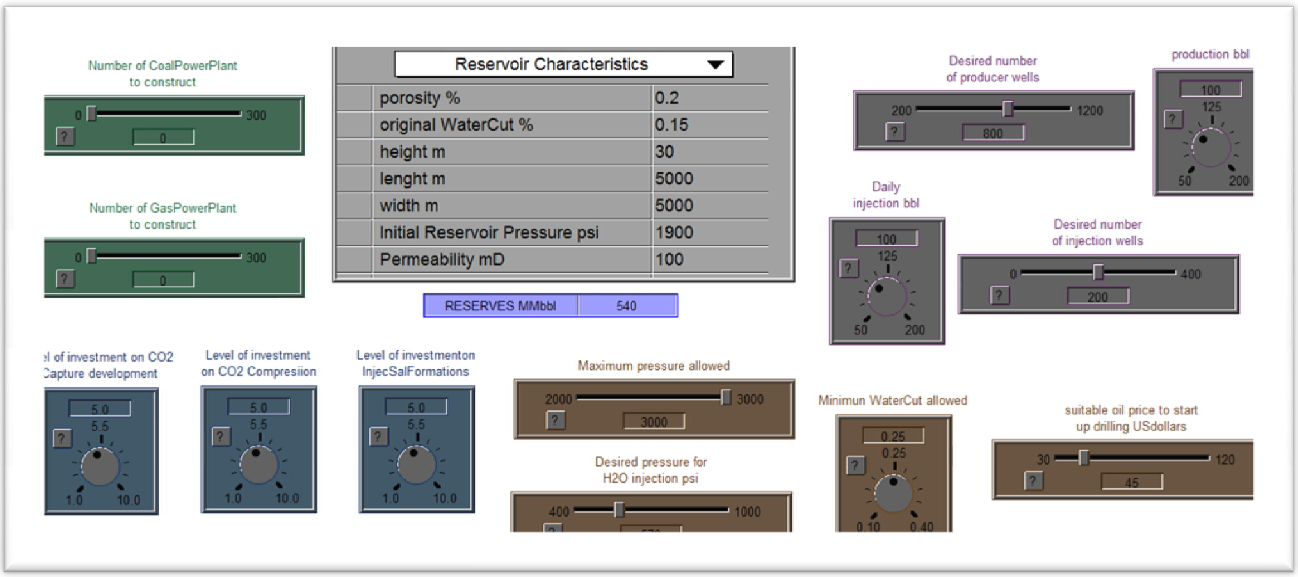


Figure 13. [xxx]'s interface.

The gray and blue rectangles (up-center) comprise the declaration of variables regarding the characteristics of the reservoir and consequently its reserves.

For example Table 1 shows the declaration of the base case and the associated total reserves (540 MMbbl).

Table 1. Declaration of the reservoir for the base case scenario.

Reservoir Characteristics	
porosity %	0.2
original WaterCut %	0.15
height m	30
lenght m	5000
width m	5000
Initial Reservoir Pressure psi	1900
Permeability mD	100

RESERVES MMbbl	540

Now, if a different, smaller and less porous reservoir is declared, is expected to be lower reserves associated as shown Table 2:

Table2. Declaration of a smaller reservoir than base case scenario. As size decrease, reserves do it as well.

Reservoir Characteristics	
porosity %	0.35
original WaterCut %	0.15
height m	20
lenght m	4000
width m	4000
Initial Reservoir Pressure psi	1900
Permeability mD	100

RESERVES MMbbl	150

This is completely true since the more room for fluids inside the reservoir, the more reserves are present and, perhaps, ready for production.

As it was previously mentioned, the exogenous *Oil_price* dictates favorability or not, for the starting up of drilling operations and therefore oil field development. The Figure 13 shows the historical, as well as the projection of the price of oil from 1990 to 2040 [31].

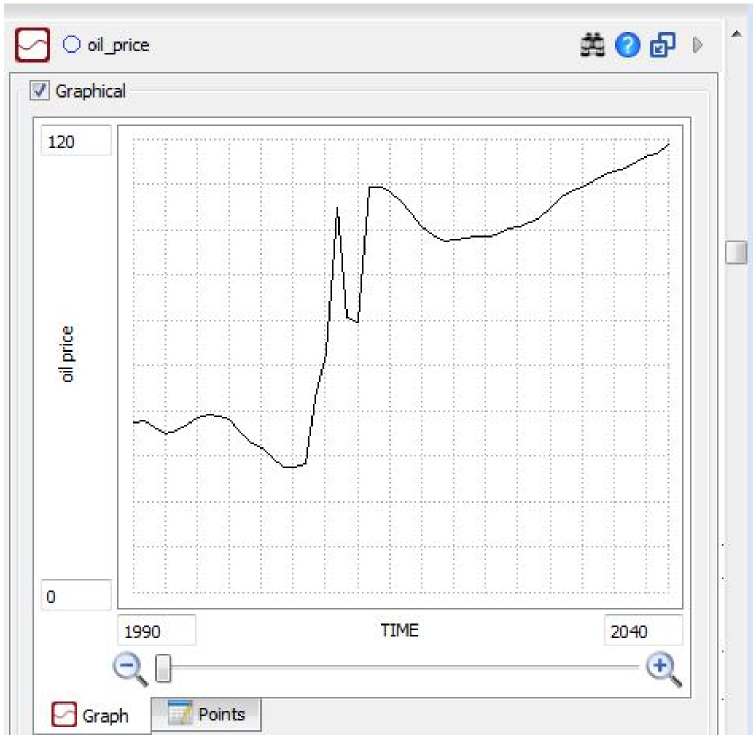
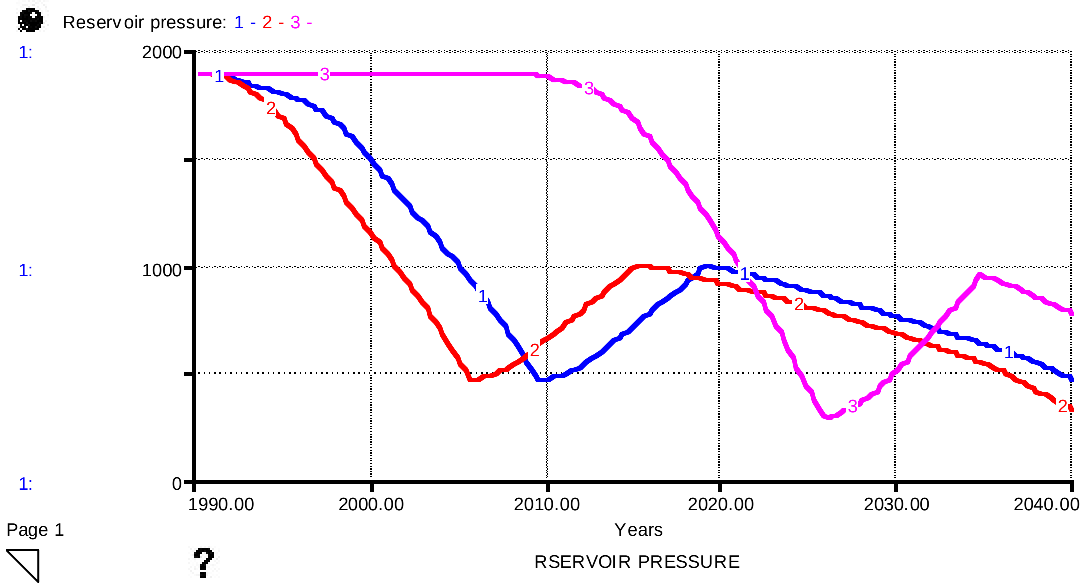
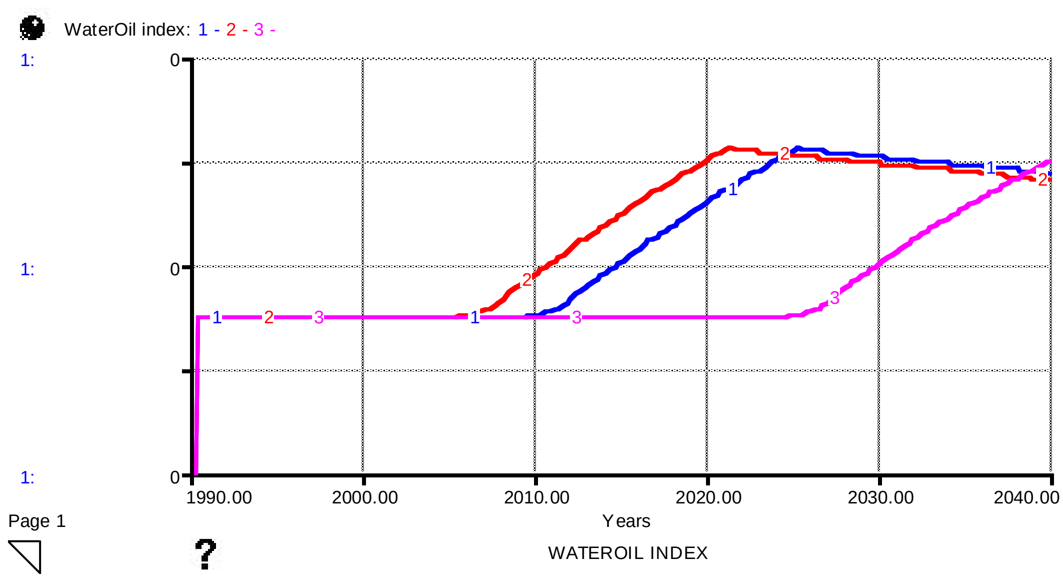


Figure 14. Graphical function corresponding to *Oil_price* since 1990 to 2040.

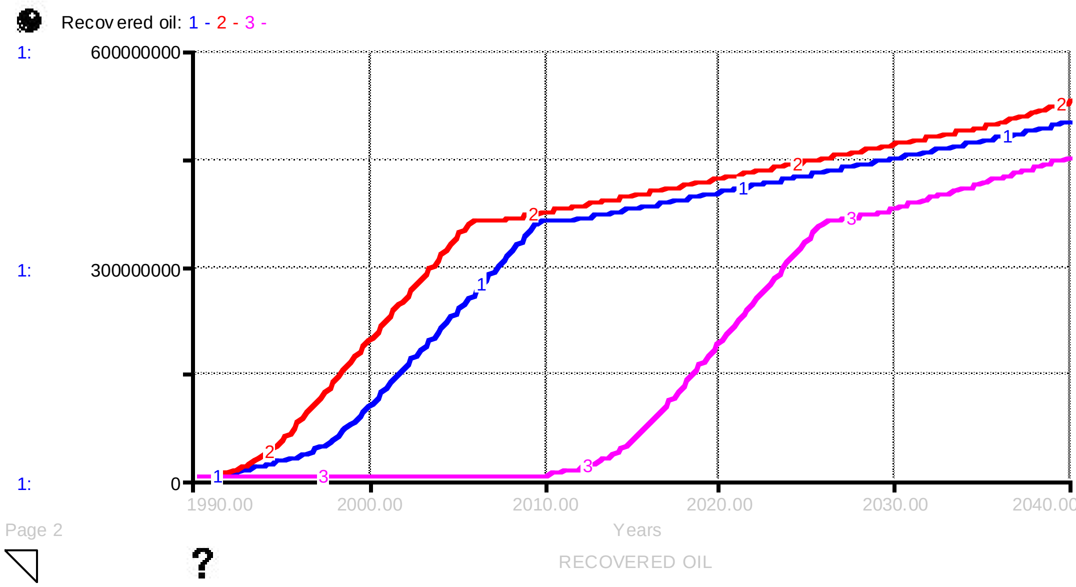
Now, the base case says that 45usd (see Figure 13 bottom right) is an appropriate price for the commencement of drilling (as *suitability_oilprice_to_start_up_drilling* policy variable), but it is crucial for complete understanding to investigate the behavior of some variables in the model (*Reservoir_pressure*, *WaterOil_index*, *recovered_oil* respectively) for different values of *suitability_oilprice_to_start_up_drilling.* See Graph 1, Graph 2 and Graph 3:



Graph 1. Reservoir_pressure for three values of suitable_oil_price_to_startup_drilling on base case scenario (blue=45usd, red=30usd, pink=85usd)



Graph 2. WaterOil_index for three values of suitable_oil_price_to_startup_drilling on base case scenario (blue=45usd, red=30usd, pink=85usd)



Graph 3. Recovered_oil for three values of suitable_oil_price_to_startup_drilling on base case scenario (blue=45usd, red=30usd, pink=85usd)

According to these three last graphs, the beginning of *oil_field* exploitation based on *oil_price* has an important impact on the total amount of *Recovered_oil* whereas this impact is low on *Reservoir_pressure* and *WaterOil_index*. To wit, it can be seen that although *Reservoir_pressure* and *WaterOil_index* change for each *oil_price*, this change is related to a time lag whereas this time lag for different functions of *Recovered_oil* mean millions of barrels in involved.

- Reservoir pressure

This sector holds some degree of complexity due to the spatiotemporal nature pretended to be schematized in this study. In the first part of this thesis the assumptions in this regard were addressed. Figure 6 shows the structure corresponding to this sector.

There are two main issues in this structure that must be clarified in order to ensure transparency of the model. The first has to deal with the physical space where *Reservoir_pressure* variable is measured. The other issue to be clarified is the effect on the viscosity with respect to pressure.

If the inflow and outflow of *Reservoir_pressure* stock is analyzed, it accounts the dynamics for both types of wells, as well as its inflow means what is injected into the reservoir (H2O & Oil) and its outflow is what comes out of the reservoir (H2O, Oil, CO2). see Figure 15.

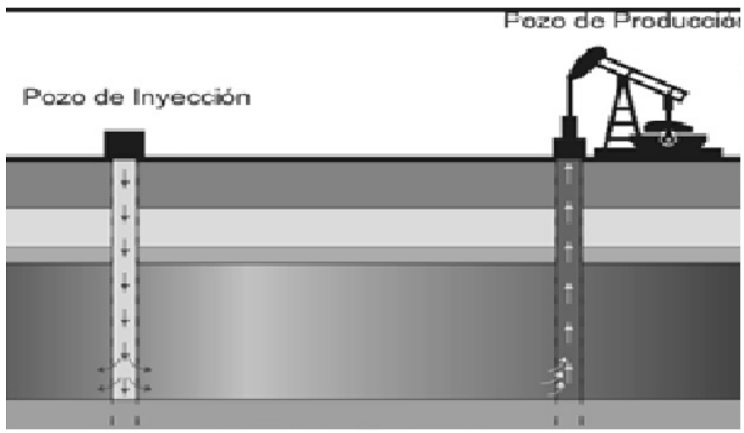


Figure 15. Basic structure of a producer (right hand side) and injection (left hand side) wells array.

However, as explained in the Oil Field sector, the reservoir size must be declared (as do the number of wells in both production and injection) and thus represents variableness in terms of distance between wells. The Figure 16 aims to show this matter of physical space and how it is addressed in this model.

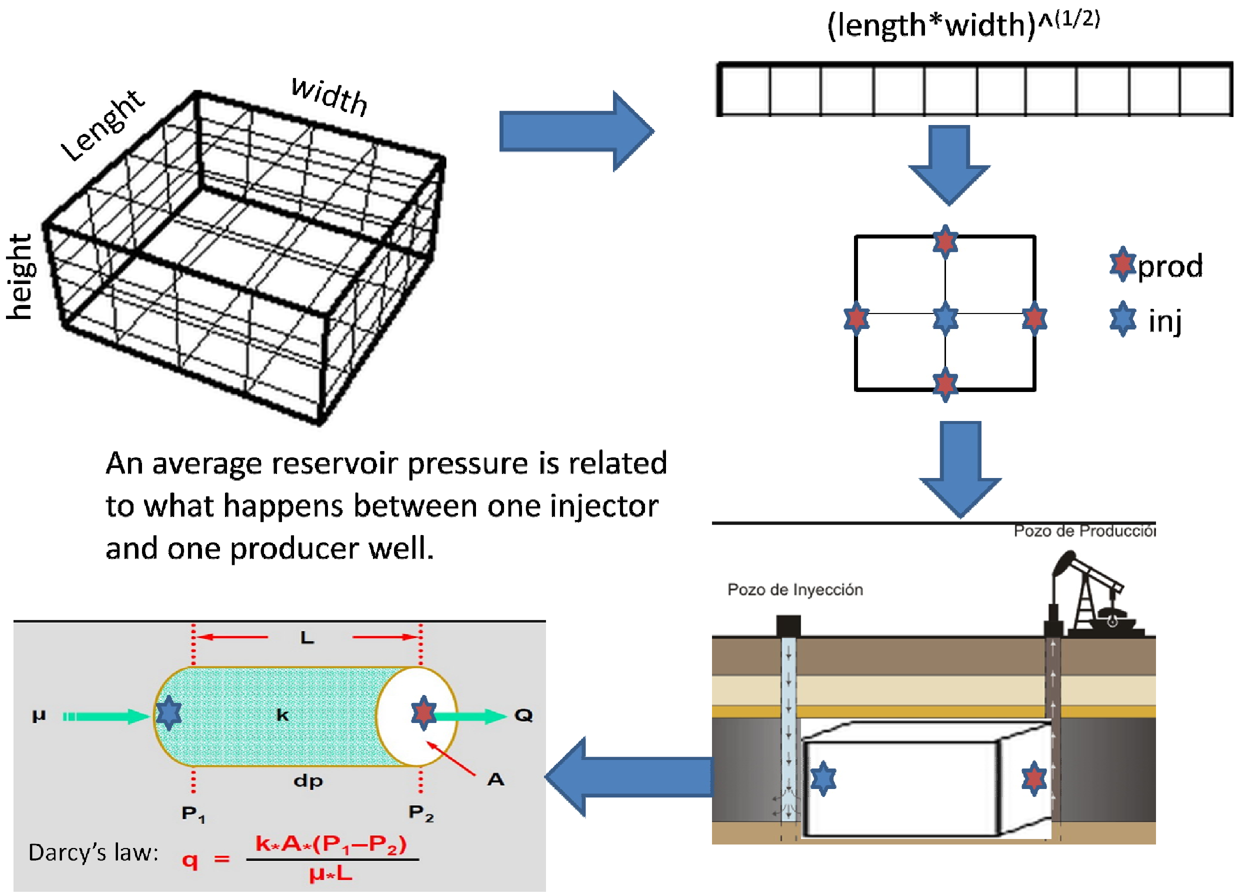


Figure 16. The physical space issue and how ECCIS cope it. In red, the Darcy's law.

Then it is expected that in a reservoir (base case), the reservoir pressure varies with the increase or decrease in the number of wells due to the dynamics of exploitation changes (injection = inflow, outflow = production). To display this dynamic, Figure 17 is presented.

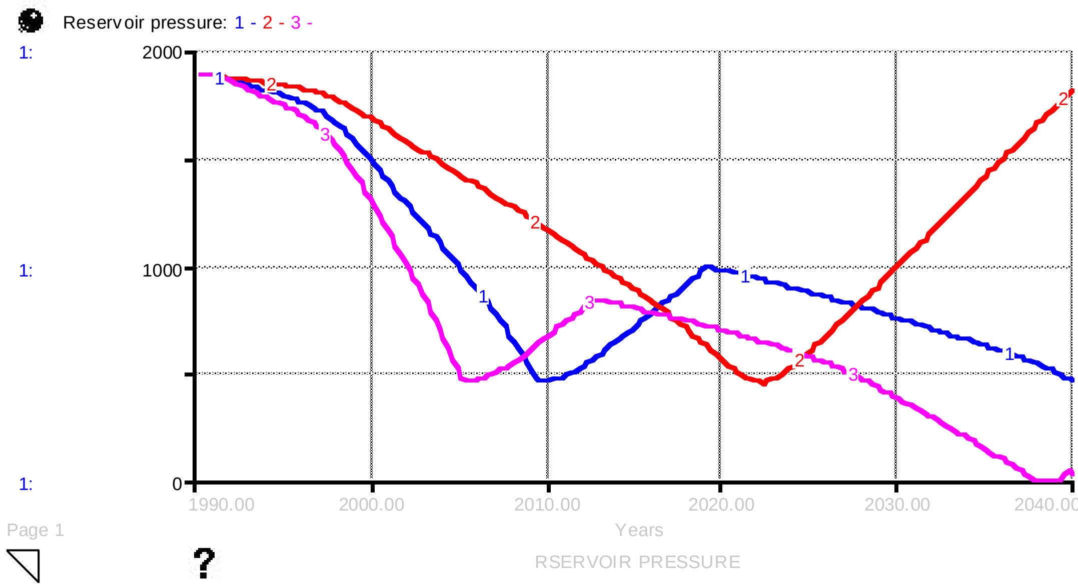
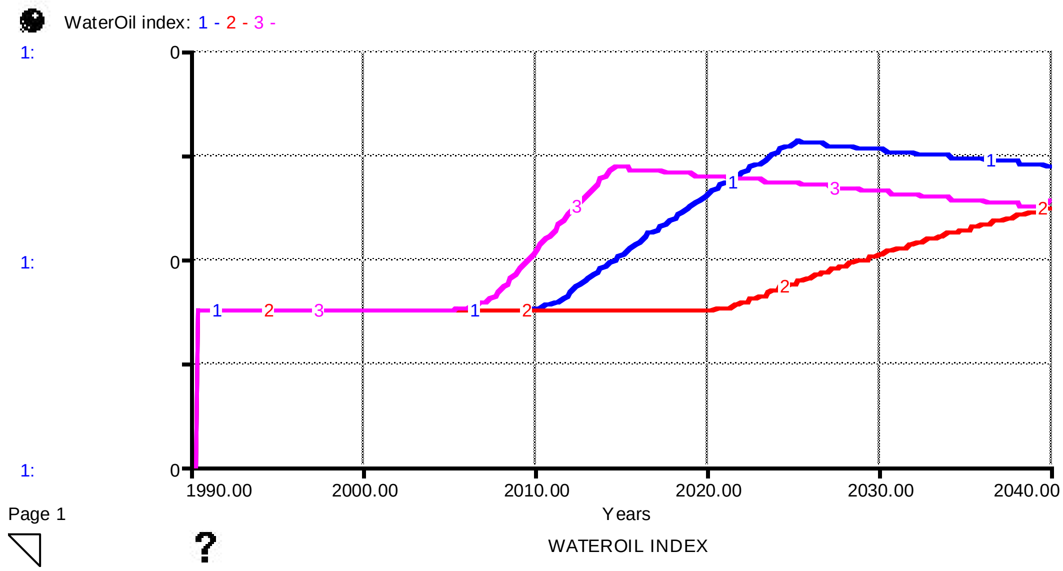


Figure 17. Reservoir_pressure behaviour for three different number of production wells. Blue=base case (800), red=400, pink=1200).

As expected, the larger the outflow (in this case represented by *Prod_Wells*) the faster the stock depletion. Red line run does not reach CO2 injection because the WaterOil_index during this run will be always under the *Minimun_WaterOil_index_allowed* (see Figure 16) therefore waterflooding goes on further the end of the simulation.



Graph 4. WaterOil_index behaviour for three different number of production wells. Blue=base case (800), red=400, pink=1200).

The effect of pressure on the viscosity of oil is displayed in the following graph function Figure 18 and according to [32].

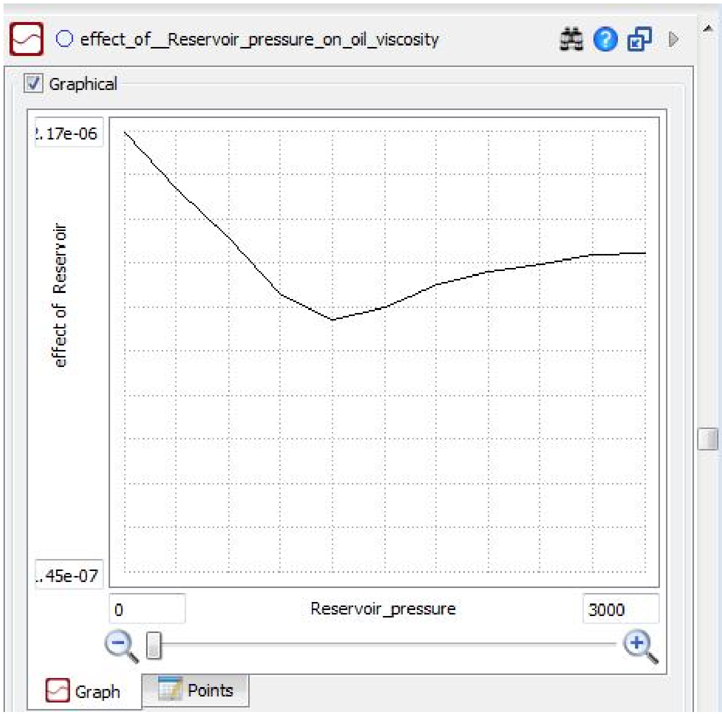


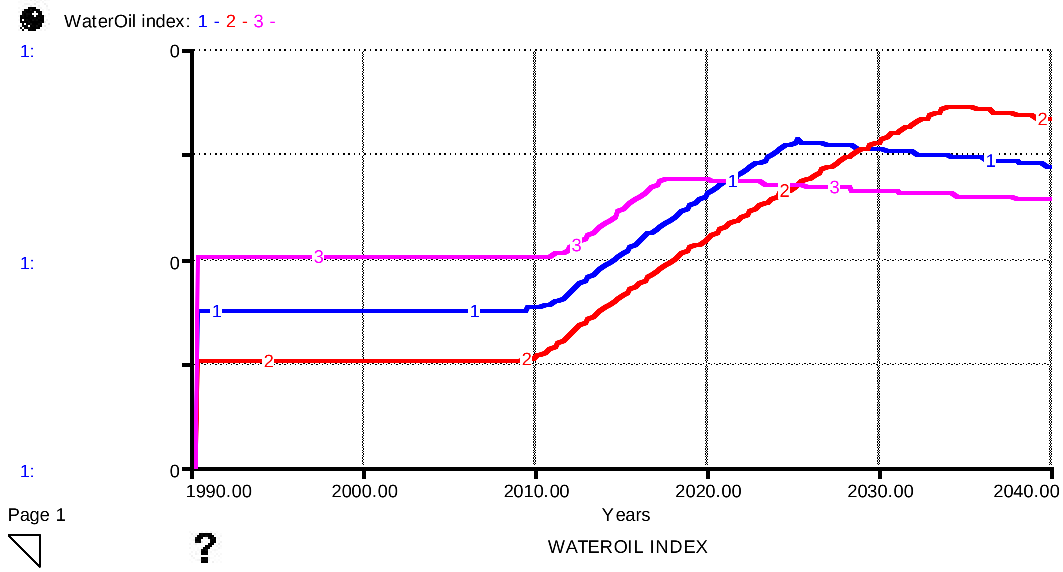
Figure 18. Effect of reservoir pressure on oil viscosity reduction.

Concerning viscosity of fluids, it should be noted that it is different at input (injection) and at output (production) of the site and that this property depends on the temperature which is not the same in both sites. ECCIS considers as standard conditions of water and supercritical state of CO_2 when injection and 60C and 14.7psi as conditions of produced fluids.

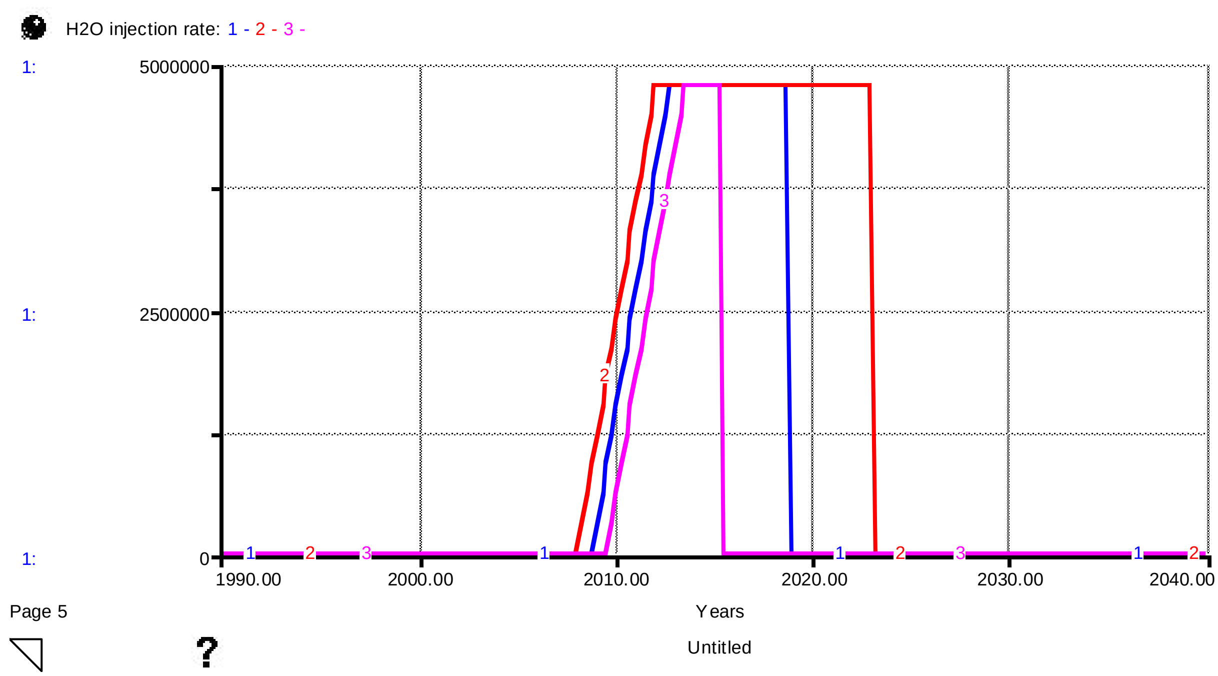
- H_2O injection

Figure 5 contains the structure of dynamics of water in the system. In this structure protrudes *WaterOil_index* because it is an indicator of the effectiveness of the injected water for displacement imposed on the oil within the pores.

Original_water_cut_% is a variable that is part of the initial declaration of variables of the system and has, as well as *minimun_WaterOil_index_allowed*, influence on the feasibility of the injection of H_2O in the reservoir. To clarify this Graph 5 and Graph 6 is shown where *WaterOil_index* and *H2O_injection_rate* are simulated for different values of *Original_WaterOil_%*.



Graph 5. *WaterOil_index* for three diferent values of *Original_water_cut_%*. Blue=base case (0.15), red=0.1, pink=0.2



Graph 6. *H2O_injection_rate* for three diferent values of *Original_water_cut_%*. Blue=base case (0.15), red=0.1, pink=0.2

It is possible to see that the greater the difference between the original and the permitted, the longest stage of secondary production (H2O injection) by the greater increase *Reservoir_pressure* and slightly increase of oil recovery.

- CO2 injection

The Figure 10 shows the structure that CO2 follows once compressed and ready for injection. As it was mentioned in the first part of this thesis, the CO2 follows the same structure both outside (wells) and within the reservoir (porous system), so the focus of this apart is associated with the dichotomy between CO2 sequestration in formations saline or CO2 for EOR operations.

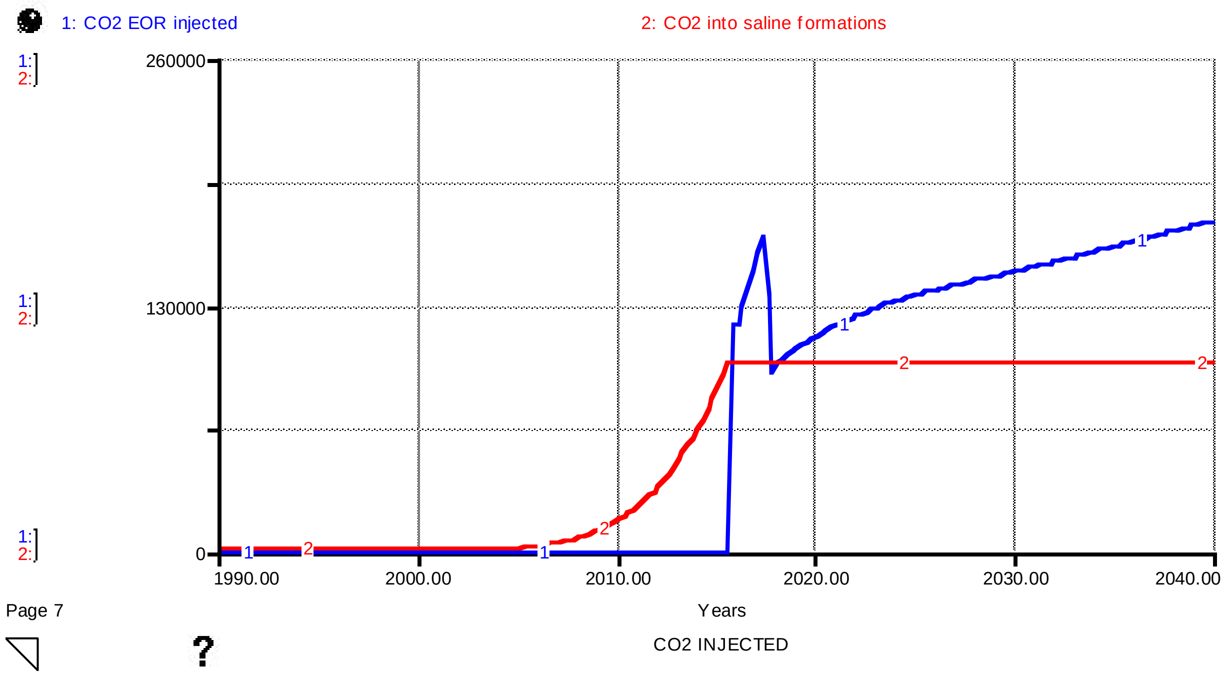
ECCIS reflects the monetary yield in this regard. This means that the injection of CO2 which represents profits is above (more important) that which is not. That said and considering that in the timeframe of the model both actions are happening: electricity production and reservoir deployment; else CO2 injection for EOR operations related to reservoir deployment occurs in the third and final stage of the reservoir's life; is expected that the CO2 produced before starting 'tertiary recovery techniques' will be driven to another sink.

ECCIS uses as a sink for CO2 *CO2inj_EOR* and *CO2inj_saline_formations* stock.

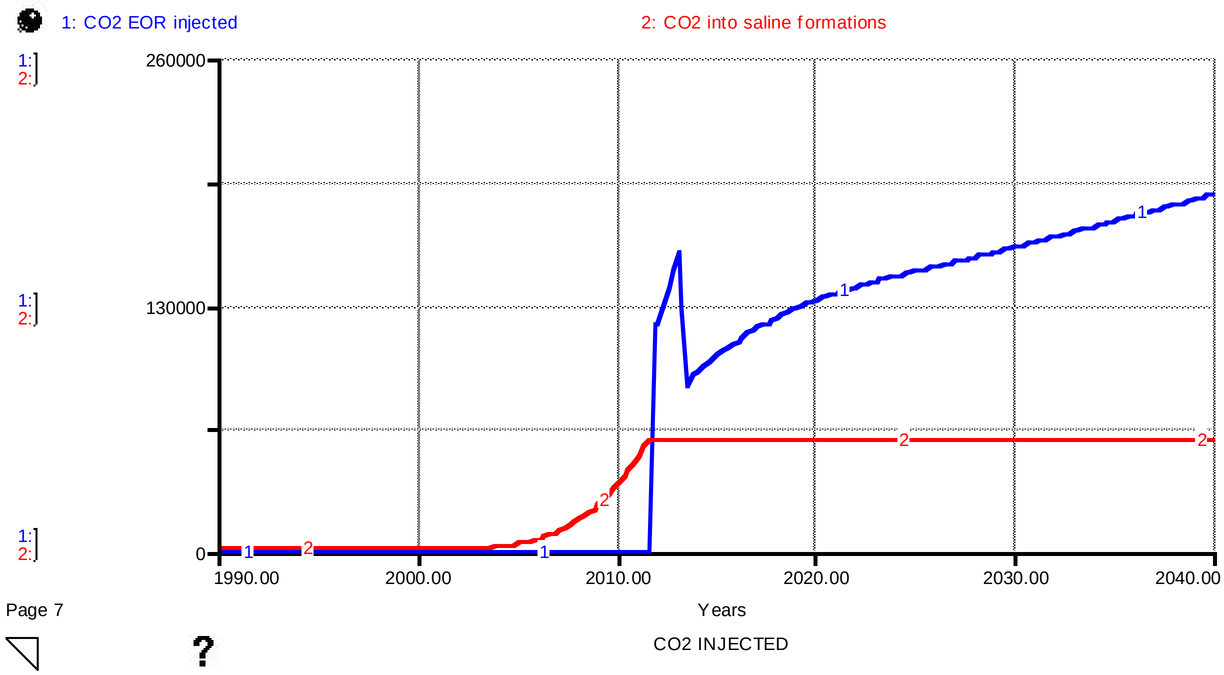
As in the real world, ECCIS considers the CO2 driven to saline formations trapped forever (no outflow) while the injected CO2 EOR operation is partially a produced fluid[2] (H2O & oil) (see Figure 10).

[2] ECCIS has a variable called *% _of_recovery* which indicates the fraction of CO2 has headed the producer wells and consequently also indicates the fraction of permanently CO2 trapped in the pores of the oil reservoir [32].

In order to show off the behavior relating to CO2 sequestration, the Graph 7, Graph 8 and Graph 9 are shown.

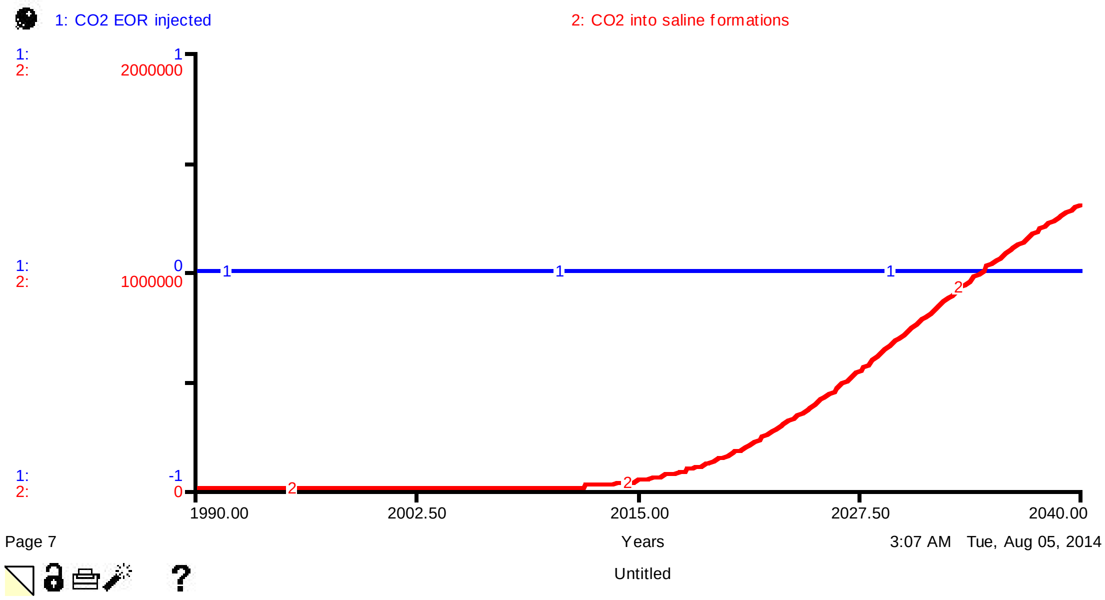


Graph 7. CO2 for both sinks at base case (45usd) for starting up drilling operations.



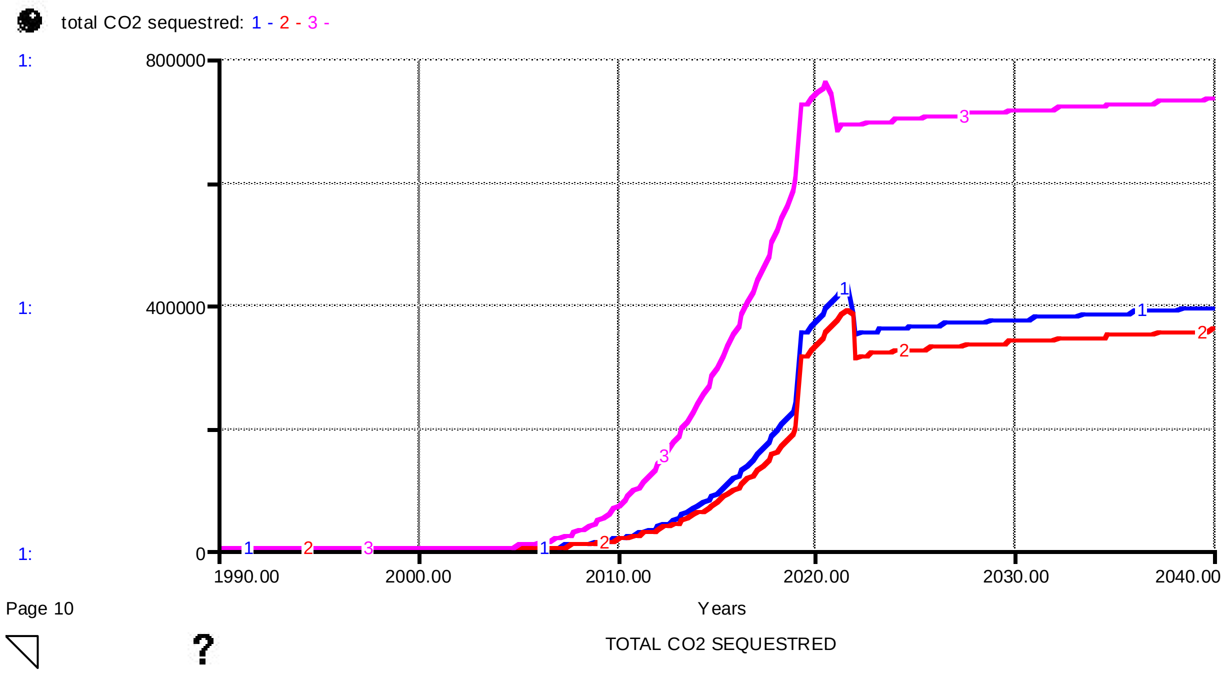
Graph 8. CO2 for both sinks at 30usd as suitable oil price for starting up drilling operations.

According to Graphs 7 and Graph 8), the lower the *Oil_price* needed to start the oil field deployment, the slower the learning process of CO2 injection into saline formation therefore the less CO2 will be sequestered.



Graph 9. CO2 injected when there is no EOR operations.

Figure 10 shows the impact of the level of investment in the total amount sequestered in saline formations according to the learning theory explained in the first part of this thesis.

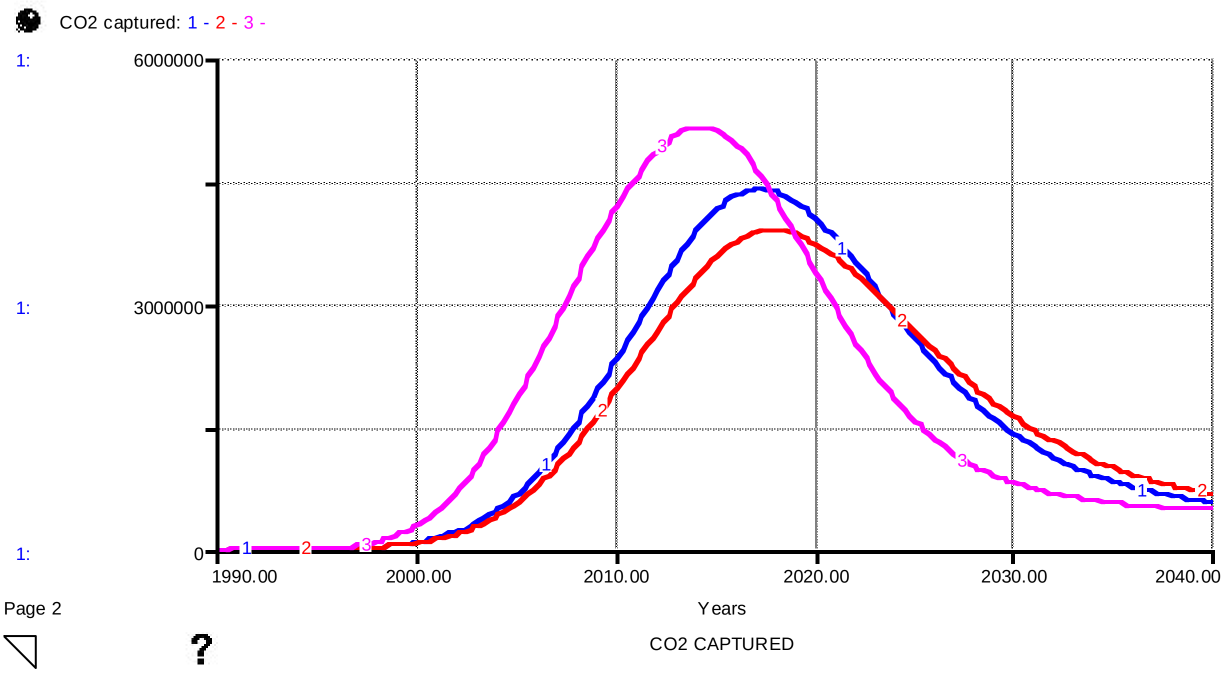


Graph 10. CO2 conduced to saline formations. Blue=base case (5.0), red=lowest investment (1.0), pink=highest investment (10.0)

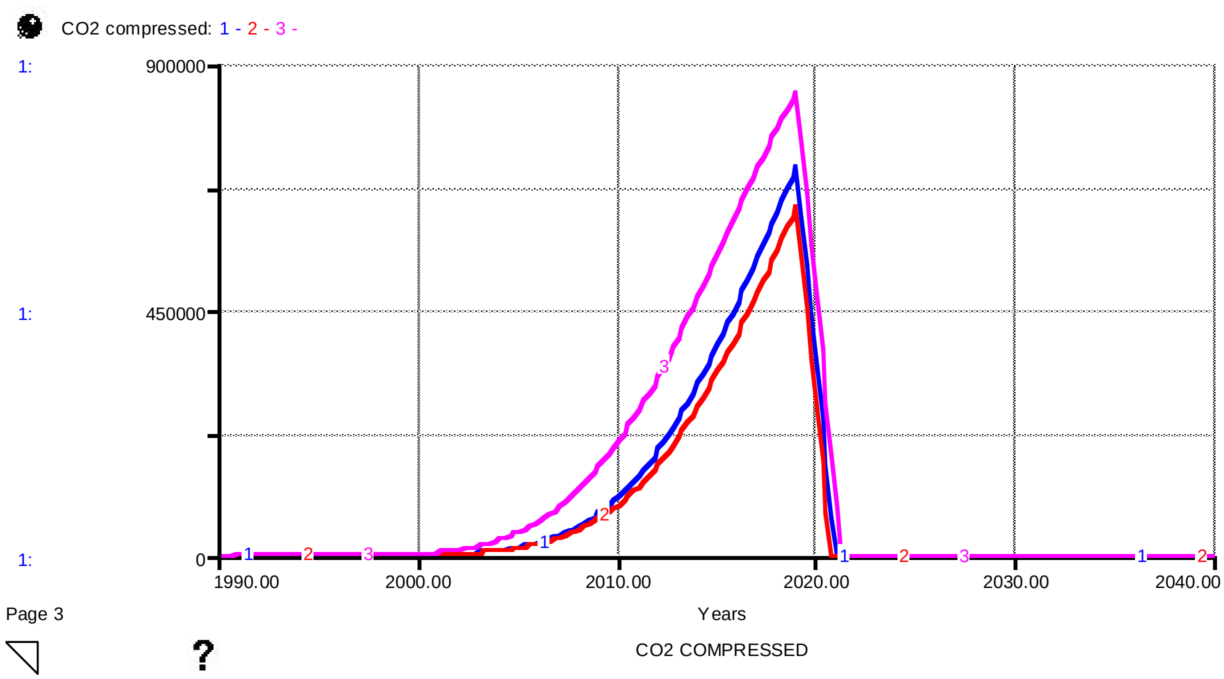
About Graph 10 It is worth to mention the strong influence that high investments triggers, in this case, for the total amount of CO_2 injected into saline formations.

- Capture and compression chain

The essence of this sector was explained in the first part of this thesis (see Figure 1) so the focus of this apart is to show off the behavior of both stock (*CO2_captured* and *CO2_compressed*) varying the level of investment. To wit:



Graph 11. CO2_captured. Blue=base case (5.0), red=lowest investment (1.0), pink=highest investment (10.0).



Graph 12. CO2_compressed. Blue=base case (5.0), red=lowest investment (1.0), pink=highest investment (10.0).

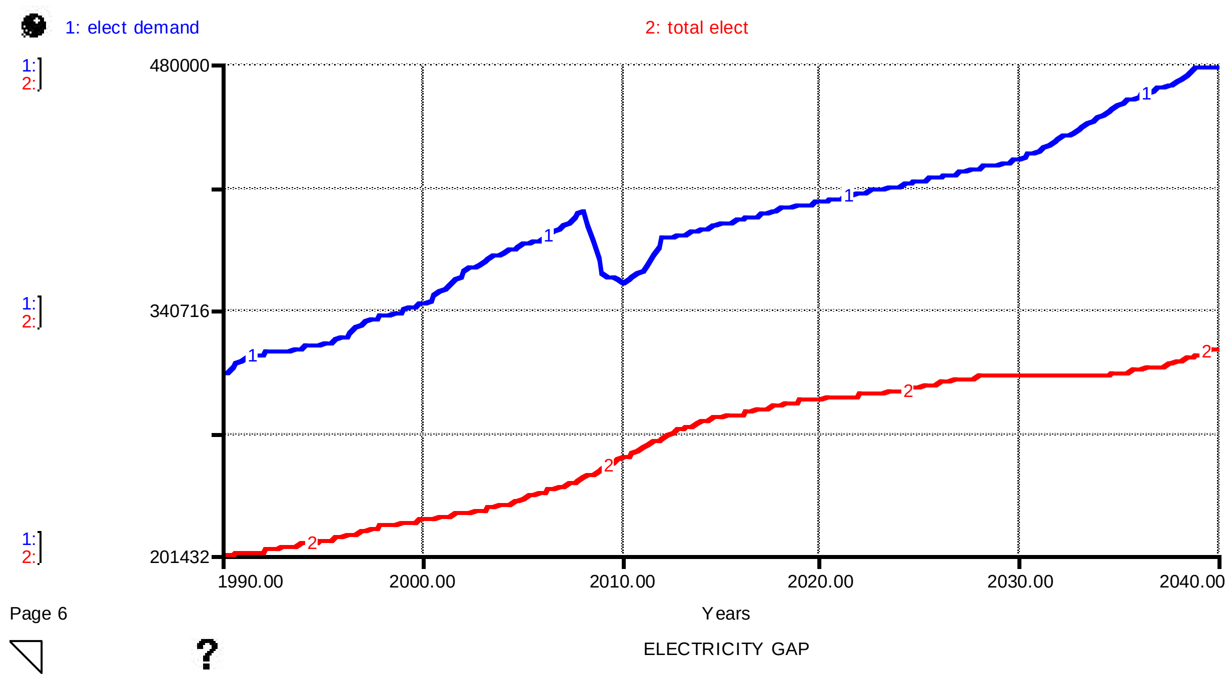
- CO2 sources

Figure 4 and Figure 3 account for the structure of production of CO2 as waste material from oil refining operations and CO2 as exhaust gas from burning fossil fuels for electricity generation respectively.

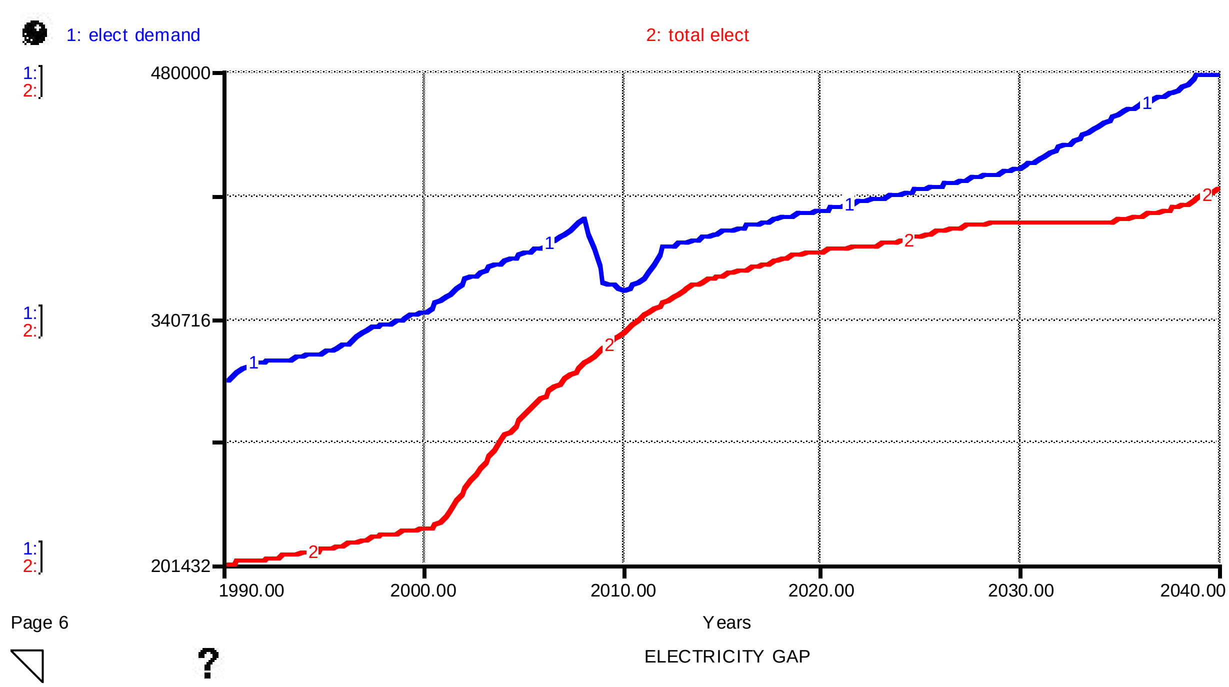
Regarding the structure of the Figure 3 worth mentioning that the data of refining (CO2/bbl) is provided by the Colombian national oil company, Ecopetrol [33] and should not be assumed the overall accuracy of this value as their units are [CO2e] (CO2 equivalent) [34] therefore is not a physical quantity of CO2 that can be effectively captured, compressed and injected. However, it is a reliable estimate in order to evaluate quasi-real scenarios.

Regarding the structure of Figure 4 and joined the above about electricity production in this model, note that ECCIS only considers Gas & Coal because those are the most widely used raw material for electric production worldwide [35]. Also the construction of new plants is a very well known process which provides reliable data that can be leveraged by ECCIS.

As mentioned above, the *GAP_electr_demand_prod* is larger than zero, unless more capacity is built. To fully appreciate what this is all about, the Graph 13 is presented.



Graph 13. Electricity Gap. Base case.

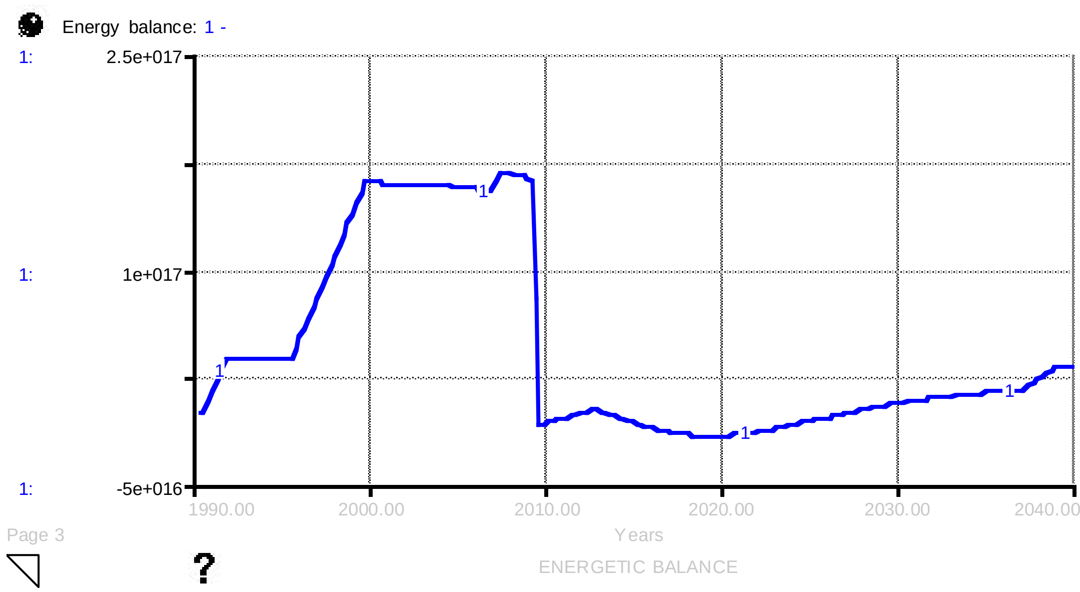


Graph 14. Electricity GAP. In 2000, 50 coal power plants and 100 gas power plants were built in the year 2000.

It can be seen the gap reduction trough capacity increase of both: coal and gas base.

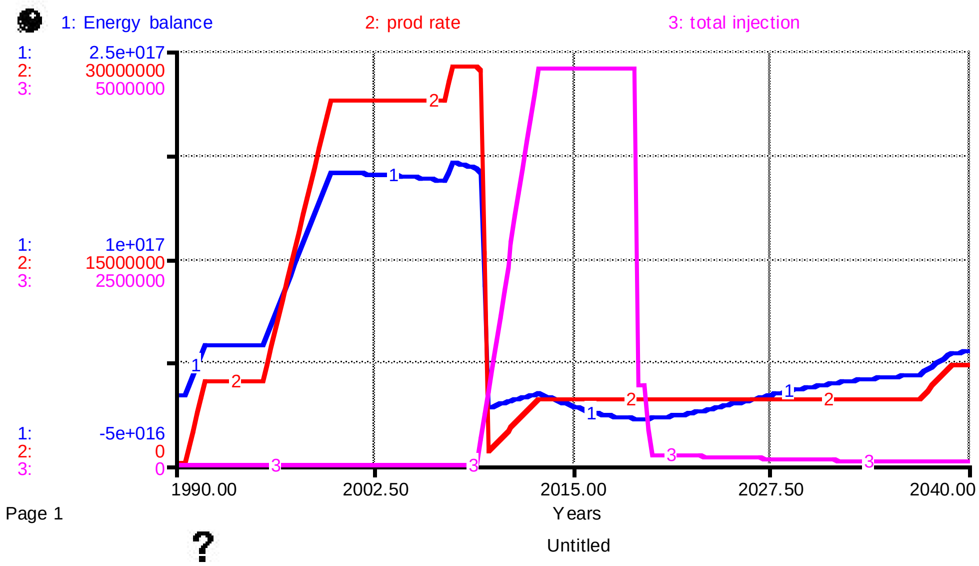
Apart: Energetic Balance.

In order to find out whether this CCS-EOR stills a wise approach to combat greenhouse gas emissions, it is presented the next Graph 15 which is showing the variable *Energy_balance* for the base case scenario.



Graph 15. *Energy_balance* run for the base case scenario.

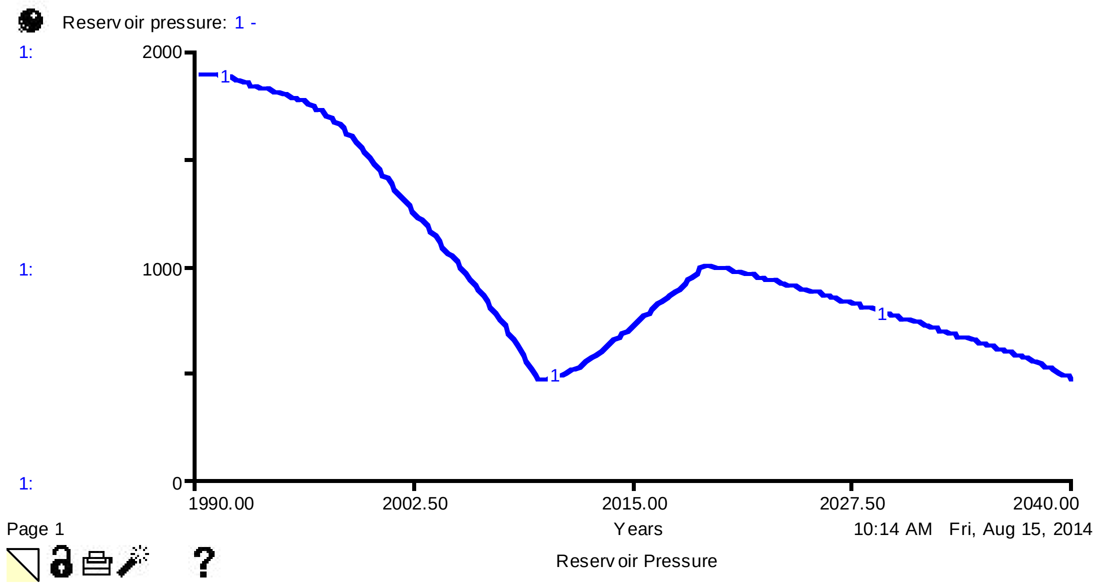
As expected, during ‘Primary Production’ stage the energetic balance is positive because there is no energy consumption on fluid injection, plus CCS chain energy consumption is low because early stages of technology deployment indicates the quantities involved (captured and compressed) aren’t ample yet so low energy requirements as well. The balance is not always positive though. From 2009 until 2011 as well as from 2013 to 2027 the balance is negative and this is due fluid injection. To have a clearer picture of this influence, please see Graph 16.



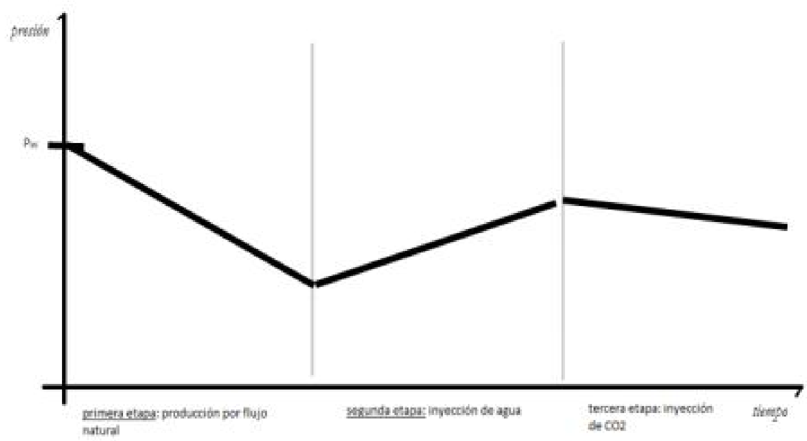
Graph 16. Influence of oil production rate and total fluid injection of the system's Energy_balance.

VALIDATION (reference modes)

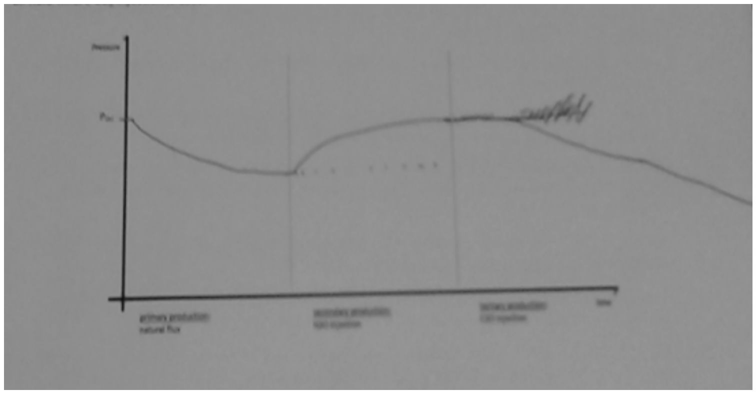
Considering this is a generic model for CCS-EOR, validation is based on expert knowledge [36], [37], [38] due to the lack of holistic information from which can be extracted a reference model of a particular case involving this same model analyze. The experts were asked to draw a graph of the behavior of the two major decision variables (*Reservoir_pressure* and *WaterOil_index*) versus time for each of the production stages of a field. These results are compared with the base case simulation.



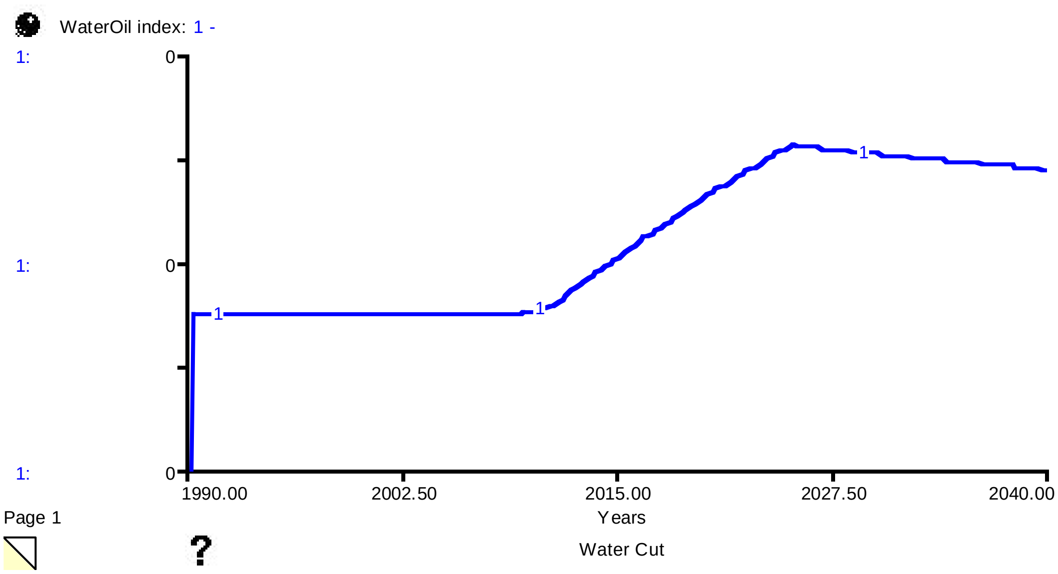
Graph 17. Reservoir_Pressure behavior using base case data.



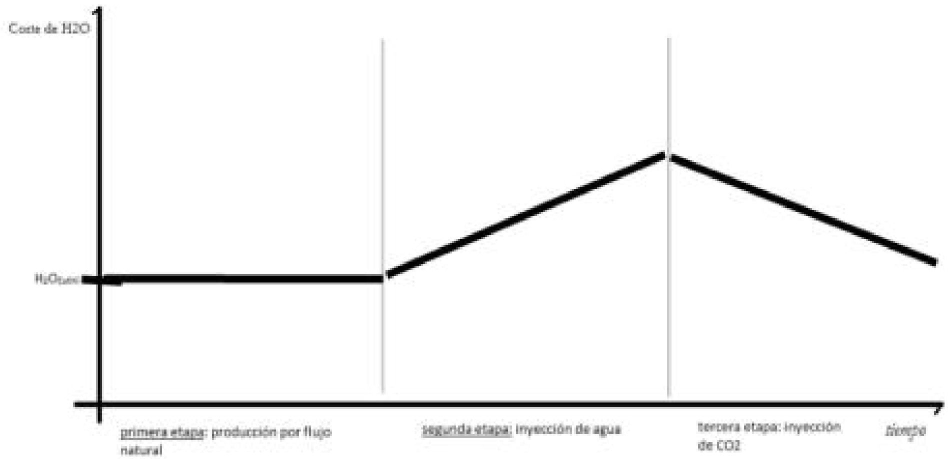
Graph 18. Reservoir_pressure profile scratch drawn by por Laura Álvarez, Geomehcanics Research Engineer. Universidad Nacional de Colombia



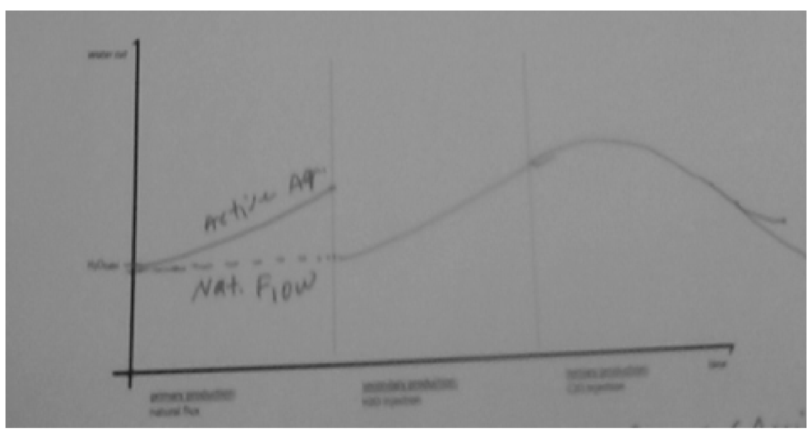
Graph 19. Reservoir_pressure profile scratch drawn by Haddy Jabbary, Assitant Professor. University of North Dakota, USA.



Graph 20. WaterOil_index behavior for the base case scenario.



Graph 21.WaterOil_index profile scratch drawn by por Laura Álvarez, Geomechanics Research Engineer. Universidad Nacional de Colombia



Graph 22. WaterOil_index profile scratch drawn by Haddy Jabbary, Assitant Professor. University of North Dakota, USA.

It results quite clear that ECCIS shows interesting behaviors in terms on similarities to real-world for these two variables. According to former figures, it can be said that the model isn't far from reproducing the real-world to the extent of the system addressed in this study.

VALIDATION (lifting up knowledge from literature)

There is an ample source of scientific information regarding every step of the CCS-EOR chain 39]. For CO_2 sources is worth to mention the work by [40] in which the authors offers a complete overview of anthropogenic CO_2 and the likelihood of it to be captured, compressed and sequestered. Regarding CO_2 capture, the scientific literature debates which of the existing technologies is the best and for which cases. For instance, [41] offer and overview of the all set of available technologies for CO_2 capture, their particularities and suitableness. [42] is a study that analyzes several types of CO_2 compression processes using the concept of –exergy [43].

The petroleum engineering literature has addressed the EOR and CO_2-flooding extensively [44] since 70's. There is ample consensus that CO_2 injection to EOR operation is feasible and worthy [45].

There are a few studies that seek to offer holistic analysis of CCS-EOR system. [11] [39] [46] offer three sort of virtual tools that integrate two or more stages of the CCS-EOR system. However, even though these tools exist, the authors acknowledge a lack of this type of approaches.

DESCRIPTION OF THE INFORMATION SOURCES

As the author's background is Petroleum Engineer, most of the details of the system were addressed by his expertise. However, to be completely transparent, there are variables in which the author asked for a second opinion. This was true for several of the AT's (adjustment times) used in the model due colleagues experience in the real world. In the 'Model Documentation and Validation Documentation' apart appears their names, jobs and emails.

CCS is an emergent technology that needs to be leaded by those countries where greenhouse gas emission mitigation is a must. In this vein, several ONG's have started to have serious look on this technology. The main international organization leading this out is the 'International Energy Agency' which provides an accurate and unbiased report every five years about the advances and flaws of CCS development. This thesis takes into consideration the 'Technology Roadmap. Carbon Capture and Storage. 2013 edition' [29] and all the possible data that it provides has been included within ECCIS structure.

MODEL DOCUMENTATION AND VALIDATION DOCUMENTATION

In order to document every variable for model transparency purposes, Annex 1 contains all the stocks, flows and variables of the model. Also, Annex 2 offers all the equation that constitutes ECCIS.

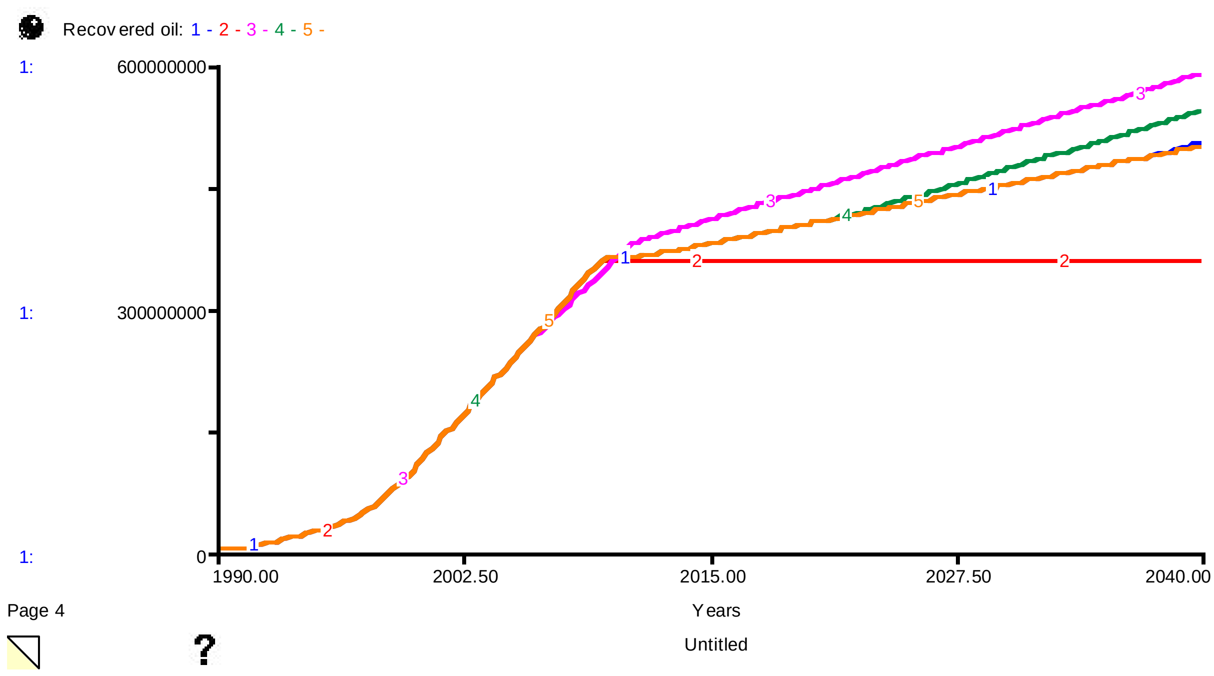
POLICY DESIGN

There is an ample room for policy design and testing using ECCIS.

As seen in Figure 13) it is possible to design everything according to the reality. In this vein, it is allowed to model almost any kind of oil reservoir according to its volume and petrophysical parameters. Else, ECCIS has included the possibility to design the deployment of an oil field base on the number of producer and injector wells and last but not least, ECCIS allows testing different scenarios of investment on CCS.

Now, ECCIS has the potential to become a managerial tool for stakeholders decision making. Most likely a user of ECCIS for managerial purposes will have as his/her main goal to increase oil production as much as possible. Therefore a proper set of policies for incremental oil production can be:

First, a control scenario must be declared. The 'base case' can be used for this purpose. This means that several parameters remain constant although could be designed. Those constant parameters are related to the oil field development policy variables, for instance, the total amount of producer and injector wells must remain constant so an increase in oil production comes by decisions designed on policy variables and taken over other sectors, for instance, oil reservoir and its variables *Desired_pressure_for_H2Oinj* or *WaterOil_index* and its policy design variable *Minimun_WaterCut_allowed*. Graph 23 is presented to show off the behavior of *Recovered_oil* under five different scenarios:



Graph 23. *Recovered_oil* run for different scenarios of reservoir pressure allowed and *WaterOil_index*

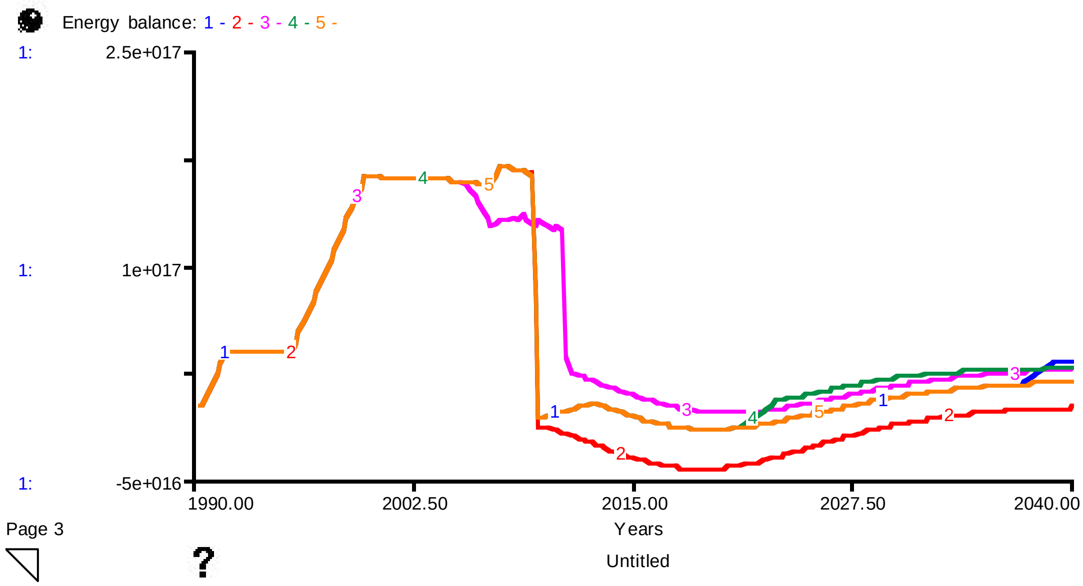
The blue line corresponds to the –base case. The red line shows the *Recovered_oil* when

Minimun_WaterCut_allowed is constant (the same value as –base case scenario) and *Desired_pressure_for_H2Oinj* is at its lowest level (400psi). The pink line combines constant *Minimun_WaterCut_allowed* and *Desired_pressure_for_H2Oinj* at his highest value (1000psi). Green and Orange line corresponds to *Desired_pressure_for_H2Oinj* as constant (base case, 570psi) and *Minimun_WaterCut_allowed* a low value (0.20) and a high one (0.4), respectively.

Hinting the worst and the best scenario of Graph23, worth to explain that:: for the red line, as the pressure that triggers waterfooding is never reached (because is very low), this operation isn't made thus oil recovery diminishes conversely to what happen on the pink line scenario in which the rapid starting of waterflooding allows to recover more oil due further fluid displacement.

ECCIS can serve also as a educational tool for petroleum engineering students. In this regard, is worth to take a look on the oil field deployment and the dynamics of drilling and wells conversion.

This model offers a great opportunity to study the interaction of the parts that compound the CCS-EOR chain. One way to asses such interactions is analyzing the energy balance. In this vein a proper policy to design would strive for the more possible 'positive' balance, considering the main motivation of global warming mitigation. As very many set of policies can be tested in this regard, Graph 24 shows the behavior of *Energy_balance* for the same scenarios of Graph 23.



Graph 24. *Energy_balance* run for different scenarios of reservoir pressure allowed and *WaterOil_index*.

As well as in Graph 23, the red line is the worst scenario as it remains negative for than a half of the timeframe whereas the pink line is the best scenario as it goes below zero for a very short period of time. However, it can be seen that green line surpasses the pink one in 2021 because waterflooding is rapidly replaced by CO2-flooding.

CONCLUTIONS

- The Process: during half year the author had as goal the development of this thesis. There were experts involved from the 'Institute for Energy Studies' of the University of North Dakota and one System Dinamicist colleague, classmate, roommate and friend (Eduard Romanenko) and our supervisor professor Pål Davidsen from Univertisty of Bergen and our tutor at UND, professor Scott Johnson.

The author acknowledges the suitability of this topic as his master thesis given his background in petroleum engineering, which undoubtedly generated synergies between engineering and SD. This suggests that SD is an adequate methodology that this engineering requires, especially concerning innovative solutions for new challenges that oil industry is facing nowadays.

- Where we are now: after the development of this thesis, there is now a new and usefull tool for holistic analysis of CCS-EOR systems. However, as -all models are wrong- and this one it isn't the exception, it should strive for including: - validation of results of ECCIS based on historical data and -assumptions improvement based on feedback from the real system.
- Future steps: Research, the author considers of great importance to delve into the accuracy of the energy balance of the system. This recommendation considers that the main motivation for developing CCS technology is emission mitigation for the sake of a greener world but this technology would only be a pledge of allegiance if the energy balance is negative.

  Managerial, the author considers that ECCIS must be tested with real data and thereby improve largely the accuracy of its assumptions thus becoming a great virtual representation of the real world.

  Educational, the author considers that ECCIS can be used in engineering faculties as an optional approach for simulation in petroleum engineering. Also considers as a next step to venture to include other fluid (gas dissolved in the oil) within the model. In this sense, the author also considers the possibility of extrapolating this analysis to CCS-CBM systems (Carbon Capture and Storage - Coal Bed Methane).

REFERENCES

[1] EIA Energy Information Administration. Available: http://www.eia.gov/forecasts/ieo/electricity.cfm [consulted 14 of June 2014]

[2] A. Gore, "An Inconvenient Truth: the Planetary Emergency of Global Warming and What We Can Do About It". Emmaus, Pennsylvania, US: Rodale Press, 2006, p. 10.

[3] J. de Juana, Energías Renovables Para el Desarrollo, Madrid, España: Editorial Paraninfo, 2003, p.23 – 275.

[4] Energy Transition Germany. Available: http://energytransition.de/ [consulted 15 of July 2014].

[5] OECD/IEA International Energy Agency. Technology Roadmap Capture Carbon and Storage, Paris, Francia: IEA, 2013, p. 1.

[6] Global CCS Institute. Available: http://www.globalccsinstitute.com/understanding-ccs/how-ccs-works-storage [consulted 14 of June 2014].

[7] J. Meyer, "Summary of Carbon Dioxide Enhanced Oil Recovery (CO_2EOR) Injection Well Technology". Plano, Texas, US: American Petroleum Institute, API, June 2009, p. 1 – 10.

[8] R. Allis et al, "Natural CO2 Reservoirs on the Colorado Plateau and Southern Rocky Mountains: Candidates for CO2 Sequestration". Salt lake City, Utah, US: Utah Geological Survey, November 2002, p.14 – 19.

[9] (K. Sasaki, et al, "CO2 Solubility Characteristics of Crude Oils related to Carbon Capture and Utilization (CCU)". Fukouka, Japón: Department of Earth Resources Engineering, Newsletter, Volume 8, June 2013, p. 250 – 254.

[10] E. Moniz and S. Tinker, MIT Energy Initiative and Bureau of Economic Geology at UT Austin Symposium. Boston, Massachusetts, US: MIT Press, July 2010, p. 4.

[11] J. Koornneef, "Development of an Environmental Performance Assessment tool for Carbon Capture & Storage chains". Energy Procedia, Vol 37, 2013, p. 2856 – 2863.

[12] Global CCS Institute. Available: http://www.globalccsinstitute.com/content/how-ccs-works-capture [visited 14 of June 2014].

[13]The free Encyclopedia. Available: http://en.wikipedia.org/wiki/Logarithm. [visited 17 June 2014].

[14] Aguilar, O, et al. Petróleo y Desarrollo. CORPES. Orinoquia, Colombia. Universidad Nacional de Colombia. June, 2000.

[15] Energy Information Administration. Available: http://www.eia.gov/forecasts/aeo/er/early_prices.cfm. [consulted 17 June 2014]

[16] Office of Fossil Energy. Available: http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery. [visited 17 of June 2014].

[17] The Free Encyclopedia for the Oil Industry. Available: http://petrowiki.org/Glossary%3AConnate_water. [visited 20 of July 2014].

[18] Rocky Mountain Institute. Available: http://www.rmi.org/RFGraph-US_electricity_demand. [visited 14 of June 2014].

[19] Energy Information Administration: http://www.eia.gov/coal/. [visited 14 of June 2014].

[20] Energy Information Administration: http://www.eia.gov/naturalgas/. [visited 14 of June 2014].

[21] Bailey, B et al. Water Control. Oil Field Review. Slumberger. Summer 2000. P 2.

[22] Reservoir Engineer Handbook. Ahmed, T. Third Edition. Elsevier, 2006. P 4.

[23] A Theory for Pressure Transient Analysis in Naturally Fractured Reservoirs. Humberto L. Najurieta, Ins. Mexicano del Petróleo. Journal of Petroleum Technology. July 1980. SPE 6017. P 1241 – 1250.

[24] Petroleum Engineering Handbook for Practicing Engineer, Vol 2. M. A. Mian, Mohamed A. Mian. P. 15.

[25] The Free Encyclopedia. Available: http://en.wikipedia.org/wiki/Continuity_equation. [visited June 14 2014].

[26] The Free Encyclopedia for the Oil Industry. Available. http://petrowiki.org/Fluid_flow_through_permeable_media. [visited June 14 2014]

[27] AIR LIQUIDE. Gas Encyclopaedia. Available: http://encyclopedia.airliquide.com/encyclopedia.asp?LanguageID=11&GasID=26. [visited 17July 2014].

[28] Carbon Dioxide Enhanced Oil Recovery (CO2 EOR). Factors Involved in Adding Carbon Utilization and Storage (CCUS) to Enhance Oil Recovery. Melzer, S. 2012.

[29] OECD/IEA International Energy Agency. Technology Roadmap Capture Carbon and Storage, Paris, France: IEA, 2013, p. 16.

[30] Leading the Energy Transition. Bringing Carbon Capture & Storage to Markets. SBD Energy Institute. P 115.

[31] Energy Information Administration. Available: http://www.eia.gov/forecasts/aeo/er/early_prices.cfm. 'Reference case' was used. [visited 1st of August 2014].

[32] CO_2 Eor and Storage in Oil Reservoir. F. Gozalpour, S. R. Ren and B. Tohidi. Institute of Petroleum Engineering. *Oil & Gas Science and Technology - Rev. IFP*, Vol. 60 (2005), No. 3, pp. 537-546.

[33] Ecopetrol. Available: http://www.ecopetrol.com.co/english/. [visited July 17].

[34]Ecopetrol. Available: http://www.ecopetrol.com.co/especiales/ReporteGestion2012/cambio_climatico_02.html. [visited July17].

[35] World Coal Association. Available: http://www.worldcoal.org/resources/coal-statistics/. {visited July 17 2014].

[36] J. Sterman, "Bussines Dynamics. System Thinking and Modelin for a Complex World". Cambridge, Massachusetts, US:Massachusetts Institute of Technology. Mc Graw Hill, 2000, p. 160 – 163.

[37] J. Vennix, "Group Model Building: Facilitating Team Learning Using System Dynamics". Nijmegen, The Netherlands: John Wiley & Sons, 1996, p. 51.

[38] J. Forrester, "Industrial Dynamics – After the First Decade". Management Scence, Vol 14, 1968, p. 398 – 415.

[39]Incorporating Carbon Capture and Geological Storage in an Integrated Assessment Model. Aernie, S. Master Thesis. University of Bern. 2010 P 15 -23.

[40] Reginald E. Newell and Thomas G. Dopplick, 1979: Questions Concerning the Possible Influence of Anthropogenic CO2 on Atmospheric Temperature. *J. Appl. Meteor.*, 18, 822–825.

[41] Leading the Energy Transition. Bringing Carbon Capture & Storage to Markets. SBD Energy Institute. P 106.

[42] CO2 compression and waste heat recovery. Pei, P et al. 2014.

[43] The Free Encyclopaedia. Available: http://en.wikipedia.org/wiki/Exergy. {visited 17 of July 2014].

[44] CO2 Flooding: Its Time Has Come. L.W. Holm (Union Oil Co.). SPE-11592-PA. Journal of Petroleum Technology. Vol 34. Issue 12. P 2739 – 2745.

[45] Practical aspects of CO2 flooding. Jarrel, Perry M et al. SPE Monograph Series; volume 22. 2012.

[46] A scalable infrastructure model for carbon capture and storage: SimCCS. Middleton, Richard S. Bielicki, Jeffrey M. Energy Policy. Vol 37. Issue 3. P 1052 – 1060.

Annex 1

Oil field sector:

Table 1. Stocks of Oil Field sector

STOCKS		
name	*units*	*documentation*
Recovered_oil	*bbl (barrel)*	As there is no produced oil at the beginning of the simulation, the initial value should be 0 though isn't the case because of the mathematical treatment on 'WaterOil_index' variable which cannot have a 0 in the denominator.
Techn_Recov_fluids	*bbl*	The initial value of this stock is given by the total volume of the reservoir multiplied by the porosity and the recovery factor.
OFIP (Original Fuilds in Place)	*bbl*	The initial value of this stock is given by the total volume of the reservoir multiplied by the porosity minus the same amount multiplied by the recovery factor.
Inj_Wells	*wells*	These wells used to be producer wells. Now they aim is to raise up the reservoir pressure in order to keep oil production.
Prod_wells	*wells*	The initial value is 1 considering the exploration well that must be drilled on order to prove reserves and reservoir particularities.

Table 2. Flows of Oil Field sector

FLOWS		
name	*units*	*documentation*
Prod_rate	*bbl/yr*	This flow considers the oil produced therefore uses the number of producer wells and the amount of fluid that each well produces. Also, subtracts the connate water outflow and the injected fluids that are produced.

Feasibility_rate	*bbl/yr*	This flow considers the fluid that is injected into the reservoir thus displace the original fluids by a mass balance. It will stop once has fallen the 'Total amount of fluids that can be recovered' because this value is the maximum possible volume of fluids that can be produced by primary, secondary and tertiary recovery techniques.(Enhanced Oil Recovery with CO2 Capture and Sequestration, Maria Andrei et al, 2010).
Drilling_rate	*wells/yr*	This inflow works under two conditions: -As long as the desired number of producer wells has not be reached, and -As long as the oil price is suitable for the drilling activity. When it is flowing depends on the field area and the demand of area of each well and the time needed for drilling.
Convertio_ rate	*wells/yr*	This inflow works under three conditions: -As long as the desired number of injection wells has not be reached, and -As long as the desired number of producer wells has not be reached, and -As long as reservoir pressure indicates that is time to start the secondary recovery (H2O injection). When it is flowing depends on the field area and the demand of area of each well and the time needed to convert a producer into injection well.

Table 3. Variables of il Field sector

VARIABLES		
name	*units*	*documentation*
Suitable_oil_price_to_start_ up_drilling_Usdollars	US Dollars/bbl	This is a variable for policy design. It indicates at which oil price the drilling activities can commence or must stop.
Oil_price	US Dollars/bbl	http://www.eia.gov/forecasts/aeo/er/early_prices.cfm. 'Reference case' was used.
AT_to drill_a_well	years	This number (6) takes into consideration the time needed to asses and evaluate a prospect reservoir until the drilling begins. This information was provided by: Ing. Gabriel Jaime Ramirez Palacio. AIP, production and well log engineering. gramirez@aip.com.co
Width_m	meters	Reservoir's width.
Length_m	meters	Reservoir's length
Field_area	square meters	This is the total area of the field.
Producer_wells per_square_meter	wells/square meters	This variable is a fraction of injection well that is present in one square meter. Although physically this measurement lacks of sense (considering one well cannot be split off), for modeling purposes it makes sense considering its role on -drilling rate-

MaxNumber wells_allowed	Unitless	This variable is works as a key to close off the inflow once the number of 'Producer wells' has reached its desired level.
Desired_number of_producer_wells	wells	This is variable for policy design. It is the total amount of producer wells that should be present in the field area.
Desired_number of_injection_wells	wells	This is variable for policy design. It is the total amount of injection wells that should be present in the field area.
Injection_wells per_square_meter	wells/square meters	This variable is a fraction of injection well that is present in one square meter. Although physically this measurement lacks of sense (considering a well cannot be split out), for modeling purposes it makes sense considering its role on -conversion rate-.
Desired_pressure_for H2O injection psi	pounds per square inch	This is a variable for policy design. It is the suitable pressure at which is proper to start the secondary recovery techniques, namely pressure increase due H_2O injection.
AT_to injection_well convertion	yeas	6 years is an appropriate time for evaluation, preparation and development of the plans to carry on a well conversion from producer to injector well. This information was provided by: Ing. Gabriel Jaime Ramirez Palacio. AIP, production and well log engineering. gramirez@aip.com.co
Original_ WaterOil _ndex	Unitless	This is a constituent variable. This value should be known from fluids reservoir assessment prior production and won't change during the simulation.
RESERVES MMbbl	bbl	This quantity is total oil in place.
Total_amount of fluids that cannot be recovered	bbl	This quantity never leaves the reservoir according to primary, secondary and tertiary recovery techniques' percentage of recovery.
AT_for_max_ injection	years	As the injection goes on at a constant rate, 2yr is a proper approximation given the continuous nature of the injection though isn't lower because physically does not make much sense that such a huge amount of fluids can be injected at higher rates.
Max_injection_per_ well	bbl/wells	Is the total amount of barrels (H_2O or CO_2) injected per well every year
Daily injection_bbl	bbl/wells-days	This is a variable for policy design. It is desired caudal of injected fluids (H_2O or CO_2) through each well expressed in barrels per day.
Days_per year	days	Days per year = 365
Max_production pe_ well	bbl/wells	Is the total amount of barrels produced per well every year
Daily production_bbl	bbl/wells-days	This is a variable for policy design. It is desired caudal of produced fluids in each well expressed in barrels per day.
H2O production_rate	bbl/yr	Takes into account the total H_2O injected, the time it takes to go al the way through the producer well.

CO2 prod_rate	bbl/yr	Takes into account the total CO2 injected, the time it takes to go al the way through the producer well and the amount of CO2 that remains trapped into the reservoir.
Effect_of_CO2 on_oil_swelling	Unitless	As CO2 dissolves into solution, the oil formation volume factor increases expanding the apparent volume of the oil in place and enhancing drive energy. (The use of Carbon Dioxide as an enhanced recovery agent for increase heavy oil production. Bennion, B., Thomas, B. 1993) (The prediction of C)2 Solubility and Swelling factor for Enhanced Oil Recovery. Mulliken, CH., Sandler, S. 1980)
CO2_cut	Unitless	This is a relation between total CO2 injected and the oil that still into the reservoir.
AT_for oil_production	years	As the production goes on at a constant rate, 1yr is a proper aproximation given the continuos nature of the production though isn't lower because phisically does not make sense that such a huge amount of fluids can be produced at higher rates.

Reservoir pressure

Table 4. Stocks of Reservoir Pressure sector

STOCKS		
name	*units*	*documentation*
Reservoir_pressure	psi	The initial value is a number chosen 'randomly' among a range *that makes sense in the static pressure values of oil reservoirs suitable for CO2 flooding.*

Table 5. FLows of Reservoir Pressure sector

FLOWS		
name	*units*	*documentation*
Pressure_increase rate	psi/yr	his inflow is dictated by the injection operations. Either Waterflooding or CO2-flooding influences it.
Pressure_decrease rate	psi/yr	his outflow is dictated by the fluids production. Oil, water or CO2 production is influencing this outflow.

Table 6. Variables of Reservoir Pressure sector

VARIABLE		
name	*units*	*documentation*
AT_for pressure_decrease	years	As the pressure drop of Darcy's law used here is in terms of psi-s, the time to trace this pressure increase should be as small as possible, in this case the same as DT.
AT_for_pressure increase	years	This can be a very tricky number due the effect of the pressure diffusivity present in oil reservoir. I consider this graphical function as a proper estimate due the non-linearity inherent in this aggregation.
Effect_of_ Reservoir pressure_on_oil viscosity	pounds per square inch-seconds	http://petrowiki.org/File%3AVol1_Page_287_Image_0002.png
Oil_ Viscocity_ 65celsius	pounds per square inch-second	Oil (30API) viscosity at 65celsius and atmospheric conditions. http://www.monografias.com/trabajos73/disminucion-viscocidad-petroleos-disminucion-temperatura/disminucion-viscocidad-petroleos-disminucion-temperatura2.shtml
pressure_change due_oi_ production	pounds per square inch	This variable uses the pressure drop established in the Darcy's law.This law say that through a porous media, the pressure drop depends directly on the flowing caudal, the length of the 'pipe', the viscosity of the fluid (in this case oil) and inversely on the flow area and the permeability of the media
Bblyr_to_ cubmeterSec	cubic meters-years/bbl-seconds	conversion fator [bbl/yr] to [cubic meter/sec]
Width_m	meters	Reservoir's width.
Length_m	meters	Reservoir's length.
Line_lenght	meters	This variable is the length of single 'line' of wells inside the field area. This is done in order to obtain the space (in meters) between one injection and one producer well needed to apply the Darcy's law.
total numbre of welss	wells	Is the total amount of drilled wells inside the field area.
Wells_per line	Unitless	This is the total number of wells present in a single 'line' of field length. This is to apply the Darcy's law between one injection and ne producer well.

Milidarcy_to squaremeters	square meters/mD	Conversion factor. square meters/mD
Permeability_mD	mD	This is an index of the level of interconnection of the pores of the reservoir. It is a petrophysical property established prior oil production.
Height_m	meters	Reservoir's height
L	meters	This is the distance between two wells, one injector and one producer.
K	square meters	This is an index of the level of interconnection of the pores of the reservoir. It is a petrophysical property established prior oil production.
A	square meters	This is the flow area.
Pressure_ change_due CO2_produciton	pounds per square inch	This variable uses the pressure drop established in the Darcy's law. This law say that through a porous media, the pressure drop depends directly on the flowing caudal, the length of the 'pipe', the viscosity of the fluid (in this case CO2) and inversely on the flow area and the permeability of the media
CO2_ viscocity_ 65celsius	pounds per square inch-seconds	CO2 viscosity at atmospheric pressure (outside reservoir) and 65celsius. http://www.peacesoftware.de/einigewerte/wasser_dampf_e.html
CO2_ prod_rate	bbl/yr	Takes into account the total CO2 injected, the time it takes to go al the way through the producer well and the amount of CO2 that remains trapped into the reservoir.
Pressure_change due_H2O_ production	pounds per square inch	This variable uses the pressure drop established in the Darcy's law.This law say that through a porous media, the pressure drop depends directly on the flowing caudal, the length of the 'pipe', the viscosity of the fluid (in this case H2O) and inversely on the flow area and the permeability of the media
H2O_ production_ rate	bbl/yr	Takes into account the total H2O injected, the time it takes to go al the way through the producer well.
H2O_viscosity_ 65cesius	pounds per square inch-seconds	Water viscosity at atmospheric pressure (outside the reservoir) and 65celsius. http://www.peacesoftware.de/einigewerte/wasser_dampf_e.html

Pressure_change due_H2O_injection	pounds per square inch	This variable uses the pressure drop established in the Darcy's law. This law say that through a porous media, the pressure drop depends directly on the flowing caudal, the length of the 'pipe', the viscosity of the fluid (in this case H2O) and inversely on the flow area and the permeability of the media.
H2O_injection_ rate	bbl/yr	This inflow is triggered by the 'policy variable' -Minimum water cut allowed- or -Minimum pressure allowed- and its value depends also on the number of wells used for injection, the amount of fluid that can be injected and the time it takes for injection.
H2O_viscosity_ 20celsius	pounds per square inch-seconds	Water viscosity at standard conditions (20 Celsius, atmospheric pressure). http://www.peacesoftware.de/einigewerte/wasser_dampf_e.htm
Pressure_ change_due_ CO2 injected	pounds per square inch	This variable uses the pressure drop established in the Darcy's law. This law say that through a porous media, the pressure drop depends directly on the flowing caudal, the length of the 'pipe', the viscosity of the fluid (in this case CO2) and inversely on the flow area and the permeability of the media
CO2_injection rate	bbl/yr	This flow takes into account the total CO2 that is compressed as well as the time that takes to assess the details of the injection for EOR operations. Plus, 'desired water cut' serves as triggering. To wit, once certain value of water cut is reached; the flow starts because the oils reservoir commences to demand the CO2.
CO2_viscosity_0celsius10Mpa	pounds per square inch-seconds	Supercritical CO2 viscosity in psi-s. (0celsius & 10Mpa)This state is used in CO2 flooding.(CO2 compression and waste heat recovery. Pei, P et al. 2014 page 2)http://www.peacesoftware.de/einigewerte/co2_e.html

H2O injection

Table 7. Stocks of H2O injection sector

STOCKS

name	units	documentation
H2O_injected	bbl	The initial value is 0 because the reservoir does not need injection of any kind at the early stages of production, namely Primary Recovery. Only after a while when the Reservoir Pressure has declined to certain number. This process is called Secondary Recovery (Enhanced Oil Recovery with CO2 Capture and Sequestration, Maria Andrei et al, 2010).
H2O_produced	bbl	The initial value is 0 because the reservoir does not need any H2O (only after a while when the 'Reservoir Pressure' reaches certain value) thus non H2O is produced either.
Total_inj_H2O_ produced	bbl	This stock records the total amount of injected water that's been produced.
H2O_connate _produced	bbl	The initial value is 0 because at the beginning of the simulation non fluid has been produced from the reservoir.

Table 8. Flows of H2O injection sector

FLOWS		
name	*units*	*documentation*
H2Oinj_rate	bbl/yr	This inflow is triggered by the 'policy variable' -Minimum water cut allowed- or -Minimum pressure allowed- and its value depends also on the number of wells used for injection, the amount of fluid that can be injected and the time it takes for injection.
H2Oprod_rate	bbl/yr	Takes into account the total H2O injected, the time it takes to go al the way through the producer well.
H2O_recycling _rate	bbl/yr	Takes into account the H2O produced and the time to recycled (split it out from oil and inject it again).
Prod_rate_of H2Oinj	bbl/yr	As 'H2O production rate', this flow takes into account the total H2O injected, the time it takes to go al the way through the producer well.
H2O_connate prod_rate	bbl/yr	This inflow takes into account the water that shares the reservoir pores with the oil and consequently the producer wells sweep the oil, this water is also drained.

Table 9. Variables of H2O injection sector

VARIABLES		
name	*units*	*documentation*
AT_for max_injection	years	As the injection goes on at a constant rate, 2yr is a proper approximation given the continuous nature of the injection though isn't lower because physically does not make much sense that such a huge amount of fluids can be injected at higher rates.
Max_injection per_well	bbl/wells	Is the total amount of barrels (H2O or CO2) injected per well every year
Desired_pressure for_H2O_injection psi	pounds per square inch	This is a variable for policy design. It is the suitable pressure at which is proper to start the secondary recovery techniques, namely pressure increase due H2O injection.
Maximum_ pressure_allowed	pounds per square inch	This is a variable for policy design. It can be seen as the fracture pressure so it a value which should no be reached in order to avoid reservoir damages.
AT_for production_ H2O_injected	years	This value is related with the 'AT for pressure increase' because the 'H2O injected' is produced once has gone all the way from injectors to producers wells. Though isn't 10yr as 'AT for pressure increase' because this flux is not directly affected by the diffusivity phenomena. I consider as a half (10/2) as a proper approximation.
Max_production per_well	bbl/wells	Is the total amount of barrels produced per well every year
Original_ WaterOil_index %	Unitless	This is a constituent variable. This value should be known from fluids reservoir assessment prior production and won't change during the simulation.
AT_for H2O recycling	years	There is no strong scientific base for this number. However 2yr makes sense to the extent that is a good approximation of the time that would take in order to recycle around 70% of the amount of H2O using the facilities of the oil field.
WaterOil_index	Unitless	This variable is the relation between the total water and oil produced.
Minimun_ WaterOil_index _allowed	Unitless	This is a variable for policy design to the extent that is the minimum value that indicates when the reservoir is suitable to stop H2O injection and begin the CO2 injection.
Desired_ waterOil_index	Unitless	This variable either stops or starts CO2 or H2O injection.

CO2 injection

Table 10. Stocks of CO2 injection

STOCKS		
name	*units*	*documentation*
CO2inj_EOR	bbl	The initial value is 0 because the reservoir does not need any CO2, only after a while when the 'Water cut' reaches certain value. Namely Tertiary Recovery (Enhanced Oil Recovery with CO2 Capture and Sequestration, Maria Andrei et al, 2010).
CO2prod_from reservoir	bbl	The initial value is 0 because the reservoir does not need any CO2 (only after a while when the 'Water cut' reaches certain value) thus non CO2 is produced either.
CO2_inj_sal_form	bbl	the initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment of my theory onwards. Anyway, 1.01 does not represent a huge concern in terms of the total amount of CO2 that is -injected into saline formations- later on the simulation.
Inj_Sal_Form efficiency	unitless	The initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment. To wit, if it's 0 then won't be any 'CO2 into saline formations' because the inflow would be 0 as well.
Inj_Sal_Form potencial_learning	unitless	As its name suggest, the initial value of 1 is the potential learning that can be accomplished.

Table 11. Flows of CO2 injection sector

FLOWS		
name	*units*	*documentation*
Prod_rate	bbl/yr	This flow considers the oil produced therefore uses the number of producer wells and the amount of fluid that each well produces. Also, subtracts the connate water outflow and the injected fluids that are produced.

Feasibility_rate	bbl/yr	This flow considers the fluid that is injected into the reservoir thus displace the original fluids by a mass balance. It will stop once has fallen the 'Total amount of fluids that can be recovered' because this value is the maximum possible volume of fluids that can be produced by primary, secondary and tertiary recovery techniques.(Enhanced Oil Recovery with CO2 Capture and Sequestration, Maria Andrei et al, 2010).
Drilling_rate	wells/yr	This inflow works under two conditions: -As long as the desired number of producer wells has not be reached, and -As long as the oil price is suitable for the drilling activity. When it is flowing depends on the field area and the demand of area of each well and the time needed for drilling.
Conversion_rate	wells/yr	This inflow works under three conditions: -As long as the desired number of injection wells has not be reached, and -As long as the desired number of producer wells has not be reached, and -As long as reservoir pressure indicates that is time to start the secondary recovery (H2O injection). When it is flowing depends on the field area and the demand of area of each well and the time needed to convert a producer into injection well.

Table 12. Variables of CO2 injection sector

VARIABLE		
name	*units*	*documentation*
AT_for_max CO2_injection	years	TechnologyRoadmapCarbonCaptureandStorage IEA 2013 page17
Max_injection per_well	bbl/wells	Is the total amount of barrels (H2O or CO2) injected per well every year
AT_for Cos_injected production	years	This value is related with the 'AT for pressure increase' because the 'CO2 injected' is produced once has gone all the way from injectors to producers wells. Though isn't 10yr as 'AT for pressure increase' because this flux is not directly affected by the diffusivity phenomena. I consider as a half (10/2) as a proper approximation.
Percentage_of recovery	Unitless	Enhanced Oil Recovery with CO2 Capture and Sequestration, Maria Andrei et al, 2010. page 5
Max_production per_well	bbl/wells	Is the total amount of barrels produced per well every year.

AT_for CO2_recycling	years	There is no strong scientific base for this number. However 3yr makes sense to the extent that is a good approximation of the time that would take in order to recycle 70% of the amount of CO2 using the facilities of the oil field.
Total_CO2 sequestred	bbl	This stock represents the full amount of CO2 which was prevented of being released to atmosphere and it is now trapped underground instead.
AT_for InjSalForm	years	TechnologyRoadmapCarbonCaptureandStorage IEA 2013 (1) page17
Level_of investment_ on_ InjecSalFormations	Unitless	This is a variable for policy design. My theory is that the more investment in the injection of CO2 into saline formations, the more rapidly the increment of efficiency of these technologies will be. Thereby more injection will be as well. I established a range from 1 to 10, being 1 a very low investment and 10 a high one.
Importance_of total_CO2_into SalForm_learning efficiency_imp	Unitless	This is a graphical treatment to become higher number of 'level of investment...' into low numbers. I does no go below 1 because the logarithmic function used later is defined as negative and this would be irrelevant.
LN_Stock Ln_importance of_injecSalForm	Unitless	iThink does not have the option of the Log function in which be allowed to change the base. Therefore, I use the formula Ln(x)/Ln(y)=Z in which Z is be the base of any Log function. This means that Y is the exponent to which Z should be elevated in order to obtain X. The usefulness of this approach is that it takes into account both quantities (the 'CO2 into saline formations' and 'level of inv...') to establish the rate of improvement of efficiency and consequently the 'CO2 for saline formation rate' improvement.
Effect_of_total CO2_InjSalForm on_efficiency improvemt	Unitless	As 'Inj into sal formation potential learning' goes from 0 to 1 (0 non knowledge, 1 total knowledge) and the prior logarithmic function allows to get values hardly above 40 (no matter how huge that stock is);then this relationship establish that the more CO is injected into saline formations (included the level of investment), the higher the learning rate.
AT_for InjSalForm_ learning	years	As learning by doing is a continuous process, this adjustment time reflects this continuity in terms of simulation times.

Capture & Compression

Table 13. Stocks of Carpture and Compression sector

STOCKS		
name	*units*	*documentation*
CO2_captured	tonn CO2	The initial value is 0 because there is no CO2 captured at the simulation starting stage.
Total_CO2_ captured	tonn CO2	the initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment onwards. Anyway, 1.01 does not represent a huge concern in terms of the total amount of CO2 that is captured later on the simulation.
Capture_potential learning	unitless	As its name suggest, the initial value of 1 is the potential learning that can be accomplished.
Capture_efficiency	unitless	The initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment. To wit, if it's 0 then won't be any 'CO2 captured' because the inflow would be 0 as well.
CO2_compressed	bbl/yr	The initial value is 0 because there is no CO2 captured at the simulation starting stage. I also use the Non-negative option as does not make sense to have to have a backlog in this one-direction supply chain. Though given the demand for injection this non-sense negativity could occur.
Total_CO2_ compressed	bbl/yr	the initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment of my theory onwards. Anyway, 1.01 does not represent a huge concern in terms of the total amount of CO2 that is compressed later on the simulation.
Compression_ potential_learning	unitless	As its name suggest, the initial value of 1 is the potential learning that can be accomplished.
Compression_ efficiency	unitless	The initial value cannot be cero because this would cause the dynamics of learning unable to occur given the mathematical treatment. To wit, if it's 0 then won't be any 'CO2 compressed' because the inflow would be 0 as well.

Table 14. Flows of Capture and Compression sector

FLOWS		
name	*units*	*documentation*
Capturing_rate	tonn CO2/yr	This flow takes into account the total CO2 that can be captured as well as the efficiency improvement dynamics and the time that takes to assess the improvement.
Total_capt_rate	tonn CO2/yr	Is the same 'capturing rate' because it is used for different purposes though I'm talking about the same fluid.
Learnig_rate	per yr	This rate must be understood as a learning-by-doing process. (the Economic Implication of Learning by Doing. Kennet J. Arrow. The Review of Economic Studies. Vol 29, Issue 3. June 1962. 155-173)
Compression_rate	tonn CO2/yr	This flow takes into account the total CO2 that can be compressed as well as the efficiency improvement dynamic and the time that takes to assess the improvement.
Total_comp_rate	tonn CO2/yr	Is the same 'capturing rate' because it is used for different purposes though I'm talking about the same fluid.
Learnig_rate	per yr	This rate must be understood as a learning-by-doing process. (the Economic Implication of Learning by Doing. Kennet J. Arrow. The Review of Economic Studies. Vol 29, Issue 3. June 1962. 155-173)

Table 15. Variables of Capture and Compression sector

VARIABLE		
name	*units*	*documentation*
AT_for_ capturing	years	As the capturing rate is governed by the level of efficiency and the improvements in this sense, 4 years is a proper time to asses those developments. (Learning rates for energy technologies. Environmentally Compatible Energy Strategies Project. IIASA. Vol 29, 2001. P 255-261).
Level_of investment_on CO2_Capture development	Unitless	This is a variable for policy design. My theory is that the more investment in the development of Capture technologies, the more rapidly the increment of efficiency of those technologies will be. Thereby the more capture will be as well. I established a range from 1 to 10, being 1 a very low investment and 10 a high one.

Importance_of total_CO2 captured_on efficiency_ improvement	Unitless	This is a graphical treatment to become higher number of 'level of investment...' into low numbers. I does no go below 1 because the logarithmic function used later is defined as negative and this would be irrelevant.
Ln_Stock Ln_Importance of_capturing	Unitless	iThink does not have the option of the Log function in which be allowed to change the base. Therefore, I use the formula Ln(x)/Ln(y)=Z in which Z is be the base of any Log function. This means that Y is the exponent to which Z should be elevated in order to obtain X. The usefulness of this approach is that it takes into account both quantities (the 'Total CO2 captured' and 'level of inv...') to establish the rate of improvement of efficiency and consequently the 'capturing rate' improvement.
Effect_of totalCO2capt_on improved_ efficiency	Unitless	As 'Capture potential learning' goes from 0 to 1 (0 non knowledge, 1 total knowledge) and the prior logarithmic function allows to get values hardly above 40 (no matter how huge that stock is); this relationship establish that the more CO2 is captured (included the level of investment), the higher the learning rate.
AT_for capture_learning	years	As learning by doing is a continuous process, this adjustment time reflects this continuity in terms of simulation times.
AT_for compression	years	As the compression rate is governed by the level of efficiency and the improvements in this sense, 2 years is a proper time to asses those developments. This is due CO2-compression ir more deployed than CO2-capture then a half of its AT may be consider appropriate.
Level_of investment_ on_CO2 Compresiion	Unitless	This is a variable for policy design. My theory is that the more investment in the development of Compression technologies, the more rapidly the increment of efficiency of those technologies will be. Thereby more compression will be as well. I established a range from 1 to 10, being 1 a very low investment and 10 a high one
Importance_of total_CO2 compressed_on efficiency_ improvement	Unitless	This is a graphical treatment to become higher number of 'level of investment...' into low numbers. it does not go below 1 because the logarithmic function used later is defined as negative and this would be irrelevant.

Ln_Stock Ln_importance of_compression	Unitless	iThink does not have the option of the Log function in which be allowed to change the base. Therefore, I use the formula Ln(x)/Ln(y)=Z in which Z is be the base of any Log function. This means that Y is the exponent to which Z should be elevated in order to obtain X. The usefulness of this approach is that it takes into account both quantities (the 'Total CO2 compressed' and 'level of inv...') to establish the rate of improvement of efficiency and consequently the 'compression rate' improvement.
Effect_of totalCO2comp_on improve_efficiency	Unitless	As 'Compression potential learning' goes from 0 to 1 (0 non knowledge, 1 total knowledge) and the prior logarithmic function allows to get values hardly above 40 (no matter how huge that stock is); this relationship establish that the more CO is compressed (included the level of investment), the higher the learning rate.
AT_for compression_ learning	years	As learning by doing is a continuous process, this adjustment time reflects this continuity in terms of simulation times.

CO2 sources

Table 16. Stock of CO2 sources sector

STOCKS		
name	*units*	*documentation*
Refined_oil	bbl	This stock represents the obtained fluids after oil refining.
CO2_from_ downstream	tonns CO2	*this stock represents the CO2 produced related to downstream operations (including refining).*
CO2_produced	tonns CO2	*This stock represents the theoretical maximum amount of CO2 of the system*
Elect_by_Coal	gigawatt	*there is in total 3050200GW-h of electricity capacity in 1990 and 53%(market share) of it is due Coal base. So: Initial value: (305200[GW-h/yr]*0.53= 161756*

Coal_power_ capacity	gigawatt	*Initial value: there is in total 3050200GW-h of electricity capacity in 1990 and 53%(market share) of it is due Coal base. So: Initial value: (305200[GW-h/yr]*0.53/ (365[day/yr]* 24[h/day])) /0.65[GW/plant]=28.4 =28plan*
Elect_by_Gas	gigawatt	*there is in total 3050200GW-h of electricity capacity in 1990 and 13%(market share) of it is due Gas base. So: Initial value: (305200[GW-h/yr]*0.53= 39676*
Gas_power_ capacity	gigawatt	*Initial value: there is in total 3050200GW-h of electricity capacity in 1990 and 13%(market share) of it is due Gas base. So: Initial value: (305200[GW-h/yr]*0.13/ (365[day/yr]* 24[h/day])) /0.34[GW/plant]=13.3 =13plant*

Table 17. Flows of CO2 sources sector.

FLOWS		
name	*units*	*documentation*
Oil_from_upstrem_rate	bbl/yr	This flpw represent the produced oil that goes through a refinery to become highly valuable fluids such as gasoline, jet A-1 fuel, diesel, kerosene and so on.
Rate_of CO_ from_ refining	tonn CO2/yr	It is a coflow of the refinement operations which releases CO2 as a waste material.
CO2_for_upstream_rate	tonn CO2/yr	This is the rate of CO2 provision from downstream waste operations towards upstream operation in which it is consider as a highly valuable component.
Elect_rate_by_coal	gigawatt/yr	The production of electricity in power plants of post combustion is a continuous process in which a fossil fuels feed up a boiler (in this case).

Consumption_rate	gigawatt/yr	DELAYN(elect_rate_by_coal,5,3) There is no strong scientific ground for '5' as the order of the delay and '3' as its duration. It is thought that as the 'total elect' is a measurement of how the state of electricity supply is (as it has to be compared with the exogenous demand) then '5' is a proper approximation for demand forecast thereby '3' production planning as well.
Coal_capacity_rate	gigawatt/yr	this is not expressing the construction itself of buildings, boilers, turbines installation and so on. Instead, this inflow refers to the product (electricity) delivered by those machines and buildings.
Elect_rate_by_gas	gigawatt/yr	The production of electricity in power plants of post combustion is a continuous process in which a fossil fuel feeds up a boiler (in this case).
Consumption_rate	gigawatt/yr	DELAYN(elect_rate_by_gasl,5,3) There is no strong scientific ground for '5' as the order of the delay and '3' as its duration. I was thinking that as the 'total elect' is a measurement of how the state of electricity supply is (as it has to be compared with the exogenous demand) then '5' is a proper approximation for demand forecast thereby '3' production planning as well.
Gas_capacity_rate	gigawatt/yr	this is not expressing the construction itself of buildings, boilers, turbines installation and so on. Instead, this inflow refers to the product (electricity) delivered by those machines and buildings.

Table 18. Variables of CO2 sources sector

VARIABLES		
name	*units*	*documentation*
AT_for refinement	years	5yr as an adjustment time for oil refinement it is adjusted to reality due energy trade and market delays, oil transportation issues and facility's capacity.
Prod_rate	bbl.yr	This flow considers the oil produced therefore uses the number of producer wells and the amount of fluid that each well produces. Also, subtracts the connate water outflow and the injected fluids that are produced.
Tons_of_CO2_per_barrel of_refined_oil	tons CO2/bbl	http://www.ecopetrol.com.co/especiales/ReporteGestion2012/cambio_climatico_02.html
AT_for_CO2 to_upstream	years	As CO2 production is a continuous process, 1yr is a proper estimate.

Number _of CoalPowerPlant_ to_construct	Unitless	This is a variable for policy design. It is the number of Coal power plants that are planed and consequently will be constructed.
Pulse_CoalPower_Plants	Unitless	This variable triggers 'shots' of Coal Power Plants into the inflow of CoalPowerPlantCapacity
AT_for new_CoalPower_plant	years	Vanessa Perez, 2013 The Colombian Electricity Market. UiB Master Thesis.
Average_ capacity_ CoalPower_Plant	gigawatt	http://www.eia.gov/forecasts/capitalcost/
Coal_ market_share	Unitless	http://www.eia.gov/coal/
AT_to_produce_its full_average_ Coal _PowerPlant	years	Vanessa Perez, 2013 The Colombian Electricity Market. UiB Master Thesis.
CO2_per_ gigawatt_ CoalPower_Plant	tons CO2/gigawatt	http://en.wikipedia.org/wiki/Fossil-fuel_power_station (Enviromental impacts)
Number_of GasPower_Plant to_construct	Unitless	This is a variable for policy design. It is the number of Gas power plants that are planed and consequently will be constructed.
Pulse_GasPower_Plants	Unitless	This variable triggers 'shots' of Coal Power Plants into the inflow of CoalPowerPlantCapacity
AT_for new_GasPower_plant	years	Vanessa Perez, 2013 The Colombian Electricity Market. UiB Master Thesis.
Average_ capacity_ GasPower_Plant	gigawatt	http://www.eia.gov/forecasts/capitalcost/
Gas_ market_share	Unitless	http://www.eia.gov/naturalgas/
AT_to produce_its full_average_ Gas_ PowerPlant	years	Vanessa Perez, 2013 The Colombian Electricity Market.UiB Master Thesis.

CO2_per_ gigawatt_ GasPower_Plant	tons CO2/gigawatt	http://en.wikipedia.org/wiki/Fossil-fuel_power_station (Enviromental impacts)
Number_of hours_per_year	Unitless	360*24= 8760
Total_elect	gigawatt	it is the addition of coal and gas base electricity
Elect_demand	gigawatt	http://www.rmi.org/RFGraph-US_electricity_demand 'Maintain' case was used. else: http://sequestration.mit.edu/pdf/David_and_Herzog.pdf
GAP_electr_ demand_production	gigawatt	The difference between what is needed and is given.

Reservoir Characteristics

Table 19. Variables of Reservoir Characteristics calculations

VARIABLES		
name	*units*	*documentation*
Length_m	meters	Reservoir's length
Width_m	meters	Reservoir's width
Height_m	meters	Reservoir's height
Porosity_%	Unitless	Reservoir's porosity.
Bbl_to cubicmeters	bbl/cubic meters	Conversion factor. [bbl/m3]
Initial_value Technically_recoverable fluids	bbl	This is the total amount of fluids that can be recovered with secondary recovery techniques, namely pressure increase and maintenance due H2O injection.
Initial_value Original_Fluids in_place	bbl	This is the total amount of fluids that can be recovered by primary production (natural flux) when the reservoir has enough energy (pressure) to rise up the fluids from the reservoir to the surface.

Secondary_ recovery_ factor_%	Unitless	Carbon Dioxide Enhanced Oil Recovery (CO2 EOR). Factors Involved in Adding Carbon Utilization and Storage (CCUS) to Enhance Oil Recovery. Melzer, S. 2012
Total_amount_of_fluids that_cannot_be recovered	bbl	This quantity never leaves the reservoir according to primary, secondary and tertiary recovery techniques' percentage of recovery.
Terciary_recovery factor_%	Unitless	Carbon Dioxide Enhanced Oil Recovery (CO2 EOR). Factors Involved in Adding Carbon Utilization and Storage (CCUS) to Enhance Oil Recovery. Melzer, S. 2012

Energetic balance

Table 20. Flows of Energetic balance calculations

FLOWS		
name	*units*	*documentation*
Prod_rate	bbl/yr	This flow considers the oil produced therefore uses the number of producer wells and the amount of fluid that each well produces. Also, subtracts the connate water outflow and the injected fluids that are produced.
Capturing_rate	bbl/yr	This flow takes into account the total CO2 that can be captured as well as the efficiency improvement dynamics and the time that takes to assess the improvement.
Compression_rate	bbl/yr	This flow takes into account the total CO2 that can be compressed as well as the efficiency improvement dynamic and the time that takes to assess the improvement.
CO2_injection rate	bbl/yr	This flow takes into account the total CO2 that is compressed as well as the time that takes to assess the details of the injection for EOR operations. Plus, 'desired water cut' serves as triggering. To wit, once certain value of water cut is reached, the flow starts because the oils reservoir commences to demand the CO2.

H2O_injection rate	bbl/yr	This inflow is triggered by the 'policy variable' -Minimum water cut allowed- or -Minimum pressure allowed- and its value depends also on the number of wells used for injection, the amount of fluid that can be injected and the time it takes for injection.

Table 21. Variables of Energetic balance calculations.

VARIABLES		
name	units	documentation
Joules_per_bbl	joule/bbl	http://en.wikipedia.org/wiki/Barrel_of_oil_equivalent
Joules_from_oil	joule/yr	This is the energy out of the oil which is been produced.
Joules_pe_ tonCO2_capt	joule/tons CO2	Economic assessment of natural gas fired combined cycle power plant with CO2 capture and sequestration. H, Undrum. O, Bolland. E, Aarebrot. 2012
Joules_to_capture	joule/yr	This is the energy consumed by CO2 capture
Joules_per_tonCO2_ comp	joule/tons CO2	CO2 compression and waste heat recovery. Pei, P et al. 2014 page 3
Joules_to_compression	joule/yr	This is the energy consumed by CO2 compression.
Total_injection	bbl/yr	CO2 injection plus H2O injection
Bbl_per_yr to_ gallon_per_min	hp/pounds per square inch-bbl	This must be read carefully as its units appear non sense. The explanation for this is that Joule is a unit of work whereas HP is of power and even though they're not intimate related, both can be gathered by Watt unit (which is the work made by one joule during one second).
Pressure_of-injection	psi	This value is a parameter of the Hydraulic HP equation. (http://www.calcunation.com/calculators/machinery/fluid%20 power/hydraulic-horsepower.php). And it is also a policy design variable!
HP_equation	hp/yr	http://www.calcunation.com/calculators/machinery/fluid%20power/hydraulic-horsepower.php

HP_to_joules	joule/hp	it must be said: joules are understood here as [joule/s]. Which makes sense according to the units of 'joules to injection' variable [joule/time(yr)].
Joules_to_ injection	joule/yr	This is the energy consumed by injection
Energy_balance	joule/yr	This variable answers the question whether to invest energy in CCS development is inherently a positive thus wise approach or conversely the energy spent in CCS technologies is fundamentally a flaw (negative balance).

Annex 2

Next all the equations, parameter's values, stock's initial values and graphical functions of ECCIS:

Desired_number_of_injection_wells = 200

Desired_number_of_producer_wells = 800

Desired_pressure_for_H2O_injection_psi = 570

desired_WaterCut = if(WaterOil_index<=Minimun_WaterCut_allowed)then(1)else(0)

effect_of_CO2___on_oil_swelling = GRAPH(CO2_cut)

(0.001, 1.18), (0.00245, 1.23), (0.00391, 1.26), (0.00536, 1.29), (0.00682, 1.31), (0.00827, 1.34), (0.00973, 1.39), (0.0112, 1.47), (0.0126, 1.55), (0.0141, 1.64), (0.0155, 1.74), (0.017, 2.00)

effect_of_totalCO2capt_on_improved_efficiency = GRAPH(Ln_Stock_Ln_Importance_of_capturing)

(0.00, 0.00), (4.00, 0.00962), (8.00, 0.0199), (12.0, 0.0296), (16.0, 0.0399), (20.0, 0.0495), (24.0, 0.0598), (28.0, 0.0698), (32.0, 0.0797), (36.0, 0.0897), (40.0, 0.0993)

effect_of_totalCO2comp_on_improve_efficiency = GRAPH(Ln_Stock_Ln_importance_of_compression)

(0.00, 0.00), (4.00, 0.00997), (8.00, 0.0203), (12.0, 0.0306), (16.0, 0.0402), (20.0, 0.0502), (24.0, 0.0601), (28.0, 0.0698), (32.0, 0.0797), (36.0, 0.09), (40.0, 0.1)

effect_of_total_CO2__InjSalForm_on__efficiency_improvemt = GRAPH(LN_Stock_Ln_importance_of_injecSalForm)

(0.00, 0.00), (4.00, 0.00997), (8.00, 0.0203), (12.0, 0.0299), (16.0, 0.0395), (20.0, 0.0502), (24.0, 0.0601), (28.0, 0.0698), (32.0, 0.0794), (36.0, 0.0897), (40.0, 0.0993) effect_of__Reservoir_pressure_on_oil_viscosity = GRAPH(Reservoir_pressure)

(0.00, 2.16e-006), (300, 1.9e-006), (600, 1.68e-006), (900, 1.42e-006), (1200, 1.3e-006), (1500, 1.36e-006), (1800, 1.47e-006), (2100, 1.52e-006), (2400, 1.56e-006), (2700, 1.6e-006), (3000, 1.61e-006)

elect_demand = GRAPH(TIME)

(1990, 305200), (1991, 313700), (1992, 315800), (1993, 315800), (1994, 319000), (1995, 321100), (1996, 325300), (1997, 333800), (1998, 336900), (1999, 340100), (2000, 344300), (2001, 351700), (2002, 362300), (2003, 367600), (2004, 372800), (2005, 377100), (2006, 381300), (2007, 387600), (2008, 397100), (2009, 360300), (2010, 356100), (2011, 361700), (2012, 380700), (2013, 382800), (2014, 385600), (2015, 389100), (2016, 391900), (2017, 394000), (2018, 397500), (2019, 399600), (2020, 401700), (2021, 403800), (2022, 406600), (2023, 408700), (2024, 410800), (2025, 413600), (2026, 415700), (2027, 418500), (2028, 420700), (2029, 422800), (2030, 426300), (2031, 429800), (2032, 436800), (2033, 443100), (2034, 450100), (2035, 456400), (2036, 461400), (2037, 465600), (2038, 469100), (2039, 478900), (2040, 478900)

Field_area = lenght_m*width_m

GAP_electr_demand_production = elect_demand-total_elect

Gas__market_share = GRAPH(TIME)

(1990, 0.13), (1991, 0.13), (1992, 0.133), (1993, 0.137), (1994, 0.137), (1995, 0.137), (1996, 0.137), (1997, 0.137), (1998, 0.133), (1999, 0.14), (2000, 0.151), (2001, 0.158), (2002, 0.165), (2003, 0.172), (2004, 0.186), (2005, 0.196), (2006, 0.204), (2007, 0.207), (2008, 0.228), (2009, 0.246), (2010, 0.253), (2011, 0.253), (2012, 0.26), (2013, 0.256), (2014, 0.256), (2015, 0.263), (2016, 0.27), (2017, 0.274), (2018, 0.274), (2019, 0.267), (2020, 0.27), (2021, 0.27), (2022, 0.27), (2023, 0.27), (2024, 0.27), (2025, 0.274), (2026, 0.274), (2027, 0.274), (2028, 0.274), (2029, 0.267), (2030, 0.267), (2031, 0.267), (2032, 0.267), (2033, 0.267), (2034, 0.267), (2035, 0.27), (2036, 0.274), (2037, 0.277), (2038, 0.281), (2039, 0.298), (2040, 0.305)

H2O_viscosity_20celsius = 1.4469e-07

H2O_viscosity_65cesius = 6.284e-08

height_m = 30

importance_of_total_CO2_captured_on_efficieny_improvement = GRAPH(level_of_investment_on__CO2_Capture_development)

(0.00, 12.3), (1.00, 9.02), (2.00, 7.96), (3.00, 6.98), (4.00, 6.00), (5.00, 4.98), (6.00, 3.93), (7.00, 3.02), (8.00, 2.07), (9.00, 1.19), (10.0, 1.19)

importance_of_total_CO2_compressed_on_efficiency_improvement = GRAPH(Level_of_investment_on_CO2_Compresiion)

(0.00, 12.3), (1.00, 9.02), (2.00, 7.96), (3.00, 6.98), (4.00, 6.00), (5.00, 4.98), (6.00, 3.93), (7.00, 3.02), (8.00, 2.07), (9.00, 1.19), (10.0, 1.19)

importance_of_total_CO2_into__SalForm_learning_efficienci_imp = GRAPH(Level_of_investment_on_InjecSalFormations)

(0.00, 12.3), (1.00, 9.02), (2.00, 7.96), (3.00, 6.98), (4.00, 6.00), (5.00, 4.98), (6.00, 3.93), (7.00, 3.02), (8.00, 2.07), (9.00, 1.19), (10.0, 1.19)

inicial_value_Original_Fluids_in_place = (lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters)-

(lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters*secondary_recovery_factor_%)

Initial_Reservoir_Pressure_psi = 1900

initial_value_Technically_recoverable_fluids = (lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters*secondary_recovery_factor_%)

injection_wells_per_square_meter = Desired_number_of_injection_wells/Field_area

K = Permeability_mD*milidarcy_to_squaremeters

L = line_lenght/wells_per_line

lenght_m = 5000

Level_of_investment_on_CO2_Compresiion = 5

Level_of_investment_on_InjecSalFormations = 5

level_of_investment_on__CO2_Capture_development = 5

line_lenght = SQRT(lenght_m*width_m)

Ln_Stock_Ln_Importance_of_capturing = LN(total_CO2_captured)/LN(importance_of_total_CO2_captured_on_efficieny_improvement)

Ln_Stock_Ln_importance_of_compression = LN(total_CO2_compressed)/LN(importance_of_total_CO2_compressed_on_efficiency_improvement)

LN_Stock_Ln_importance_of_injecSalForm = LN(CO2_into_saline_formations)/LN(importance_of_total_CO2_into__SalForm_learning_efficienci_imp)

Maximum_pressure_allowed = 3000

MaxNumber_wells_allowed = If(Prod_Wells<=Desired_number_of_producer_wells)then(1)else(0)

Max_injection_per_well = Daily_injection_bbl*Days_per_year

Max_production_per_well = Days_per_year*Daily_production_bbl

milidarcy_to_squaremeters = 1e-12

Minimun_WaterCut_allowed = 0.25

Number_of_CoalPowerPlant_to_construct = 0

Number_of_GasPowerPlant_to_construct = 0

number_of_hours_per_year = 8760

oil_price = GRAPH(TIME)

(1990, 45.0), (1991, 45.5), (1992, 43.8), (1993, 42.1), (1994, 42.9), (1995, 44.6), (1996, 46.3), (1997, 47.2), (1998, 46.7), (1999, 45.9), (2000, 42.5), (2001, 39.6), (2002, 38.3), (2003, 35.8), (2004, 33.3), (2005, 33.3), (2006, 34.1), (2007, 51.4), (2008, 63.6), (2009, 102), (2010, 72.8), (2011, 71.6), (2012, 107), (2013, 107), (2014, 106), (2015, 104), (2016, 100), (2017, 96.8), (2018, 94.7), (2019, 93.1), (2020, 93.5), (2021, 93.9), (2022, 94.3), (2023, 94.3), (2024, 94.7), (2025, 96.4), (2026, 96.8), (2027, 98.1), (2028, 99.4), (2029, 102), (2030, 105), (2031, 107), (2032, 107), (2033, 109), (2034, 111), (2035, 112), (2036, 112), (2037, 114), (2038, 116), (2039, 116), (2040, 119)

oil_Viscocity_65celsius = effect_of__Reservoir_pressure_on_oil_viscosity

original_WaterCut_% = 0.15

percentage_of_recovery = 0.5

Permeability_mD = 100

porosity_% = 0.2

pressure_chande_due__CO2_produciton = ((CO2_prod_rate*bblyr_to_cubmeterSec)*CO2_viscocity_65celsius*L)/(K*A)

pressure_change_due_H2O_injection = ((H2O_injection_rate*bblyr_to_cubmeterSec)*H2O_viscosity_20celsius*L)/(K*A)

pressure_change_due_H2O_production = ((H2O_production_rate*bblyr_to_cubmeterSec)*H2O_viscosity_65cesius*L)/(K*A)

pressure_change_due_oil_production = (((prod_rate*bblyr_to_cubmeterSec)*oil_Viscocity_65celsius*L)/(A*K))

pressure__change_due_CO2_injected = ((CO2_injection_rate*bblyr_to_cubmeterSec)*CO2_viscosity_0celsius10Mpa*L)/(K*A)

producer_wells_per_square_meter = Desired_number_of_producer_wells/Field_area pulse_CoalPowerPlants = STEP(Number_of_CoalPowerPlant_to_construct, time)-delay(STEP(Number_of_CoalPowerPlant_to_construct, time), 1)

pulse_GasPowerPlants = STEP(Number_of_GasPowerPlant_to_construct, time)-delay(STEP(Number_of_GasPowerPlant_to_construct, time), 1)

RESERVES_MMbbl = (((Original_fluids_in_place_available_for_terciary_production+Technically_recoverable_fluids)*(1-original_WaterCut_%))-(Total_amount_of_fluids_that_can_not_be_recovered))*1e-6

secondary_recovery_factor_% = 0.3

suitable_oil_price_to_start_up_drilling_USdollars = 45

Terciary_recovery_factor_% = 0.3

tons_of_CO2_per_barrel_of_refined_oil = 0.054

Total_amount_of_fluids_that_can_not_be_recovered = (lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters)-

((lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters*secondary_recovery_factor_%)+(lenght_m*width_m*height_m*porosity_%*bbl_to_cubicmeters*Terciary_recovery_factor_%))

total_CO2_sequestred = CO2_into_saline_formations+CO2_EOR_injected

total_elect = Electricity_by_gas+Electricity__by_coal

total_numbre_of_welss = Injec_Wells+Prod_Wells

WaterOil_index = (H2O_connata_produced+total_injected_H2O_produced)/(Recovered_oil)

wells_per_line = SQRT(total_numbre_of_welss)

width_m = 5000