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*Lastly, I am deeply indebted to my PhD colleagues Omar Enrique Chinque, Valentina Marla Aiello, Luca Mellina and Milica Marinkovich. Without those incredible people my system dynamics journey would have definitely been less bright.*

*July 5, 2017*

# Abstract

Traditionally carbon dioxide (CO2) emissions has been viewed and treated as a "bad" rather than a "good". This mental model is of little surprise due to a well-established consensus on carbon dioxide as a pollutant constraining the sustainability of economic and social development at a global scale.

In the world where so many actors are preoccupied with shifting towards a low- carbon economy the very idea of carbon dioxide being a commodity (literally and not in the form of carbon caps or quotas trade, in which case a "commodity" is in fact the right to emit carbon, which is in its essence a very different concept) might be a big of a statement. However, this idea is not a mere perspective but a reflection of an already existing and developing market for CO2 with well-defined supply and demand sides. Paradoxically, the supply side of this nascent market was originally motivated by the intention to decrease CO2 emissions but now is giving rise to CO2 as a commodity. Ironically, the demand side (CO2 buyers) is the part of the market which is "hungry" for the commodity not being supplied in a demanded quantity.

This thesis provides a conceptual overview of the market for CO2 where the supply is coming from CCUS industry and the demand originates in the enhanced oil recovery (EOR) industry. The paper is based on the research project (the working title "CCUS Market Dynamics") conducted recently as a part of master thesis and currently PhD research. The project started in late 2013 as a system dynamics modelling effort focused on specific problem of CCUS technologies commercialization. However, eventually the problem necessitated the construction of the model of an integrated CCUS-EOR system, similar to the demand-pull market for carbon dioxide currently developing in the Permian Basin, TX.

As viewed by the author, it is the market perspective towards CO2 which turned out to be the most insightful part and result of the modelling process. The system dynamics method and its endogenous approach appeared to be instrumental in grasping intricate interconnections between various dispersed (at least within conventional mental models) elements of the market for this new commodity.

This thesis presents the first stone towards a comprehensive research on the feedback mechanisms between the CCUS and EOR industries which shape the CO2 market. It is the author's highest aspiration to provoke interest to this topic in the system dynamics community and create momentum for its further progression.

# List of Acronyms

$bn: billion US dollars

$mn: million US dollars

CCS: carbon capture and storage

CCS-EOR: enhanced oil recovery using anthropogenic (captured) $CO_2$

CCUS: carbon capture, utilization and storage

CCUS PP: power plants equipped with CCUS

$CO_2$-EOR: $CO_2$-based enhanced oil recovery

CTCP: Carbon Tax Credit Policy

EOR: enhanced oil recovery

FOAK: first-of-a-kind

IES: Institute for Energy Studies

$MtCO_2$/yr: million tonnes $CO_2$ per year

ND: North Dakota

NEORI: National Enhanced Oil Recovery Initiative

NGCC: natural gas combined cycle

OXY: oxy-combustion capture

PCC: post-combustion capture

R&D: research & development

RD&D: research, development & demonstration

US DOE: US department of energy

WEO: world energy outlook

WTP: willingness to pay

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# Chapter 1. Introduction

## 1.1 Problem Description and Problem Definition

The purpose of this study is to investigate the economics of carbon capture, utilization and storage technologies by way of a model- and simulation- based analysis.

In this study, we will consider carbon gas products in general. We will have a particular focus on CO2, not only as pollutant, but also as a resource, a commodity with which there is associated a market, a production and waste cost, and an exploitation value.

There are currently a significant number of technologies for carbon capture, utilization and storage (CCUS) under development and assessment, - most of them tested in small scale. The resulting products, CO2 in particular, may be utilized for various commercial purposes. E.g. CO2 may be re-injected for enhanced oil recovery (EOR), which calls for additional carbon capture. The economics of CO2 depends on the technologies used for carbon capture, utilization, and storage and the alternative pollution costs associated with waste, - i.e. the market conditions for CO2 and the products resulting from the exploitation of this resource, e.g. the oil recovered.

Our purpose is, moreover, to develop robust strategies and policies to facilitate decision-making regarding the investments in and exploitation of the CCUS technologies under prevailing uncertainty. To do so, our model must constitute a comprehensive, causal representation of the fundamental characteristics of the market and the technologies.

The context for this study will be the World Energy Market, both fossil fuels and renewables that will provide the scenarios under which an economic assessment must take place.

The uncertainties associated with our analysis encompass the technology characteristics such as effectiveness and efficiency as well as the time required for research, development, implementation, and utilization. Moreover, there are significant uncertainties associated with the world energy market and the CO2 commodity market.

The method employed in this study will be system dynamics modeling and simulation based analysis. This will allow us to explicitly represent our hypotheses and theories in by way of simulation models.  In that way, we may facilitate a variety of formal analyses that enhances our understanding of the CCUS economy and allows us to formulate and assess the impact of strategies and policies intended to govern the development and utilization of CCUS technologies.

The CCUS technology development and utilization takes place in a highly dynamic environment, characterized by massive feedback, interaction between a variety of subsystems and uncertainty. System dynamics has been developed specifically to facilitate the analysis of the relationship between the structure and behaviour in non-linear feedback systems under uncertainty.

Traditionally carbon dioxide (CO2) emissions has been viewed and treated as a “bad” rather than a “good”. This mental model is of little surprise due to a well-established consensus on carbon dioxide as a pollutant constraining the sustainability of economic and social development at a global scale.

In the world where so many actors are preoccupied with shifting towards a low- carbon economy the very idea of carbon dioxide being a commodity (literally and not in the form of carbon caps or quotas trade, in which case a “commodity” is in fact the right to emit carbon, which is in its essence a very different concept) might be a big of a statement. However, this idea is not a mere perspective but a reflection of an already existing and developing market for CO2 with well-defined supply and demand sides. Paradoxically, the supply side of this nascent market was originally motivated by the intention to decrease CO2 emissions but now is giving rise to CO2 as a commodity. Ironically, the demand side (CO2 buyers) is the part of the market which is “hungry” for the commodity not being supplied in a demanded quantity.

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As viewed by the author, it is the market perspective towards CO2 which turned out to be the most insightful part and result of the modeling process. The system dynamics method and its endogenous approach appeared to be instrumental in grasping intricate interconnections between various dispersed (at least within conventional mental models) elements of the market for this new commodity.

The thesis is structured in the following way. First, it introduces the context and defines the problem which motivated the research and eventually gave rise to the market/ commodity perspective. Second, the conceptual framework of CO2 market is described in the form of the system dynamics model. Third, the challenges of the emerging CO2 market at its current phase and the policy suggestions to overcome those challenges are analyzed by simulating the model. The paper finishes with the report on the results and conclusions.

The CCUS Market Dynamics represents a system dynamics project dealing with the contexts characterized, besides dynamic complexity, a relatively high degree of uncertainty among the key stakeholders over what constitutes the problems itself (what in system dynamics literature is referred to as "messy problems"). The project has been following a highly non-linear path and even at the moment the author is still investigating which aspects of the problem context had been intended to be grasped and which ones were actually grasped.

This paper presents the first stone towards a comprehensive research on the feedback mechanisms between the CCUS and EOR industries which shape the CO2 market. It is the author's highest aspiration to provoke interest to this topic in the system dynamics community and create momentum for its further progression.

One of the most famous commercial purposes of captured $CO_2$ utilization, at least in the US, is enhanced oil recovery. This represents a separate from CCUS industry, which we refer to as the second issue area the client was interested in.

$CO_2$-based enhanced oil recovery ($CO_2$-EOR) is a technique to sustain oil production on otherwise depleting oil fields. It was pioneered in West Texas in 1972. The mechanism is based on injecting $CO_2$ coming from either natural or anthropogenic sources into existing oil fields to free up additional crude oil trapped in rock formations. This technique allows significantly extent the lifespan of mature oil fields by revitalizing the production from them (National Enhanced Oil Recovery Initiative, 2012).

As extensively described in the literature, $CO_2$ for the first projects came from natural gas processing facilities. Later, however, companies became aware that naturally occurring $CO_2$ source fields could offer large quantities of the necessary carbon dioxide. As demand grew, these underground formations in New Mexico, Colorado, and Mississippi came to dominate the $CO_2$ supply. Pipelines were constructed in the early 1980s to connect the $CO_2$ source fields with the oil fields in West Texas. This system led to more and more EOR projects and expansion to other US regions, including the Rocky Mountains and Gulf Coast. As reported by the National Energy Technology Laboratory, "over the past 40 years the EOR industry has grown to include over twenty companies that deploy new technologies and practices to improve understanding of the subsurface and to locate hard-to-find oil pockets, as well as boost oil production efficiency" (National Energy Technology Laboratory, 2011).

The historical development of $CO_2$-EOR industry in the US is best portrayed by Figure 1.

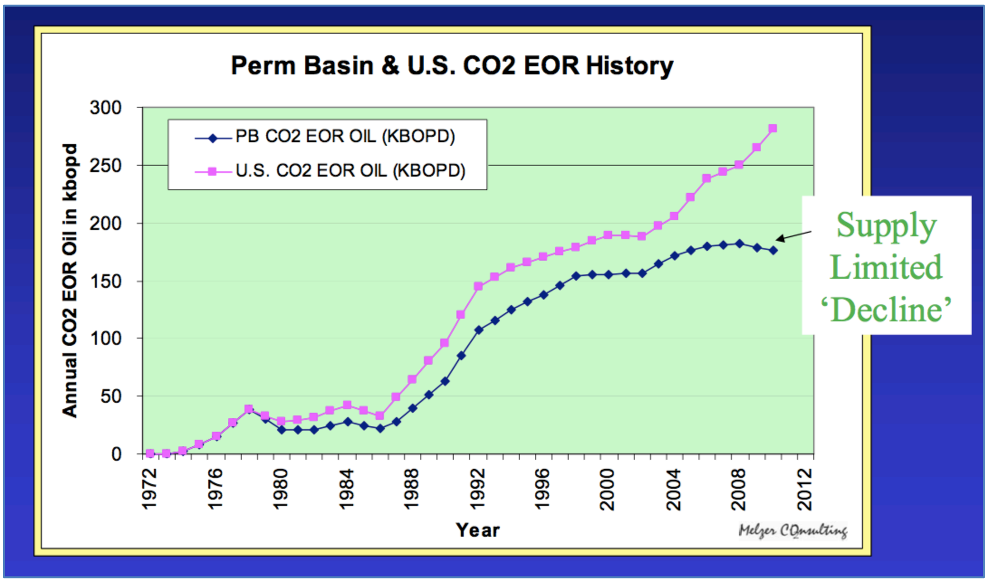

**Figure 1. US and Permian Basin CO2-EOR Production Growth (1972-2010)**
**Source: Hargrove B., et al. (2010)**

This somewhat s-shaped growth dynamics is usually called by $CO_2$-EOR industry analysts as "the case history of a $CO_2$ supply constrained market" (Hargrove B., 2010). Figure 1 clearly demonstrated the major problem the $CO_2$-EOR industry is facing now: EOR development is constrained by insufficient supply of $CO_2$. Natural sources of $CO_2$, which the industry has been relying on for 40 years, are approaching the point of depletion and do not have the capacity to satisfy all the demand, generated by the industry. Without significantly expanding the volume of CO2 available for use in EOR, the production of vital domestic oil will fall short of its potential.

The two issue areas described above pose an example of interesting interconnection of their key problems. On the one hand, there is CCUS industry with a number of successfully tested at a pilot scale technologies able to capture $CO_2$ but not being commercially deployed due to unfavorable economics of costs and potential benefits. On the other hand, there is $CO_2$-EOR industry with a tremendous potential of technically and economically recoverable oil reserves but being severely constrained in its development by limited supply of natural $CO_2$, it has been relying on for 40 years before.

For the CCUS developers like the IES, $CO_2$-EOR represents an excellent source of demand, which has the potential to pay additional costs of CCUS commercialization. Moreover, for $CO_2$-EOR operators CCUS represents the excellent source of supply of anthropogenic $CO_2$ under the condition that it is affordable. Thus, the client was interested in understanding how these two industries could be brought together to find the solutions to their mutually dependent challenges and what kind of policies could forester the interaction of the industries to generate the growth of both $CO_2$-EOR and CCUS.

We note here that even though, as it follows from the description above, the IES's interest was primarily in CCUS side of the project, $CO_2$-EOR is of equal importance to the client as currently this method of oil extraction is being considered for application in the Bukken oil field of the Williston Basin in the western part of the state of ND.

To complete the problem formulation, we bring the last important dimension of the project issue. While $CO_2$-EOR needs anthropogenic $CO_2$ from CCUS industry, it needs so at an affordable price. The currently estimated maximum willingness to pay for $CO_2$ by oil operators is \$40 per $tCO_2$, which still insures the profitability of $CO_2$-EOR oil projects (National Enhanced Oil Recovery Initiative, 2012). The costs of $CO_2$ capture are presently in the range of \$50-120 per $tCO_2$ in power generation compared to \$2 per tone of natural $CO_2$ (SBC Energy Institute, 2012). Consequently, as it is now, $CO_2$-EOR industry cannot rely on CCUS as a supplier of affordable $CO_2$. The conceptualization of this important aspect is illustrated by Figure 2.

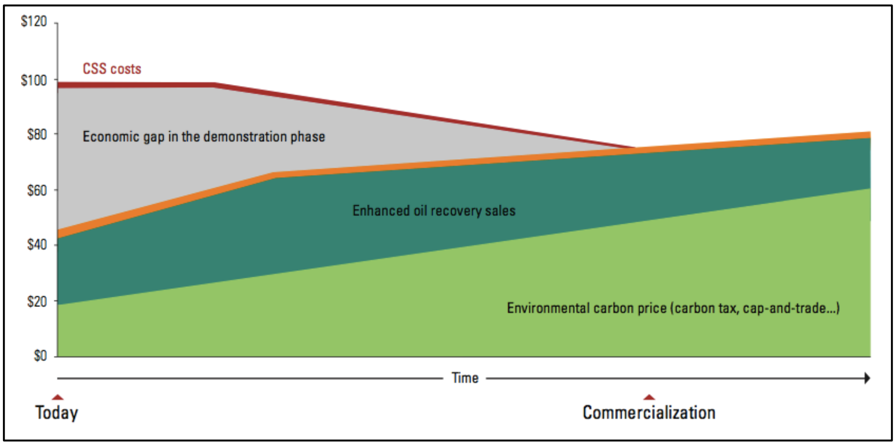

Figure 2. Conceptual Portrayel of CCUS Economics. Source: SBC Institute (2012)

There is, however, a well-justified expectation that the costs of $CO_2$ capture will be decreasing, which will be driven primarily by the learning effect accompanying the accumulation of experience in $CO_2$ capture (SBC Energy Institute, 2012). Yet, the learning effect cannot operate within the current status of CCUS, as the industry has not simply "captured" enough $CO_2$ to accumulate the necessary for learning experience.

Thus, based on the description of the issue surrounding the project work, the problem, which this project is supposed to address, can be formulated as the following: CCUS is facing the challenge of commercializing its technologies and could have fostered commercialization by supplying the captured product to $CO_2$-EOR industry with a tremendous demand for new $CO_2$ sources, but currently CCUS captures $CO_2$ at costs exceeding the maximum willingness to pay by EOR operators yet there is a potential for costs reduction attributed to expected learning effect.

The logical question following this problem definition is what kind of policies might support the interaction of CCUS and $CO_2$-EOR so that the learning effect starts improving the economics of $CO_2$ as a commodity and the mutually beneficial interaction of the two industries becomes self-supporting.

## 1.2 Research Objectives and Research Questions

The two fundamental research objectives correspond directly to the purposes of this research project described in the Introduction.

**Research Objective 1:**

**To investigate a comprehensive, causal representation of the fundamental characteristics of the CCUS market and the technologies.**

**Research Objective 2:**

**To develop robust strategies and policies to facilitate decision-making regarding the investments in and exploitation of the CCUS technologies under prevailing uncertainty.**

To address the stated research objectives, we focus on the following **research questions:**

1. What is the role of EOR in CCUS, namely can CO2 reuse for EOR accelerate CCUS uptake?
2. How beneficial is CO2 reuse through EOR as a transitional measure to CCS?
3. To what extent might the implementation of CO2 reuse through EOR bring forward the date at which high-cost forms of CCS such as power generation become viable?
4. What is a realistic level of revenue to be expected from the sale of CO2 for reuse?
5. How much does CCS cost now, and how much will it cost in the future?
6. What is the carbon price expected to be in the future?
7. What is the current CO2 market-supply and demand balance and pricing of bulk CO2?
8. What is the commercial framework for CCUS - what carbon emissions pricing or regulatory requirements might be imposed in the future, and how they relate to the costs of CO2 capture and storage?

## 1.3 Methodology Choice and Research Strategy

The method employed in this study is quantitative system dynamics modeling and simulation based analysis. This allows us to represent, explicitly, coherently and consistently, relevant hypotheses and, eventually, theories by way of simulation models. In that way, it is possible to facilitate a variety of formal analyses that enhance our understanding of the market for $CO_2$ and CCUS and allow us to formulate and assesse the impact of strategies and policies intended to govern favorably the development and utilization of CCUS technologies so that $CO_2$-EOR industry could be supplied with anthropogenic $CO_2$ according to its needs.

The CCUS technology development and utilization as well as the use of the captured carbon for $CO_2$-EOR takes place in a highly dynamic environment, characterized by massive feedback, interaction between a variety of subsystems, significant time delays and uncertainty. System dynamics has been developed specifically to facilitate the analysis of the relationship between the structure and behavior in such non-linear feedback systems under uncertainty.

In the context of the chosen method, the Research Strategy can be characterized as a combination of Grounded Theory and Experiment.

The Grounded Theory is used to address the first research objective of the study. The extensive analysis of various industry reports and $CO_2$ flooding conferences presentations reflecting the state of the CCUS and $CO_2$-EOR as well as the mental models governing the operators' decisions constitute the backbone of the qualitative and quantitative data used for this project. Then the analysis of the industry reports and conference presentations was enhanced with the interviews and conversations with "insiders"/experts to make sure that our understanding of the system correspond to the reality.

Based on the documents analysis and conversation with the experts a theory of what governs the market for $CO_2$, its supply and demand side and their interaction, is constructed and represented in a quantitative system dynamics model.

At the next stage, while addressing the second research objective, an experimental strategy employed. However, rather than being a laboratory experiment, in a context of system dynamics method the experimental strategy employs using simulation of the constructed model as an "computer laboratory" for testing various investment policies and uncertainty scenarios. This approach allows conducting a relatively cheap evaluation of policies aimed at stimulating CCUS market dynamics that are extremely risky and costly to do in reality.

## 1.4 Literature Overview

As it was mentioned in paragraph 1.3, the backbone of the quantitative and qualitative data for the constructed system dynamics model was obtained from the extensive analysis of the documents and literature related to the defined problem. This section provides an overview of the literature employed throughout the research project. We would like to note here that publicly available sometimes served as both sources of literature (to form an understanding of perspectives on the issue) and sources of data (provided estimations, structural knowledge, etc.).

Conceptually, the analyzed literature is divided into two blocks. The first block relates to the CCUS industry and, thus, is called here CCUS literature. The second block relates to the $CO_2$-EOR and, thus, is referred to here as $CO_2$-EOR literature. This distinction is important to note as the two literature take two different perspectives. After describing each of them, a clarification on which perspective is employed for the current study and the corresponding model will be made.

The CCUS literature takes the perspective of CCUS technologies and market as a starting point. Normally the motivation for CCUS departs from environmental concerns, under which CCUS is considered first and foremost as a $CO_2$ and climate change mitigation lever. $CO_2$-EOR is perceived as one of the way of beneficial reuse of $CO_2$ captured by CCUS. Yet, it is often emphasized in this literature that the potential for beneficial reuse of $CO_2$ through $CO_2$-EOR is limited, and fundamentally not at the scale required to mitigate climate change. Also, the storage capacities of $CO_2$-EOR are often questioned (Pacific Nothwest National Laboratory, 2010).

Even though the linkage between CCUS and $CO_2$-EOR is not very well emphasized in CCUS literature, this block provides a crucial understanding of the industry, its status, the major challenges it faces, the reasons for those challenges and the outlook of the industry into the future. In most cases this literature is represented by the industry reports based on the surveys of actors directly involved into CCUS operation, which makes this literature an invaluable source of secondary data based on which the theory of how CCUS industry operates can be constructed for our model.

The central document from CCUS literature is the report *Leading the Energy Transition: Bridging Carbon Capture & Storage to Market* by SBC Energy Institute (2012). The SBC Energy Institute is a non-profit foundation established in the Netherlands with the purpose of studying the private sector's experience of the energy transition. Between June and September 2011 the Institute interviewed more than 40 CCS insiders worldwide to understand private-sector RD&D activity, and potential actions to increase that activity. Participants included public organizations, utilities, oil and gas companies, service companies, equipment manufacturers, specialty chemists, and financiers. Interviews were supplemented by SBC Energy Institute analysis, Bloomberg New Energy Finance, and publicly available information sources. As follows from this description, the way the data for SBC Energy Institute (2012) was collected is consistent with the operational perspective we take in system dynamics and, thus, this document was used for formulating a grounded theory about how CCUS sector in the model works.

The main technical literature used to form understanding of CCUS in conjunction with SBC Energy Institute (2012) is IPCC (2005), IEA(2008), KAPSARC (2012), and Global CCS Institute (2009).

The $CO_2$-EOR literature takes the perspective of $CO_2$-EOR industry. Environmental concerns are normally not the major ones used to motivate the analysis. The key departing question is how to realize the tremendous reserves of technically and economically recoverable oil through the existing $CO_2$-EOR technology. Then the CCUS is treated is a source of anthropogenic $CO_2$ supply which can encourage the desired increase in oil production. This block of literature can be divided into sub-blocks.

First, there is a number of industry reports and analysis by the industry consultants which provide the description of the industry, its current status and the outlook, the estimations for the key variables and technical descriptions of the major physical processes (Melzer, 2012), (NETL, 2011, 2014), (ARI, 2010, 2011). Melzer Consulting, the National Energy Technology Laboratory and Advanced Research International are the key providers of the structural knowledge behind our understanding of $CO_2$-EOR sector.

Second, the analysis of various conference presentations, the most important of which is the annual $CO_2$ Flooding Conference in Texas, provided the invaluable access to a huge depository of both quantitative but most importantly qualitative data in the form of mental models used by decision-makers in the industry. The presentations also deliver an industry perspective on the status of $CO_2$-EOR and their expectation of $CO_2$ supplies, which appeared to be a crucial factor for the system dynamics model.

Third, a significant source of quantitative data for the model came from the Oil & Gas Journal's (OGJ) biannual enhanced oil recovery survey which is considered to be the "gold standard" for information on enhanced oil recovery operations in the US. The information in the survey is collected at an EOR project level. Providing very detailed, highly valuable data on the nature, location, reservoir settings and oil production from EOR for each of the major EOR technologies, including $CO_2$-EOR. The OGJ survey (2014) provided a most valuable snapshot of the status of EOR used for the system dynamics model in this project.

The described two block of literature take two different perspectives. Which one is employed for this research project? The answer to this question is important to understand what the focus of the system dynamics model is.

Even though the project started with CCUS being in the center of the client's attention, the aspect chosen to be addressed specifically by this project is its close interconnection with the $CO_2$-EOR. In other words, in accordance with the formulated problem definition, research objectives and research questions, CCUS and $CO_2$-EOR are indispensably interconnected as the development of the one requires the development of the other. Thus, in this project both the number of deployed CCUS technologies (reflected in $CO_2$ capture) and the resulting incremental oil production are considered to be equally important.

## 1.5 Key Concepts

As the issue, this project is devoted to, involves a number of technical aspects, a concise note on the key technical concepts is required before the description of the system dynamics model. Moreover, a number of modeling assumptions described in Chapter 2 can be understood better after a short introduction to the central technical aspects of the CCUS and $CO_2$-EOR systems. This paragraph covers the following key concepts:

### *Anthropogenic $CO_2$ vs Natural $CO_2$*

Anthropogenic $CO_2$ is the $CO_2$ produced as a result of industrial activities (captured at a CCUS plant), as opposed to natural $CO_2$, which is pumped out of naturally occurring $CO_2$ (SBC Energy Institute, 2012).

### *CCUS value chain: sources of $CO_2$ capture and technology designs*

The long value chain of CCS is demonstrated by the Figure 3:

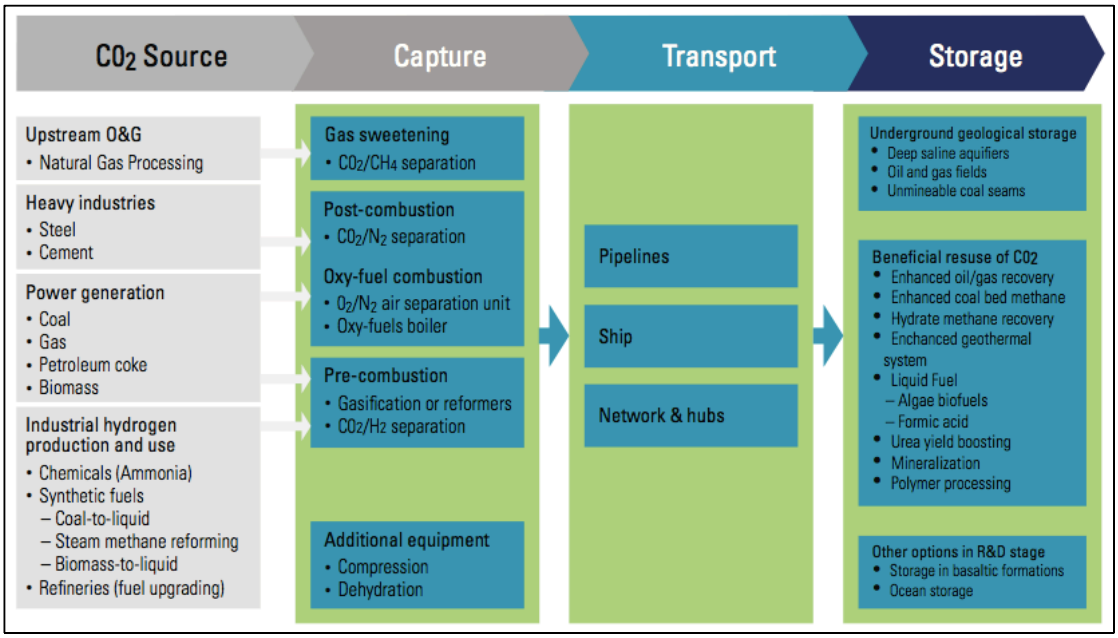

**Figure 3. CCUS Supply Chain. Source: SBC Institute (2012)**

According to Figure 3, there are four types of plants which are suitable for CCUS:

- Natural gas processing plant. The related $CO_2$ capture process is called "natural gas sweetening", and is the lowest-cost opportunity for CCS.
- Industrial plants:

- Industrial hydrogen refers to all plants that have hydrogen production from hydrocarbons (as opposed to electricity) as an intermediate step in their process. Those plants include chemical plants for ammonia production and synthetic fuel plants. This group represents the second least costly opportunity for CCS.
- Heavy industries (iron, steel, cement, refineries, pulp and paper) which are responsible for 17% of global anthropogenic emissions. Over 90% of total $CO_2$ emissions can be captured by the existing technology. There is no low-cost opportunity for CCS in heavy industry.

- Power plants (30% of global anthropogenic $CO_2$ emissions) with coal-fuelled units being the most carbon-intensive. There are three designs of CCS power plants: pre-, post- and oxy-combustion. A post-combustion power plants is the most well-known design, but which one of the three technologies will prevail remain uncertain until they have all been demonstrated at large scale. There is no low-cost opportunity for CCS in power generation.

According to the IEA, 50% of the long-term potential for $CO_2$ mitigation with CCS lies in the power generation.

Another concept from Figure 2 is the four main capture process designs:

- Natural gas sweetening: $CO_2$ is separated from raw natural gas at a gas processing plant;
- Post-combustion: $CO_2$ is separated from flue gas after combustion, and can be retrofitted to existing power and heavy industrial plants with relatively high costs and energy penalty.
- Oxy-combustion: fuel is combusted in pure oxygen instead of air, producing a concentrated $CO_2$ stream in the fuel gas, which is almost ready to be transported.
- Pre-combustion: a hydrocarbon fuel source – coal, gas, biomass – is gasified into “shifted syngas” (a $H_2$ and $CO_2$ mix), from which the $CO_2$ is separated.

### $CO_2$-EOR process

$CO_2$-EOR: injection of $CO_2$ into nearly depleted petroleum reservoirs acts as a solvent that reduces the viscosity of the oil and allows enhanced oil recovery of the reservoir. Once the field is depleted, it can be utilized to store additional $CO_2$ permanently.

Primary recovery in the Permian basin typically recovers 15% of the original oil in place. Water injection allows recovery of 45% while $CO_2$ enhanced recovery ($CO_2$-EOR) gives recovery rates of up to 60% by injecting supercritical $CO_2$ into the oilfield where it dissolves and lowers the viscosity of oil. The process of $CO_2$-EOR injection is portrayed at Figure 4.

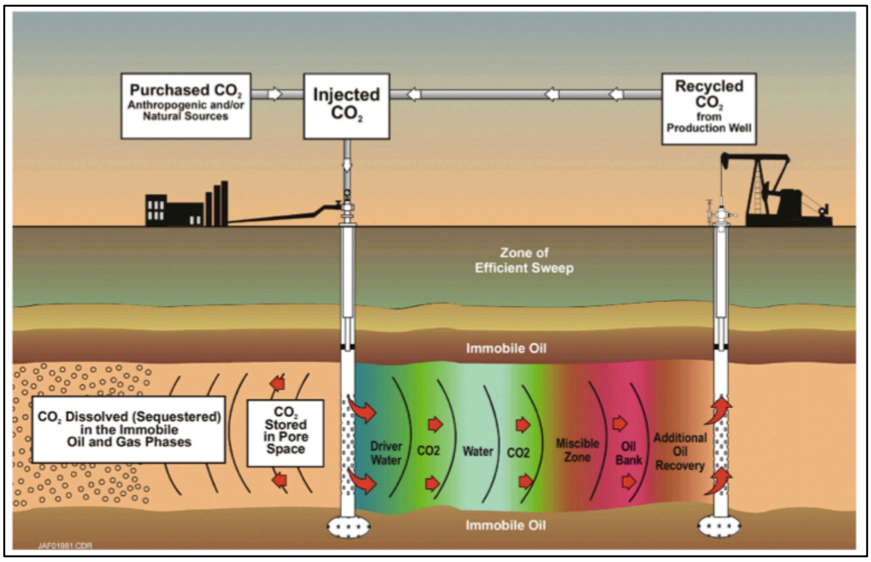

Figure 4. CO2-EOR Mechanism. Source: NEORI, 2012

# Chapter 2. Model Description

## 2.1 Model Overview

The previous chapter described extensively the problem definition and a number of issues related to the research design aimed at addressing the stated problem. In accordance with the research objectives and research questions, the scope, spacing and timing of the model were specified. This section describes what the model does (namely, the dynamics of which variables is generated, or, a scope of the model), at which space (geographical context) and for which time period. Based on this description, the purpose of the model is explained.

Together all these elements provide an overview of the model so that the reader can understand what generally the model is about without referring to exact specifications used in the model. The next section discusses how the chosen scope, spacing and timing of the model translate into the model's assumptions. Then the discussion shifts to a much more detailed level of describing the structure of the model's sectors in terms of stocks and flows and major formulations. After that a step back to a less detailed perspective structure will be taken, whereby the major feedback loops and their interactions will be presented.

The Global Case Model was inspired by Global CCS Document on commercial framework for CCUS. The model was built June 2016, discussed with Pal Davidson, modified November 2016 for Petroleum Forum in Stavanger, Norway and then revisited again January-February 2017 based on discussions with Pal Davidson.

The utilization of Global CCS Report is dual. On the one hand, the report serves as a source of hypothesis with a set of questions consistent with some of the research questions that the present research follows. In this sense, our system dynamics model effectively tests the claims suggested in the report. On the other hand, the report serves as a source of important knowledge to inform our modeling effort. Namely, it provides what the report calls commercial framework for CCUS that is practically the only available approach to put together climate change policies, reflected in carbon price, the market for CO2 formed by CCUS and EOR industries and the relationships between CO2 storage and utilization.

More precisely, this framework distinguishes explicitly between three important economic variables pertaining to CCUS-EOR interaction: CO2 costs, CO2 bulk price and Carbon Price. With regard to the latter argument, it is not uncommon in the news, reports, analysis and even scientific papers to see the term CO2 price. However essentially and for the purposes of our analysis it is important to recognize that there are at least two concepts that are quite often called by the same term: CO2 Price as a purchase price of CO2 by EOR industries for the purposes of EOR (in the report called as bulk CO2 price) and Carbon Price in the form of carbon tax or carbon trading scheme or other regulatory form. The distinction is crucial since the two prices pertain to fundamentally different mechanisms (and consequently underlying feedback loops). Bulk CO2 Price is the result of economic mechanisms, balancing of supply and demand for CO2 as a commodity. Carbon Price is a regulatory concept, a policy tool. The potential confusion between the two prices is even more worrisome since both prices affecting the deployment paths of CCUS. This model utilizes the feedback perspective to see the effects of those two prices separately and potential interactions between the two.

In this sense, this work is a substantial step forward in relation to the previous author's work [Master Thesis], which did not incorporate any climate change aspects underlying CCUS and looked at it exclusively from CCUS that serves EOR perspective. While there is a strong rationale for taking this approach, namely, that the scale of CCUS for climate mitigation is so huge in comparison for any potential coming from EOR that it would not make sense to bring the two aspects quite different in their magnitude on the scale of one model. However, by doing so we see only the interactions of CCUS and EOR in the realm of non-changing societal carbon constraints. Since this project has an ambition to look at CCUS and EOR within the global context of carbon constrained society, it is important to include that aspect into our analysis.

Coming back to the second mode of utilizing Global CCUS Report for this model. We take the framework and concepts that serve us (and those are backed up by operational knowledge) and besides testing them (checking whether those claims make sense from the feedback perspective), we also simply construct our model based on that knowledge and see what behaviors this model generates irregardless of the report's claims.

Why does it make sense to test the claims of the report? The perspective underlying the report's analysis is partially feedback-based. There is a certain recognition of feedback, however lots of changes and effects are tracked on a conventional "one-to-one" effect bases holding all else equal (ceteris paribus).

However, we assume that the processes under our analysis  exhibit strong feedback relationships where the effects from one variable could be not only direct but also indirect through another. Let’s say we look at the effects of Carbon Price on CCUS deployment and we are also interested in CCUS-EOR interaction. While Carbon Price will most likely lead to more CCUS deployment, it can actually dump down the price EOR would be willing to pay and stimulate CCUS operators to send more CO2 to storage rather than for EOR.

The key of the model: CCUS deployment trajectories/paths. The model focuses on the dynamics of supply and demand for $CO_2$ and their interaction at the level of the US. As such the model generates the dynamics of the following key variables at the national level:

- Annual demand for anthropogenic $CO_2$;
- Annual supply of anthropogenic $CO_2$;
- $CO_2$ costs;
- $CO_2$ price in the form of the willingness to pay for $CO_2$ by oil operators;
- Annual incremental oil production from $CO_2$-EOR industry.

The model incorporates Carbon Price as a carbon price regulatory policy.

The time frame of the model simulation is 50 years from the starting point, which is the current year of 2014. The choice of 50 years is dictated by the following reasons:

- A common perspective in the analysis of the issue for both practitioners and analysts does not exceed the period of 40 years, which is reflected in the forecasts and discussions during the Flooding Conference and the major reports on the issue (National Enhanced Oil Recovery Initiative, 2012). This is also based on the lifetime of $CO_2$ EOR projects (normally around 30-40 years) and the lifetime of power plants equipped with CCUS (also around 30-40 years).
- The policy tool as being proposed for consideration of the US Congress constitutes 30 years. A 20 years follow-up period is added to observe the effects of the policy lasting beyond the period of policy execution (National Enhanced Oil Recovery Initiative, 2012).

As such, the model can be described as the scoping model in a sense that it provides a highly aggregate overview of the system comprised of complex interactions between the physical process of $CO_2$-EOR, $CO_2$ demand generation within the EOR industry, natural $CO_2$ supply and CCUS industry. As the scoping model, it is characterized by the following crucial features characterize:

- $CO_2$ is considered as a commodity with 2 sectors (supply and demand) being clearly identified and their interaction being at the core of the model;
- The model incorporates an important feedback mechanism between supply and demand for anthropogenic $CO_{2.}$ While the statement that demand influences supply sounds pretty trivial (open loop thinking), the reverse statement that supply drives demand as well is usually omitted (closed loop thinking) by the analysts. Yet, this feedback mechanism was found to be central to the system being modeled for this project.
- A crucial variable that makes the link between supply of $CO_2$ and demand for $CO_2$ explicit is the expectations of future $CO_2$ supply. As most of the complex social systems, the one under our consideration is driven to a great extent by expectations. As similar to macroeconomics, a good monetary policy maker is bound to fail without understanding how to manage private actors' expectation about inflation, in our model expectations about $CO_2$ are playing the central role in determining whether new $CO_2$-EOR projects will be launched and generate more demand for $CO_2$.
- Learning effect, $CO_2$ costs development, market mechanism of CCUS deployment, demand formation and physical process of EOR are all very simplified representations, which, however, together generate a non-trivial dynamics resulting from the interaction of those elements.

## 2.2 Model Assumptions

The scope of the model along the three dimensions described above (chosen variables, space and time) both dictates and is manifested in a set of assumptions made throughout the modeling process. This section provides an explicit discussion of those assumptions, justification for them and potential consequences of their utilization in the model. The discussion of the model's assumptions brings the description of the model from a very general overview level employed in the previous section to a more detailed description as the assumptions clearly demonstrate how the chosen scope of the model translated into particular modeling choices. Yet, we are still operating at a general level allowing the reader seeing a big picture rather than the details of each model's sector.

### 2.2.1 Assumption 1: system boundaries

Two important variables are chosen to be exogenous in the model, namely:

- Oil price is treated as exogenous. We recognize the important role of oil price in determining the economically recoverable oil reserves and a simple mechanism, which varies those reserves depending on how far the oil price is from the break-even price ensuring 20% return on $CO_2$-EOR projects, is incorporated in the model. Yet, the oil price is generated by a much bigger world energy market, which is beyond the scope of this modeling effort. The forecasts for oil price over the 50 years period is used.
- Natural $CO_2$ supply. We do not develop an endogenous structure for natural $CO_2$ supply as currently it is at its maximum capacity and approaching the point of depletion. However, a simple Natural $CO_2$ sector is incorporated in the model, as it is a part of the global feedback in the model.

### 2.2.2 Assumption 2: sources of anthropogenic $CO_2$ and capture design

As described in paragraph 1.6, there are 4 sources of anthropogenic $CO_2$ and four capture designs. While their composition in separate states might be skewed towards a particular type of source, it is natural to believe that at the level of the US all the four sources with four capture designs are represented. If this were to be reflected by our system dynamics model, this would imply four different supply chains of CCUS sources under four different designs each. Technically this would be solved by using an array function, yet in practice this means estimating around 16 versions for different initial values, conversion parameters, costs of $CO_2$ capture and learning effects as all of those elements are different for different sources of $CO_2$ capture under different designs.

While this clearly laborious work would make the model comprehensive, two considerations are important in this discussion. First, some of the crucial initial values, parameters and effects representations are highly uncertain. Multiplying those values by 16 would effectively increase the uncertainty of our model by 16 times. Thus, a more simple representation of the structure is needed at this stage of the model-building process. Second, based on the problem definition and research objectives in Chapter 1, we are primarily interested in the interaction between crucial elements of the market for $CO_2$ at a very general, scoping level. We are interested not in exact numerical outputs but in behavioral outcomes of the feedback mechanisms, the scales for which in reality might be smaller or bigger (dynamic precision rather than numerical one). For this purpose using arrays along 16 dimensions under a high degree of uncertainty might not be justified. Moreover, the model is expected to be used further for enhancing conversation about the issue with potential stakeholders. A complicated model risks not serving such a purpose.

Following these arguments the choice was made to model just one source of $CO_2$ capture under one capture design. In the model the only source of $CO_2$ capture is a baseload one-GW coal-fired power plant assuming 7 MMmt/yr of CO2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity (ARI, 2011)

The choice for this source of $CO_2$ capture is motivated by two reasons.

First, as stated in ARI (2011) “large numbers such as billions of tons of $CO_2$ demand and storage capacity are different to grasp and thus often of limited value”. To communicate better to policymakers and general public what exactly a certain amount of $CO_2$ is there is an alternative way. This conventional alternative is to use the metric of the number of one-GW size power plants that could rely on $CO_2$-EOR for purchasing and storing their captured $CO_2$.

Second, our system dynamics model even though created for the national US market is constructed within the project related to ND and with the further perspective of calibrating the national model to the one of the state of ND (even though outside od the scope of this particular project this thesis is related to). In this context, the key experts and stakeholders in ND as well as the client stated that for their case only coal-fired power plants could be considered as the source of $CO_2$, which enhances further our justification for incorporating this assumption into the model.

### 2.2.3 Assumption 3: no technological progress in $CO_2$-EOR technology

A long discussion has been provided so far with regard to technology development for CCUS, the supply side of $CO_2$. However, the demand side of the problem – $CO_2$-EOR sector – is also experiencing technological development. The

$CO_2$-EOR literature usually employs the distinction between a “State of Art” (SOA) and “Next Generation” technologies (NETL, 2011). SOA reflects the $CO_2$-EOR technology as practiced today, while the Next Generation technology reflects the estimated future technology about to come in the near future (roughly within a 10 year period).

The key issue is that incorporating next generation $CO_2$-EOR technologies would increase the initial value for technically recoverable reserves of oil. More precisely, we would need to incorporate a structure in the model that allows for increase in the technically recoverable reserves throughout the simulation period due to the introduction of next generation technologies.

However, in this model the choice was made not base the system on SOA technologies. Operating in the realm of constrained $CO_2$ supply a large amount of technically recoverable reserves would not influence the dynamics of the model, as we would simply have a longer time to enjoy incremental oil production. Also, estimation related to the next generation technologies exhibit a high degree of uncertainty. Thus, with a purpose of minimizing the uncertainty pressure in our model only SOA-based estimations are used.

### 2.2.4 Assumption 4: no $CO_2$ pipeline structure

A crucial aspect of the joint CCUS-EOR system the pipeline network as the $CO_2$ captured by the CCUS needs to be transported to the oil field for EOR injections. In this respect, the pipeline network represents another constraint on $CO_2$-EOR industry. However, during the forty years of $CO_2$-EOR activities an extensive pipeline network has been developed in the US covering over 3,900 miles (Dooley, et al., 2009) and transporting currently approximately 65 million tons of CO2 (Melzer, 2012) that the oil industry purchases for use in EOR, which is still far from the maximum capacity. Thus, for the purpose of this project, the pipeline network is not modeled. It is assumed that whatever amount of $CO_2$ is captured by the CCUS could be delivered to the EOR projects. Why relaxing this assumption for a more comprehensive model might be crucial is discussion in the Limitation and Further Research part of Conclusions to this thesis.

### 2.2.5 Assumption 5: $CO_2$ costs are the costs of $CO_2$ capture

This assumption follows from the previous one. A key determinant of $CO_2$ economics from the supply side is the costs of $CO_2$. Generally the costs of $CO_2$ are broken down into two main components: the costs of capture and the costs of transportation, where the costs of capture constitute around 80% of the total costs (SBC Energy Institute, 2012). As the pipeline structure is not modeled and capture costs constitute that much of the total $CO_2$ costs, the decision was made to omit the transportation costs.

### 2.2.6 Assumption 6: $CO_2$-EOR is an aggregate of typical $CO_2$-EOR projects

As the model portrays a very general and simplified representation of supply and demand sides for $CO_2$, the $CO_2$-EOR system was modeled as an aggregate of typical $CO_2$-EOR projects. This leads to two implications: one is distributional and another one is dynamic.

First, while each and every $CO_2$-EOR project is different in terms of the key parameters characterizing the $CO_2$ injection-oil production system (such as the time $CO_2$ spends in a reservoir, the fraction of $CO_2$ that can be recycled, etc.), there is enough evidence to believe that on aggregate the industry might be reasonably well characterized by the average values of those parameters featuring a typical $CO_2$-EOR project. This is the distributional implication of the assumption.

Second, the dynamic implication refers to the fact that if the modeling choice were made to portray the $CO_2$-EOR sector from a project perspective (meaning that there would be a maturation chain of those projects) we would have taken into account the project life. A crucial consequence of that modeling choice would have been the dynamics of key parameters characterizing the $CO_2$ injection-oil production system (such as, again, the time $CO_2$ spends in a reservoir, the fraction of $CO_2$ that can be recycled, etc.), which would have been no longer stable but dependent on the life time of a project and the dynamics happening within it. The work incorporating these aspects have been performed within this project by another modeler from the project team – Julian Andres Gill Garcia – and documented in his thesis. Based on his work and consultations with him, the most reasonable static values for the key parameters were chosen.

An important example of the value, which is constant in the model but is dynamic in reality depending on the lifetime of the project, is the converter from $CO_2$ to incremental oil produced (in the industry called the $CO_2$ utilization factor).

### 2.2.7 Assumption 7: CCUS market mechanism is based on $CO_2$ costs and WTP

A marginal perspective on formalization of CCUS market mechanism is taken in the model. Namely, it is assumed that power plants operators decide whether to install CCUS equipment or not based on comparison of $CO_2$ costs and $CO_2$ benefits (associated with the Willingness to Pay for $CO_2$ on behalf of oil operators). This process is characterized by distribution: some operators are willing to install CCUS equipment while the costs are below the benefits, yet the higher the befits are above the costs, the more operators are willing to install the equipment.

While the exact work of the mechanism in the model will be described in the paragraphs 2.3 and 2.4, it is important to note here only the attributes of $CO_2$ as the outcome commodity of the CCUS industry is considered as a driving factor of CCUS deployment. A more complete analysis would also incorporate the fixed costs of installing the CCUS technology and amortizing the fixed costs along the CCUS power plant lifetime to incorporate into unit costs. For the purposes of this project, however, such an analysis would imply a more extensive endogenous structure behind the CCUS sector and, thus, the complexity of the model would increase beyond the requirements posed by the problem definition, research objective and corresponding research questions.

### 2.2.8 Assumption 8: the current build-up of CCUS capacity is exogenous

An interesting question arises from the following comparison of the chosen model boundaries and the behavior of the real system.

On the one hand, the chosen model boundaries aim at explaining the development of CCUS capacity endogenously by the work of the market mechanism, underpinned by the market conditions for $CO_2$ as a commodity generated by CCUS. And the current status of CCUS is such that those market mechanisms are dormant.

On the other hand, we already have a build-up of CCUS capacity standing behind the 14 Gt of anthropogenic $CO_2$ supplied per year to the EOR industry (AIR, 2011). The question arises which forces if not the ones of the market are responsible for the accumulation of that capacity and how should we incorporate them in our system dynamics model?

Clearly, with respect to the defined system boundaries, the forces behind the initial build-up of CCUS capacity are exogenous. Among those forces, the expectations of power plants operators about carbon policies play an important role. After all, a significant part of existing build-up of CCUS capacity in the US was accumulated as the result of regulations of carbon emissions and business expectations about possible restrictions of those regulations. Thus, the system dynamics model starts already with some initial value of CCUS capacity installed exogenously. Moreover, it is assumed that the new CCUS power plants are being deployed to compensate for the depreciation rate.

## 2.3 Model Structure

This section is organized in the following way. First, we present the overall mechanism of the model. Then, each of the four sectors is described in details. The general idea of the section is to refrain from giving exact formulations of model equations. Only when such formulations are crucial to understanding the functioning of the model those details are provided.

The completed documentation of the model, which includes all the equations, units for the variables and reference to the sources for estimated values as well as general comments to some of the variables and formulations, is contained in Appendix B. In addition, Appendix A contains the screenshots of the model interface. The model itself can be fined in Stella Architect file accompanying this thesis.

### 2.3.1 Overall mechanism

As portrayed in Figure 5, the system dynamics model of the study consists of three sectors:

1. CCUS sector,
2. EOR sector,
3. Policy/Scenario sector

The last sector does not contain any feedback and serves as a repository of scenarios for oil price and carbon price.

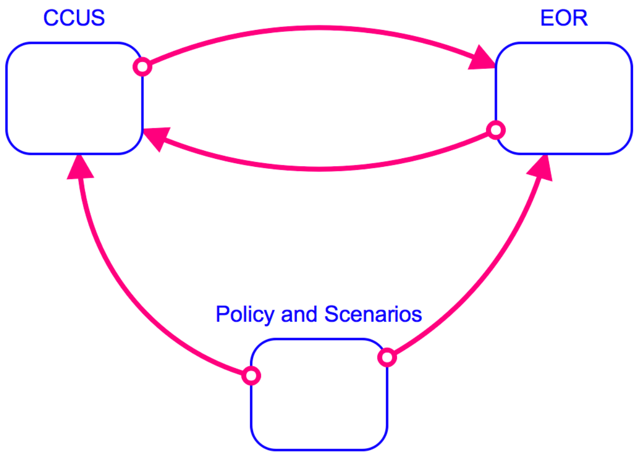

Figure 5. Model Overview

The Key Variables for this analysis are:

1. CO2 Supply,
2. CO2 Demand,
3. Bulk CO2 Price = CO2 Purchase Price
4. Carbon Price = Carbon Emissions Penalty
5. CO2 Price
6. CO2 Costs

The goal of the system dynamics model is to generate those key variables endogenously to the extent whether it is realistic. The only exception is Carbon Price. Since it is an existing policy mechanism, it is modelled as a scenario variable. Namely, three scenarios for carbon price are chosen: zero carbon price, weak and strong carbon price.

The following overview guides through the landmark stages of Global Context SD model, corresponding behavior modes and interpretations.

### 2.3.2. Cut 1. Simple Stock-and-Flow Diagram

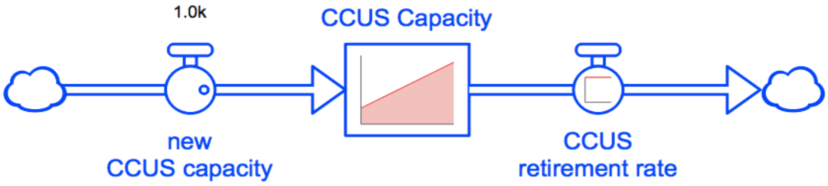

Figure 6. Simple SFD for CCUS

CCUS Capacity represents the actual global carbon capture, storage and utilization capacity. This stock concept aggregates how much CO2 is globally being captured, stored and used (regardless of usage purposes). The corresponding inflow accounts for new CCUS capacity being dispatched annually in terms of CO2 units being capture/utilized/stored etc per year. Since the source of CCUS in this model is coal-fired power plants, the corresponding outflow accounts for the physical process of power plants retirement.

### 2.3.4. Cut 2. Simple SFD with Endogenous Outflow

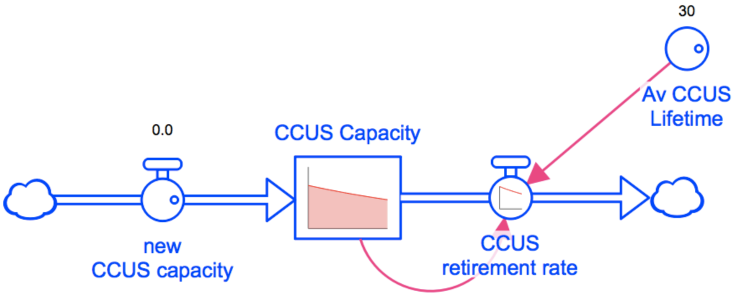

Figure 7. Simple SFD with Endogenous Outflow

Since the average lifetime of a coal-fired power plant is well-documented and constitutes 30 years, we use that parameter and the assumption of the first-order distribution at the outflow to model the CCUS Retirement Rate endogenously. This allows us to make the first step towards creating a simple system dynamics model for our analysis.

### 2.3.5. Cut 3. First Endogenous Structure: Ideal CCUS Conversion

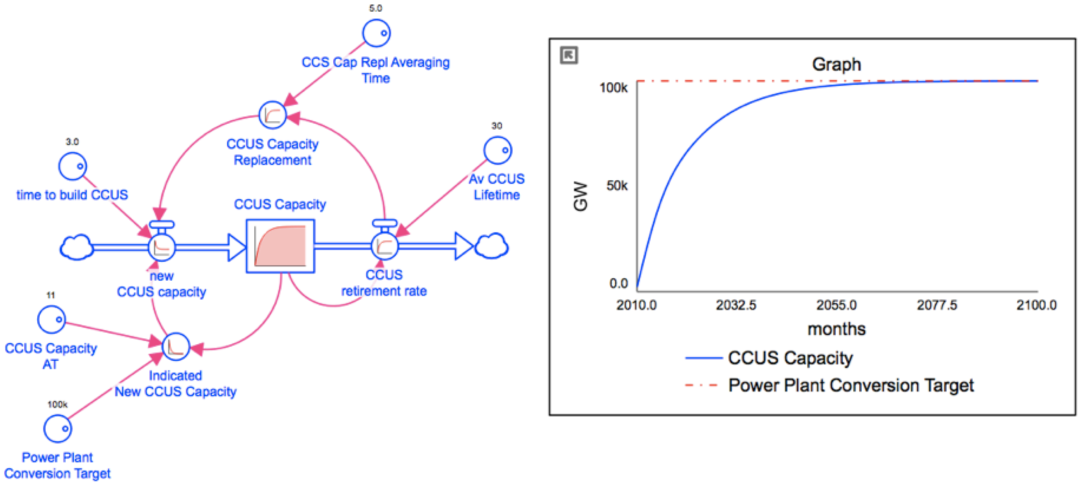

Figure 8. First Endogenous Structure: Ideal CCUS Conversion

The first cut of endogenous SD model focuses on the simple first-order negative feedback loop adjusting the current CCUS Capacity towards an exogenously set target. The structure also considers the replacement of CCUS capacity.

It is important to note that this very simple structure includes the variables that bear actual real-life meaning and generates behavior that have a meaningful interpretation.

The whole adjustment mechanism reflects the global idea of how many power plants should be converted to CCUS power plants. This conversion target corresponds to the actual explicit targets used by US Department of Energy in its various analysis. The CCUS Capacity Adjustment Time is more implicit but is based on the inferred idea over which time horizon the conversion is expected to happen. Thus, the adjustment time was calibrated to fit this idea.

This model cut generates a smooth exponential adjustment of CCUS Capacity towards the target. In its essence, it demonstrates that if a “global policy maker” expects to achieve the set power plant conversion target by 2060s, which is not a very aggressive scenario, this would be an implied deployment trajectory.

It is interesting that even this simple behaviour could be counter-intuitive to policy-makers working on the issue, since it reveals a non-linear nature of the deployment path and the need to be relatively more aggressive in the first period of conversion. This is something that is necessarily inferred from stated policy proposals but not necessarily understood by their authors and/or proponents. System Dynamics model, even though very simple, brings implicit details about announced policies to the surfaces.

### 2.3.6. Cut 4. Adding Commercialization Challenges: More Realistic CCUS Deployment Scenarios

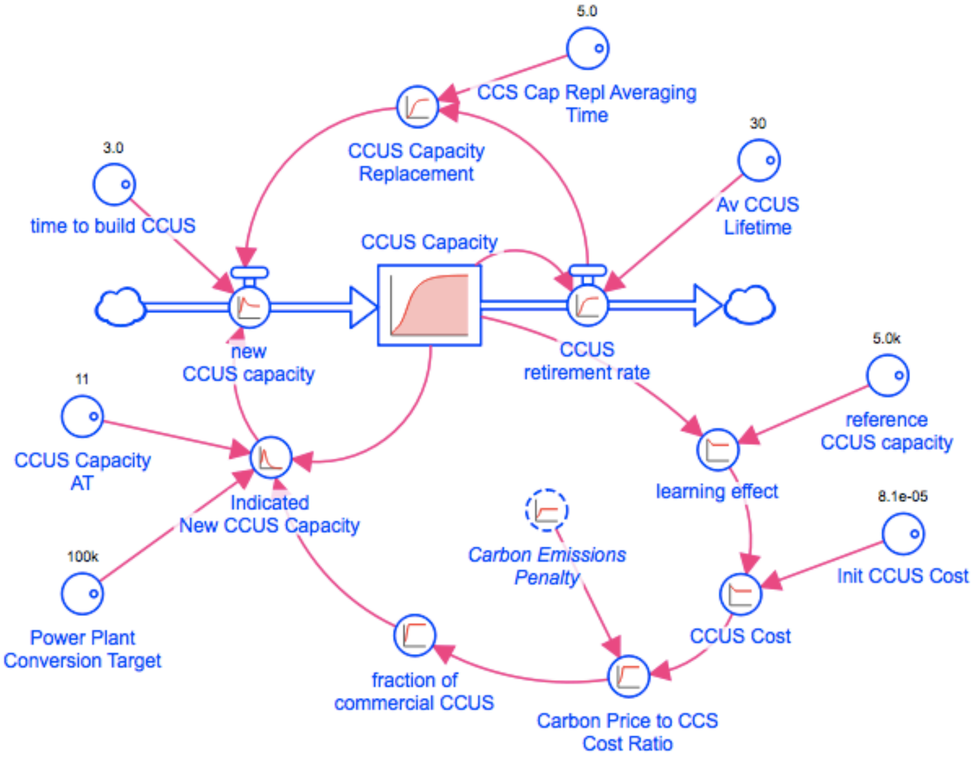

Figure 9. More realistic CCUS Deployment Scenario

At this step, we enhance the simple model of CCUS deployment with the observed commercialization challenges. Those challenges are attributed to the economics of CCUS, which comes as the result of interaction between the costs of CCUS and the Carbon Price as a regulatory input. What makes this model endogenous is the utilisation of a well-established fact that CCUS costs are endogenously influence by the current size of CCUS Capacity through anticipated learning effects (learning-by-doing, economies of scale, etc.).

### 2.3.7. Cut 5. CCUS-EOR System

We go through a similar in its essence but different in details process of modelling in the simplest way the CO2-based Enhanced Oil Recovery (EOR). We conceptualize it as a CO2 EOR Capacity (bbl of oil recovered per year), with corresponding inflow (CO2 EOR Deployment Rate) and outflow (CO2 EOR Retirement Rate).

For the purposes of this thesis, EOR Production is defined as oil production through CO2-flooding/injection. This method of oil production is generally termed as CO2-based Enhanced Oil Recovery, and since the term “recovery” already implies “oil production”, we could have just settled on CO2 EOR. However, to distinguish between the method of oil production and actual oil production we use a more generic concept Production identified with EOR, which stands for this particular method of oil production. This choice also allows us to stay consistent with the conventional petroleum structures in SD literature and practice. We could have also used a more complete name CO2 EOR Production. However, since the only EOR method considered in this research is CO2-based, adding an extra word to the name seems to be unjustified.

By definition, EOR Production is a flow concept expressed in Bbl/year. There are two stock-and-flow structures generating EOR Production. The most proximate structure is the one, of which EOR Production is a part of: the stock of EOR Reserves depleted by the flow of EOR Production. This first stock-and-flow structure is depicted by Figure 10.

Figure 10. Simple SFD for EOR

EOR Reserves refer to technically recoverable reserve of oil remaining after primary and secondary oil production (residual oil remaining). The estimates for EOR Reserves vary and are subjected to uncertainty. Moreover, essentially, conceptualized as a stock, EOR Reserves has the inflow of the maturing oil fields applicable for EOR. For the purposes of this model and simplicity of the overall structure it is appropriate to treat EOR Reserves as a finite stock with no inflow. This choice, however, dictates the initial value for the stock that would be consistent with the underlying assumption. This has to be a value of residual oil from oil fields maturing within the near-to-medium term (around 30 years) and considered to be applicable for EOR at a reasonable degree of uncertainty.

We use a standard formulation for EOR Production:

**EOR Production = EOR Capacity * CUF,**

Where

CUF is Capacity Utilization Factor.

EOR Capacity is conceptualized as a stock with a unit Bbl/year. It corresponds to the potential production rate by EOR industry, given the realized values of investments into new production capacity. Thus, investments into new EOR capacity are in physical terms (Bbl per year/year) and conceptualized as the inflow into the stock of EOR Capacity (new EOR Capacity). A more complete stock-and-flow structure of EOR Capacity taking into account capacity retirement is depicted in Figure 11.

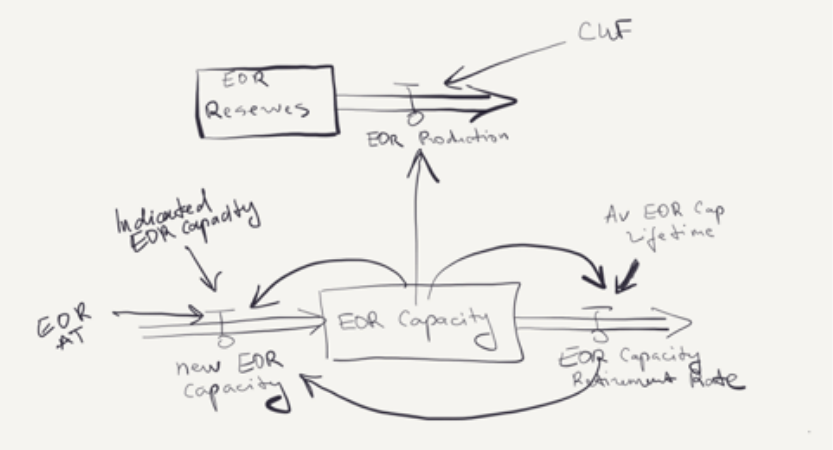

Figure 11. A more detailed SFD for EOR

New EOR Capacity follows similar formulation as new CCUS: we apply a first-order adjustment towards Indicated EOR Capacity and then adjust for a retirement rate to avoid a steady-state error.

So far, the formulation for EOR Capacity, underlying EOR Production, has been analogous to the one for CCUS. Both structures are essentially first-order negative controls, adjusting the current level of the stock towards indicated level. However, there is a difference in the nature of the indicated value in those two structures. Indicated CCUS was conceptualized more as a policy variable, constrained by CO2 economics. We cannot apply the same approach towards EOR structure.

To formulate Indicated EOR Capacity we need to move through several progressive steps reflecting the investment decision making process by EOR operators (whether to invest into EOR or not?).

The starting point is the Potential Production from Reserve, which is anchored towards to resource remaining and, thus, is subjected to depletion and also accounts for geological and pipeline constraints. In other words, this variable indicates a technically possible production of oil through EOR.

Production from CO2 in anchored towards Indicated EOR Capacity is the minimum of two:

**Indicated EOR Capacity = MIN (Potential Production from Reserve; Potential Production from CO2)**

Production from CO2 is based on affordable (Delivered Price/Indicated Purchase Price) and available CO2. Available CO2 is anchored towards available CO2 before the allocation between storage and utilization (EOR) is made by a CCUS operator.

CO2 Delivery Price incorporates two components: CO2 costs and Effect from Supply/Demand Balance

It is important to anchor correctly Supply and Demand to achieve the correct effect to be applied to CO2 Delivery Price. Since S/D adjustment reflects a short-term market adjustment mechanism (in the long run it is the capacity that is being adjusted), the appropriate Demand will be Requirements for CO2 from the current EOR Capacity (maybe at normal CUF) and appropriate Supply is whatever is being supplied AFTER the allocation between storage and utilization has been made. Note on intertemporal aspects: the decisions on CO2 supply and CO2 requirements (EOR capacity) has already materialized. The current supply/demand ratio reflects that and brings adjustment to price.

We already took account of distribution of EOR operators with regard to break-even CO2 price. This is now reflected in installed capacity for EOR. And, thus, in the demand for CO2. They are buying whatever they committed to. The only constrained is whether CCUS operator actually delivers that CO2. The key decision is whether to store or utilize. This depends on comparison between the costs of capture and the materialized purchase price: if purchase price covers costs of capture and delivery, they start selling more to EOR. If the price is less than cost and delivery, they send more to storage.

The interaction of the CCUS and CO2 EOR structures is delicate and forms the basis for intricate feedbacks.

The previous model cut focused on the key decision that a CCUS operator faces: whether to emit or capture?

The current model cut builds on that by challenging a CCUS operator who decided to capture: whether to store the captured CO2 or sell it to CO2 EOR operators for re-use? This decision is based on the interaction between the CCUS Costs and Bulk CO2 Price. An interesting part is that Bulk CO2 Price is influenced by both CO2 supply proportional to CCUS Capacity and CO2 Demand coming from CO2 EOR Operators themselves. The interaction of CCUS Costs and Bulk CO2 Price influences CO2 available for EOR and, thus, the planning of CO2 EOR projects. This interaction also influences directly the deployment of CCUS Capacity by offsetting a part of CCUS costs.

The resulting model is more complex and allows to analyze the endogenous interaction between the key economic variables of this research: CCUS Costs, Bulk CO2 Price and Carbon Emissions Penalty (Carbon Price).

### 2.3.8. Sector 1: demand for $CO_2$

Sector 1 generates the pressure in the overall model that sector 2 then addresses by a correcting feedback loop mechanism. The structure of the sector is exhibited in Figure 13.

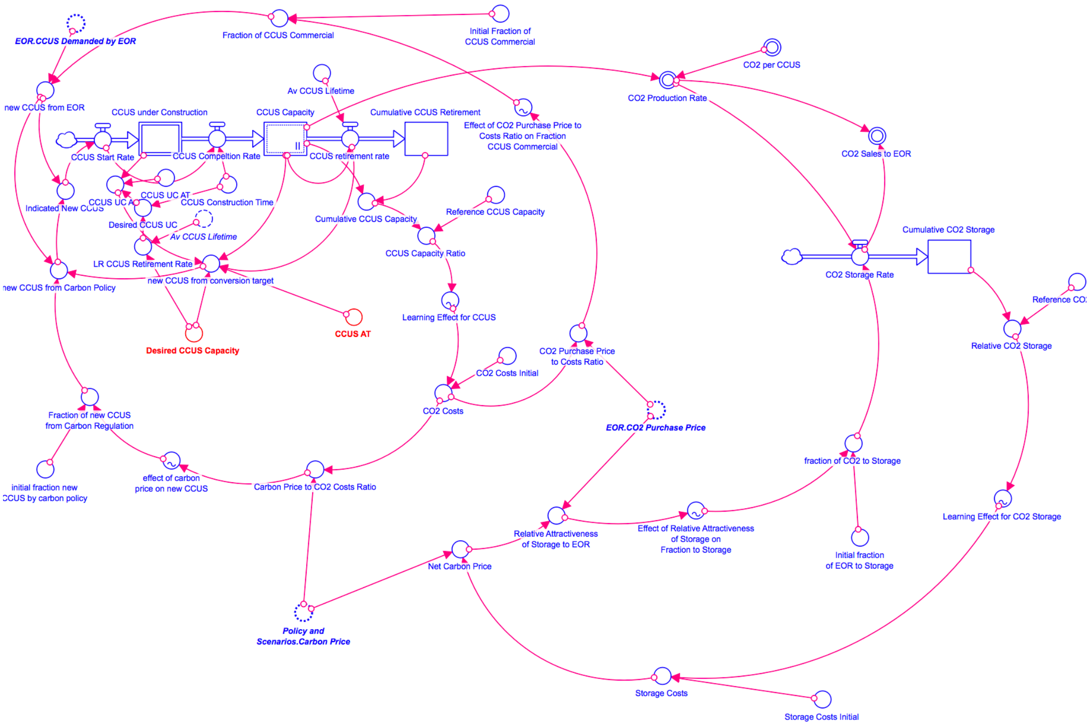

Figure 12. CCUS Sector

The mechanism of pressure generation, as described in 2.3.1 forms a so-called demand chain with the technically recoverable EOR reserves in the upstream of the chain and demand for anthropogenic $CO_2$ to be addressed by the CCUS sector in the downstream. The chain reflects the theory of how demand for $CO_2$ is being formed by the $CO_2$-EOR industry.

In economic theory demand is normally understood as the desire to acquire a product or a service supported by the ability to pay. This clearly distinguishes demand from just a wish. Similar logic has been applied to the demand for $CO_2$ as a commodity required by $CO_2$-EOR for most of the time since 1970s, when the first $CO_2$ EOR project was launched. Accordingly, the main driver of $CO_2$-EOR growth has been attributed to the oil price as that factor was considered to be important for decision making with regard to whether to launch a new $CO_2$ EOR project. In 2000s, when cheap natural sources of $CO_2$ started approaching the point of depletion, both the industry operators and the analysts began recognizing the importance of expected affordable $CO_2$ supplies. Without those supplies even in the presence of oil price above the benchmark the economically recoverable reserves of oil cannot be turned into oil production, as they remain just a wish not being supported by available $CO_2$ sources.

This important idea has been explicitly stated several times at $CO_2$ flooding conferences (Melzer, 2013) as well as implicitly in the $CO_2$-EOR Survey (OGJ, 2014).

In accordance with the established theory, 2 “filters” are placed in the upstream of the demand chain in sector 1. The first filter converts technically recoverable reserves into economically recoverable ones reflecting the importance of the first $CO_2$ demand determinant – oil price. The benchmark oil price is \$85 per barrel of oil, which is the price that ensures 20% return on $CO_2$-EOR projects. The variation of the actual oil price around the benchmark price changes the fraction of technically recoverable reserves, which can be economically recoverable at current oil prices. The effect of the oil price on *Fraction Economically Recoverable* is formulated as a graphical function.

The second filter converts the economically recoverable reserves into actual EOR projects to be announced based on the $CO_2$ supply expectations. In this way, the model takes a proper account of the second determinant of $CO_2$ demand.

The remaining two conversions are more trivial. First, using the $CO_2$ utilization factor (in the model, $CO_2$ per oil recovered) we translate planned oil production into corresponding demand for $CO_2$. Then we subtract the re-injected $CO_2$ rate to determine the demand for purchased $CO_2$. As a final step, the natural $CO_2$ supply rate is removed to arrive at demand for anthropogenic $CO_2$ only, which is the one links, the integrated CCUS-EOR system.

The sector contains three stocks. The first stock is *EOR Reserves*, which represent the technically recoverable oil reserves with the SOA EOR technology. It forms the basis for determining the demand for anthropogenic $CO_2$ in the demand chain. The reserves are depleted by the flow of *Incremental $CO_2$ EOR Production*. The term incremental is usually employed in the $CO_2$-EOR industry to distinguish this oil from the oil recovered by conventional techniques of primary and tertiary production. The flow of oil production accumulates into the stock *Cumulated Oil Recovered*. Even though this stock does not participate in any of the feedbacks in the system, it can be used as an evaluation criterion for how much oil can be ultimately recovered under that or another scenario.

The third stock, which is of crucial importance in the whole model, is Expected $CO_2$ Supply. It is formulated as a first-order information delay structure updating the *Expected $CO_2$* in accordance with the *Indicated Expected $CO_2$ Supply*. The indicated expected $CO_2$ supply is formed by two components: *CO2 Production Rate,* which is based on current CCUS Capacity and *Expected Anthropogenic $CO_2$ Supply*, based on supply line of CCUS Capacity (Capacity under construction). The expected anthropogenic $CO_2$ supply rate is based on the $CO_2$ capture expected from the current stock of CCUS power plants and the ones that are under construction, that is, expected to be deployed in the future (the construction time is around 5 years).

### 2.3.9 Sector 2: CCUS: supply of $CO_2$

This sector generates anthropogenic $CO_2$ supply and represents the core structure of the model. The sector is exhibited by Figure 7.

The backbone structure of the sector is the correcting feedback mechanism which eases the pressure in the system created by unsatisfied demand for $CO_2$, entering the sector as an input.

*$CO_2$ Capture Rate* is the central flow of the sector, which provides the output to the rest of the model (namely, sector 2). There is a physical stock-and-flow structure behind $CO_2$ capture, which is the *CCUS Power Plants* as the sources of $CO_2$ capture. As it takes time to construct and deploy CCUS power plants the sector contains a physical chain of CCUS Power Plants with the stocks of *CCUS Power Plants under Construction* and CCUS Power Plants actually operating.

The correcting feedback mechanism is represented by the CCUS Control System of two balancing feedback loops. The core of the mega CCUS control structure is the archetypal stock management structure described extensively in the fundamental system dynamics literature (Sterman, 2000).

Namely, the demand for anthropogenic $CO_2$ determines the desired number of CCUS plants (*Desired CCUS PP*), which is then being compared to the actual number of CCUS power plants. The comparison produces *Adjustment for CCUS PP* in accordance with the desired goal and the appropriate adjustment time. However, this adjustment is not the ultimate value for the corrective action necessary to close the balancing feedback loop which corrects the number of CCUS PP. Rather, adjustment for CCUS PP is one of the three components of the corrective action, or more accurately, as it will follow later, the indicated corrective action.

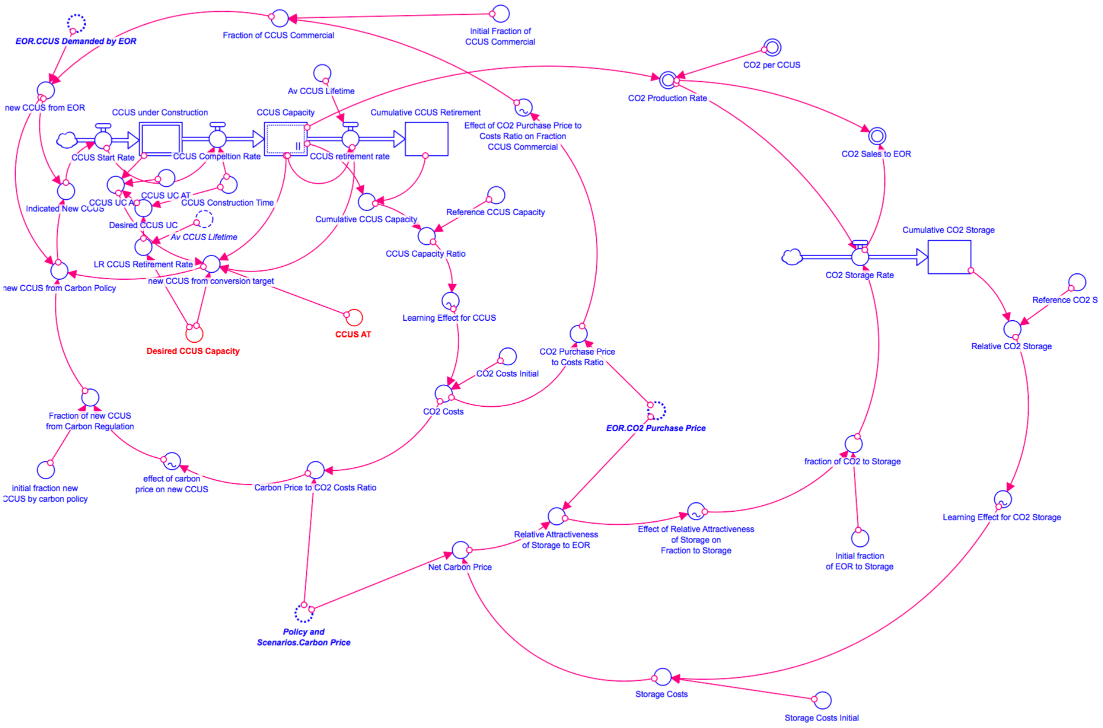

Figure 13. EOR Sector

The second component of the indicated corrective action in accordance with Sterman (2000) should be the adjustment for depreciation rate of CCUS PP, which is based on the expected depreciation rate. Together with the first component they form *Desired CCUS PP Deployment Rate* or the desired value for the inflow to the stock of CCUS PP. The inclusion of the adjustment for depreciation is crucial both from structural point of view (it is expected to anchor the investment decisions based on expected loss rate – the evidence for decision makers actually using this heuristics is described in Sterman (2000) and the technical perspective (to avoid the steady-state error – again, based on Sterman (2000).

However, the construction and deployment of CCUS power plants is a long process involving significant time delays in planning and construction. This aspect necessitates the inclusion of the stock of CCUS PP under Construction, which represents the supply line of power plants that were put into planning but have not been deployed yet. The presence of the supply line in the stock management structure leads to the third component of the indicated corrective action – *Adjustment for the*

*Supply Line*. Neglecting this component in the correcting CCUS mechanism would lead to oscillatory behavior in the sector[1].

The resulting corrective action (new CCUS PP into Planning) is not necessarily the actual corrective action that will be implemented but the one indicated by the demand pressure and supply line requirements. Whether all, some or any of those power plants will be actually put in planning depends on whether the market mechanism characterizing the economics of CCUS can support this correction. Thus, the second key structure of the sector is the CCUS market mechanism.

The central variable of the CCUS market mechanism is the *Fraction of CCUS PP from the Market*. As the name indicates, it shows which fraction of the indicated corrective mechanism can be satisfied by the CCUS industry based on the market conditions. Effectively, the fraction represents the strength of the market mechanism to satisfy the demand for $CO_2$.

As noted a number of times above, the market for CCUS is determined by the economics of the outcome commodity of the CCUS sector, which is anthropogenic $CO_2$. The economics of $CO_2$ in the model means the interaction of $CO_2$ costs and $CO_2$ WTP.

The conceptual idea is that the ratio between the costs of $CO_2$ and the maximum willingness to pay for it drives the market mechanism stimulating the

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[1] Here it is necessary to digress slightly to a discussion on oscillation and accounting for the supply line. It is documented evidence that oscillatory behavior is often a characteristic feature of a number of industries (including construction) and the common endogenous reason for that is the improper account of the supply line by decision-makers. Thus, the question arises if we intend to model the system the way it is (in the spirit of the structural approach), will it be correct to portray an ideal mechanism of correction, which might not exist in the reality? By portraying a perfect from system dynamics point of view mechanism do not we impose too high a degree of rationality on the system, an assumption that is being so much criticized by system dynamists with regard to other modeling approaches? The modeling choice is dictated by the purpose of the model, as it is normally the case. Namely, the modelers of this case intended to portray the control mechanism in a stylized setting. Stylized means that in this model we would like to see how the interaction of demand, supply and supply expectation coupled with the physical process of enhanced oil recovery works in the presence of ideal or close to ideal function of corrective mechanisms. In this way we can focus on the interactions between the elements of the system rather than the endogenously generated by corrective mechanism oscillations.

operators of power plants to install CCUS equipment. The status of the $CO_2$ economics is indicated by the *$CO_2$ Ratio* (the ratio of the WTP to Costs). The market mechanism is then represented by the graphical function, which relates the status of $CO_2$ economics to the CCUS market mechanism. The graphical function incorporates an important behavioral assumption about how CCUS operators respond to the changes in the market conditions for the $CO_2$. The market fraction would be increasing at an increasing speed up to a certain point, then satiates and then continues approaching 1 but at a decreasing speed. This idea of diminishing returns is reflected in an S-shape of the graphical function.

The final important mechanism of the CCUS sector is the learning effect, which is expected to lower the costs of $CO_2$ capture in the future and, thus, improve $CO_2$ and CCUS economics. While the learning effect mechanism is crucial one for the whole system, its comprehensive modeling is complicated by a very high degree of uncertainty. In this context the following approach to formalizing the learning effect was chosen. Let us say we admit we do not know what exactly the learning effect is but there is a reference value for accumulated over time $CO_2$ capture, after which the costs will start decreasing. However, let us also say we do not know what exactly the reference value for the accumulated $CO_2$ capture is. But let us assume this value is a certain number (in fact based on the existing estimations of how quickly the cost reduction can be achieved) so we could simulate the system dynamics model with this simple structure. This approach has a clear advantage of allowing us to concentrate the high degree of uncertainty into just one parameter value – the reference accumulated $CO_2$ capture, which can generate the reinforcing mechanism of cost reduction in the model and then be tested under various sensitivity scenarios.

Thus, the model incorporates the learning effect in the following way: the $CO_2$ capture rate is accumulated in the stock of *Accumulated $CO_2$ Capture* and there is the *Reference Accumulated $CO_2$ Capture* corresponding to the anticipated learning effect. As the accumulated $CO_2$ capture approaches the reference value, the costs of $CO_2$ capture start decreasing. The model uses the conservative estimation for the reference value, according to which the gap between $CO_2$ costs and $CO_2$ price would be closed the 50 years period in absence of any stimulating policies (SBC Energy Institute, 2012).

We emphasize here that the learning effect mechanism is portrayed by the graphical function. As in the case for the CCUS market mechanism, the learning mechanism exhibits the diminishing returns. However, the diminishing returns could be portrayed by both an S-shaped function and a simple concave function. The choice for the shape of the graphical function reflects which assumption about the work of the market mechanism we incorporate into the model.

Concavity of the graphical function would mean diminishing returns in the following sense: first small changes beyond ratio 1 (of accumulated $CO_2$ capture to the reference one) would lead to significant learning, but gradually the marginal effect will be shrinking. More precisely, we start with a certain high rate of increase, which then slows down.  The S-shaped form also suggests the diminishing effect but at a later stages. First we observe the increase in the effect with each step forward at an increasing rate (meaning, when we are just above the reference point we do not learn much as there is still a lot to accumulate but then the progression accelerates). Later the rate of increase satiates and starts growing in a declining fashion: once we accumulated past the tipping point new gains in experience are not of much of help. Based on the experiences of learning effects from other green technologies, the assumptions leading to s-shaped graphical function are more realistic (SBC Energy Institute, 2012).

Another crucial output of the sector is Anthropogenic $CO_2$ expectation supply.

## 2.4 Feedback Perspective

Figure 10 portrays the causal loop diagram of the model. Such representation allows us to employ explicitly the feedback perspective to the current analysis. In its turn, the feedback perspective both presupposes and leads to the endogenous view on the issue. Under endogenous view we mean here the explanation of behavior patterns under concern by the presence and interaction of feedback loops constituting the system we are modeling. As roughly paraphrased from *Feedback Thought in Social Science and Systems Theory* by George Richardson, a good social scientist is a feedback thinker (Richardson, 1999). Taking this idea as an inspiration for our analysis, we will focus on the description of feedback loops and how they produce the behavior that the model exhibits.

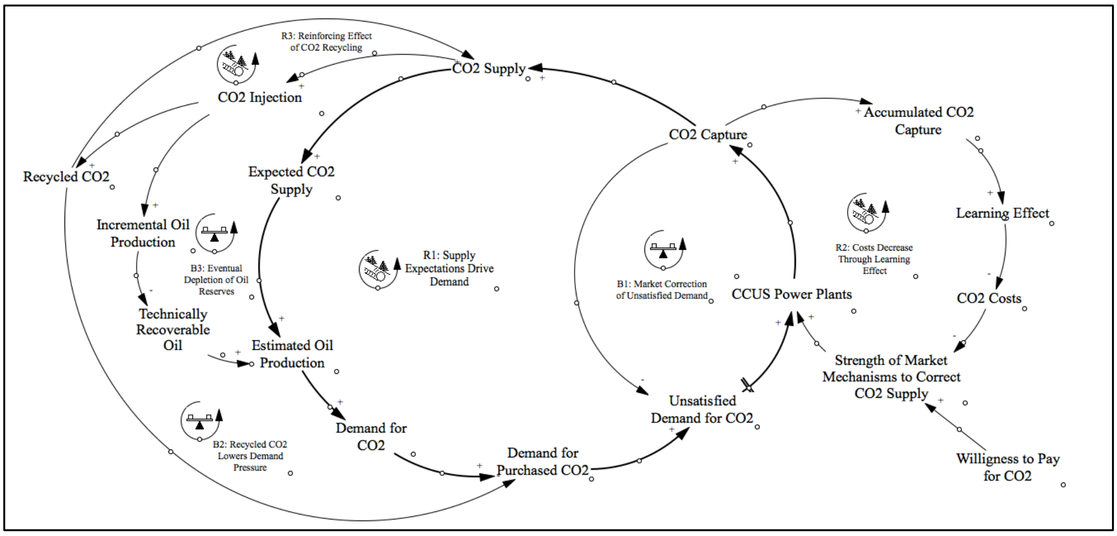


Figure 14. CLD

In summary, the CLD tells the whole story behind the model in an extremely concise way.

The problem which motivated the model building process from the feedback perspective is that reinforcing loop R1 is currently dormant and as such does not produce the growth in $CO_2$ supply and, thus, in incremental oil production. In other words, the desired growth of $CO_2$ EOR activities is constrained by the lack of affordable $CO_2$. That is how the short version of the problem definition presented in Introduction Chapter can be formulated. However, the feedback perspective allows seeing a deeper problem behind this short formulation already at the scope of one feedback loop. Namely, the fact that insufficient $CO_2$ supply constraints $CO_2$ EOR projects growth is quite trivial. What is not trivial is that the oil operators plan $CO_2$

EOR projects based on their expectations of future $CO_2$ supply. Currently $CO_2$ EOR industry is characterized by unsatisfied demand for $CO_2$ of a relatively high level. The inability to satisfy this demand in the present context not only halts the deployment of already planned $CO_2$ EOR projects but over time through expectations formation blocks the design of new projects and thus erodes the demand for $CO_{2.}$

The concept of demand for $CO_2$ applied to the industry context is crucial to understanding the work of R1. The demand theory was extensively described in 2.3.2. Following that theory the demand for $CO_2$ in the model is anchored to the estimated oil production, which is based on expectations about $CO_2$ supply.

If the reinforcing loop R1 is dormant, the logical question arises why it is so. Apparently unsatisfied demand pressure does not lead to installation of new CCUS equipment at power plants. In other words, balancing loop B1, which is the control loop for correcting unsatisfied demand does not work. Here we see the first important interaction between feedback loops: loop R1 responsible for desired growth in the system is dormant because the controlling mechanism represented by loop B1 does not work.

The next question is logically why the loop B1 is dormant. The CLD shows explicitly that fulfilling unsatisfied demand does not depend just on the presence of that demand. Counteractive loop B1 is called in the model Market Correction meaning that the correction of unsatisfied demand is based on market mechanisms. Market mechanisms is a general term for the process whereby power plants operators decides whether to install CCUS equipment or not based on comparison of $CO_2$ costs and $CO_2$ benefits (associated with the Willingness to Pay for $CO_2$ on behalf of oil operators). The process is characterized by distribution: some operators are willing to install CCUS equipment while the costs are below the benefits, yet the higher the befits are above the costs, the more operators are willing to install the equipment. While the model contains a simple formalized structure representing this idea, the CLD employs the variable Strength of Market Mechanisms to Correct $CO_2$ Supply. Namely, depending on the comparison of $CO_2$ costs and willingness to pay for $CO_{2,}$ a smaller or higher fraction of unsatisfied demand can be fulfilled.

At the moment the significant gap between $CO_2$ costs and benefits does not make market mechanism strong enough to match $CO_2$ capture with the demand pressure. Thus, loop B1 is not operating to the desired extent so that loop R1 can produce the growth in oil activities. Consequently, the focus of the problem shifts to how to lower costs of $CO_2$ capture. Reinforcing loop R2 represents the potential realistic mechanism, which can lead to lowering $CO_2$ costs. We should be very careful about this loop as on the one hand it drives the whole system: of R2 is operational then B1 corrects for unsatisfied demand and awakens reinforcing loop R1 bringing the desired growth. Yet, on the other hand there is a great deal of uncertainty surrounding the mechanism behind loop R2. This requires some clarification: the fact that the costs of $CO_2$ capture has the room for decrease is quite solid. First, high present costs are explained by the little experience of using CCUS technology. Thus, with the increase in accumulated $CO_2$ capture we can safely expect the learning effect kicking in and bringing the costs of $CO_2$ to a lower level. Second, industry comparisons supported by extensive studies (SBC Energy Institute, 2012) not only portray learning effect as an inevitable stage of a technology development but also provide reliable estimations for the lower bounds of $CO_2$ costs evolution and time required to reach those bounds. As mentioned by Scott Jonson during one of the interviews and model building sessions, this costs dynamics represents someone's dream. This is absolutely true in the sense that the crucial parameters behind the learning effect mechanism are uncertain. Yet, based on the arguments above is loop R2 is someone's dream this is not a completely naïve one.

Thus, three feedback loops are at the focus of the model and are responsible for the model's behavior. R2 though learning effect lowers $CO_2$ costs and induced more power plants operators to install CCUS equipment. This essentially allows for loop B1 working properly in filling the gap between $CO_2$ capture and demand posed by $CO_2$ EOR. Increasing actual $CO_2$ supplies raise expectations of oil operators about future $CO_2$ supplies and, thus, lead to more $CO_2$ EOR projects being planned which drives the demand for $CO_2$ even further – reinforcing loop R1 is in full operation. Another important interaction between the feedback loops in the system: loop R2 enables loop B1 to bring $CO_2$ capture closer to demand for $CO_{2,}$ yet after B1 closes the gap the goal of the balancing loop (demand for $CO_2$) shifts further as loop R1 shifts expectations about $CO_2$ supply up. In short, the balancing mechanism B1 enabled by R2 makes loop R1 operational and producing growth. Another side of this important interaction is that for the learning effect to keep working there should be a constant increase in $CO_2$

capture, which can only be achieved if balancing loop B1 keeps installing more CCUS equipment. But for this to happen, the demand for $CO_2$, which serves as the goal of the balancing loop B1, should constantly go up. This is achieved by loop R1 operating.

Consequently, the model grasps an interesting interaction: reinforcing loop R1 can work ultimately only if another reinforcing loop R2 is operating, yet the strength of R2 depends on the work of R1. The counteractive loop B1 serves as an intermediary between those two reinforcing loops. In a way, the model contains the feedback mechanism between two reinforcing loops.

However, in the present context this meta-feedback mechanism is not operational and the problem can be attributed exactly to the described interaction between the feedback loops. Namely, currently there is not enough accumulated $CO_2$ capture for the learning effect to kick in. Yet, the only way to increase the accumulated capture is through installing more CCUS equipment at power plants for which there are no active incentive mechanisms for both supply side (unfavorable market conditions for power plants operators manifested in a week loop R1) and demand side (lack of $CO_2$ supply lowers expectations of oil operators about future $CO_2$ supply and consequently lowers the demand for $CO_2$). This is a much broader problem description presented by the CLD than the one we started with in the beginning of this section.

Moreover, as portrayed by the CLD, the story from the feedback perspective already suggests hints for potential policy options. The described analysis identifies clearly the need for building up accumulated $CO_2$ capture through the mechanisms other than described in the model so that the level where learning effect starts operation could be reached. This requires a certain policy, which would substitute the work of the corrective loop B1 until the market mechanisms will take over and interaction of the three loops can start producing the growth dynamics. The policy structure is described in the Policy Chapter.

The CLD exhibits other feedback loops, which are not at the core of problem definition as R1, R2, and B1, yet are still important for the model’s dynamics.

Loop B3 serves to recognize the fact that increasing incremental oil production will eventually deplete the reserves of technically recoverable oil. Yet, the actual state of the modeled system is too far from this situation. On the contrary, there is a great interest in extracting those reserves. Thus, loop B3 *per se* does not pose a source of concern as a limiting factor (potential limits to growth).

Loops R3 and B2 are more relevant to the current state of the system. Both of them represent two consequences of the fact that a part of injected $CO_2$ can be recycled. As an additional source of $CO_2$ supply, recycled $CO_2$ on the one hand represents an inherent reinforcing mechanism within the $CO_2$ EOR process depicted by loop R2. Thus, even when the model is simulated with no B1 operating we can still observe some growth in incremental oil production. On the other hand, recycled $CO_2$ has the potential to lower demand pressure posed by oil operators. In this way, recycled $CO_2$ serves as an inherent balancing mechanism represented by B2. Yet, the degree to which recycled $CO_2$ can lower the demand pressure is not enough at the present time. The role of this mechanism, however, will appear to be important later when $CO_2$ supplies will increase dramatically through increased $CO_2$ capture. It is important to note that besides not having much importance in fulfilling unsatisfied demand, recycled $CO_2$ does not stimulate the learning effect and thus the strength of loop R2 together with the rest mechanism of the model. For these reasons, while recognizing the importance of loops B2, B3, and R3, we do not relate them to the core of the model.

The feedback perspective is crucial for explaining behavior through structure. However, the interaction of loops is characterized by non-linearities resulting in some of the loops being dormant or having different strength throughout the time. The resulting behavior of multiple loops interacting together cannot be predicted and can be counterintuitive. That is why in system dynamics methodology we conduct simulation: to test what we cannot grasp by deduction or induction only. This chapter described the major feedback loops and their interactions. The resulting behavior will be portrayed in the next chapter but the explanation of that behavior will be traced back to the feedback loop description. In this way this section builds the basis for understanding the simulation runs and serves as a reference point for explanations in the next chapter.

# Chapter 3. Simulation Results

This thesis considers the broader economic and commercial framework for CO2 utilization, with the purpose of exploring the following question:

How can CO2 reuse accelerate the uptake of CCS?

It is fundamental to understand the following aspects in order to be able to explore this question:

- The current CO2 market – the supply/demand balance, and the pricing of CO2 as a commodity (bulk CO2), and
- The commercial framework for CCUS – considering what carbon emissions pricing or regulatory requirement might be imposed in the future, and how they relate to the costs of CO2 capture and storage.

The primary purpose of the system dynamics model, which forms foundation for the research carried out within this thesis, is to generate a number of CCUS deployment scenarios. The model should allow to identify intricate interconnection between social, economic, geological and technological feedbacks underpinning those deployment scenarios.

Since the system dynamics model underlying this thesis was constructed with the purpose of generating primarily CCUS deployment scenarios and explaining those scenarios by analyzing feedback mechanisms pertaining to the economics of CCUS and EOR, this part will focus primarily on the outputs of the model related directly to these aspects of the issue.

Since the model behavior is based on 3 distinct scenarios for oil price and 3 distinct scenarios for carbon price, 9 comparative scenarios for CCUS Deployment are generated by the model. Figure 15 exhibits all the nine scenarios.

The key simulation outputs pertain to the scenario incorporating Strong Carbon Price and High Oil Price, which we call Reference Run, even through strictly speaking this is not a typical business-as-usual simulation output. However, since all the other simulation outputs will be considered in relation to the depicted key one. Strong Carbon Price/High Oil Price scenario serves as a reference simulation output for this analysis.

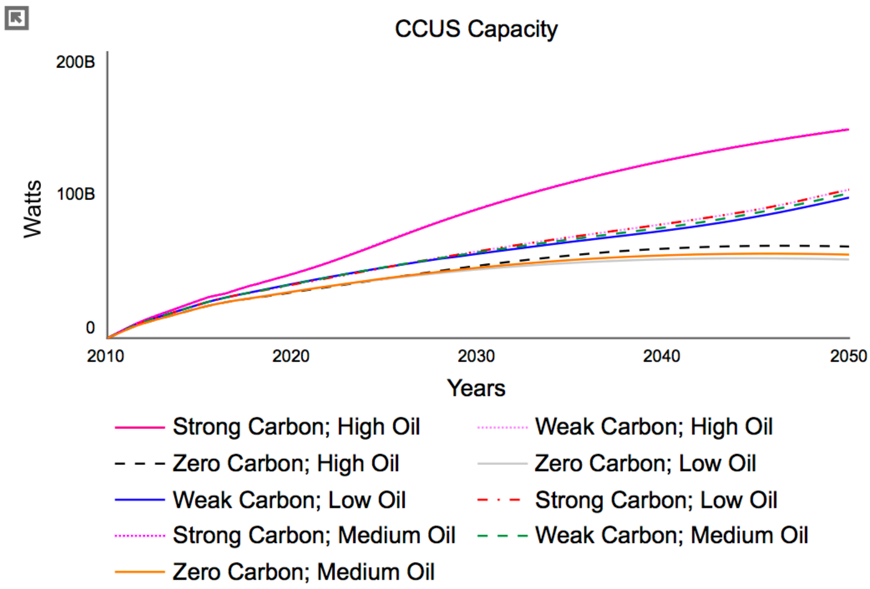


Figure 15. CCUS Capacity Deployment Scenarios

The motivation for such choice is based on the idea of testing how the integrated CCUS-EOR system behaves under relatively optimistic assumptions. If CCUS-EOR system does not generate expected growth in CCUS deployment under relatively optimistic conditions, it would definitely underperform under less than optimistic assumptions. Additionally, the optimistic condition of High Oil Price is not that unrealistic, since there is a strong evidence to believe the fossil fuel prices in the medium/long-term will rise. Moreover, utilizing the assumption of Strong Carbon Price allows to see potential effects of such policy should this policy be incorporated.

For some specific observations, comparisons between other scenarios and the Reference Run will be made. This will be indicated specifically when the need for such comparison arises.

The immediate conclusion that one can make from analyzing Figure 16 is that Carbon Price has the most profound effect on CCUS Deployment and Carbon Price as a policy variable is the driving force for CCUS commercializing and wide-scale deployment.

The pink line depicting the Reference Run generates the largest value for the stock of deployed CCUS capacity, that is, coal-fired power plants equipped with CCUS. Interestingly, all other eight scenarios are grouped around the Carbon Price Scenario Parameter. Namely, holding Carbon Price scenario constant, oil price alone has little effect on the dynamics of the CCUS deployment.

Consequently, the Reference Run generates the most profound reduction in the costs of capture for CO2. Figure 16 shows the costs of CO2 trajectories for all nine scenarios.

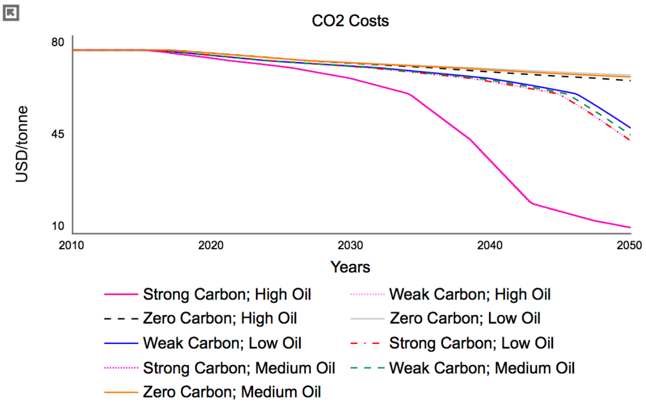


Figure 16. CO2 Costs Trajectories

In the following sections we will look in more details at the discussed simulation runs.

## Simulation Run 1: Reference Run

The reference run is characterized by Strong Carbon Price and High Oil Price.

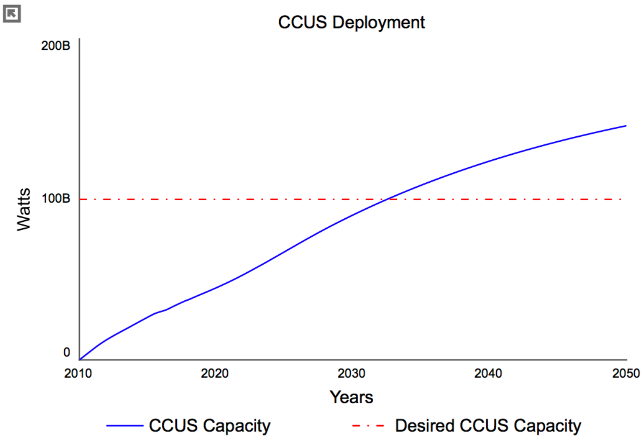


Figure 17. CCUS Deployment: Strong Carbon Price, High Oil Price

As Figure 17 portrays, Reference Run generates CCUS Capacity which by the end of the simulation period exceeds the policy goal for Desired CCUS

Capacity. Note that even though the CCUS structure employs the first-order negative adjustment of CCUS Capacity towards its goal, the model does allow for "overshooting" the policy goal. The reason for that is that the first-order negative feedback is applied towards the Carbon Policy input towards CCUS deployment only. On the contrary, CCUS deployment supported by EOR is feeding the CCUS structure in independently of CCUS carbon policy goals. Yet, the model looks at the feedbacks between those two different channels of CCUS deployment.

To support the latter claim, Figure 18 demonstrates the CCUS Deployment Scenario without EOR (based on Carbon Price regulations only). To generate this scenario Adjustment Time for CCUS first-order negative feedback was decreased from 15 to 10 years to ensure that the target for CCUS deployment is achieved by the end of the simulation period. This change is done entirely for illustrative purposes as the dynamics of the model adjusts in the same way towards the policy goal with the exception that adjustment time stretches the adjustment a few decades longer in time.

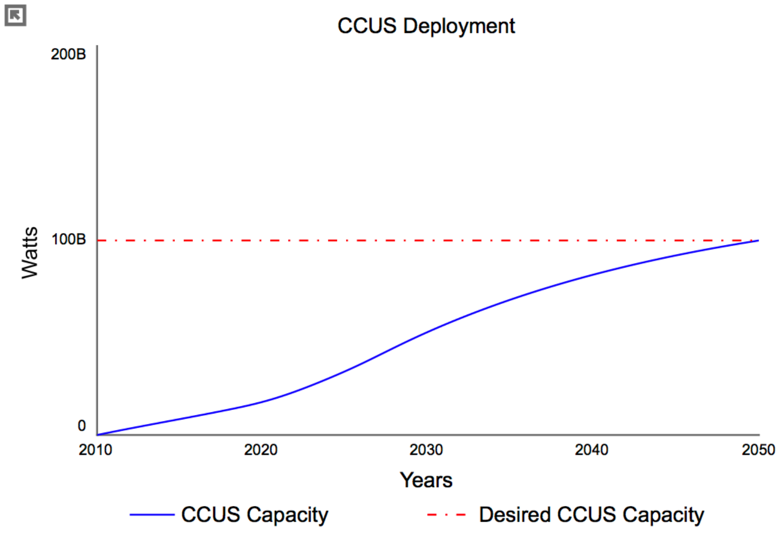


Figure 18. CCUS Deployment without EOR

It is important to note, however, that even though Carbon Price has been identified as the driving force for CCUS deployment, EOR generates at least two important effects:

1. It allows to facilitate CCUS deployment, as the adjustment towards the policy goal is accomplished sooner and within the model's simulation time;

2. It allows for capacity build-up above the stated policy goal for coal-fired power plant conversion.

Since our analysis of CCUS Deployment is based on the dynamics of the key variables comprising economic and commercial framework for CCUS, Figure 15 depicts the three main economic variables at the Reference Run: CO2 Costs, CO2 Purchase Price and Carbon Price.

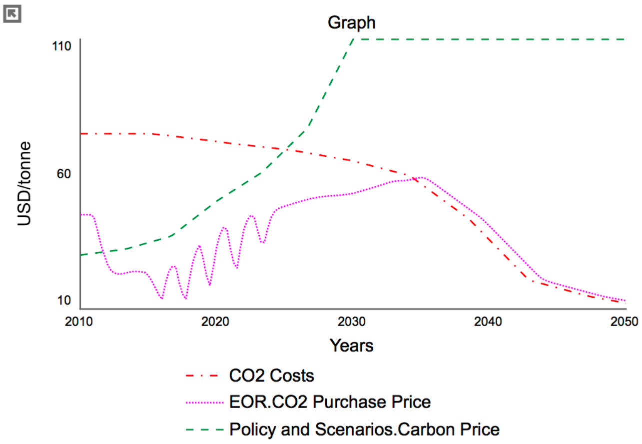


Figure 19. Economics of CCUS EOR: Reference Run

Figure 19 above is a graphical representation that shows the relativity between the carbon price trajectory, the cost of conventional CCS for power generation, and the potential revenue from CO2 reuse, expressed in the form of CO2 Purchase Price. The interactions between these variables is complex. The graph, as the model output, is intended to demonstrate the medium path within upper and lower limits of each variable and to give an indication of the relative impact of carbon price and reuse revenues on CCS costs.

The green dashed line represents the potential carbon-price over the period, bounded by the 450 Scenario (an alternative scenario in which the CO2 price is weaker is represented by the Weak Carbon Price scenario). In principle, the carbon-price will depend on a number of variables such as national and international emissions limits, and the implementation of effective regional & global CO2 markets, and so is difficult to predict. However, since the model is calibrated to the US, a specific path is chosen based on the available information on the most realistic proposals for carbon price regulations and the ones expected by CCUS operators. It is assumed that the carbon-price will grow in the long term and so is shown as a general upward trend.

Potential revenues for reuse are shown in pink dotted line and represented by CO2 Purchase Price. The revenue from reuse at the outset is assumed to be US$45/t which is equivalent to the current typical revenue from EOR. Over time, reuse revenues are expected to fall as the carbon-price increases and there is greater incentive to capture and either store or reuse CO2. In this environment, CO2 is expected to become a surplus commodity, which in turn will exert a downward pressure on the CO2 Purchase Price. As such the reuse revenues are shown as a general downward trend.

It should be noted that the revenue from reuse is modest, relative to the costs of CCS and therefore reuse will at best provide only a moderate offset to the costs of capture.

The point at which the cost for CCS and the carbon-price intersect, is the point at which it becomes more economical to implement CCS, than to continue to pay the carbon-price. At this point, CCS can be said to be commercially viable.

From the graph, it can be concluded that, at current technology maturity levels, a strong carbon price is key to the acceleration of CCS. Reuse revenues will, by contrast, only provide a modest offset to the costs, and cannot be considered to be a commercial driver of CCS.

### Simulation Run 2: Weak Carbon Price/High Oil Price Run

Figure 20 depicts the CCUS deployment trajectory under the assumptions of Weak Carbon Price and High Oil Price. Compared to the Reference Run, this scenario accomplishes the carbon policy goal for CCUS deployment over the simulation period of 40 years. However, this run practically does not generate CCUS capacity in excess of the carbon policy goal. Additionally, the adjustment towards the desired CCUS Capacity determined by the carbon policy power plants conversion target is accomplished later than in the Reference Run.

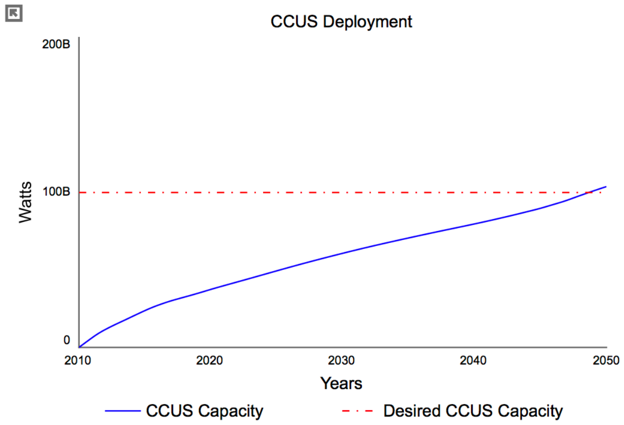


Figure 20. CCUS Deployment: Weak Carbon Price/High Oil Price

Figure 21 portrays the dynamics of the economic variables underlying CCUS deployment. As we can see, the commercialization point, where CO2 Costs and Carbon Price trajectories meet, happens much later in this simulation run and practically towards the end of the model's simulation. CO2 Purchase Price remains lower than costs of CO2 capture throughout the entire period of the model's simulation.

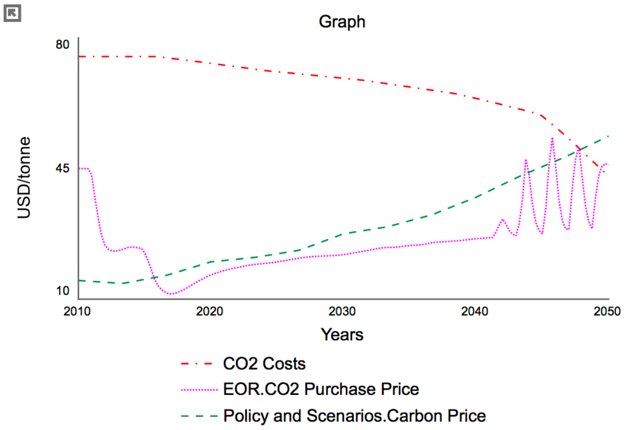


Figure 21. Economics of CCUS: Weak Carbon Price/High Oil Price

It is interesting to observe the effects of feedback and the power of a system dynamics model like this to capture those feedbacks and provide us with visual and numerical implications of intricate feedback interconnections. Namely, the reason for purchase price of CO2 staying below CO2 Costs trajectory is partially due to the fact that the weak Carbon Price does not allow for a significant reduction in CO2 costs through most of the model's simulation period. However, the costs themselves, manifested through carbon price, have an effect on CO2 purchase price which is contained within the model due to lower EOR activity levels due to lower expectations of CO2 supply.

### Simulation Run 3: Zero Carbon Price/High Oil Price

Zero Carbon Price scenario generates CCUS deployment path that runs short of the target for CCUS deployment coming from policy makers' goal for the conversion of coal-fired power plants. Figure 22 demonstrates the relevant CCUS deployment path and its relation to Desired CCUS Capacity corresponding to the carbon policy goal.

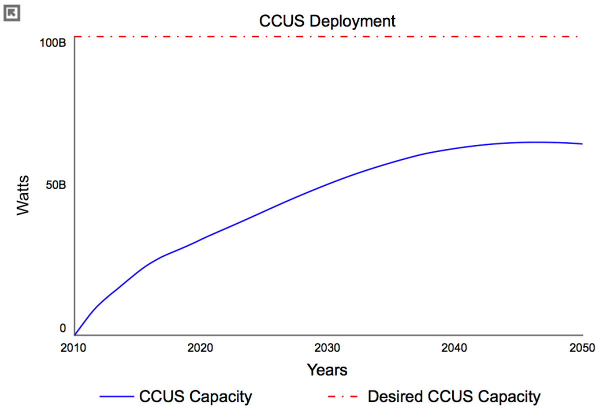


Figure 22. CCUS Deployment: Simulation Run 3

The economics of the scenario is depicted by Figure 23. As could be seen from the Figure, the point of commercialization for CCUS technology is never reached. CO2 costs stay relatively high throughout the entire model's simulation horizon. As CO2 Purchase Price is anchored in this model towards oil price, the variable simply follows the trajectory of forecasted oil price.

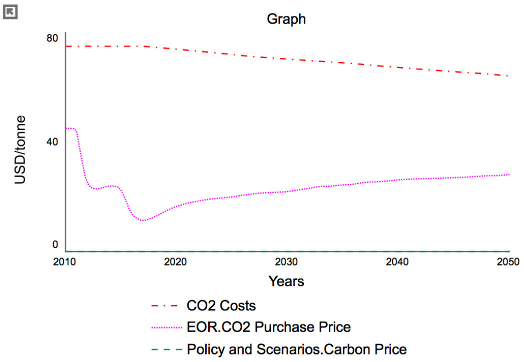


Figure 23. Economics of CCUS: Simulation Run 3

The question that arises logically after the analysis of the presented simulation runs is how do we evaluate them? Do they make sense based on the knowledge about the system we are modeling? Can those results be considered credible so as relevant policies could be simulated with the help of the model?  Whether the presented simulation runs as well as the structure generating them are valid for making conclusive statements with regard to the issue is the matter of the next two chapters.

The policy choice, structure and corresponding simulation runs will be presented in Chapter 5.

# Chapter 4. Validation

## 3.1. General considerations of model validation

This chapter is aimed at establishing confidence in the model described in the previous parts. Once the confidence is established, we can treat the model as the theory that with an adequate degree of credibility explains the issue under the discussion. Perceiving the model as the credible theory of the issue, we can then test various policies of interest to make conclusions about their effects. Without a credible simulation environment, represented by the valid system dynamics model, policy testing cannot possible. That is why, this chapter is entirely devoted to validation of the model.

This section gives a short discussion on the definition of the validation as employed in this thesis and an overview of the validation tests relevant to this model. Out of the validation procedures, a special emphasize is placed on sensitivity analysis. As some of the elements of the model are characterized by a high degree of uncertainty, due to the reasons discussed above, sensitivity testing is crucial in identifying how drastically the conclusions we have made about the model behavior so far and the ones we will made about the policies might change depending on specifications for a number of parameter values and graphical functions.

There is no agreed formal definition of the concept of validation in the system dynamics literature. However, there is a certain consensus that validation is a gradual process on establishing confidence in the soundness and usefulness of a model (Forrester & Senge, 1980). According to (Barlas, 1996), model validity means usefulness with respect to a purpose. The approach to validation in this thesis is performed in accordance with these definitions. As it follows this approach dictates an explicit formulation of the model’s purpose.

In line with the problem definition, the research objectives, the research question and the model’s overview stated in Chapter 1 and Chapter 2, the purpose of this system dynamics model is to portray the feedback structure underlying a complex dynamic integrated $CO_2$-EOR system, which can serve as a simulation environment for designing and testing various policies aimed at unleashing the reinforcing mechanisms able to generate a sustained growth within this system.

The validation procedure for this system dynamics model is conducted in accordance with (Barlas, 1996). As discussed in Chapter 1, due to the nature of the problem (the model does not reproduce the past behavior) and the lack of conventional reference mode (what is modeled has not happened yet), the focus of the validation procedures is primarily on the validity of the structure of the model. This is also in line with the general approach in system dynamics methodology to model validation. Accuracy of the model's behavior will also be evaluated but with the use of different criteria than the ones usually employed: namely, we cannot rely on any formal statistical procedures.

In line with (Barlas, 1996), this chapter follows three groups of test:

- Direct structure tests,
- Structure-oriented behavior tests,
- Behavior pattern tests.

Finally, this chapter focuses on validation testing with regard to the explanatory part of the model. The crucial validation and sensitivity tests for the model with the policy part will be described in a designated section of Chapter 5.

## 4.2 Direct Structure tests

By performing this group of tests, we assess the validity of the model structure by direct comparison with the knowledge about real system structure. These tests do not involve simulation.

### Structure-confirmation test

Structure-confirmation procedures were being performed constantly during the model-building process. The project started with extensive conversations and interviews with the key sources of the knowledge about the issue (various CCUS and EOR operators) and then every time a certain structure was built it was discussed and confirmed with the client to make sure that the model reflects the real structures and decision-making processes. Moreover, the conceptual foundation of the model is grounded in the extensive literature review. When it was possible the model was presented to the industry experts/operators to obtain a feedback from them (as part of conference or board meetings). The application of these test procedures can be characterized as a mix of empirical and theoretical approaches. On the one hand, first the modelers received the general idea about the issue from the client (empirical perspective), then based on the literature the model sectors were constructed (theoretical perspective) and then the model elements were confirmed with the owners of the industry knowledge (empirical perspective). The final model was presented to the client and the feedback was received and incorporated further in the model-building process.

A good example of structure-confirmation performed during the modeling process relates to the structure of $CO_2$ capture and $CO_2$ supply/injection in the model. Currently, as portrayed by Figure 17, the flow of Purchased $CO_2$ Injection Rate includes the flow $CO_2$ Capture as one of the components of $CO_2$ Supply.

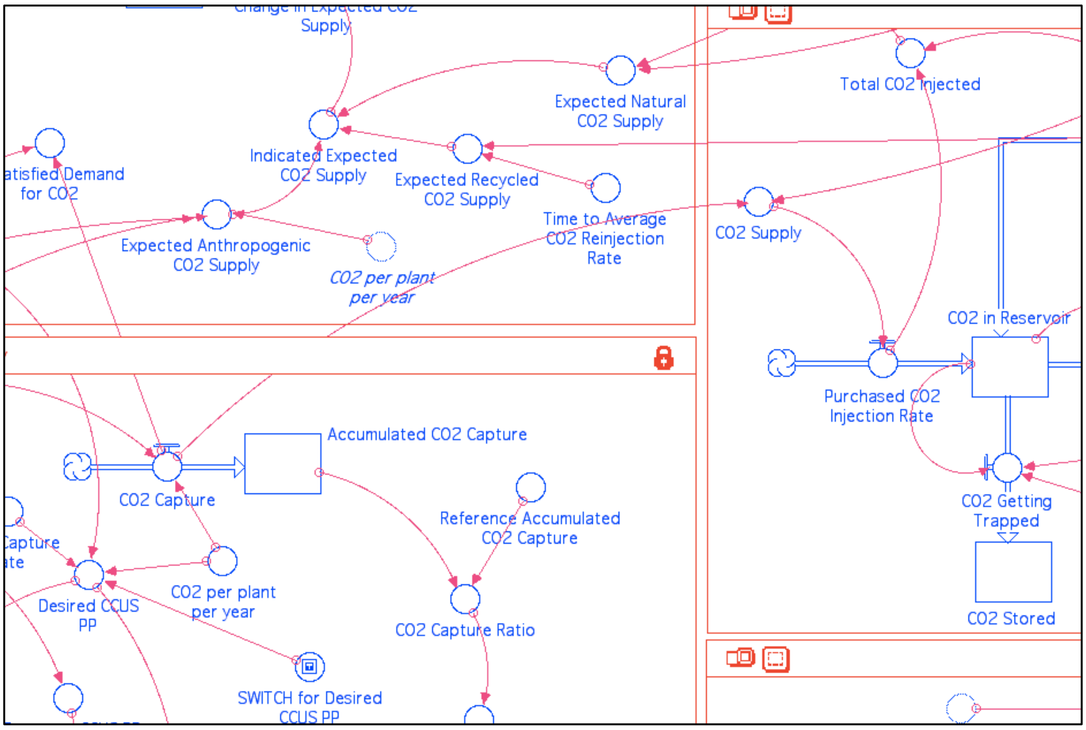


**Figure 24. Structure Confirmation Test**

However, initially the idea was to accumulate $CO_2$ Capture flow in the stock of $CO_2$ Captured, which is then being delivered to $CO_2$-EOR operators based on the purchases agreements. This would have implied that the information feedbacks governing this structure would have been linked to the inventory of $CO_2$, which has been captured and is not waiting to be purchased and delivered. As it was quickly revealed through the consultations with the client and review of the $CO_2$ purchase contracts, this structure is contradictory to how the real system is organized. In reality, there is no inventory of $CO_2$. The supply contracts are anchored to the capture capacity of a particular CCUS source and thus a better structure in the model reflecting this aspect is the one eventually implemented: $CO_2$ capture rate enters the $CO_2$ injection rate.

### Parameter-confirmation test

There are two ways how parameter-confirmation test was carried out throughout the modeling process. First, most of the parameters were derived directly from the literature and then their values were confirmed with the client. The examples of such variables are: $CO_2$ per Plant per Year, Oil Recovered per $CO_2$ Injected, etc. Second, the key parameters from the $CO_2$-EOR process sector were determined based on the literature but in consultation with the relevant CCUS EOR operators. As the sector represented an aggregated construct, which does not exist in reality but can, with a good approximation, replicate it, he knowledge about the parameters in such a construct could not be obtained from the real system or literature. Yet, based on the literature those parameters could and were derived throughout extensive consultations with the technical experts. All the parameters are supported by the relevant sources in documentation to the model (Appendix B).

### Direct extreme-condition test

By this test we evaluate the validity of model equations under extreme conditions, by assessing the plausibility of the resulting values against the knowledge/anticipation of what would happen under a similar condition in real life (Barlas, 1996).

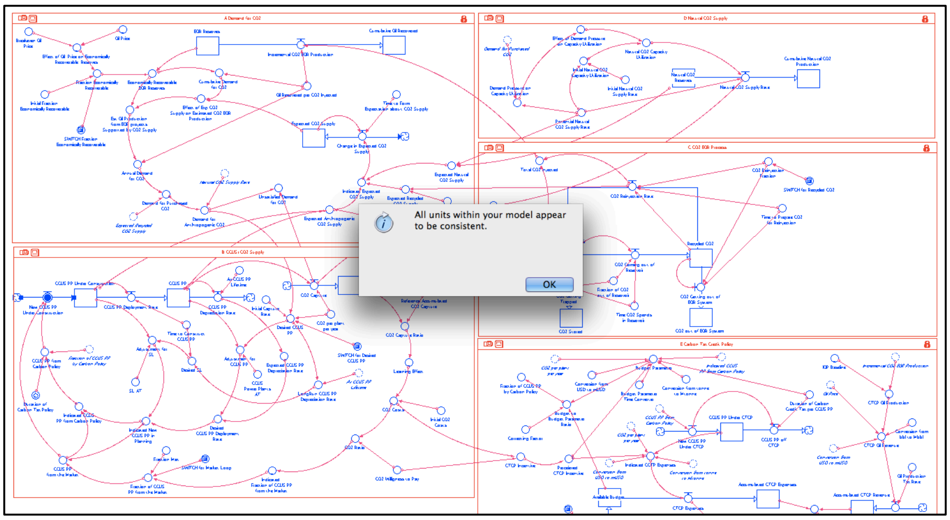
We provide here one example of this test. An important element of the model is the flow New CCUS PP Under Construction. It represents the resulting corrective action of the loop B1 in CCUS sector. The flow is formulated by the following equation:

**New CCUS PP Under Construction =**
**MAX(CCUS_PP_from_Carbon_Policy+CCUS_PP_from_the_Market,0)**

Let us assume an extreme-condition situation when demand for $CO_2$ drastically drops down. Then the suggested by the market or carbon policy value would be negative. However, we cannot cancel the deployment of CCUS PP already under construction. The formulation through the MAX function ensures that the flow does not take on negative values. The test shows that even though the extreme-condition employed is not plausible as the real system always operates under a strong positive demand pressure, the formulation of the corrective action would not have been robust without taking this condition into account.

### Dimensional consistency test

The dimensional consistency test has been performed automatically by the system dynamics software employed for this project (Stella Architect and its function "Unit Consistency Check"). As Figure 25 proves, all the units in the model appear to be consistent.



All units within your model appear to be consistent.

Figure 25. Unit Consistency Test

One note should be made with regard to the unit consistency here. For the theoretical unit consistency test performed by the software to be meaningful, it should also be accompanied by the conceptual parameter-confirmation test. Namely, the model should have no dummy "scaling" parameters that have no meaning in real life. While this test has been done, a number of the so-called technical variables used in the policy sector of the model should be emphasized now. Namely, the conversion factors from USD to million USD and from barrels to million barrels are used in the policy sector to match the difference in tax, costs or WTP units (per tonne) and the related quantities of oil or gas (mtonne and mbarrels). One variable is use

d to convert the flow of Indicated New CCUS PP into the stock concept (namely from Mwt per year to Mwt concept) while calculating the budget parameter to reflect our thinking about the variable (while calculating the budget parameter we should no longer perceive the flow as the flow due to the fact that the assessment of 10 year expenses is conducted one-time). The details on this last variable can be found in the model documentation (Appendix B).

## 4.3. Structure-oriented behavior tests

By performing this group of tests we assess the validity of the structure indirectly by applying certain behavior tests on model-generated behavior patterns. These tests involve simulation and are considered to be strong behavior tests that can help the modeler uncover potential structural flaws.

### Extreme-condition test

This test involves assigning extreme values to selected parameters and comparing the model-generated behavior to the observed (or anticipated) behavior of the real system under the same extreme condition.

A perfect candidate for the extreme-condition test is the oil price. This parameter is exogenous in the model and plays important role in determining the potential for growth in the system: higher oil prices would mean increase in economically recoverable oil reserves, while lower prices would result in the corresponding decrease.

An extreme-condition test involving the oil price can help test whether the described mechanism follows the robust formulation. This is particularly important due to the fact that oil prices are volatile and sometimes exhibit a shock behavior. Thus, the sudden change in this parameter is not unrealistic.

Ideally for the extreme-condition test we change the oil price itself. However, the oil price is represented by the time series. Luckily, for the mechanism described above not the oil price itself but the ratio between the actual oil price and the breakeven oil price matters. Thus, it is enough just to change the breakeven price, which is only one value. Currently, the breakeven price is \$85/barrel. We bring this value to \$200/barrel. What would happen in the real system? $CO_2$-EOR projects under such condition would become unprofitable and oil production would be planned resulting in no additions to the currently operating oil facilities.

Figure 19 shows the model’s response to the extreme condition. As the figure portrays, the estimated oil production indeed remains at zero value until the year of 2040 when the oil price from the time series would increase enough to catch up with the new value for the breakeven price. The incremental oil production during that period is not expanding. The tested formulation is robust.

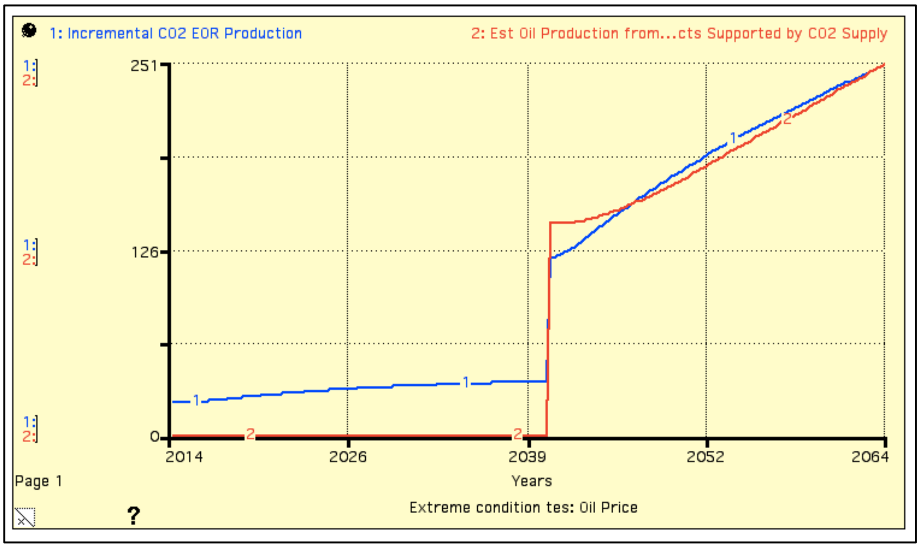


Figure 26. Extreme-condition test: Oil Price

### Behavior sensitivity test

This test consists of determining the parameters to which the model is highly sensitive, and asking if the real system would exhibit similar high sensitivity to the corresponding parameters.

In the explanatory version of the model there are three sources of uncertainty:

- oil price, as it is an exogenous variable and as it follows from the extreme condition test a shock in oil price can shut the whole $CO_2$-EOR production down;
- Learning effect mechanism: the *Reference Accumulated $CO_2$ Capture* and the shape of the graphical function for the learning effect;
- CCUS Market Mechanism: the shape raphical function for the *Indicated Fraction for CCUS PP from the Market.*

The rest of the parameters in the system exhibit relatively high degree of confidence with regard to the chosen level of aggregation (discussed in section 2.2 Model Assumptions).

As there are not that many sources of uncertainty, we can test sensitivity of the model towards all of them in this section.

### *Oil Price*

Again, we employ the approach of changing the breakeven oil price. Figure 20 demonstrate the response of the incremental oil production towards changes in the breakeven oil price: run 1 is the base run at the breakeven price 85, run 2-10 progress from the value 85 to 200. We do not test for the value below 85, as all of them would produce the base run behavior. Note that we conduct the sensitivity test on the unconstrained policy simulation run. The base run does not exhibit much of the dynamics in its underlying mechanism due to the fact that the reinforcing loops are dormant. Also, testing on the "ideal" run is meaningless, as the growth is not driven by the $CO_2$ costs dynamics there but exogenously. Thus, even though the policy and policy runs will be discussed in Chapter 5, we use the unconstrained policy run now as it keeps all the mechanisms in the model endogenous. From the behavior point of you it reproduces the "ideal" run.

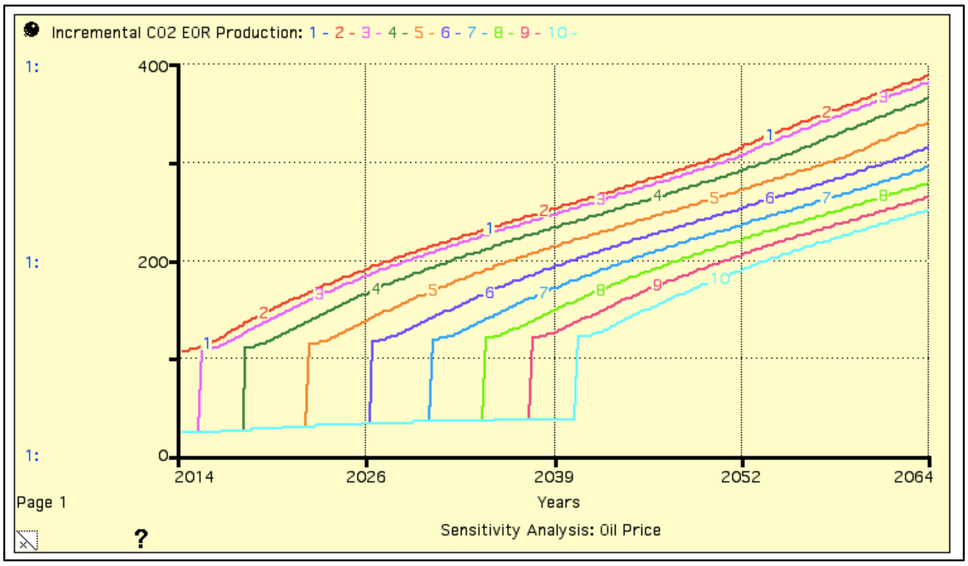


Figure 27. Sensitivity test: oil price

The results indicate an expected sensitivity towards oil prices. As the breakeven price progressively rises (simulating the drop in oil prices), there are longer periods of no additional oil production (until the prices catch up). Again, this is an expected behavior and it is absolutely natural for the $CO_2$-EOR industry to be dependent on oil prices. Our model focuses on studying endogenous sources of dynamics while recognizing that exogenous determinants are still important.

Testing of the remaining two sources of uncertainty is more crucial as they represent an imperfection of our knowledge about the real system. Thus, we would like to be sure that the model results are not extremely sensitive towards that imperfection.

### *Reference Capture Ratio*

10 policy runs vary the reference capture ratio from 300 to 1100 incrementally (the tested range is +/- 400 which is more than 50% of the central value). It is important to observe the test responses on both the base run and the unconstrained policy run (producing the same behavior as "ideal" run but all the endogenous mechanisms are "open"). Testing on the base run may reveal whether under certain specifications the reinforcing loops would start working without any policy stimulus.

Figure 21 exhibits the base run responses. Only Run 1 (the value 300) exhibits complete closure of the gap between $CO_2$ costs and the WTP during the simulation period which gives rise to growth dynamics after the year of 2052 (still not very soon). All other runs while differing for $CO_2$ costs produce almost identical dynamics for the oil production.

This means that even though the value for the Reference Capture was essentially our best guess, the conclusion about the inability of reinforcing loops to produce growth without a policy is still robust. Moreover, an extreme value of 300 is quite unrealistic based on the current cost studies (SBC Energy Institute, 2012).

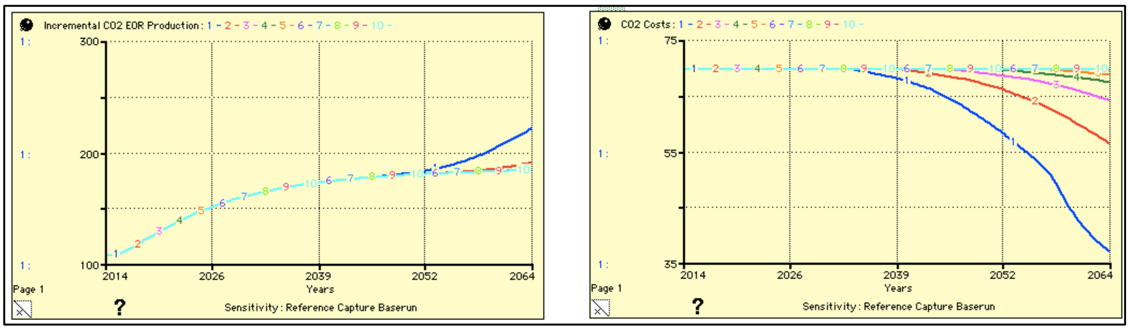


**Figure 28. Sensitivity test: Reference Capture, Base run**

The same runs are simulated on the unconstrained policy run (Figure 22). Here the costs dynamics changes drastically as they are influenced both by a lower (or higher) reference ratio and by stimulating forces of the unconstrained policy. Thus, in a policy setting the system is very sensitive to the value for the reference ratio. This does not destroy the credibility of the model with regard to its purpose but should serve as a caution: any policy testing should be conducted with an idea in mind that the learning mechanism contains a significant source of uncertainty. One should either rely on the assumption as the best guess or invest further research on removing the uncertainty. For the purpose of this model announced in the beginning of the chapter, the specified mechanism is adequate.

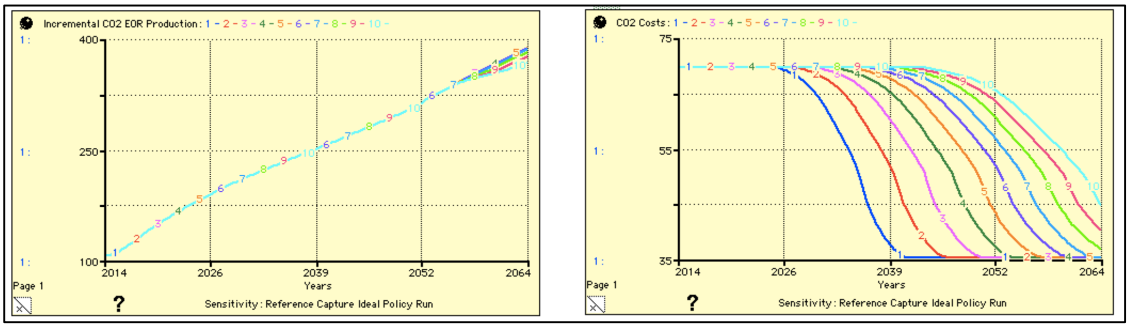


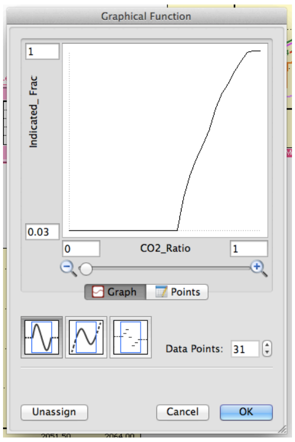
Figure 29. Sensitivity test: Reference Capture, Unconstrained Policy run

Incremental oil production scenarios are mostly identical due to the fact that the unconstrained policy always ensures that enough CCUS capacity is installed even if the high reference ratio does not lead to strong market mechanisms.

## *Shape of the Learning Curve and CCUS Market Fraction*

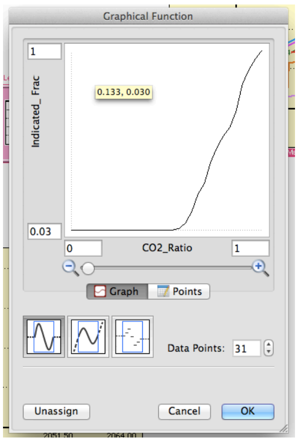
Chapter 2 provided a detailed discussion on the assumptions underlying the graphical functions behind the learning curve and the CCUS mechanism. The choice for s-shaped curves was justified. However, in this section we can test whether the model is sensitive towards the shape of the curve specification.

For the Learning Curve we test three specifications: Run 1 corresponds to the s-shape, Run 2 – concave, and Run 3 – linear (or close to linear). Figure 23 and Figure 24 exhibit those alternative specifications.



Data Points: 31

Figure 30. Concave LE



Data Points: 31

Figure 31. Close to Linear LE

We test sensitivity only on “ideal policy” run as the base run with the baseline reference capture does not show any costs dynamics. Figure 25 exhibits the effect on $CO_2$ costs. The new shapes of $CO_2$ costs reproduce the ones portrayed by the graphical functions, but quantitatively they remain within the same ranges. Thus, the produces inputs for other parts of the model will be similar.

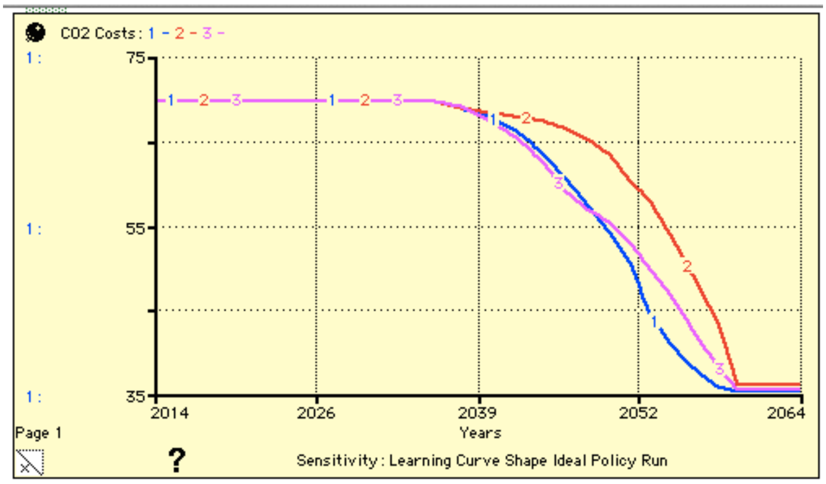


Figure 32. Sensitivity test: Learning Curve, CO2 costs

A similar test was conducted for the Fraction of CCUS PP from the Market. The results are depicted by Figure 26. The conclusion is similar to the previous case.

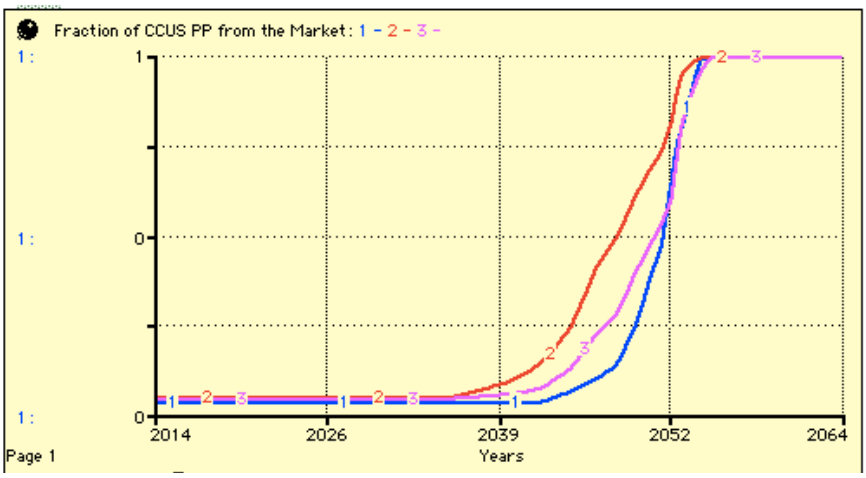


Figure 33. Sensitivity test: Market Fraction

We can conclude that the model is not sensitive to the shape of the graphical functions in the CCUS sector.

### Partial Model testing

Partial model testing or “cutting loops” was effectively performed when in Chapter 3, while analyzing simulation runs, we were using the installed switches to turn off the CCUS sector (SWITCH for Desired CCUS PP), the possibility to recycle $CO_2$ (SWITCH for Recycled $CO_2$), and the effect of market mechanisms to check the work of loop B1 under ideal circumstance (SWITCH for Market loop) as well as combinations of them. Namely, producing Run 3, which sets the model in equilibrium, was essentially switching off all the mechanisms within the sectors and observing what happens in the demand sector. Thus, the partial model testing confirmed the functioning of sectors separately as intended. Each switch is accompanied with the relevant description in the model documentation (Appendix B).

## 4.4. Behavior pattern tests

These procedures are served to evaluate whether the behavior generated by the model corresponds to the one observed in the real system. Normally this involves comparing the generated behavior with the reference mode. However, there is no reference mode for our problem.

The nature of the problem created the context where we are modeling something that does not exactly exist now but will exist in the future. We anticipate with a great degree of confidence (based on comparable studies) certain developments (learning effect), we know how the decisions are being made by operators on the supply and demand side (surveys, conferences), we chose the simplest approximations for modeling those decisions (expectations for demand and costs/willingness to pay for supply), we know the current state (surveys, interviews, studies) and the idea about perspective (though very uncertain). This knowledge can give us idea about reference modes or something that might serve as a reference mode. Though already we can see that the nature of the case imposes a great degree of uncertainty. Thus, sensitivity analysis is crucial for the model.

The starting points or initial values are important. The starting point of the model is now and there is data about this point in time. Crucial numbers about the current status are:

- Current demand pressure – unsatisfied demand. In principle we need to know demand, which can be roughly estimated by the amount of announced projects.

Knowing the potential of reserves we can infer the value for supply expectations. Yet, supply expectations can roughly be estimated by announced $CO_2$ supply projects. So there is a possibility to double check.

- Current $CO_2$ supply, including $CO_2$ capture, number of CCUS can be deduced from there. Yet this is an illustrative number: in reality power plants are not the only sources of carbon capture.
- Current incremental oil production – supplied by data.
- Carbon costs and willingness to pay are known. Initial estimation of the strength of market mechanism is the one that gives the depreciation rate of the current stock of CCUS so that in the absence of unsatisfied demand we would have equilibrium.

The purpose of reference mode is to have the behavior that we want to replicate. In our case we are modeling the future. So we cannot replicate the future. Yet, we have credible estimations, which we can use. However, we should not focus on replicating them. They can be used for providing the general idea about whether the model results make sense. We take the approach that if we have enough confidence in the structure (face validity) and initial values corresponding to the current reality, the behavior produced by the model is credible. Thus for this model it will be very important to establish confidence about the structure (face validity).

In other words, in evaluating the generated behavior we have to rely on the face validity. More precisely, all the generated behavior patterns were presented to the client and confirmed whether they represent a reasonable behavior or not. Moreover, we also employed the general guideline that lack of policy measures (Run 1) is not expected to produce growth in the system, why the policy stimulation (Run 2) would lead to continuous growth. That is we check mainly the pattern of behavior.

A complementary approach is to compare the simulation runs against the existing forecasts of oil production and $CO_2$ capture. There are two problems with this approach. First, any forecast is dependent on the underlying assumptions, which are rarely made transparent. This means, that we are never sure that the comparison of the model's behavior with another model's behavior is meaningful. Second, none of the forecasts exceed the horizon beyond 2020 and by that year our model simulates just 7 out of 50 years. This would mean a poor benchmark for comparison. The only exception is the NEORI model (National Enhanced Oil Recovery Initiative, 2012) which extends over long enough horizon and which assumptions are partially documented.

Concluding this chapter, the validation of the model relies primarily on the structure and structure-oriented behavior tests. The behavior validation can be conducted only informally based on the face validity of generated results: whether they look reasonable to the experts or not. However, this is justified by the nature of the model and its purpose. The sensitivity analysis revealed that only one parameter exhibits a high degree of uncertainty within the model and the model is sensitive to that (the reference accumulated carbon capture in the CCUS sector). However, taking into account the purpose of the model, we can tolerate both the uncertainty and the sensitivity.

# Chapter 5. Dynamic Performance Management (DPM) Analysis

## 5.1 Dynamic Performance Management

Traditional PMS may deliver a static analysis of value creation processes and, therefore, may not consider the time delays existing between the adoption of a policy and the achievement of the related results. In addition, not tangible variables and non-linearity often considerably influence strategic resources, and the associated performance drivers and end-results. For example, some of the strategic resources are hard to express and measure in a quantitative way but rather as a level 0-1, or 0 to 100%. For overcoming such undesired effects, it is possible to facilitate decision-makers' understanding and to achieve that, DPM based on the SD model has been chosen as a framework to foster accountability and performance improvement.

Firstly, strategic resources can be presented as stocks (or levels) of available tangible or intangible resources in a given time. Consequently, the stock levels are influenced by the value of corresponding inputs and outputs over time (inflows and outflows). Exactly this influence is used to test different policies in the modelling process. Identification of the strategic resources and the most important factors that are influencing their change (drivers) is essential to shed light on the business areas important for the performance improvement. They can be measured in relative terms (i.e. as a ratio between the business performance perceived by clients and a benchmark, or target). Finally, end-results are a measure of the efficiency and effectiveness expressed in terms of volumes or impact. They are flows affecting the accumulation of corresponding strategic resources

Using an instrumental dynamic performance management (DPM) model, we divided the performance into three linked levels: strategic resources→ performance drivers→ end-results (see Figure 34), which are separated into three sections.

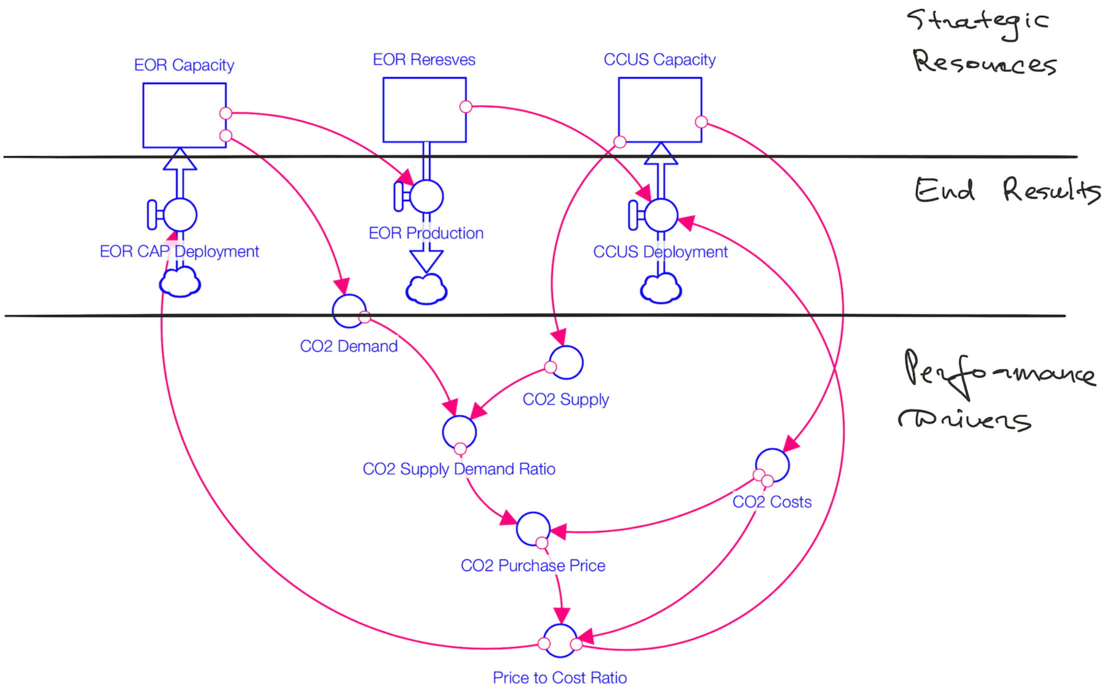


Figure 34. DPM Analysis

## 5.2. Policy Overview

In the previous chapter we built the confidence in the system dynamics model developed for addressing the research objectives of this study. Once the confidence is established, we can claim that we have a valid theory explaining why "the things behave as they do". In other words, we have an explanatory model at hand. However, an explanatory model is often not enough to address the initial problem, which motivated system dynamics application in the first place. Often we invest into our understanding of a system with an idea to design improvements that may hopefully alter its behavior. More formally, an explanatory system dynamics model be would normally followed by a policy model, incorporating the policy structure(s).

An interesting circumstance of the current case is that the explanatory model was already being built with a concrete idea of which policy would be incorporated into the structure. Essentially, the explanatory model was tailored to provide the simulation environment for testing a concrete policy. Thus, a choice for the policy structure was somewhat predetermined. This can be explained by the following reasons.

First, the explanatory version of the model describes the behavior as it is, which is "stuck" in an almost constant dynamics of non-functioning dormant feedback loops (namely, the core feedback loops R1, R2, and B1 from Figure 10). To see how in principle those loops might function we relied on hypothetical simulation runs using various switches (Chapter 3). Even though this was important for the analysis of the model, pretty soon in the course of the modeling process we need to employ policy measures, which can generate the desired behavior. Otherwise, the model is essentially generating nothing. For this reason the consideration of the policy structure has commenced in parallel with the model building process.

Second, the scope of policy measures with regard to the issue is not broad. In fact, the measures are of one kind: any of the policies would imply a certain government incentive for CCUS operators, which would compensate for the lack of strong market mechanisms. The variation would be observed in exact choice of the designs for those policies with the most common examples as government subsidies and tax policies. Among a few of those policy designs, carbon tax credit policy (CTCP) is the one that looks the most money saving as it implies an ultimately self-financing reinforcing mechanism. The advocates of the policy often use the argumentation reflected by Figure 27.

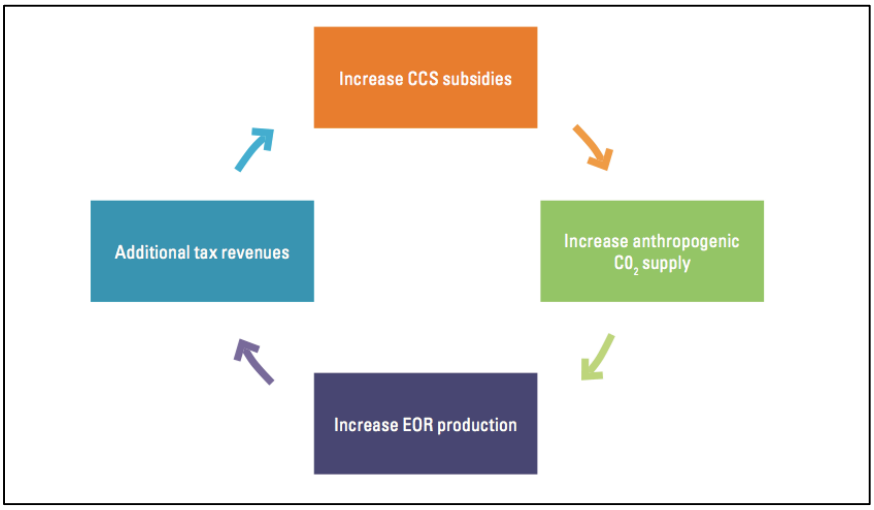


Figure 35. Reinforcing mechanism of carbon policy. Source: NEORI (2012)

As Figure 27 illustrates, the carbon tax credit policy relies on an implicit reinforcing mechanism allowing for achieving the point of payback after which the program can support itself through the revenues generated by the policy.

Third, the CTCP is a relevant for the current time policy measure, which is being heavily discussed among the policy-makers, is characterized by a detailed proposed design, and has been supported extensively by modeling efforts.

The last point is particularly crucial. The main source of our understanding of carbon tax credit policy design is National Enhanced Oil Recovery Initiative (NEORI, 2012). The document contains the exact proposal for the policy design as well as the documentation of the model used to justify the policy. An important feature is that the model was constructed and tested in a participatory fashion, whereby the chosen industry experts, policy makers and analysts were involved into discussion of model's assumptions and results.

However, from the system dynamics perspective, a key shortcoming of the model is that the dynamics series for crucial variables such as $CO_2$ supply and incremental oil production are based on forecasts. The forecast were discussed with the participants of the modeling sessions to establish whether they reflected the reasonable and/or expected behavior of those variables. This feature of the carbon tax policy model used in (National Enhanced Oil Recovery Initiative, 2012) clearly increases the transparency of the modeling effort and improves the validity of the results. Yet, the fact that the dynamics of the key variables is based on forecasts that do not reflect how the interaction of other variables of the model might influence their dynamics is a major shortcoming.

In that respect, the system dynamics model instead of relying on exogenous forecasts generates the important variables, chosen to be within its boundary, endogenously. In this way we can clearly see how the variables in the model influence each other through the feedback loops comprising the structure of the system.

Thus, for the reasons discussed above, Carbon Tax Credit Policy or CTCP as described in (National Enhanced Oil Recovery Initiative, 2012) was chosen for the policy analysis. The underlying exogenous model and its results, which (National Enhanced Oil Recovery Initiative, 2012) is based on, are used as a benchmark for comparison with the system dynamics model. Yet, we would like to emphasize here that no direct comparison of the system dynamics and NEORI model is meaningful due to the difference in a number of underlying assumptions (e.g., our model uses only one source of carbon capture, while the NEORI model differentiates between three sources). What is really important is the opportunity to use the knowledge of industry experts the NEORI model is based on to aid the understanding of the ranges for certain variables generated by the system dynamics model.

## 5.3 Policy Description

This section gives an overview of the proposed federal production tax credit as described in (National Enhanced Oil Recovery Initiative, 2012). The goal of the section is to describe the salient features of the policy, which will then be formalized and included into the system dynamics model.

The proposed legislation has a strong historical base: the U. federal policy has long encouraged the capture and geologic storage of $CO_2$ emissions, or CCUS, from power plants and other industrial facilities. This support has been consistently bi-partisan and extended across several Presidential Administrations. Grants, loan guarantees, and federal assistance from agencies such as the US Department of Energy (DOE) have played a vital role in advancing research, development, and demonstration of key $CO_2$ capture technologies. The commercial and operational experience of the $CO_2$-EOR industry in capturing, transporting, and injecting CO2 for oil production has greatly informed and contributed to the federal CCS effort. Indeed, DOE has increasingly come to view commercial EOR as a key pathway to facilitating CCUS deployment.

Thanks to the efforts of private industry and DOE, many $CO_2$ capture technologies are already commercially proven, and only a modest incentive is needed to help close the gap between the market price of $CO_2$ and what it costs to capture and transport that $CO_2$. In the case of emerging technologies, companies need a larger incentive to help shoulder the additional financial and operational risk of deploying new, pioneer capture projects for the first time in a commercial setting.

Therefore, the NEORI participants recommended in (National Enhanced Oil Recovery Initiative, 2012) a carefully targeted and fiscally disciplined production tax credit program to be administered by the US Department of the Treasury. Performance-based and competitively awarded, the program is designed to provide just enough incremental financial support, and nothing more, to enable important $CO_2$ capture and pipeline projects to come into commercial operation and begin supplying $CO_2$ to the EOR industry.

The tax credit includes the following key features designed to foster the commercial deployment of anthropogenic $CO_2$ capture and pipeline projects, while ensuring project performance and a revenue- positive outcome for the taxpayers. These features constitute the design description of the CTCP. According to this design, the CTC will be:

- Provided to owners of $CO_2$ capture equipment, installed on a broad range of industrial processes, with the potential to supply significant volumes of $CO_2$ to the EOR industry;
- Limited to covering the additional incremental costs of $CO_2$ capture, compression, and transport at new and existing industrial facilities and power plants;
- Allocated through competitive bidding in pioneer project, electric power and industrial tranches (so that like technologies with similar costs bid against each other);
- Awarded to qualifying projects over a ten-year period based on performance (the credit can only be claimed upon demonstrating the capture and oil field storage of the $CO_2$);
- Designed with transparent registration, credit allocation, certification, and public disclosure (to provide project developers and private investors the financial certainty they need to move forward with projects);

- Created with no limits on project scale or on the aggregation of different $CO_2$ sources into a single project (to enable smaller industrial $CO_2$ suppliers to participate effectively);
- Measured to ensure that the program achieves ongoing technology innovation, $CO_2$ emission reductions, and cost reductions for capture, compression, and transport; and
- Designed with explicit safeguards to penalize non- compliant projects, limit taxpayer expenditure, and modify the program to ensure net positive federal revenues (within the ten-year Congressional budget scoring window and over the long term).

A section-by-section analysis of the proposed federal production tax credit can be found in Appendix A and B to (National Enhanced Oil Recovery Initiative, 2012).

The conclusion that NEORI (2012) makes is the following: if a program remains in place for several decades it will enable a build-out of projects at sufficient scale to result in significant cost reductions in $CO_2$ capture costs from currently more expensive sources. These cost reductions will allow many technologies to supply $CO_2$ to EOR projects without an incentive in later phases and after the program ends.

Based on the design description and the results of the model, the CTCP seems to be the right candidate to be incorporated and tested in our system dynamics model. However, it needs to be emphasized that we do not aim at replicating the CTCP policy exactly as it is described and modeled by the NEORI. For the purposes of this study, the work, which has been performed by NEORI, is of informative purpose. It is used primarily to aid our understanding of the policy aspect of the issue and to form some bounds/ranges for assessment of the generated by the system dynamics model results.

## 5.4 Policy Structure

This section describes the policy structure, which should be perceived as a generic version of the CTCP policy described above. It is generic in a sense that a number of details noted in section 5.2 are omitted in the system dynamics model: the bidding mechanism, the differentiation between three different sources of $CO_2$ capture, etc. Yet the policy structure reflects the key features of the CTCP, namely:

- It compensates for the work of the CCUS market mechanism while it is not operational yet due to unfavorable economics,

- It contains the inherent reinforcing mechanism allowing achieving the point of the program's payback.

Figure 28 exhibits an overview of the model with the policy structure in place.

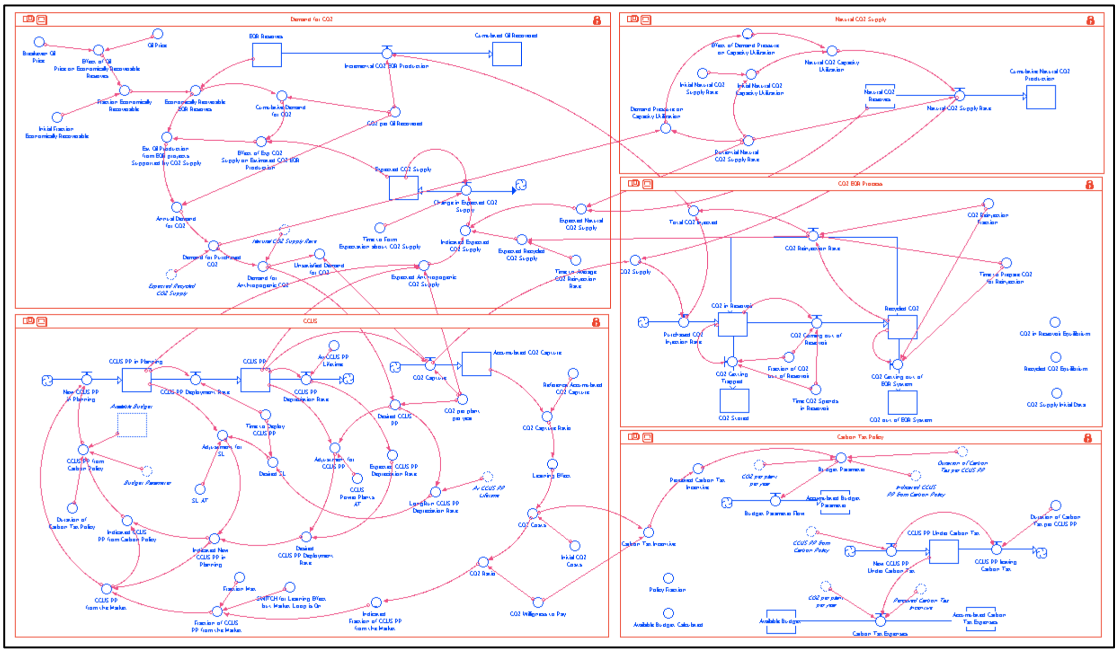


Figure 36. Model Overview with Carbon Policy

As follows from the figure, the policy structure changes the system in two ways. First, it stimulates the existing structure by enabling B1 to work and, thus, stimulate the co-dependent growth of R1 and R2. This is reflected in the fact that the policy structure is incorporate in sector 2 (CCUS). Second, the structure introduces another reinforcing mechanism: a self-sustaining policy. That is why there is a technical need for a separate sector for the policy (Sector 5) with the policy budget, its formation and its effect on the system.

Figure 29 exhibits the feedback structure of the system containing the carbon policy. It makes explicit the modifications discussed above. First, B4 is added to aid the work of B1. This way the CTCP fuels R1 and through this mechanism another reinforcing loop R4, which portrays the self-sustaining mechanism of the policy. However, this is not the end of the story. Through its correcting loop B4, the policy fuels R2, which eventually lowers the costs of $CO_2$, and together with them the required tax incentive which allows for financing more CCUS power plants.

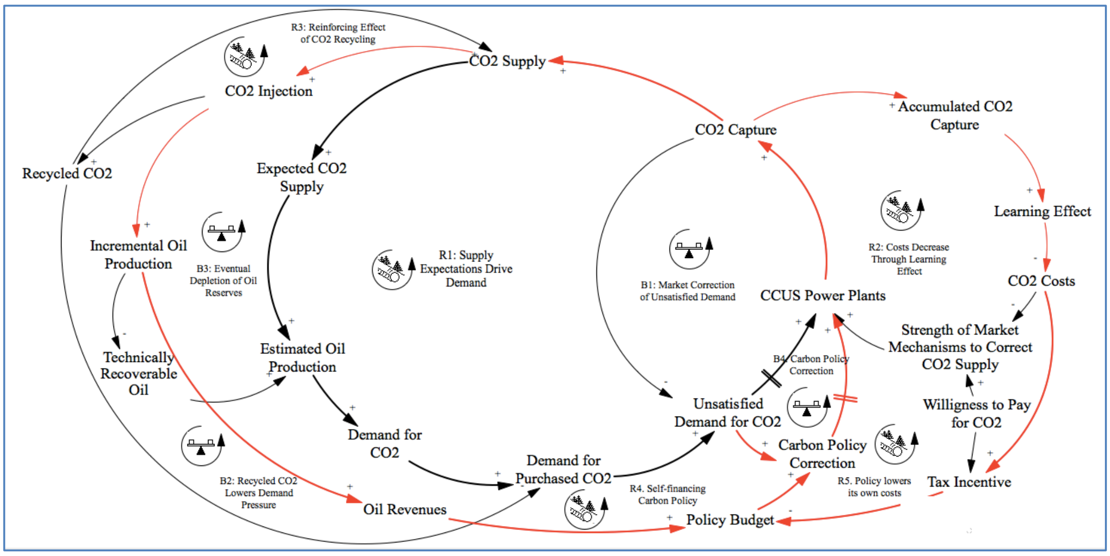


**Figure 37. CLD for the Model with Carbon Policy.**

Figure 30 portrays the CCUS sector with a policy structure. It is relatively easy to incorporate the CTCP in the existing CCUS sector, as ultimately it fulfills the same function as the CCUS market mechanism: supplies new CCUS PP. Thus, now the inflow to the CCUS PP supply line is comprised of two components: the contribution of the market and the contribution of the policy.

The key in ensuring the robustness of the structure is that the policy should only satisfy that part of demand, which cannot be fulfilled by the market mechanisms. Along these lines, the balancing feedback loop is now structured in the way that first generates the Indicated New CCUS PP Under Construction, then allows the CCUS Market to fulfill whatever portion of the corrective action it is able to fulfill. The remaining part is the indication for the policy. Whether that part would be supported by the CTCP or not depends on the dynamics within the CTCP sector.

Sector 5, as exhibited by Figure 31, is solely dedicated to the policy structure specifications. The sector includes a few simple stock-and-flow structures representing the design of the CTCP and a number of specifications, or calculated variable, used in the CCUS sector to ensure the proper functioning of the policy mechanism.

The new CCUS power plants supported by the CTCP, besides entering the supply line of CCUS power plants in the CCUS sector, also enter a simple co-flow structure in sector 5. Thus, at any point in time, there is a stock of *CCUS PP under CTCP*. CCUS PPs entering the stock leave it after 10 years, according to the policy duration specification.

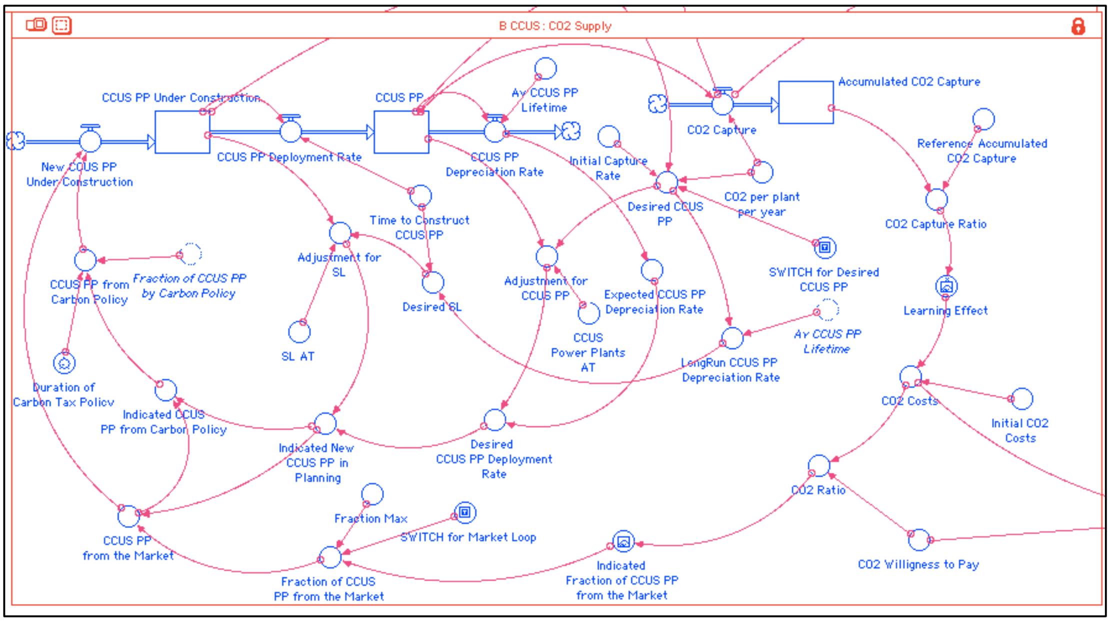


Figure 38. CCUS Sector with Carbon Policy

The stock of CCUS PP under CTCP represents the first component necessary to calculate the annual policy expenses. The second component is the *Perceived CTCP Incentive*, which is the averaged gap between the $CO_2$ costs and WTP. As a policy-maker aims at closing the costs-WTP gap, this gap determines the amount of the incentive per unit of $CO_2$ generated by a CCUS power plant under the designed policy.

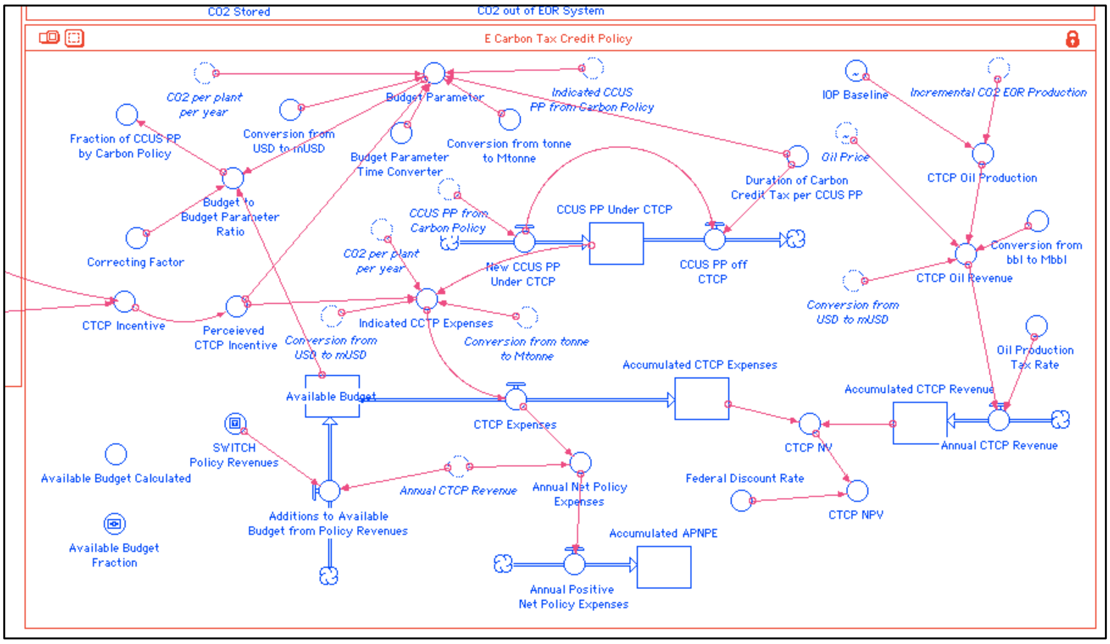


Figure 39. CTCP Sector

The *CTCP Expenses*, calculated on the bases of a number of power plants under the policy and the value of the policy incentive, together form the flow depleting

*Available Budget*, allocated for the policy implementation, and accumulating in the *Accumulated CTCP Expenses*.

A crucial calculated variable in the sector is the *Budget Parameter*. Every time the balancing feedback loop of the CCUS sector provides the number of *Indicated New CCUS PP under Construction* that cannot be supported by the market mechanism, the virtual policy-maker in the model evaluates whether the financing of those plants over the 10-year period is compatible with the available budget. Thus, for every new indicated inflow of CCUS PP delegated to the Carbon Policy, there needs to be determined the expense associated with that inflow over a 10-year period. This, yet potential, expense is represented by the *Budget Parameter*. If the budget parameter is less than or equal the available budget, the indicated inflow is indeed supported by the CTCP. If the budget parameter exceeds the budget available, only a fraction of the indicated CCUS PP supported by the remaining budget can be launched for construction. If the available budget is zero, no CCUS PPs can be enabled by the policy mechanism. The exact formulation of the work of the budget parameter and related parts of the carbon policy are described in the documentation to the model (see Appendix B).

The policy sector incorporates an important feature of the CTCP design, which is usually used to advocate for its implementation by interested stakeholders. In addition to incurring expenses, the CTCP generates additional federal budget revenues as the incremental oil production, attributed to the CTCP, is subjected to taxation. To take that crucial aspect into account, the sector determines the *CTCP Oil Production*, which is the difference between the incremental oil production happening in the system and the baseline oil recovery in accordance with the base run (Chapter 3; no policy scenario). These additional revenues are then accumulated in the stock *Accumulated CTCP Revenue*.

The comparison of Accumulated CTCP Expenses and Accumulated CTCP Revenue produces the Net Value (NV) of the CTCP. After application of the Federal Discount Rate, the Net Present Value (NPV) of the CTCP is determined. The NPV can serve as an important criterion for evaluating that or another version of the CTCP design. It explicitly shows whether the policy becomes self-sustaining or not and, if it does, how quickly that happens in the course of the implementation.

The self-sustaining part of the policy comes from the fact that annually generated tax revenues from the incremental oil production are then injected back to the available budget, which creates a reinforcing mechanism within the model allowing to spend less financial resources and even generate additional value.

The challenging question underlying the formulation of the policy and the analysis of policy choices is the determination of initial value for *Available Budget*. Namely, for a policy-makers the question is how much money do we need to put into the program now to ensure its functioning until it gets self-supporting?

The major concern here is to avoid over-spending. The policy is operating in a highly complex dynamics system and is aimed at activating a number of reinforcing loops within that system which can generate self-sustained growth in the future. On top of that, the policy itself adds a reinforcing process of potential self-financing in the future. The problem is that in such a dynamic system with a dynamic policy a policy-maker is left uncertain about when exactly the interaction of various feedback loops would result into self-supporting mechanisms becoming active. If this moment happens to be much earlier than expected, the dedicated money would have been overspent meaning that the financial resources were directed at something that could have supported itself with no additional stimulus. If, however, not enough money is injected into the policy for the system to reach self-sustaining growth, the initial success of the policy would be followed by an undesired stagnation.

In practice out of the two potentially dangerous cases described above, the first one is less problematic as once the generated by the policy revenues start financing the program, the originally allocated resources would still remain and can be redirected for other purposes. Yet, having a better idea of how much financing a policy exactly requires might improve the bargaining position at the stages of advocating for a certain policy design.

In the context of our system dynamics model, however, the issue of not over-investing becomes critical, as the model needs to be initialized with a certain value of the Available Budget. Why is this so crucial?

If the stock of Available Budget starts with a too small value, the indicated new CCUS power plants will not be supported by the carbon policy. The policy does not start and the system does not reach the moment when the self-supporting mechanism enters into operation. Following from the description of the policy-based correction within the CCUS sector, in the presence of the reinforcing mechanism injecting additional money from the taxed oil revenues, it is simply enough to have the initial budget around the maximum value for the budget parameter within the first year of the program. In the absence of the reinforcing mechanism, we would needed to make sure that the budget can satisfy all the accumulated CTCP expenses, which is a much higher amount than the one indicated by the budget parameter.

A variable that enhances our understanding of how the initial available budget should be determined is the Accumulated Annual Positive Net Policy Expenses (further in the text and in the model, Accumulated APNPE). The APNPE represents the amount of the policy expenses not covered by the policy revenues at the moment the expenses occurred throughout the simulation time. Sector 5 accumulates APNPE into a stock of expenses that stabilizes ones the payback point is achieved by the program. Everytime we simulate the model with different initial values of the available budget, Accumulated APNPE stabilizes at different levels. The higher the initial budget the higher the level of Accumulated APNPE stabilization is, which results from being able to finance more needed CCUS power plants during the period before the payback point (more plants means more expenses).

However, after a certain value of the initial budget, the level of Accumulated APNPE stabilization will always be the same. This effectively means that setting up the budget above that value is not effective for a policy-maker. Thus we are interested in determining the MINIMUM initial value of the available budget that yields the MAXIMUM stabilization level for accumulated APNPE. This value corresponds to the maximum value of the budget parameter during the first years of the policy. In our model it is 5,355 million USD.

The determined value of the initial available budget, reflected by the variable Available Budget Calculated, forms the base for the policy tool change.

## 5.5 Policy Runs

There are two policy specifications of interest to a policy-maker. The first one is how much money to put into the available budget of the policy (already discussed in the previous section in details). The second one is for how long the policy should be maintained. Thus, the model contains two policy variables within the policy structure that could be altered by a policy-maker to test different policy designs: Available Budget Fraction and Duration of Carbon Tax Policy. First, we should see the effect of each of those policy variables on the key model's variables separately. Then we will see how they interact with each other.

The key output of the whole model is Incremental Oil Produced. It incorporates both the CCUS development (more $CO_2$ capture translates into more oil produced) and EOR industry dynamics. Figure 32 exhibits the dynamics of Incremental Oil Produced for 7 policy scenarios reflecting the Budget Fraction change.

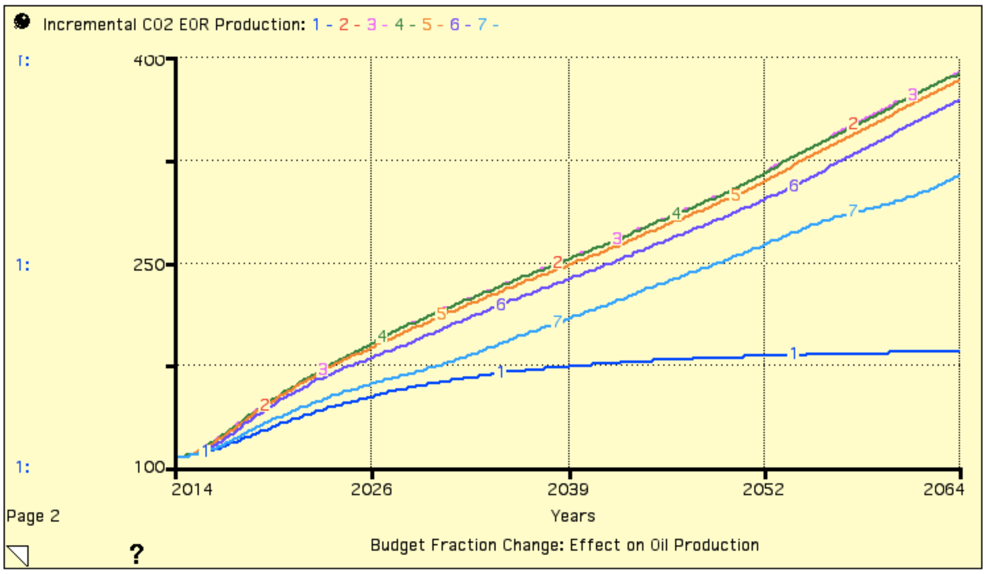


Figure 40. Budget Fraction Change: Oil Production

Here and for further policy testing, the first three runs are shown to set up the benchmark for comparison. Run 1 corresponds to the Base Run as described in Chapter 3, which is the run “as-it-is” with no stimulation for the weak non-functioning feedback loop B1 in the CCUS sector. Run 1 sets the lower bound for the system’s dynamics. Run 2 is the “ideal run” (also described in Chapter 3) of how the system would have behaved if the CCUS market mechanism were perfect. Run 2 sets the upper bound for the potential policies. Let us now see how the remaining 5 scenarios involving the CTCP structure behave within the determined bounds.

Run 3 is the first policy run representing the situation of unlimited (or exactly the one that is needed) budget for the CTCP program and unconstrained (or exactly the one that is needed) duration of CTCP program. The design of CTCP with the initial Available Budget at 5,355 million USD and 40 years of duration (as proposed by NEORI (2012)) fits the definition of run 3.

As Figure 32 demonstrates, Run 3 exactly replicates Run 2, which indicates that the constructed policy in its unconstrained form operates as intended.

As follows from the discussion above the initial value of 5,355 million represents the minimum initial value for the available program’s budget to sustain the maximum possible in the system growth (indicated by Run 2). The hypothetical policy-maker takes this value as the departing one and brings it down by altering the Budget Fraction. In this way we can see whether we can achieve the same or similar growth being more effective in terms spending the financial resources.

An interesting result is that Run 4 (Budget Fraction at 80%), Run 5 (Budget Fraction at 50%) and even Run 6 (Budget Fraction at 30%) produce only slightly lower growth curves.

A more detailed picture is portrayed by Figure 33 giving the dynamic assessment of 2 key reinforcing mechanisms in the system. The graph for Accumulated CTCP Expenses shows when exactly the accumulated policy expenses stabilize. This point indicates that loop R2 is in a full active mode and the market correction mechanism takes over the policy instrument. This is perfectly illustrated by the graph for the Fraction of CCUS PP from The Market, which characterizes the status of the CCUS economics achieved thanks to the policy.

The lower graphs characterize another reinforcing mechanism, introduced by the policy structure, which is the self-financing carbon tax credit program. The graph for Accumulated APNPE shows when and where the APNPE stabilizes, meaning that the costs of the program start being financed entirely by the revenues generated by the program itself. This is also reflected by the fourth graph in Figure 33 indicating when the program's NPV becomes positive and whether it continues growing exponentially or not.

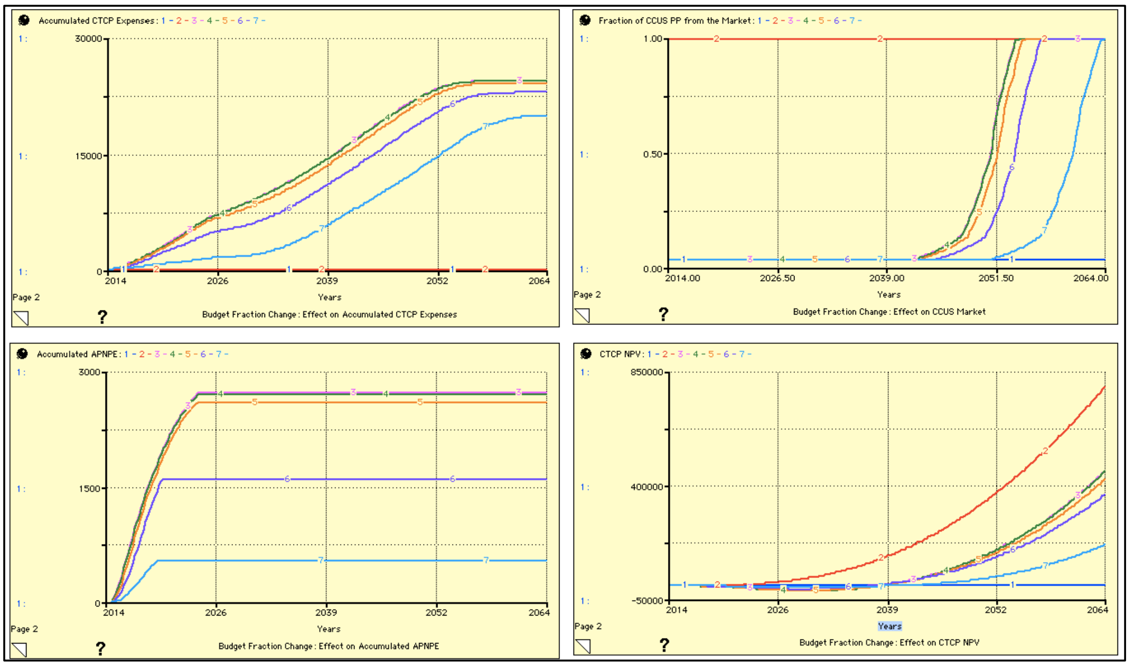


Figure 41. Budget Fraction Change: reinforcing mechanisms

From Figure 32 and Figure 33, only Run 7 (Budget Fraction at 10%) generates significantly lower growth in both oil production and NPV, and late take over by the CCUS market mechanism. Out of all the simulations, Run 6 looks very attractive as it generates a very close to ideal dynamics in oil production and NPV while costing significantly less than any of the previous 5 runs. We emphasize that in order to assess how much a particular program design costs we should look at Accumulated APNPE, which represents only the costs paid directly out of the initial budget for the program (as the program was not self-financing in that period). Looking at CTCP Expenses might be misleading as they incorporate all the costs incurred by the policy, including the ones covered by the policy itself through the generated revenues.

Logically the question arises what are the reasons for such an extremely favorable trade-off between the costs of the policy and its results. The reason is in the feedback structure underlying the operating system (Figure 29). Even with the budget below the maximum budget parameter at initial stages of the stimulation the policy still deploys a certain number of CCUS PP, which then capture $CO_2$ , which then generates oil, and, correspondingly, tax revenues. Thus at certain levels of the available budget even below the budget parameter value we can still have reinforcing loop of the CTCP policy active enough to generate further additions to the policy budget and support further deployment of CCUS capacity. The self-financing mechanism kicks in very quickly and, thus, continues generating the growth dynamics in the system.

The key insight of the policy testing by altering the budget fraction is that due to the additional reinforcing mechanism introduced by self-financing carbon policy the budget well beyond the minimum one, which replicates the “ideal” simulation scenario, can still produce significant growth at much less costs.

Figures 34 and 35 show the results of policy testing for the second policy variable – Duration of CTPC. As in the previous part we were altering the Budget Fraction while keeping the duration of the program at its least value providing the most favorable result, here we freeze the initial budget at 100% of its initial value and change just the duration of the program.

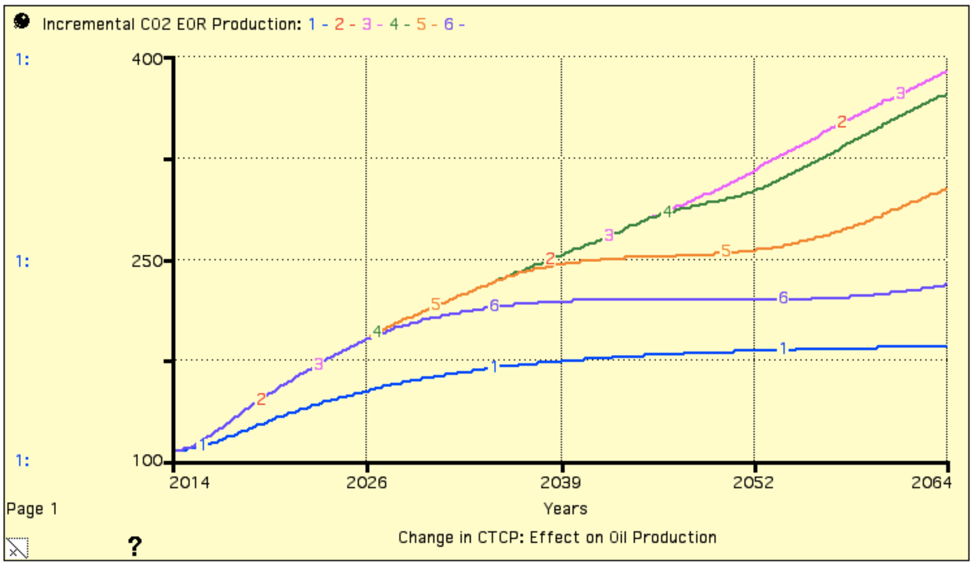


Figure 42. Change in CTCP Duration: Oil Production

Already in Figure 34 we can see how different the effect of the Duration of CTCP is from the effect of the Budget Fraction change. In none of the policy simulations with the budget fraction we could detect the change in dynamics. The magnitudes of the growth were different, but the growth dynamics still remained.

Figure 34 portrays a very different situation. The key question for this policy testing is whether after the closure of the policy program the growth continues. Only run 4 (Duration is set at 30 years) provides dynamics similar to the ideal run. Even though there is a slight slow-down after the closure of the program (year 2044), the system then manages to catch up pretty quickly and continues the growth. Run 5 (Duration at 20 years) demonstrates a much longer “recovery” of the system. Run 6 (Duration at 10 years) shows the early sign of the recovery only by the end of the simulation period. A big chunk of the potential for the recovered oil was just simply lost due to the premature closure of the CTCP.

Again, a more detailed picture incorporating the dynamics of the CCUS market and the self-financing potential of the CTCP under this design is exhibited by Figure 35.

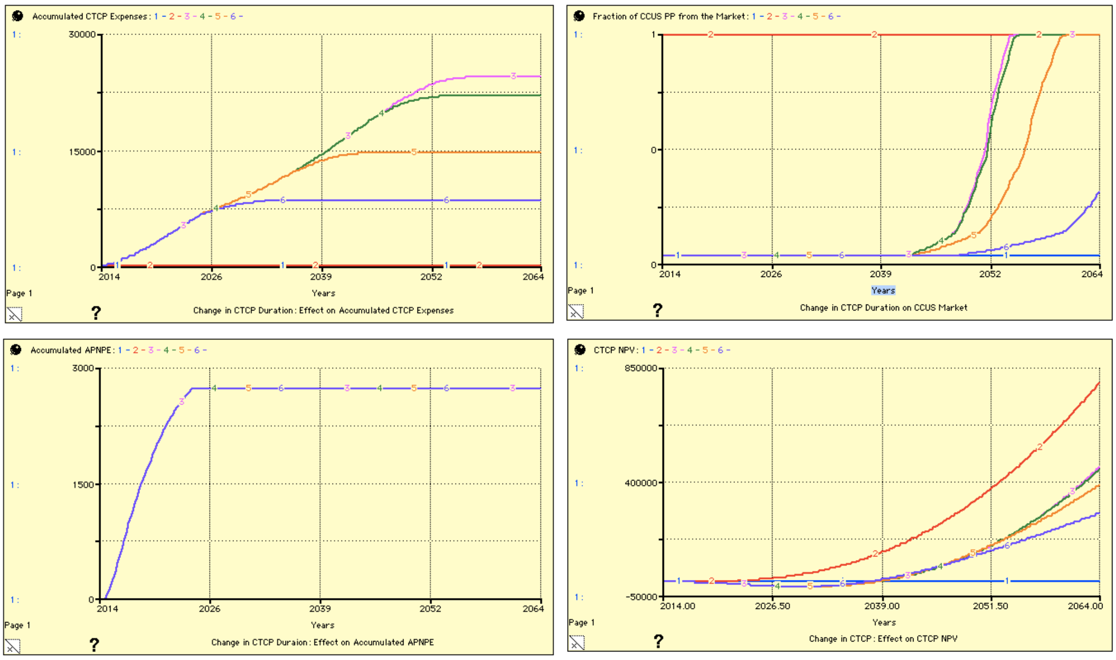


**Figure 43. Change in CTCP Duration: Reinforcing Mechanisms**

Two observations from Figure 35 strike the attention immediately. First, while changing the budget fraction always changed the level at which accumulated APNPE stabilized, none of the scenarios involving the duration of CTCP produced the difference in the dynamics of that variable. The reason for this observation is, however, trivial: with the budget at 100% of the initial value, the CTCP becomes self-financing within the first 10 years of the program. This means that whether the program shuts down after the first 10 years or after the 30 years, the APNPE costs stabilize within the 10-year period.

The second observation reveals more crucial insights. While changing the budget fraction we observed the activation of CCUS market mechanism at different time (sooner or later). With the Duration of CTCP design policies the Market Fraction initiates the change at around the same time for all the policy runs. Yet, the further strengthening of the market mechanism varies significantly for different runs. Run 6 demonstrates a very slow awakening of the market mechanism (and loop R2 behind it). This explains why the growth recovery of the Incremental Oil Production for Run 5 and Run 6 (Figure 34) are so slow: the market mechanism is simply not ready to take over the carbon policy even though this policy becomes self-financing. The market mechanism cannot gain its momentum because the carbon policy was closed too early to build up the necessary capture rate so as the learning effects would start kicking in.

The key insight of the policy testing by altering the Duration of the CTCP is that a policy-maker should be careful about closing the carbon policy prematurely even if it reaches the point of self-financing relatively quickly. A premature closure of the program would not allow the balancing loop B1 to accumulate enough $CO_2$ capture to enable the loop R2 to activate the learning effect.

The analysis of the two policy variables separately and the insights taken from such analysis motivates the simulation of hybrid policy design based on the change of both variable at the same time. In the case of the policy duration variable, a policy-maker should definitely refrain from the designs producing Run 6. However, Run 4 saves on 10 years of the policy costs but generates a similar growth dynamics as it builds up enough momentum to make the CCUS market mechanisms fully operational.

Based on the conducted *ceteris paribus* analysis we can already exclude clearly disadvantageous runs: Run 7 from the budget fraction case and Run 6 from the CTCP Duration case. Thus, we are left with the policy designs involving Budget Fraction at values 100%, 80%, 50% and 30% and CTCP Duration as values 40, 30 and 20 years. This gives us a matrix of 12 policies. Three of them have already been analyzed (all the CTCP Duration values for the Budget Fraction at 100%), yet not against each other only. Figure 36 and Figure 37 portray the dynamic comparison of the 12 hybrid policies.

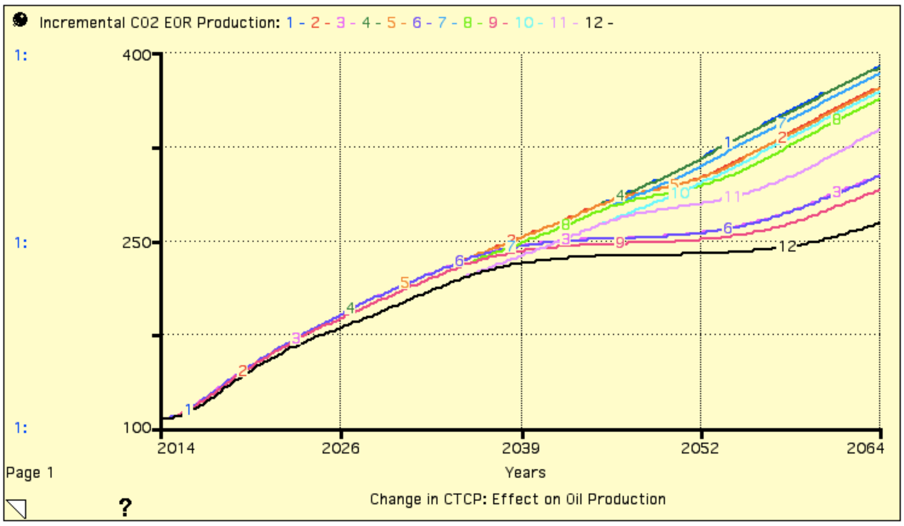


Figure 44. 12 Hybrid Policies

However, it is useful to supplement the dynamic analysis with the end-value comparison represented by Table 1. The end-values, however, are obtained from the 12 corresponding simulations.

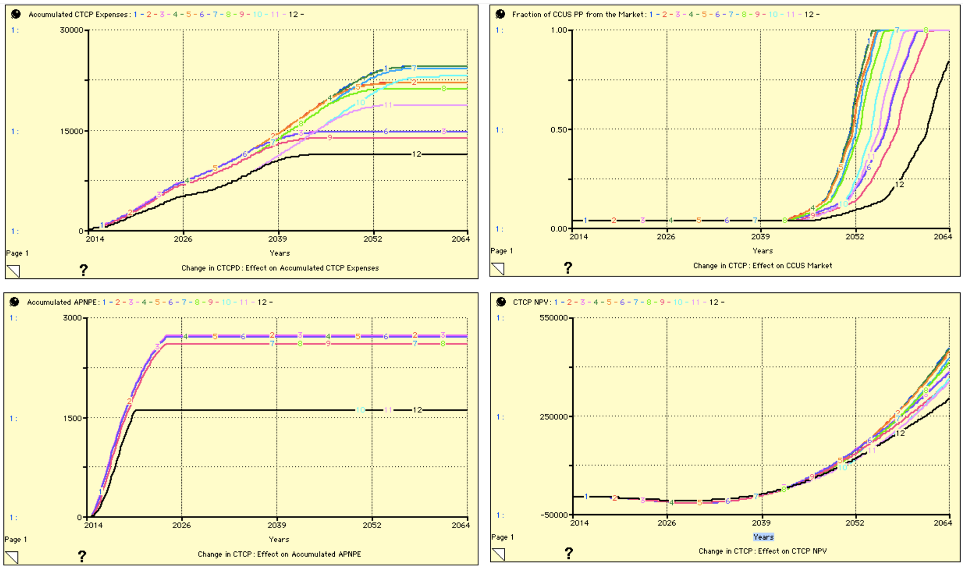


Figure 45. 12 Hybrid Policies: Dynamic Assessment

As the described policy choices involve certain trade-offs (e.g., more growth at a higher cost, while slightly less growth at a much less cost), Table 1 incorporates 4 criteria that were determined to be useful by a policy-maker in choosing a particular policy design:

1. How much oil can be recovered with this policy? This also reflects how much $CO_2$ can be captured under the policy.
2. What is the cost of the policy design (based on APNPE = the expenses not covered by the policy revenues).
3. How does the policy influence the status of CCUS market? Namely, how quickly the market fraction of 1 is achieved so as the system could rely on the market entirely.
4. How much value does the policy generate? Even though the original motivation behind the policy is not money-generation, this criterion might be useful in advocating he policy to various stakeholders.

Let us see which runs might be of interest to a policy-maker. According to Figure 36, runs 6, 3, 9 and 12 (Duration Policy = 20 years) provide comparatively insufficient growth in incremental oil production that cannot be maintained after the program closure. This means that these policy designs are not able to generate strong enough reinforcing mechanisms able to sustain the growth within the system.

Note that all the policy designs are able to generate an exponential self-sustaining growth in the NPV as all of them last longer than 10 years required for achieving the payback period. The reinforcing mechanism, which may or may not be launched by the various designs in this set of policies, is CCUS market mechanism. As the graph for CCUS Market Fraction in Figure 37 shows, the policies corresponding to simulation runs 1, 2, 4, and 5 are grouped densely together and generate an earlier and faster "awakening" of the CCUS market. This becomes the fundamental reason why those policies generate more recovered oil and higher NPV value.

**Table 1. Policy Designs Comparison**

| Simulation Run | Policy Design | | Cumulative Oil Recovered, mil barrel | Cumulative APNPE (costs), million USD | Year the Market Fraction reaches 1 | NPV, million USD |
|---|---|---|---|---|---|---|
| | Budget Fraction | Policy Duration | | | | |
| 1 | 100% | 40 years | 14075 | 2726 | 2054 | 455724 |
| 2 | | 30 years | 13816 | 2726 | 2055 | 446489 |
| 3 | | 20 years | 12700 | 2726 | 2060 | 383263 |
| 4 | 80% | 40 years | 14062 | 2712 | 2054 | 453552 |
| 5 | | 30 years | 13801 | 2712 | 2055 | 444271 |
| 6 | | 20 years | 12685 | 2712 | 2060 | 381192 |
| 7 | 50% | 40 years | 13865 | 2606 | 2055 | 423677 |
| 8 | | 30 years | 13506 | 2606 | 2056 | 413912 |
| 9 | | 20 years | 12460 | 2606 | 2062 | 353492 |
| 10 | 30% | 40 years | 13372 | 1606 | 2057 | 362172 |
| 11 | | 30 years | 12973 | 1606 | 2058 | 352313 |
| 12 | | 20 years | 11492 | 1606 | No | 299683 |

Among the chosen 4 policy designs, the one corresponding to run 5 is particularly appealing as it implies 80% budget fraction and only 30 years of duration. The oil recovery potential is only slightly lower than the one in Run 1. However, the maturation of CCUS market is achieved at around same time and the costs of the program are lower.

From Table 1 and Figure 22, Run 7 (50% budget fraction, 40 years duration) yields an equally good oil recovery and NPV at even lower costs. However, the Market Fraction graph in Figure 37 indicates an already later activation of CCUS market. Thus, if a policy-maker is less interested in the status of CCUS and only cares about the oil production, Run 7 might be preferred. On the contrary, if CCUS market status is of higher importance Run 5 may look better.

The performed analysis illustrates a few key points related to the system we have modeled and the related policies:

1. A complex integrated system such as the $CO_2$-EOR generates a number of key variables reflecting multiple objectives followed by different stakeholders. In the $CO_2$-EOR system these are at least the growth in oil production and more oil recovered (reflected by the variable Incremental Oil Produced) and the development of CCUS market (reflected by the Fraction of CCUS PP by the Market).
2. These objectives are not strictly competing: after all, the potential for achieving one through the other motivated the modeling of the integrated system to begin with. However, the differences in the starting objective might lead to different policy choices with different results. Chapter 1 discussed that in the literature there is a clear distinction between either CCUS or EOR perspective. The client of this project had expressed more interest in the CCUS rather than EOR. The consequences of such original inclination were not obvious in Chapter 2 and 3 when we analyzed the model without the policy. The structure we modeled and the behavior the model produced supported the idea that integration of CCUS and EOR has the potential to reinforce the mutual growth. However, it is the policy analysis that made it implicit: the starting point can determine a different outcome. If a policy-maker cares more about the future of the CCUS, Run 7 would most likely not be chosen no matter how efficient it sounds along the incremental oil/costs of the program dimension. Table 1 demonstrates that there is no much trade-off between the policy choices. However, there is still some space and it can be crucial.
3. The spreadsheet-based end-value analysis is not enough for making the choices about policy options in complex dynamic systems. The end-values indicate the final result. However, in dynamic systems the path towards that result also matters. Policy run 7 yields almost as high NPV value as run 2. However, it is the dynamic path of CCUS market development that might make the difference in the policy choice (revealed by Figure 37).

# Chapter 6. Conclusions

## 6.1. Results

This model constructed to address the thesis presented a broad overview of the potential of CO2 reuse technologies to accelerate the development and deployment of CCS and provided the following insights:

- Strong carbon pricing or equivalent regulatory mechanisms will ultimately be necessary to drive widespread commercial deployment of CCS. However, where demonstration projects do proceed, reuse revenues can act as a moderate offset to CCS costs and help to accelerate the demonstration phase which is an essential pre-cursor to the later commercial deployment phase of development.
- Based on current and forecast markets, the potential CO2 reuse demand is too small for it to make a material contribution to global CO2 abatement, and it does not provide a material alternative to conventional geological storage at the scale required. The value of reuse as a means of accelerating the demonstration and commercial deployment of CCS centres on the supplementary revenue that mature reuse technologies, particularly EOR, provide to demonstration project development in the absence of strong carbon prices.
- Mature CO2 reuse technologies such as EOR can play a useful role in supporting early CCS demonstration, but as the surplus of available CO2 grows and as the longer term bulk CO2 market price weakens, the scope for EOR and the longer-term permanent storage technologies will depend on recognition of their mitigation credentials and their cost competitiveness relative to alternative mitigation options.
- In a strong carbon price environment there is limited potential for reuse technologies where CO2 storage is temporary – except in circumstances where regulators accept that the process either replaces natural reservoir CO2 or the product replaces products derived from fossil fuel.

## 6.2. Limitations and Further Work

The following aspects of the model can be considered as the limitations to the current research and suggest the directions for further work.

- For a more comprehensive analysis it necessary to incorporate the $CO_2$ pipeline structure. The current version of the model assumes that the $CO_2$ capture increases all the way we want it to increase. However, there is an upper bound, which is the maximum $CO_2$ per time that could be transported taken into account the available pipeline network. This upper bound is gradually shifting thanks to the investments into pipeline capacity that also need to be modeled. Additionally, the pipeline structure might play a role in determining expectations about future $CO_2$ supply.
- For the model to be comparable with other models related to the issue and to progress from being a scoping, illustrative level to a type of model that can be used by a policy-maker for precise policy implementation, it needs to differentiate between the sources of $CO_2$ capture. Currently, all the $CO_2$ in the model is generated only by the CCUS power plants. This is perfectly consistent with the scoping nature of the model. However, for more precise purposes, all the sources should be modeled. This is important due to the fact that every source generates different amount of $CO_2$ at different costs. Such differentiation might affect the dynamics in the system.
- A more detailed approach should be taken towards $CO_2$ demand determination. A perspective of $CO_2$-EOR projects with the corresponding stock-and-flow structure of EOR projects maturation chain would generate more accurate results for a number of the variables. Also, this approach would allow a certain parameters, which are stable in the moment to behave dynamically depending on the lifetime of a project.
- The two key mechanisms of the model – the learning effect and the CCUS market mechanism – are depicted in a very simplified way by means of graphical functions. This is extensively justified in the assumptions section (Chapter 2) and corresponds to the purpose of the model. After all, the goal of the modeler was to reproduce the interaction within a complex system of several industries and markets. To focus on the interactions, each separate element had to be kept under as simple but reasonable formulations as possible. However, the further research should focus on

more detailed formulation of those mechanisms. Also, removing uncertainty for the learning effect formulation is crucial.

It is the author's deep belief grounded in his personal experience that our greatest disadvantages are also the source of our most prominent advantages. Also as a true believer into feedback, the reverse could be posed to be true.

The strongest point of this research project and the model that it is based on is the clearly-defined boundaries that allow to generate a consistent behavior relying on a handful of structures. Thus, transparency of the model. This is contrast with NEMS, IAES and other modelling tools. Since the purpose is not decision-making analysis with regard to investing (similar to company-level decisions to invest or not), but rather a strategic analysis/scenario analysis/possibility to see the unfolding of distinct scenarios based on altered assumptions but incorporating feedback loops.

Note that the behavior generated by the smaller strcutures were compared to the ones generated by more detailed structure.

Namely, the model brings up at least two added value points:

- feedback loops – engogenizing; altering assumptions and seeing not liner one-to-one effect but a more realistic perspective
- simplicity and transparency
- deeping conceptualizing part, which is still in the process even when it comes to modelling by NEMS – the golden standard of modelling in this area.

In line with an opening statement to this section, the named advantages lay grounds for model and projects' limitations. A number of things is not considered and, thus, this model cannot be used as a decision-making tool for company level or even country-level analysis. Note however the difference between a scenario level policy analysis and decision-making tool. This model can still be used for evaluating policy-options in the presence of feedbacks.

One potentially very interesting project could be an integrated field/SD model. Such a model would use a "technical", petroleum sub-model to simulate realistic physical flows of oil and CO2 based on the reservoir characteristics. SD sub-model will then use those results to feed into its system. SD model will focus on much broader feedback loops within the overall CO2 EOR and CO2 EOR – CCUS systems, generate and account for more "social" non-linearities and constructs (such as economies of scale, decision-making rules, investments and financial modelling) and in its turn produce input for a technical sub-model.

Such a model would allow to go beyond conceptualizing phase and “in principle” kind of testing/scenario analysis and lay the grounds for a model that could be used

It’s the authors close-to-heart idea of doing a similar project as a part of potential future job-assignments/post-doc etc. Certain contacts have already been made with people potentially interested and capable to cooperate.

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# Appendix A. Model Documentation

The following pages provide the complete model documentation generated by the Stella Architect software, used for the model construction. The documentation includes all the equations, units, initial and parameter values, graphical functions specifications and notes on sources for estimated values, functioning of switches, etc. We hope this documentation would be sufficient for better understanding of the model and potential reproduction by an interested reader.

Top-Level Model:

CCUS:

CCUS_Capacity(t) = CCUS_Capacity(t - dt) + (CCUS_Compeltion_Rate - CCUS_retirement_rate) * dt

INIT CCUS_Capacity = 0

UNITS: Watts

INFLOWS:

CCUS_Compeltion_Rate = DELAY3(CCUS_Start_Rate; CCUS_Construction_Time)

UNITS: Watts/Years

OUTFLOWS:

CCUS_retirement_rate = CCUS_Capacity / Av_CCUS_Lifetime

UNITS: Watts/Years

CCUS_under_Construction(t) = CCUS_under_Construction(t - dt) + (CCUS_Start_Rate - CCUS_Compeltion_Rate) * dt

INIT CCUS_under_Construction = 0

UNITS: Watts

INFLOWS:

CCUS_Start_Rate = Indicated_New_CCUS

UNITS: Watts/Years

OUTFLOWS:

CCUS_Compeltion_Rate = DELAY3(CCUS_Start_Rate; CCUS_Construction_Time)

UNITS: Watts/Years

Cumulative_CCUS_Retirement(t) = Cumulative_CCUS_Retirement(t - dt) + (CCUS_retirement_rate) * dt

INIT Cumulative_CCUS_Retirement = 0

UNITS: Watts

INFLOWS:

CCUS_retirement_rate = CCUS_Capacity / Av_CCUS_Lifetime

UNITS: Watts/Years

Cumulative_CO2_Storage(t) = Cumulative_CO2_Storage(t - dt) + (CO2_Storage_Rate) * dt

INIT Cumulative_CO2_Storage = 0

UNITS: tonne

INFLOWS:

CO2_Storage_Rate = fraction_of_CO2_to_Storage*CO2_Production_Rate

UNITS: tonne/Years

Av_CCUS_Lifetime = 30

UNITS: year

Carbon_Price_to_CO2_Costs_Ratio = Policy_and_Scenarios.Carbon_Price/CO2_Costs

UNITS: Dimensionless

CCUS_AT = 10

UNITS: years

CCUS_Capacity_Ratio = Cumulative_CCUS_Capacity/Reference_CCUS_Capacity

UNITS: Dimensionless

CCUS_Construction_Time = 3

UNITS: year

CCUS_UC_Adj = (Desired_CCUS_UC-CCUS_under_Construction)/CCUS_UC_AT

UNITS: Watts/Years

CCUS_UC_AT = 1

UNITS: years

CO2_Costs = CO2_Costs_Initial*Learning_Effect_for_CCUS

UNITS: USD/tonne

CO2_Costs_Initial = 75

UNITS: USD/tonne

CO2_per_CCUS = 0,006

UNITS: tonne/Watt/year

CO2_Production_Rate = CCUS_Capacity*CO2_per_CCUS

UNITS: tonne/Years

CO2_Purchase_Price_to_Costs_Ratio = EOR.CO2_Purchase_Price/CO2_Costs

UNITS: Dimensionless

CO2_Sales_to_EOR = CO2_Production_Rate-CO2_Storage_Rate

UNITS: tonne/Years

Cumulative_CCUS_Capacity = Cumulative_CCUS_Retirement+CCUS_Capacity

UNITS: Watts

Desired_CCUS_Capacity = 100000000000

UNITS: Watts

Desired_CCUS_UC = LR_CCUS_Retirement_Rate*CCUS_Construction_Time

UNITS: Watts

effect_of_carbon_price_on_new_CCUS = GRAPH(Carbon_Price_to_CO2_Costs_Ratio)

(0,000, 0,00), (0,100, 0,50), (0,200, 1,00), (0,300, 1,30), (0,400, 1,73), (0,500, 2,66), (0,600, 4,83), (0,700, 7,18), (0,800, 10,53), (0,900, 15,73), (1,000, 19,13), (1,100, 20,00), (1,200, 20,00), (1,300, 20,00), (1,400, 20,00), (1,500, 20,00)

UNITS: Dimensionless

Effect_of_CO2_Purchase_Price_to_Costs_Ratio_on_Fraction_CCUS_Commercial = GRAPH(CO2_Purchase_Price_to_Costs_Ratio)

(0,000, 0,40), (0,100, 0,50), (0,200, 0,60), (0,300, 0,70), (0,400, 0,80), (0,500, 0,90), (0,600, 1,00), (0,700, 1,61), (0,800, 2,41), (0,900, 4,09), (1,000, 8,24), (1,100, 15,11), (1,200, 19,01), (1,300, 20,00), (1,400, 20,00), (1,500, 20,00)

UNITS: Dimensionless

Effect_of_Relative_Attractiveness_of_Storage_on_Fraction_to_Storage = GRAPH(Relative_Attractiveness_of_Storage_to_EOR)

(0,000, 0,000), (0,100, 0,124), (0,200, 0,458), (0,300, 1,000), (0,400, 1,077), (0,500, 1,152), (0,600, 1,362), (0,700, 1,746), (0,800, 2,266), (0,900, 2,873), (1,000, 3,344), (1,100, 3,901), (1,200, 4,000), (1,300, 4,000), (1,400, 4,000), (1,500, 4,000)

UNITS: Dimensionless

Fraction_of_CCUS_Commercial = Initial_Fraction_of_CCUS_Commercial*Effect_of_CO2_Purchase_Price_to_Costs_Ratio_on_Fraction_CCUS_Commercial

UNITS: Dimensionless

fraction_of_CO2_to_Storage = Initial_fraction_of_EOR_to_Storage*Effect_of_Relative_Attractiveness_of_Storage_on_Fraction_to_Storage

UNITS: Dimensionless

Fraction_of_new_CCUS_from_Carbon_Regulation = initial_fraction_new_CCUS_by_carbon_policy*effect_of_carbon_price_on_new_CCUS

UNITS: Dimensionless

Indicated_New_CCUS = MAX(new_CCUS_from_EOR+new_CCUS_from_Carbon_Policy; 0)

UNITS: Watts/Years

initial_fraction_new_CCUS_by_carbon_policy = 0,05

UNITS: Dimensionless

Initial_Fraction_of_CCUS_Commercial = 0,1

UNITS: Dimensionless

Initial_fraction_of_EOR_to_Storage = 0,25

UNITS: Dimensionless

Learning_Effect_for_CCUS = GRAPH(CCUS_Capacity_Ratio)

(0,00, 1,000), (1,00, 1,000), (2,00, 0,950), (3,00, 0,916), (4,00, 0,867), (5,00, 0,793), (6,00, 0,579), (7,00, 0,276), (8,00, 0,195), (9,00, 0,139), (10,00, 0,127)

UNITS: Dimensionless

Learning_Effect_for_CO2_Storage = GRAPH(Relative_CO2_Storage)

(0,00, 1,000), (1,00, 1,000), (2,00, 0,950), (3,00, 0,916), (4,00, 0,867), (5,00, 0,793), (6,00, 0,579), (7,00, 0,276), (8,00, 0,195), (9,00, 0,139), (10,00, 0,127)

UNITS: Dimensionless

LR_CCUS_Retirement_Rate = Desired_CCUS_Capacity/Av_CCUS_Lifetime

UNITS: Watts/Years

Net_Carbon_Price = Policy_and_Scenarios.Carbon_Price-Storage_Costs

UNITS: USD/tonne

new_CCUS_from_Carbon_Policy = (new_CCUS_from_conversion_target-new_CCUS_from_EOR)*Fraction_of_new_CCUS_from_Carbon_Regulation

UNITS: Watts/Years

new_CCUS_from_conversion_target = (Desired_CCUS_Capacity-CCUS_Capacity)/CCUS_AT+CCUS_UC_Adj+CCUS_retirement_rate

UNITS: Watts/Years

new_CCUS_from_EOR = EOR.CCUS_Demanded_by_EOR*Fraction_of_CCUS_Commercial*0

UNITS: Watts/Years

Reference_CCUS_Capacity = 30000000000

UNITS: Watts

Reference_CO2_Storage = 1000000000

UNITS: tonne

Relative_Attractiveness_of_Storage_to_EOR = Net_Carbon_Price/EOR.CO2_Purchase_Price

UNITS: Dimensionless

Relative_CO2_Storage = Cumulative_CO2_Storage/Reference_CO2_Storage

UNITS: Dimensionless

Storage_Costs = Storage_Costs_Initial*Learning_Effect_for_CO2_Storage

UNITS: USD/tonne

Storage_Costs_Initial = 15

UNITS: USD/tonne

EOR:

EOR_Capacity(t) = EOR_Capacity(t - dt) + (new_EOR_Capacity - EOR_Capacity_Retirement_rate) * dt

INIT EOR_Capacity = 281000*365

UNITS: bbl/Years

INFLOWS:

new_EOR_Capacity = DELAY3(Indicated_new_EOR_Capacity; Av_EOR_Cap_Construction_Time)

UNITS: bbl/Years/Years

OUTFLOWS:

EOR_Capacity_Retirement_rate = EOR_Capacity/Av_EOR_Cap_Lifetime

UNITS: bbl/Years/Years

EOR_Reserves(t) = EOR_Reserves(t - dt) + ( - EOR_Production) * dt

INIT EOR_Reserves = EOR_Reserves_Initial

UNITS: bbl

OUTFLOWS:

EOR_Production = Effective_EOR_Capacity*CUF

UNITS: bbl/Years

Av_EOR_Cap_Construction_Time = 3

UNITS: years

Av_EOR_Cap_Lifetime = 30

UNITS: year

CCUS_Demanded_by_EOR = ((EOR_Production_from_Reserve*CO2_to_Oil_Conversion_Factor)*Effect_of_CO2_Purchase_Price_to_Indic_Purchase_Price_Ratio_on_CCUS_Demanded_by_EOR)/CCUS.CO2_per_CCUS

UNITS: Watts/Years

CO2_Demand_by_EOR = Effective_EOR_Capacity*CO2_to_Oil_Conversion_Factor

UNITS: tonne/Years

CO2_Production_Rate_from_CCUS_UC = CCUS.CCUS_under_Construction*CCUS.CO2_per_CCUS

UNITS: tonne/Years

CO2_Purchase_Price = SMTH3( MIN(CCUS.CO2_Costs; Indicated_CO2_Purchase_Price_by_EOR); 1; 45)

UNITS: USD/tonne

CO2_Purchase_Price_to_Inidcated_CO2_Purchase_Price_Ratio = CO2_Purchase_Price/Indicated_CO2_Purchase_Price_by_EOR

UNITS: Dimensionless

CO2_Supply_Demand_Ratio = CCUS.CO2_Sales_to_EOR/CO2_Demand_by_EOR

UNITS: Dimensionless

CO2_to_Oil_Conversion_Factor = 0,29

UNITS: tonne/bbl

Contract_fraction_of_oil_to_CO2_price = Fraction_of_Oil_Price_to_CO2_Priice/CO2_to_Oil_Conversion_Factor

UNITS: bbl/tonne

CUF = (CCUS.CO2_Sales_to_EOR)/CO2_Demand_by_EOR

UNITS: Dimensionless

Depletion_Effect = GRAPH(EOR_Reserves/EOR_Reserves_Initial)

(0,000, 0,000), (0,200, 0,150), (0,400, 0,300), (0,600, 0,380), (0,800, 0,450), (1,000, 1,000)

UNITS: Dimensionless

Desired_EOR_Capacity = MIN(EOR_Production_from_Reserve; EOR_Production_from_CO2)

UNITS: bbl/Years

Effect_of_CO2_Purchase_Price_to_Indic_Purchase_Price_Ratio_on_CCUS_Demanded_by_EOR = GRAPH(CO2_Purchase_Price_to_Inidcated_CO2_Purchase_Price_Ratio)

(0,000, 0,030), (0,100, 0,100), (0,200, 0,200), (0,300, 0,300), (0,400, 0,400), (0,500, 0,500), (0,600, 0,600), (0,700, 0,700), (0,800, 0,800), (0,900, 0,900), (1,000, 1,000), (1,100, 1,000), (1,200, 1,000)

UNITS: Dimensionless/year

Effect_of_CO2_Purchase_Price_to_Indic_Purchase_Price_Ratio_on_planned_EOR_Production = GRAPH(CO2_Purchase_Price_to_Inidcated_CO2_Purchase_Price_Ratio)

(0,000, 0,030), (0,100, 0,100), (0,200, 0,200), (0,300, 0,300), (0,400, 0,400), (0,500, 0,500), (0,600, 0,600), (0,700, 0,700), (0,800, 0,800), (0,900, 0,900), (1,000, 1,000), (1,100, 1,000), (1,200, 1,000)

UNITS: Dimensionless

Effect_of_Supply_Demand_Balance_on_Fraction_of_Oil_Price_to_Indicated_CO2_Price = GRAPH(CO2_Supply_Demand_Ratio)

(0,000, 2,000), (0,100, 2,000), (0,200, 1,865), (0,300, 1,784), (0,400, 1,541), (0,500, 1,360), (0,600, 1,234), (0,700, 1,144), (0,800, 1,072), (0,900, 1,072), (1,000, 1,000), (1,100, 0,982), (1,200, 0,829)

UNITS: Dimensionless

Effective_EOR_Capacity = EOR_Capacity*Depletion_Effect

UNITS: bbl/Years

EOR_AT = 3

UNITS: years

EOR_Production_from_CO2 = (Expected_CO2_Supply*Effect_of_CO2_Purchase_Price_to_Indic_Purchase_Price_Ratio_on_planned_EOR_Production)/CO2_to_Oil_Conversion_Factor

UNITS: bbl/Years

EOR_Production_from_Reserve = EOR_Reserves/Production_Reserve_Ratio

UNITS: bbl/Years

EOR_Reserves_Initial = 60204E6

UNITS: bbl

Expected_CO2_Supply = SMTH3(CCUS.CO2_Production_Rate+CO2_Production_Rate_from_CCUS_UC; 3)

UNITS: tonne/Years

Fraction_of_Oil_Price_to_CO2_Priice = normal_fraction_of_oil_to_CO2_price*Effect_of_Supply_Demand_Balance_on_Fraction_of_Oil_Price_to_Indicated_CO2_Price

UNITS: Dimensionless

Indicated_CO2_Purchase_Price_by_EOR = Policy_and_Scenarios.Oil_Price*Contract_fraction_of_oil_to_CO2_price

UNITS: USD/tonne

Indicated_new_EOR_Capacity = MAX((Desired_EOR_Capacity-EOR_Capacity)/EOR_AT+EOR_Capacity_Retirement_rate; 0)

UNITS: bbl/Years/Years

normal_fraction_of_oil_to_CO2_price = 0,09

UNITS: Dimensionless

Production_Reserve_Ratio = 50

UNITS: years

Policy_and_Scenarios:

Carbon_Price = (Switch_User_Carbon_Price)*User_Carbon_Price+Carbon_Price_Scenario*(1-Switch_User_Carbon_Price)

UNITS: USD/tonne

DOCUMENT: Carbon Price 2 scenarios: upper and lower bounds (stronger "450 Scenario" and weaker caron prices) Figure 4.2

Carbon_Price_Scenario = (Carbon_Price_Strong*Switch_Carbon_Price_Strong+Carbon_Price_Weak*(1-Switch_Carbon_Price_Strong))

UNITS: USD/tonne

Carbon_Price_Strong = GRAPH(TIME)

(2010,00, 30,0), (2013,33333333, 32,2), (2016,66666667, 37,0), (2020,00, 50,0), (2023,33333333, 60,7), (2026,66666667, 77,1), (2030,00, 110,0), (2033,33333333, 110,0), (2036,66666667, 110,0), (2040,00, 110,0), (2043,33333333, 110,0), (2046,66666667, 110,0), (2050,00, 110,0)

UNITS: USD/tonne

Carbon_Price_Weak = GRAPH(TIME)

(2010,00, 15,0), (2013,33333333, 14,2), (2016,66666667, 16,4), (2020,00, 20,0), (2023,33333333, 21,2), (2026,66666667, 23,1), (2030,00, 27,5), (2033,33333333, 29,4), (2036,66666667, 32,6), (2040,00, 37,3), (2043,33333333, 43,0), (2046,66666667, 48,0), (2050,00, 53,7)

UNITS: USD/tonne

High_Low_Oil_Price_Scenario = (Oil_Price_High*Switch_Oil_Price_High+Oil_Price_Low*(1-Switch_Oil_Price_High))

UNITS: USD/Bbl

Oil_Price = (Switch_Oil_Price_Medium)*Oil_Price_Medium+High_Low_Oil_Price_Scenario*(1-Switch_Oil_Price_Medium)

UNITS: USD/Bbl

DOCUMENT: Carbon Price 2 scenarios: upper and lower bounds (stronger "450 Scenario" and weaker caron prices) Figure 4.2

Oil_Price_High = GRAPH(TIME)

(2010,00, 72,19), (2011,00, 87,96), (2012,00, 88,79), (2013,00, 93,9955649872), (2014,00, 90,98), (2015,00, 49,35), (2016,00, 42,78), (2017,00, 48,94), (2018,00, 57,43), (2019,00, 64,38), (2020,00, 68,85), (2021,00, 71,85), (2022,00, 74,6), (2023,00, 76,01), (2024,00, 77,54), (2025,00, 80,08), (2026,00, 82,36), (2027,00, 83,57), (2028,00, 84,07), (2029,00, 85,05), (2030,00, 87,59), (2031,00, 89,98), (2032,00, 92,71), (2033,00, 92,85), (2034,00, 94,83), (2035,00, 95,58), (2036,00, 98,47), (2037,00, 98,97), (2038,00, 100,15), (2039,00, 101,87), (2040,00, 102,86), (2041,00, 103,52), (2042,00, 103,77), (2043,00, 104,36), (2044,00, 104,94), (2045,00, 105,6), (2046,00, 106,58), (2047,00, 107,69), (2048,00, 107,92), (2049,00, 109,37), (2050,00, 110,35), (2051,00, 110,35), (2052,00, 110,35), (2053,00, 110,35), (2054,00, 110,35), (2055,00, 110,35), (2056,00, 110,35), (2057,00, 110,35), (2058,00, 110,35), (2059,00, 110,35), (2060,00, 110,35), (2061,00, 110,35), (2062,00, 110,35), (2063,00, 110,3), (2064,00, 110,3), (2065,00, 110,3), (2066,00, 110,3), (2067,00, 110,3), (2068,00, 110,3), (2069,00, 110,3), (2070,00, 110,3), (2071,00, 110,3), (2072,00, 110,3), (2073,00, 110,3), (2074,00, 110,3), (2075,00, 110,3), (2076,00, 110,3), (2077,00, 110,3), (2078,00, 110,3), (2079,00, 110,3), (2080,00, 110,3), (2081,00, 110,3), (2082,00, 110,3), (2083,00, 110,3), (2084,00, 110,3), (2085,00, 110,3), (2086,00, 110,3), (2087,00, 110,3), (2088,00, 110,3), (2089,00, 110,3), (2090,00, 110,3), (2091,00, 110,3), (2092,00, 110,3), (2093,00, 110,3), (2094,00, 110,3), (2095,00, 110,3), (2096,00, 110,3), (2097,00, 110,3), (2098,00, 110,3), (2099,00, 110,3), (2100,00, 110,3)

UNITS: USD/Bbl

Oil_Price_Low = GRAPH(TIME)

(2010,00, 72,19), (2011,00, 87,96), (2012,00, 88,79), (2013,00, 93,9955649872), (2014,00, 90,98), (2015,00, 49,35), (2016,00, 42,78), (2017,00, 45,8), (2018,00, 47,0), (2019,00, 47,7), (2020,00, 47,9), (2021,00, 48,9), (2022,00, 49,6), (2023,00, 49,8), (2024,00, 50,5), (2025,00, 51,0), (2026,00, 51,2), (2027,00, 51,7), (2028,00, 51,9), (2029,00, 52,1), (2030,00, 52,1), (2031,00, 52,4), (2032,00, 52,6), (2033,00, 52,6), (2034,00, 52,8), (2035,00, 53,3), (2036,00, 53,5), (2037,00, 53,5), (2038,00, 53,5), (2039,00, 53,5), (2040,00, 53,5), (2041,00, 54,0), (2042,00, 54,0), (2043,00, 54,2), (2044,00, 54,5), (2045,00, 54,5), (2046,00, 54,7), (2047,00, 54,7), (2048,00, 54,7), (2049,00, 54,7), (2050,00, 55,4), (2051,00, 55,4), (2052,00, 55,4), (2053,00, 55,4), (2054,00, 55,4), (2055,00, 55,4), (2056,00, 55,4), (2057,00, 55,6), (2058,00, 56,1), (2059,00, 56,3), (2060,00, 57,0), (2061,00, 57,0), (2062,00, 57,3), (2063,00, 57,7), (2064,00, 58,2), (2065,00, 58,2), (2066,00, 58,4), (2067,00, 58,4), (2068,00, 58,4), (2069,00, 58,4), (2070,00, 58,7), (2071,00, 59,1), (2072,00, 59,35), (2073,00, 59,6), (2074,00, 59,95), (2075,00, 60,3), (2076,00, 61,0), (2077,00, 61,3), (2078,00, 61,3), (2079,00, 61,4), (2080,00, 61,5), (2081,00, 61,7), (2082,00, 61,7), (2083,00, 61,7), (2084,00, 61,7), (2085,00, 61,7), (2086,00, 62,0), (2087,00, 62,2), (2088,00, 62,2), (2089,00, 62,2), (2090,00, 62,2), (2091,00, 62,2), (2092,00, 62,2), (2093,00, 62,4), (2094,00, 62,4), (2095,00, 62,4), (2096,00, 62,4), (2097,00, 62,7), (2098,00, 62,7), (2099,00, 62,7), (2100,00, 62,9)

UNITS: USD/Bbl

Oil_Price_Medium = GRAPH(TIME)

(2010,00, 72,19), (2011,00, 87,96), (2012,00, 88,79), (2013,00, 93,9955649872), (2014,00, 90,98), (2015,00, 49,35), (2016,00, 42,78), (2017,00, 48,94), (2018,00, 53,3), (2019,00, 54,7), (2020,00, 55,9), (2021,00, 56,8), (2022,00, 58,0), (2023,00, 58,7), (2024,00, 59,9), (2025,00, 61,7), (2026,00, 62,9), (2027,00, 64,1), (2028,00, 65,0), (2029,00, 65,5), (2030,00, 66,4), (2031,00, 67,8), (2032,00, 68,6), (2033,00, 69,4), (2034,00, 69,75), (2035,00, 70,4), (2036,00, 70,5), (2037,00, 70,6), (2038,00, 71,3), (2039,00, 71,8), (2040,00, 72,0), (2041,00, 72,5), (2042,00, 73,4), (2043,00, 73,9), (2044,00, 74,1), (2045,00, 74,6), (2046,00, 74,95), (2047,00, 75,3), (2048,00, 75,65), (2049,00, 76,0), (2050,00, 76,45), (2051,00, 76,9), (2052,00, 77,25), (2053,00, 77,6), (2054,00, 77,85), (2055,00, 78,1), (2056,00, 78,3), (2057,00, 78,3), (2058,00, 78,3), (2059,00, 78,45), (2060,00, 78,6), (2061,00, 78,8), (2062,00, 79,0), (2063,00, 79,2333333333), (2064,00, 79,4666666667), (2065,00, 79,7), (2066,00, 79,9333333333), (2067,00, 80,1666666667), (2068,00, 80,4), (2069,00, 80,6333333333), (2070,00, 80,8666666667), (2071,00, 81,1), (2072,00, 81,25), (2073,00, 81,4), (2074,00, 81,6), (2075,00, 81,8), (2076,00, 81,8), (2077,00, 81,8), (2078,00, 81,8), (2079,00, 82,1), (2080,00, 82,2), (2081,00, 82,3), (2082,00, 82,4), (2083,00, 82,5), (2084,00, 82,5), (2085,00, 82,5), (2086,00, 82,5), (2087,00, 82,5), (2088,00, 82,5), (2089,00, 82,5), (2090,00, 82,5), (2091,00, 82,5), (2092,00, 82,8), (2093,00, 83,0), (2094,00, 83,0), (2095,00, 83,0), (2096,00, 83,2), (2097,00, 83,2), (2098,00, 83,5), (2099,00, 83,5), (2100,00, 83,9)

UNITS: USD/Bbl

Switch_Carbon_Price_Strong = 0

UNITS: Dimensionless

Switch_Oil_Price_High = 1

UNITS: Dimensionless

Switch_Oil_Price_Medium = 0

UNITS: Dimensionless

Switch_User_Carbon_Price = 0

UNITS: Dimensionless

User_Carbon_Price = GRAPH(TIME)

```
(2010,00, 0,000), (2014,00, 0,000), (2018,00, 0,000), (2022,00, 0,000), (2026,00, 0,000), (2030,00, 0,000), (2034,00, 0,000), (2038,00, 0,000), (2042,00, 0,000), (2046,00, 0,000), (2050,00, 0,000)
  UNITS: USD/tonne
{ The model has 103 (103) variables (array expansion in parens).
 In root model and 3 additional modules with 2 sectors.
 Stocks: 6 (6) Flows: 7 (7) Converters: 90 (90)
 Constants: 25 (25) Equations: 72 (72) Graphicals: 15 (15)
 There are also 42  expanded macro variables.
 }
```