Carbon Capture Utilization and Storage Market Dynamics: Matching CO_2 Supply and Demand for Enhanced Oil Recovery

By

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Abstract

This thesis describes the project, which is a part of a wider collaboration between the University of Bergen, Norway and the University of North Dakota (UND) and the Institute for Energy Studies (IES), US established in March 2013. The project was performed by Eduard Romanenko, the author of this thesis, together with his European Master in System Dynamics colleague Julian Andres Gill Garcia, who focused on a different but related aspect of the issue, under the supervision of Prof. Pål Davidsen (University of Bergen) and Scott T. Johnson, a Principal Advisor in the IES. The fieldwork was conducted in March-May 2014 in Grand Forks, ND.

There is currently a significant number of carbon capture, utilization, and storage (CCUS) technologies under development and assessment in the US and globally. Most of these technologies have been tested in small scale. The IES has developed and successfully tested the UND technology called CACHYS. Yet, the further commercialization of this and similar technologies is constrained by unfavorable economics of high costs and uncertain potential benefits. On the other hand, there is the CO_2-Enhanced Oil Recovery (EOR) industry whose current development is constrained by the lack of CO_2 supplies. 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. The challenge is that there is a gap between the maximum willingness to pay for CO_2 by EOR operators and the costs of CO_2 capture by the CCUS. Yet, there is a potential for costs reduction attributed to anticipate learning effect in the CCUS industry.

To study the problem, the system dynamics model of an integrated CO_2-EOR-CCUS system, similar to the demand-pull market for carbon dioxide currently developing in the Permian Basin, TX, has been constructed. By making explicit the key feedback structure behind the CO_2-EOR-CCUS system, the model reveals the reinforcing mechanisms that can potentially generate the self-sustaining growth and provides a simulation environment where policies aimed at activating those mechanisms can be tested on their robustness.

The thesis is structured as following. Chapter 1 defines the context, problem, research objectives and research questions. Chapter 2 describes the structure of the model both from stock-and-flow and feedback perspective. Chapter 3 is devoted to the behavior that the model produces. Chapter 4 establishes the confidence in the model through validation analysis. Chapter 5 deals with policy design and testing. The thesis concludes with the summary of results, a discussion on limitations and directions for further work.

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 Client, Problem Description and Problem Definition

The project, which the described in this thesis model-building effort refers to, is a part of a wider collaboration between the University of Bergen, Norway and the University of North Dakota (UND), US established in March 2013.

The oil boom that North Dakota (ND) currently experiences leads to a number of complex and interrelated problems of socio-economic, ecological and environmental development of the area. While the description of this broad set of problems is beyond the scope of this thesis, it is important to note that the system dynamics approach was specifically requested by the UND to develop tools for coherent balance planning of sustainable development of the region. This specific project deals with the economics of carbon capture, utilization and storage technologies (CCUS) as linked to the enhanced oil recovery.

The motivation for the project originates foremost in the current research interests and ongoing research activities of the client. The term client is used to refer to the Institute for Energy Studies (IES), a research group created on the basis of the UND and its Department of Petroleum Engineering with a vision to pursue "new frontiers in energy research which would enable the development of integrated energy technologies that are economically competitive, reliable, sustainable, and politically and environmentally acceptable" (und.edu/features/2013/06/carbon-capture.cfm).

Scott T. Johnson, a principal advisor in the IES and an instructor in the UND Department of Petroleum Engineering, was a primary contact person who set up the project collaboration and participated in all the stages of the project work. Another important person involved in the project on the client's side was Steve Benson, chair of the UND Department of Petroleum Engineering and director of the IES.

The problem formulation was shaped as the result of the process of matching two separate but interconnected issue areas (as both of them are too complex to be labeled just issues), which were of great interest to the client. It is important to emphasize in the very beginning that initially the client just indicated the broad issue areas of their interests with potential specifications. The precise choice of specific research within the announced issue areas was delegated to the modeling team. This choice, however, was to be made in agreement with the client.

The first area is coming from a new research activity within the IES, which to a great extent represents one of the priorities of the research work there. A great chunk of the current research efforts in the IES is directed to the issue of carbon capture.

There are currently a significant number of carbon capture and a broader set of carbon capture, utilization, and storage (CCUS) technologies under development and assessment in the US and globally. CCUS is usually defined as “a set of technologies that mitigate CO_2 emissions into the atmosphere. CO_2 is captured from a large and stationary source of emissions (power or industrial plants), compressed, and transported in a liquefied state by pipelines or ships, and definitely stored out of the atmosphere” (SBC Energy Institute, 2012). A more detailed description of CCUS value chain and designs, which are crucial for this thesis, is contained in section 1.5 of this chapter. This technological development is very important in that the successful application of these technologies will determine to what extent the fossil energy reserves may be utilized.

Most of these technologies have been tested in small scale. The work of the IES represents an example of that development. As a part of the $3.7 million project funded by the US Department of Energy and industry (ALLETE, SaskPower, and the North Dakota Lignite Energy Council), Steve Benson and his team of well-known experts in the field of fuel gas emissions control have been developing a carbon capture technology that is both more effective and cheaper than currently available carbon capture methods. The UND technology, called “CO_2 Capture by Hybrid Sorption Using Solid Sorbents” (CACHYS, pronounced “catches”) was successfully tested on a pilot case at the UND Steam Plant. Logically, the next stream of the IES efforts is directed to commercialization of the developed carbon capture technology.

The success of the pilot scale testing and the need for commercialization, led the IES research team to the realization that understanding the market for CCUS technologies is crucial for further research efforts. The necessity for pushing CCUS projects though the pilot and demonstration phases to commercialization, which characterizes the CACHYS project, is applicable to the whole CCUS industry. According to the survey conducted by the SBC Energy Institute, 89% of 27 interviews actors in the CCUS industry, indicated the main challenge to commercialization of CCUS projects as “economics do not match”, meaning that (a) market conditions -

CO_2 prices or carbon taxes – are not high enough to allows large development of CCS and (b) direct government subsidies are not sufficient (SBC Energy Institute, 2012).

The fact that at the moment CCUS technology remains too expensive to be deployed at a commercial level motivates the developers of the CCUS technologies, such as the client of our project, to look for the potential sources of demand for the captured CO_2. As mentioned by Scott T. Jonson during the project work: "We have an effective technology for carbon capture… now, a question which might interest us a lot is… if we transform all the coal power plants in the state of North Dakota into CCUS power plants, would there be enough demand for the captured CO_2 to justify this transformation?"[1]

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

[1] As discussed on April 22, 2014 during the presentation of the demo version of the system dynamics model, Grand Forks, ND, US. The participants of the meeting: Scott T. Johnson, Eduard Romanenko, Julian Andres Gill Garcia.

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.

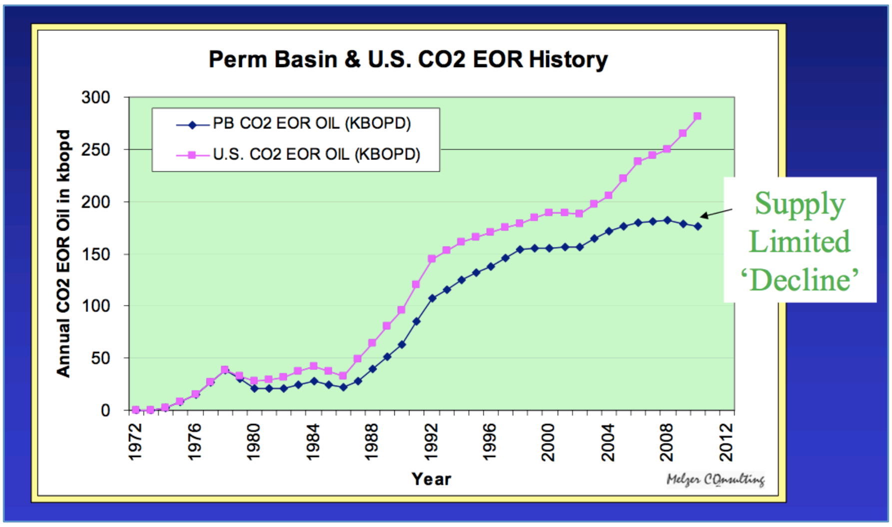

Figure 1. US and Permian Basin CO2-EOR Production Growth (1972-2010)
Source: Hargrove B., et al. (2010)

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.

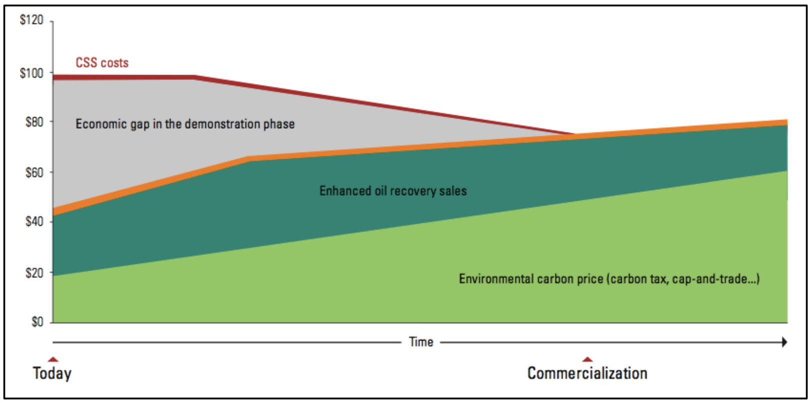

Figure 2. Conceptual Portrayel of CCUS Economics. Source: SBC Institute (2012)

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

In accordance with the problem definition in the previous section, the research objectives and corresponding research questions have been formulated. To address the defined problem, the research project was designed to follow two objectives.

The first objective is to investigate the economics of CO_2 as the factor underlying the market dynamics of CCUS technologies by way of a model- and simulation-based analysis. The fulfillment of this research objective will allow us to construct a model that will constitute a comprehensive causal representation of the fundamental characteristics of the market for CO_2 as a commodity, for which there is a supply coming from CCUS technologies and demand generated by CO_2-EOR industry. The model is also supposed to explain why currently the deployment of CCUS is not sufficient to fulfill the demand of CO_2-EOR industry.

Based on the model, it becomes realistic to achieve the second research objective: to develop robust strategies and design policies to facilitate the interaction of CCUS and CO_2-EOR so that the learning effect in CCUS market starts improving the economics of CO_2 as a commodity and the mutually beneficial interaction of the two industries becomes self-supporting.

By robust strategies and policies we mean those who's effectiveness is not sensitive to realistic variations in the context (circumstances) in which these strategies and policies should operate.

The research objectives are applied to the national market of the US. Even though the project started by the client in ND and the primary interests of the client are related to ND, it was agreed that the first step in conducting research on this issue should cover the status of CCUS and CO_2-EOR industries at the national level. This is justified by the strategy chosen (first we model nationally, then we can calibrate the model to the state level), the data and information availability (more data and information abut the structure was available for the level of the US at the moment of modeling) and the status of CCUS and CO_2-EOR at the national level provides the context for the state model which can be developed in the future. The last argument effectively means that, for instance, the idea of demand for CO_2 generated by the CO_2-EOR at the national level would be crucial for the state model as most likely not all the CO_2 potentially captured in the state of ND could be used to satisfy the local demand but could be transported to satisfy demand in other states of the US. Thus, from this perspective, having a national model of anthropogenic CO_2 market is a pre-requisite for building a state-level model.

To fulfill the stated research objectives, the following research questions were formulated for the project to answer:

1. What are the fundamental characteristics and elements of the market for CO_2 and CCUS technologies, including the CO_2-EOR as the generator of demand for anthropogenic CO_2?
2. What are the crucial causal relationships between the fundamental characteristics and elements of the market for CO_2 and CCUS technologies, including the CO_2-EOR?
3. What are the reasons explaining the currently observed inability of CCUS industry to satisfy the demand of anthropogenic CO_2 generated by the CO_2-EOR?

4. What are the core uncertainties, associated with both technological and economic aspects of CCUS and CO_2-EOR that potentially may cause a significant impact on our assessment of the economics of CO_2 and CCUS?
5. What are the robust policies with regard to stimulating the economics of CCUS under the prevailing uncertainty?

Questions 1-3 are steered to fulfilling our first research objective, while questions 4-5 are addressing our second research objective.

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:

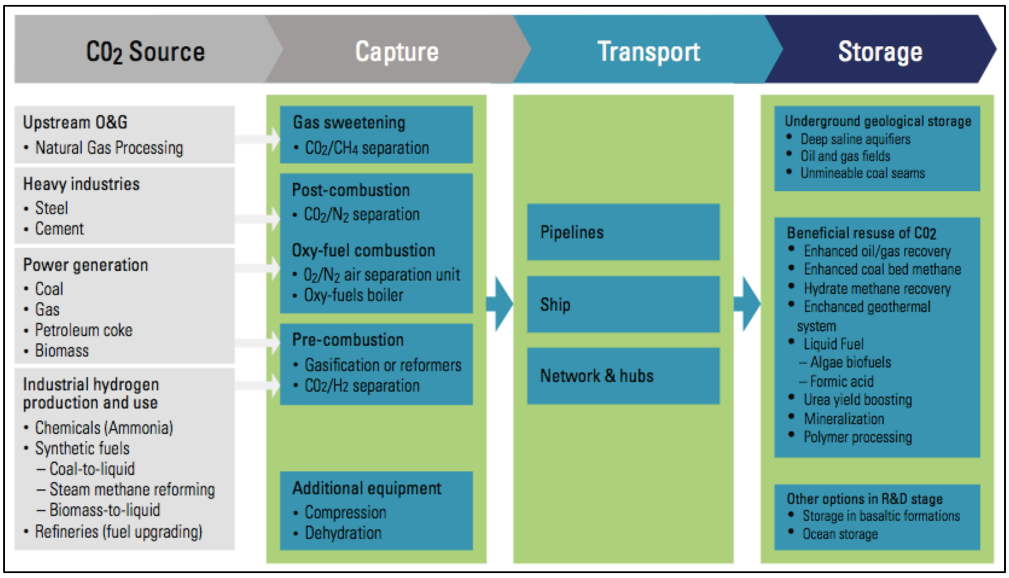

Figure 3. CCUS Supply Chain. Source: SBC Institute (2012)

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:

o 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.

o 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.

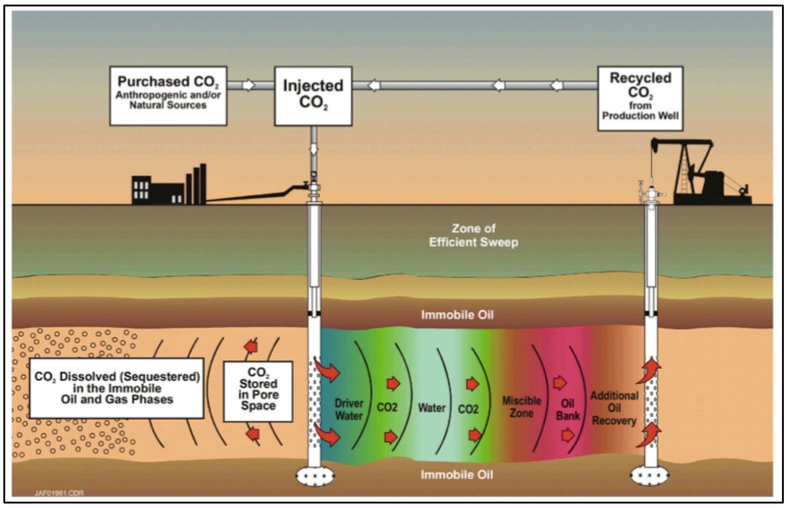

Figure 4. CO2-EOR Mechanism. Source: NEORI, 2012

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.

As presented to the client in May 2014, 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 is then used for testing carbon credit tax policy as the federal tax policy tool. The choice of this particular policy tool is described and supported by the relevant explanations in Chapter 5.

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 50 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. The sector is described in details in paragraph 2.3.4.

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 chapter describes the model without a policy structure. The description of the model with the policy structure and the corresponding simulation runs are contained in Chapter 5.

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 iThink file accompanying this thesis.

2.3.1 Overall mechanism

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

1. Demand for CO_2,
2. Anthropogenic CO_2 Supply (CCUS sector),
3. CO_2 for EOR Process,
4. Natural CO_2 Supply.

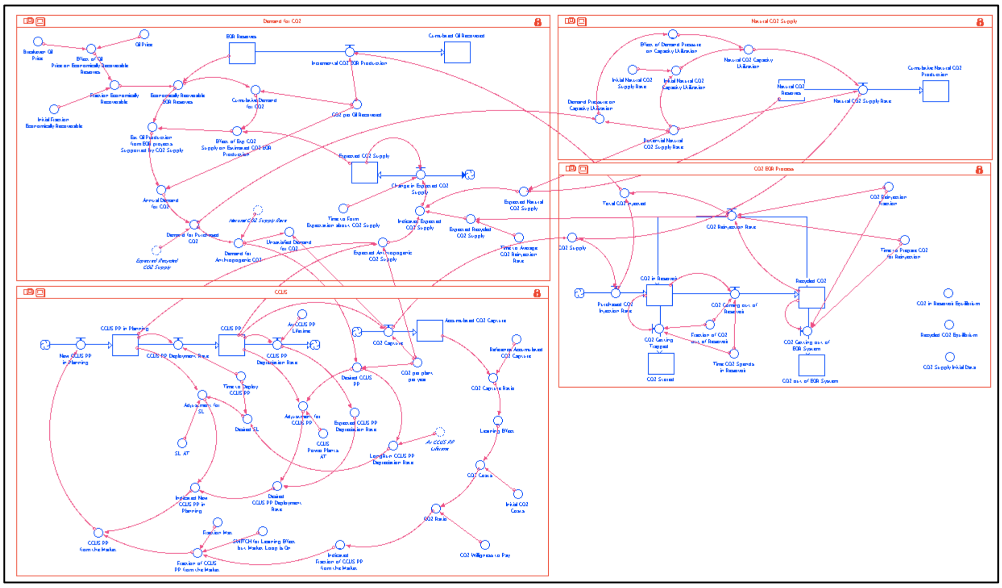

Figure 5. Model Overview

The overall mechanism of the model works in the following way. The key variables are in italics.

Sector 1 "Demand for CO_2" departs from the estimated *Technically Recoverable Oil Reserves* with the current SOA CO_2-EOR technology as a base point.

Then taking into account the dynamics of oil price *Economically Recoverable EOR Reserves* are identified. Finally, the estimation of economically recoverable EOR reserves and *Expectations about CO_2 Supply* give an idea of the *Annual Demand for CO_2* needed to support the anticipated EOR projects. The CO_2 demanded is then compared with the available CO_2 coming from three sources: *Natural CO_2*, *Anthropogenic CO_2*, and *Reinjected CO_2*. The resulting difference forms *Unsatisfied Demand for CO_2*, a variable that generates pressure for launching the correcting feedback loop in the CCUS sector.

Sector 2 "Anthropogenic CO_2 Supply (CCUS Sector)" shapes the idea of how many new CCUS Power Plants would be necessary to satisfy the existing demand pressure based on *Perceived Unsatisfied Demand for CO_2* and currently available *CCUS Power Plants under Construction* (effectively, CCUS Power Plants Supply Line). Note that the resulting variable *Desired Additional CCUS Power Plants* represents the "wish" for CCUS power plants needed to be installed regardless the financial sources associated with installing those plants. Then this "wish" (in system dynamics language, indicated CCUS power plants) may or may not be implemented by the market mechanism.

CCUS Sector incorporates the learning effect: as the *Accumulated CO_2 Capture* approaches the *Reference CO_2 Capture*, the costs of CO_2 capture start decreasing. In this way the model manifests the idea that stimulating installation of CCUS equipment during the phases when it is not economically plausible over time leads to lowering the costs and improvement of CO_2 economics.

The anthropogenic CO_2, generated by the CCUS sector, together with the natural CO_2 supplies form the total purchased CO_2 supply serving as an input for sector 3 "CO_2 for EOR Process". Sector 3 models the injection of CO_2 into reservoir which then generates incremental oil production. The sector portrays the CO_2-EOR process on a very aggregated level. In its essence, the sector describes a purely material process with no information feedbacks. However, the sector fulfills an important function by distinguishing between purchased CO_2 and re-injected CO_2. While initially the amounts of CO_2 re-injected into the CO_2-EOR system are negligible, over time those amounts turn into a substantial source of CO_2 supply, which to a certain extent eases the pressure posed by CO_2 demand on the overall system. Thus, the key outputs of the sector are *Incremental Oil Production* and *Re-injected CO_2*.

Sector 4 "Natural CO2 Supply" supplements the structure of the overall CCUS-EOR system. is predominantly exogenous. It is built on the estimation of remaining natural CO_2 supplies and the maximum supply rate, which is about to get reached at the present moment. However, the sector is a crucial part of the overall feedback loop in the model: *Demand for Purchased CO2* is the input to the sector and *Natural CO2 Supply Rate* is the output.

2.3.2. 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 6.

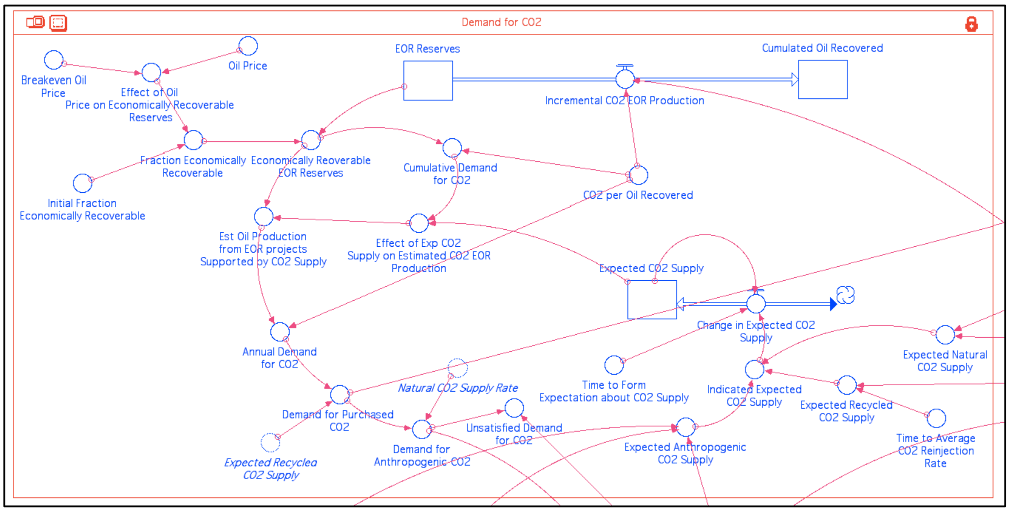

Figure 6. Demand Sector

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 three components: *Expected Natural CO_2 Supply, Expected Recycled CO_2 Supply* and *Expected Anthropogenic CO_2 Supply*. The expected natural CO_2 supply is set at the *Potential Natural CO_2 Supply Rate*, which is the maximum rate being currently approached by the system. Once the natural CO_2 reserves are depleted, the expectations drop to zero. The expected recycled CO_2 supply is the average of the re-injection rate in CO_2-EOR Process sector. 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).

2.3.3 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.

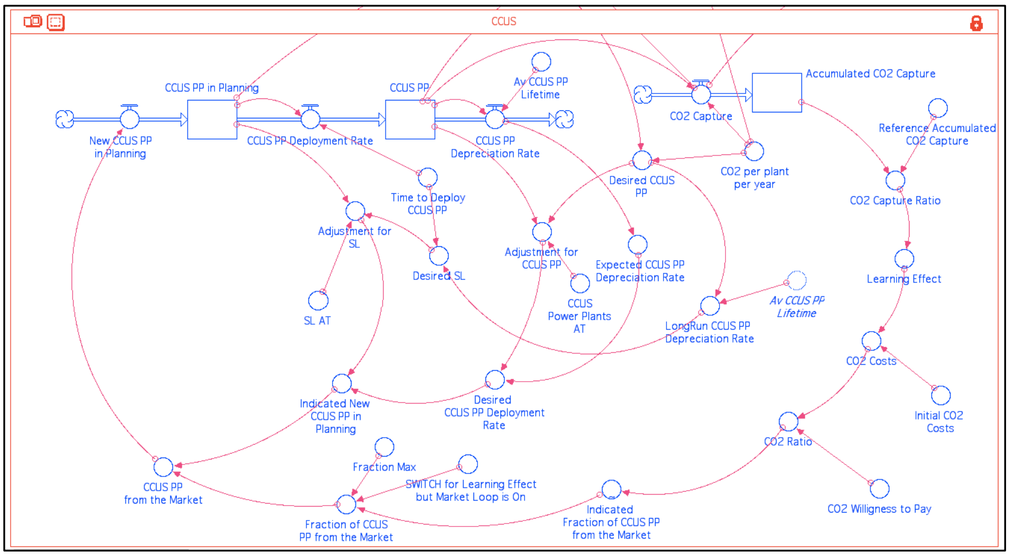

Figure 7. CCUS Sector

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.

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[2].

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.

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[2] 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.

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 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.

2.3.4 Sector 3: CO_2-EOR process

The sector is represented by Figure 8 and contains four stocks: CO_2 in Reservoir, Recycled CO_2, CO_2 Stored, and CO_2 Out of EOR System.

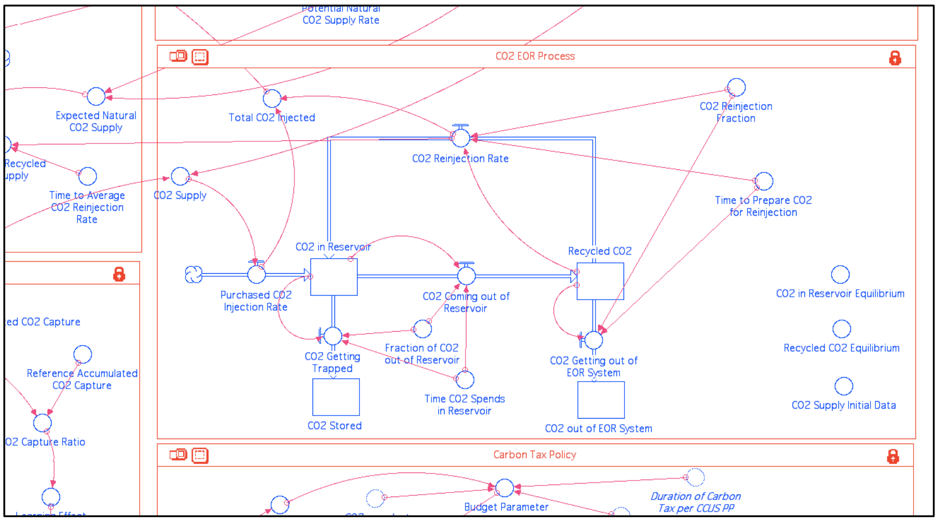


Figure 8. Sector 3: CO2-EOR Process

Stock *CO_2 in Reservoir* accumulates the *Purchased CO_2 Injection Rate*, which is the summed inflow of purchased natural and anthropogenic CO_2. After a certain time during which the purchased injected CO_2 remains in the reservoir, called *Time CO_2 Spends in Reservoir*, a certain fraction of CO_2 is coming out of the reservoir together with the incremental oil produced. The remaining CO_2 (estimated to be 30% of CO_2 in Reservoir according) is being trapped underground forever. According to the usual CO_2-EOR practice, the CO_2 does not exit the reservoir in a first-in-first-out fashion: most of the CO_2 will get out of the system initially while some of the CO_2 will still be getting out of the system later but in less quantities (AIR, 2010). To represent this technical aspect of the process adequately, both outflows are formulated as first-order exponential delays.

This second outflow might seem to be not related directly to the key outcome of the sector, which is incremental oil produced. However, it has a particular importance for some of the policymakers relevant to a broader CCUS issue. Namely, certain stakeholders are interested in CO_2-EOR as a way not just to use CO_2 for some beneficial purposes, but also to store it in a safe geological location without releasing to the atmosphere. In this regard, it is crucial to assess the storage potential of CO_2-EOR, which exhibits a great degree of uncertainty for policymakers. For these reasons, the model accumulates *CO_2 Being Trapped* into the stock *CO_2 Stored*. This stock can serve as an indicator of the CO_2-EOR storage potential.

The CO_2 that comes out of the reservoir can be re-injected back into the reservoir. There are two constraints involved into so-called recycled CO_2. First, it takes time to make CO_2 ready to be re-injected, which among other things includes separating it from the incremental oil produced from the well. Second, only a fraction of CO_2 coming out of the reservoir can be prepared for re-injection (estimated to be 60% of the CO_2 coming out of the reservoir). The remaining part of CO_2 simply gets out of the CO_2-EOR system without being either stored in geological formation of the reservoir or being re-injected back into the CO_2-EOR process.

The purchased and re-injected CO_2 together generate *Incremental Oil Production*: the summed flows are being multiplied by the conversion factor *CO_2 per Oil Recovered*. Note that in reality the conversion factors might differ for purchase and recycled CO_2. Yet, in this model the idea was to create the simplest representation of the complex CO_2-EOR process. For this purpose, refraining from differentiating between conversion factors for two different flows of CO_2 injection is a good example of not overcomplicating the model structure while preserving the crucial elements of the system.

As is was mentioned in section 2.2, all the time constants and fractions were estimated as values characterizing an typical CO_2-EOR project. The estimation was based on the extensive literature overview of CO_2-EOR processes (the central of which is AIR (2011) and Melzer (2010))) supplemented by consultations with the experts in the field (Scott Jonson and Steve Benson from the IES representing the client) and the project collaborator Julian Andres Gill Garcia whose thesis is devoted exclusively to this issue.

2.3.5 Sector 4: natural CO_2 supply

The central stock of the sector is *Natural CO_2 Reserves*, which is estimated to be 3,000 Mtonnes (AIR, 2011). The flow *Natural CO_2 Supply Rate* depletes the reserves. Natural CO_2 Supply Rate is defined as *Potential Natural CO_2 Supply Rate* multiplied by the *Natural CO_2 Capacity Utilization*. This formulation is analogous to the ones used in the Petroleum Lifecycle Model by (Davidsen, 1989). Yet, this model does not go too deep into the natural CO_2 production.

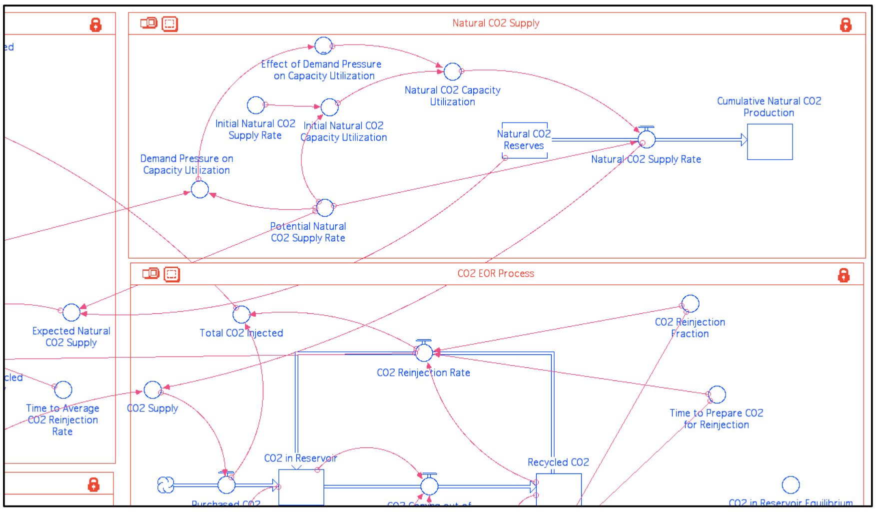


Figure 9. Natural CO2 Supply Sector

There are two fundamental aspects of the natural CO_2 supply, which the sector is based on and which are important to the rest of the model. First, natural CO_2 production rate approaches its maximum capacity (AIR, 2011). Second, the natural CO_2 reserves are about to be depleted within 20-30 years period (G. Murrell, 2013). In this respect, it is crucial to reflect the idea that the reserves of natural CO_2 are the stock and once it is depleted, it cannot be used anymore. The sector does not contain an endogenous structure that would portray the feedback from the *Natural CO_2 Supply Rate* to *Potential Natural CO_2 Supply Rate* (as similar to the one in (Davidsen, 1989)). This is justified by the reason that we would like to portray only the general idea of the resource's exhaustion. Thus, *Potential Natural CO_2 Supply Rate* is treated in the sector as a constant (estimation is taken from AIR, 2011), while the growing *Demand for Purchased CO_2*, which enters the sector as an input from sector 1, influences the capacity utilization. This choice of the structure unloads the modeler from overinvesting into constructing exogenous mechanism inside the sector, which is not expected to affect the rest of the model to a great extent. However, with the chosen structure the dynamics of this sector is still influenced by the important endogenously generated variable coming from the other sector of the model.

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.

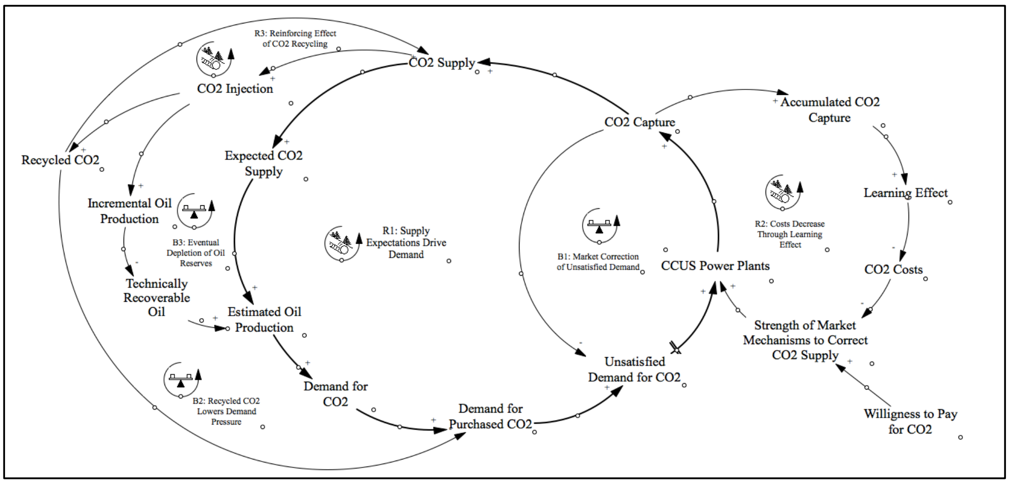


Figure 100. CLD Representation of the Model

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. Model Behavior

3.1 Base Run

The baseline run is the model simulation in "as-it-is" scenario. This means that we start the model simulation with the initial values. The market mechanism is the only one that corrects for the unsatisfied demand. The market mechanism operates under initial conditions reflected in the value of CO_2 costs to Willingness to Pay Ratio at 0.57, which is well beyond 1. The initial conditions definitely describe the market situation way below the favorable one conducive to the commercial deployment of CCUS. The key variables we look at for the baseline simulation runs are Incremental Oil Production, CO_2 Capture, and Demand for Anthropogenic CO_2. Unsatisfied Demand for CO_2 is the resulting variable derived from the last two and is important for assessing the demand pressure within the system.

Both Incremental Oil Production and Total CO_2 Injected (representing total CO_2 supply, including recycled CO_2) are portrayed in Figure 11. They exhibit a similar dynamics as there is a direct link between oil produced and CO_2 injected: a somewhat s-shaped growth which satiates at a certain level above the initial values.

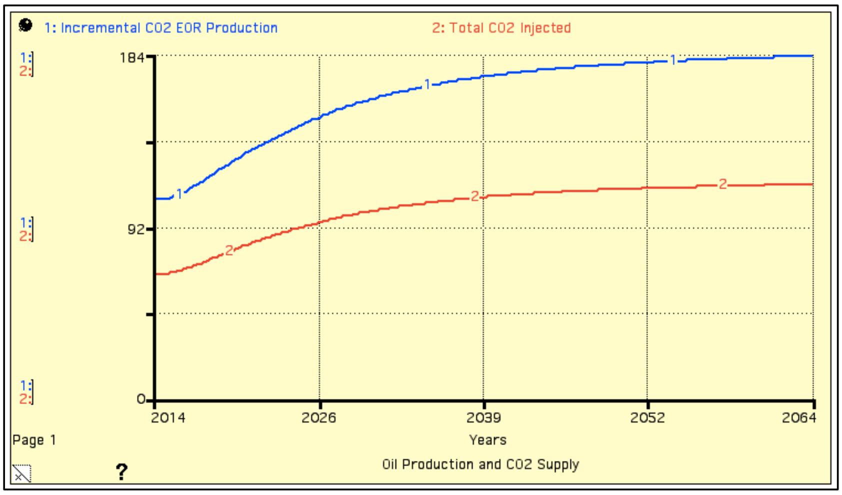


Figure 11. Base Run: CO2 Supply and Oil Production

An interesting observation can be made immediately: even though the market conditions are not supposed to stimulate CCUS deployment and, thus, the supply of anthropogenic CO_2 is not expected to increase, the model still generates the growth in total CO_2 supply and, consequently, incremental oil production.

First, we should check the dynamics of CO_2 capture, which together with the demand for anthropogenic CO_2 and unsatisfied demand are depicted in Figure 12.

Indeed, CO_2 capture remains practically stable around its initial value of 13.86. The reason why the capture rate is not absolutely stable will be described a little bit later. For now, an important observation is that the demand for anthropogenic CO_2 and, consequently, the unsatisfied demand decrease during the first ten years and then through a steady increase return to the previous values.

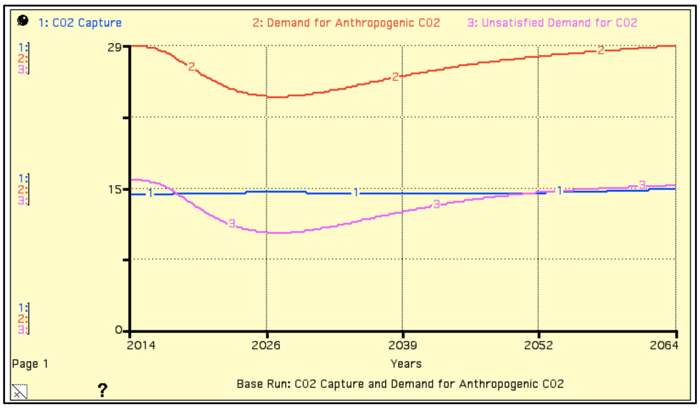


Figure 12. Base run: CO2 Capture and Demand for Anthropogenic CO2

To understand deeper the dynamics behind the demand for anthropogenic CO_2 we refer to simulation results for annual demand for CO_2 based on estimated annual oil production, which incorporates the expectations about future CO_2 supplies, the recycled CO_2 rate and the resulting demand for purchased CO_2. The dynamics of those three variables is depicted in Figure 13.

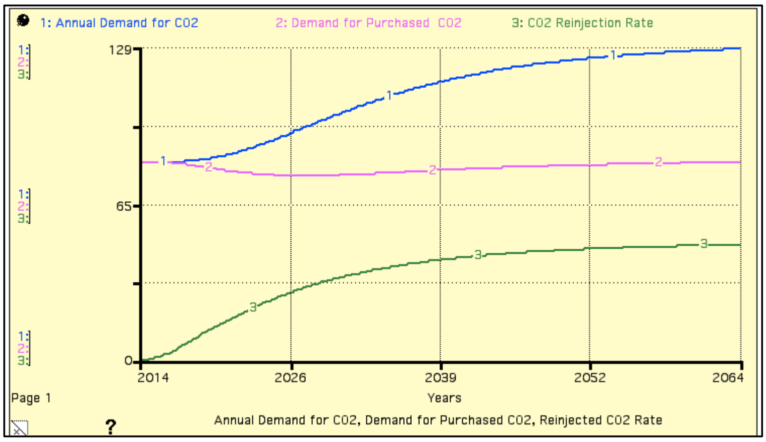


Figure 13. Base run: Demand for CO2 and CO2 Reinjection Rate

As the Figure demonstrates, annual demand for CO_2 grows in the s-shaped fashion reflecting the growth in estimated/planned oil production and expectations about future supplies of CO_2. On the other hand, demand for purchased CO_2 is consistent with the discussed dynamics of the demand for anthropogenic CO_2. The reason for a change in dynamics along the "demand chain" (annual demand for CO_2 – demand for purchased CO_2 – demand for anthropogenic CO_2) is explained by the behavior of CO_2 reinjection rate. Namely, coming back to the CLD representation of the model (Figure 10), the reinforcing mechanism inherently built-in in the physical process of CO_2 injection in a reservoir (Sector 3 of the Model: CO_2–EOR process) is responsible for activating loop R3, which through reinforcement of CO_2 supply produces growth in incremental oil production and expectations of future CO_2 supplies (and, thus, annual demand for CO_2). The generation of recycled CO_2 in the EOR sector also activates loop B2, which lowers the demand pressure and prevents the demand for purchased CO_2 from rising together with the annual demand for CO_2. In other words, expectation about availability of recycled CO_2 generates growth in estimated CO_2-EOR production but mostly covers the demand for CO_2, which follows the estimated production.

The growth in the base run is driven not by the work of loop R1 but by the loop R3. The expansion of CO_2 supply thanks to recycled CO_2 activates only one reinforcing loop – R3. However, as recycled CO_2, as noted in Chapter 2, does not contribute to the learning effect, loop R2 remains dormant meaning that B1 does not operate as a controlling mechanism and anthropogenic part of CO_2 supply expectations driving loop R1 remains stable. Recycled CO_2 supplies expectations do not activate loop R1 as the actual recycled CO_2 injection rate lowers the unsatisfied demand pressure in the system. In other words, as loop R1 gains momentum at its supply expectations part thanks to R3 loop, it looses it further down the feedback lines due to B1 loop. Thus, we observe no growth in unsatisfied demand for CO_2, which is the key output of the Demand Sector in the model and the variable of the R1 feedback loop which generates the pressure in the system and, thereby, activates the work of R2, B1 and, then, through the meta-feedback mechanism described in Chapter 2, R1 itself.

We make a note here on the s-shaped growth of total CO_2 injected and the incremental oil production. The base run describes the scenario characterized by an extremely week ability of the market mechanism to fulfill unsatisfied demand for CO_2, which implies practically constant supply of anthropogenic CO_2. Figure 14 demonstrates that the CO_2 costs remain well above the CO_2 WTP throughout most of the simulation horizon.

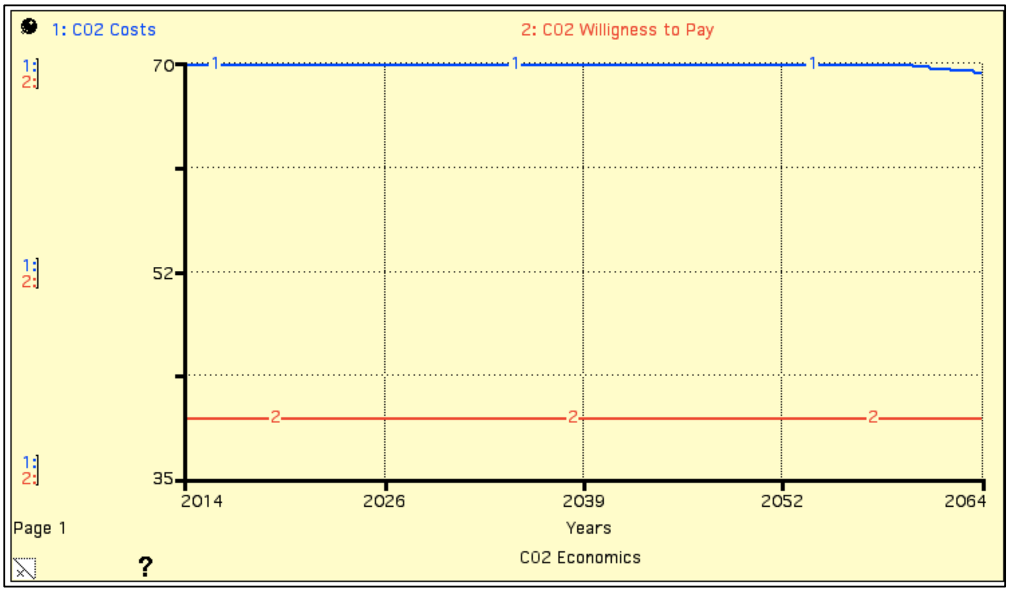


Figure 14. Base run: CO2 Economics

In this context, the only source of CO_2 supply expansion is the recycled CO_2 generated from a close to constant supply of purchased CO_2. The issue is that due to technical aspects injected CO_2 cannot be recycled infinitely as with each cycle a fraction of CO_2 remains stored in the underground formations of a reservoir. This technical feature implies another inherent, but this time balancing, mechanism that prevents the reinforcing process of expanding recycled CO_2 from growing. In the situation when the inflow to the CO_2-EOR system is constant the interaction of those two inherent reinforcing and balancing feedback mechanisms produces the s-shaped growth in total CO_2 injected and, consequently, incremental oil production.

As it was noted above, the CO_2 capture rate is not constant throughout the simulation but remains around 14. The reason for that is in the initialization of unsatisfied demand in the system and the formulation for the work of the market mechanism in fulfilling unsatisfied demand.

We start with the market mechanism. As described in the CCUS sector description, CCUS PP from the Market are defined as:

CCUS PP from the Market = Indicated New CCUS PP under Construction * Fraction of CCUS PP from the Market.

The first multiplier represents the correction necessary to close the demand gap. The second multiplier represents the degree to which the market is able to close this gap. This formulation implies that even when the economics of CO_2 remains the same (meaning that Fraction of CCUS PP from the Market stays constant), an increase in unsatisfied demand would translate into more CCUS PP being sent under construction, which would expand the supply of anthropogenic CO_2. The reverse also applies: lower demand gap with the constant fraction will translate into less new CCUS PP under Construction. The variable CCUS PP from the Market is constrained to take values no less that 73, which is the CCUS PP depreciation initial rate. This comes from the assumption that with the current CO_2 economics, 73 power plants equipped with CCUS are being launched annually. This number corresponds to the initial value for the stock of CCUS PP (2200) derived from the current CO_2 capture rate (coming from the data).

This formulation is based on the assumption that not only CO_2 economics determines how many new CCUS power plants will be deployed as the result of the market mechanism. An important factor is also the magnitude of the unsatisfied demand itself. This means that while constructing this model we believe that even though the economics of CO_2 is not favorable, the presence of significantly huge demand for CO_2 would still result in more power plants operators installing CCUS equipment. Thus the CCUS sector of the model is not constrained to generating only 73 new CCUS PP for year, which is just enough to cover the depreciation rate.

Theoretically, this is not an implausible assumption as the presence of high unsatisfied demand might produce anticipations of the government stimulations through carbon policies, for instance, among the power plants operators and induce them to convert to CCUS even if currently this is not profitable. As it was stated before, we effectively treat this initial number of CCUS PP being deployed in the current status of CCUS as exogenous: it is not CO_2 economics that stimulates the operators to install CCUS but other, exogenous to our analysis forces, among which the expectations about carbon policies might play an important role. After all, a significant part of existing build-up of CCUS capacity in the USA was accumulated as the result of regulations of carbon emissions and business expectations about possible restrictions of those regulations.

Practically, as it can be seen from the base run, the increase in carbon capture due to work of feedback loop B1 under the described formulation is relatively small and not much different from the constant equilibrium dynamics.

3.2 Equilibrium Run

If we had no recycling of CO_2 and unsatisfied demand were zero (no pressure in the system), then we would have absolutely constant CO_2 capture rate, expected CO_2 supplies and, consequently, unchanged demand for CO_2. The system would be in a completed equilibrium. This simulation run is shown in Figure 15, which is achieved by setting the Switch for recycling CO_2 to zero (meaning there is no such thing as CO_2 recycling in the EOR system) and Switch for Desired CCUS PP to 0 (meaning rather than being determined by the demand for anthropogenic CO_2 it is always 13.86 corresponding to the unsatisfied demand being zero). The dynamics of the key variables is portrayed in Figure 15.

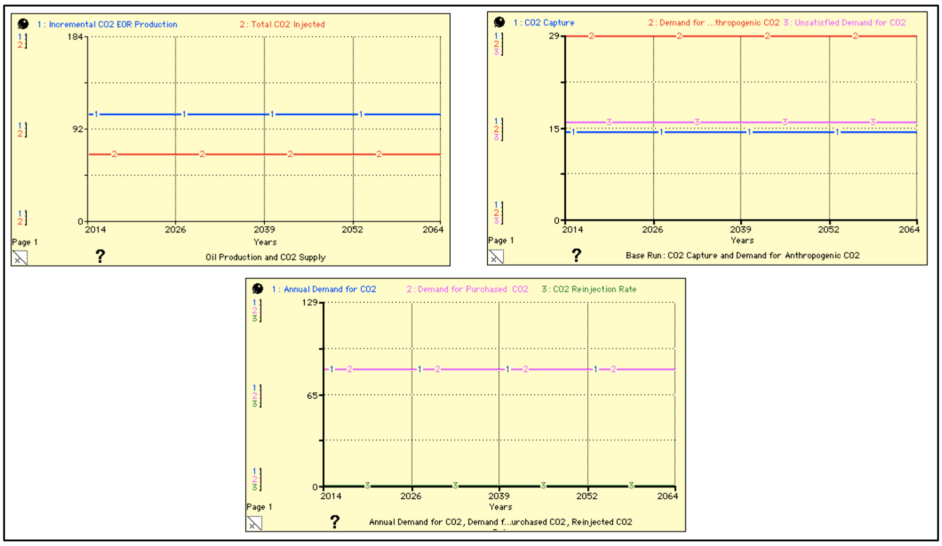


Figure 15. Equilibrium Run

Figure 15 exhibits all behavior of all the variables considered during the analysis of the base run. As can be seen from the figure, all the variables are constant. The model is in equilibrium as we expected before. It is important to emphasize, however, that even though this simulation run produces equilibrium, we do not consider it as a base run. Normally in system dynamics practice the base run is the one that keeps a model in equilibrium, yet in this case the conditions for equilibrium are clearly artificial. The settings for the switches that produced this model run do not reflect the current status of the system and are introduced for us to see how in principle the system would behave in equilibrium (and whether the model can produce equilibrium at all as a part of validation testing – see validation chapter).

The need for this run is important as there is no "natural way" to produce equilibrium in the model, that is, to have an equilibrium within the base run. While initializing the model we have to take account of the fact that we start at the moment when the system is already under a certain unsatisfied demand pressure. The presence of the pressure would trigger the market mechanism to deploy a certain small fraction of the necessary CCUS PP, which would result in new power plants being deployed beyond the amount necessary to compensate for the depreciation rate. Once this happens, the stock of CCUS PP and, correspondingly, the CO_2 capture rate get out of the equilibrium. Together with the stock of CCUS PP, expectations about future CO_2 supplies also get out of equilibrium which eventually instigates a further round of increase in the demand for anthropogenic CO_2. However, the newly deployed number of CCUS plants is no longer enough to match the newly increased demand in CO_2. Thus, the new round of R1 circulation continues. Note that even though R2 is effectively dormant and B1 is operating weekly, this partial functioning of the controlling mechanism still produces some upward shift in CO_2 capture, CO_2 supply expectations and demand for CO_2.

In this system, the only way to have absolutely constant CO_2 capture rate is to take Desired CCUS PP effectively out of the influence of R1 loop. Otherwise it will also be changing as it changes initially due to the presence of initial unsatisfied demand. This is achieved by introducing the Switch for Desired CCUS PP.

3.3 "Ideal" Run

The third and the final run to be considered is what can be called an "ideal run". As the baseline run produces the behavior where none of the three core loops identified in the section 2.4 is active (or significantly active), it is important to see how in principle the system would operate if the CO_2 economics were ideal. For this we employ a similar technique to the one employed for equilibrium run: we introduce the Switch for Market Loop. When the switch is on, the market control loop functions as it does in the base run. When the switch is off, we allow the market loop B1 to fulfill all the existing unsatisfied demand for CO_2, even though the economics of CO_2 is at its current status. This simulation run would allow us to see the dynamics of the key variables under ideal conditions of CO_2 economics, even though they are not achieved yet. The comparative graphs for the selected variables are depicted in Figure 16.

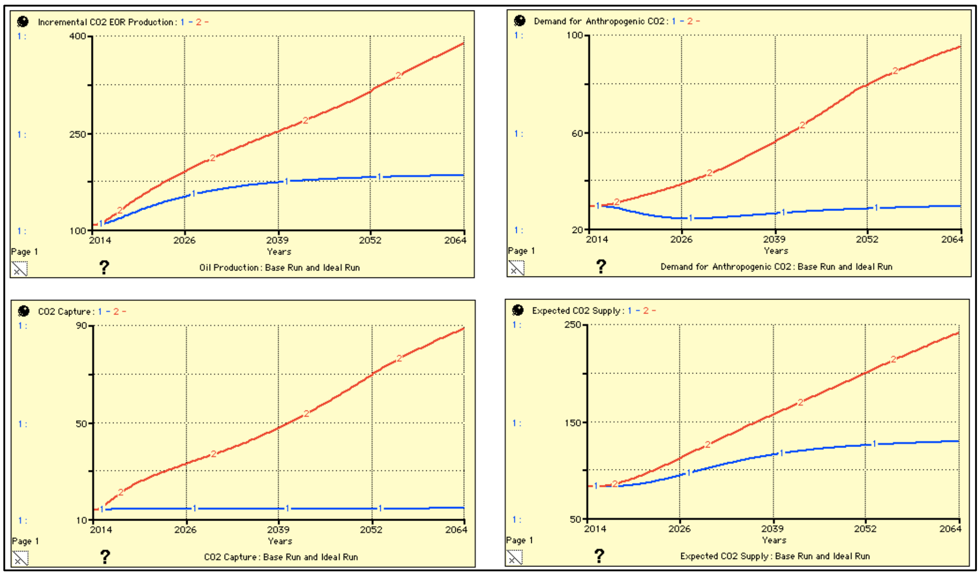


Figure 16. "Ideal" Run

Figure 16 demonstrates the dynamics of the system where the feedback loops described in the previous section are operating at their full fledge. The system does produce the desired growth in incremental oil production: by the end of 50-year simulation period incremental oil production reaches almost 400 units per year which more than three times higher than what the base run produces.

The reasons for such a significant increase in annual oil production is that the base run growth is based on the feedback loop R3 which potentially can not generate significant growth in oil production and is subjected to the balancing mechanisms inherent in the CO_2-EOR system (which explains stabilization of a somewhat s-shaped growth curve).

On the contrary, the growth depicted by the "ideal" scenario characterizing mature market for commercialized CCUS is generated by reinforcing loop R1 (as well as loop R3). Loop 1 produces a much stronger growth dynamics, to which we cannot see the limits within the simulation horizon (the limits are the reserves of technically recoverable oil). As artificially we brought market to its fully commercial scale, loop R1 operates at its maximum strength (as if loop R2 would have enabled so). Expanding CO_2 capture drives expectations about CO_2 supply further up which supports generation of more demand for CO_2, which can be easily satisfied by the market forces generating further expectations about CO_2 supply.

The run provides the upper bounds for the dynamic paths of the model's variables. This is important for the current analysis as the base run and this run together provide the space for improvements that can be achieved by potential policy measures. The "ideal" run characterizes the dynamics of mature CCUS market that have reached the stage of commercialization. The comparison of two runs suggests for policy-makers to address the need in bringing the system up to this stage so as the reinforcing self-supporting feedback mechanisms can generate a continuous growth in CO_2 capture and incremental oil production.

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

4.1. 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 abut the issue on the client side (Scott Jonson and Steve Benson) and then everytime 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.

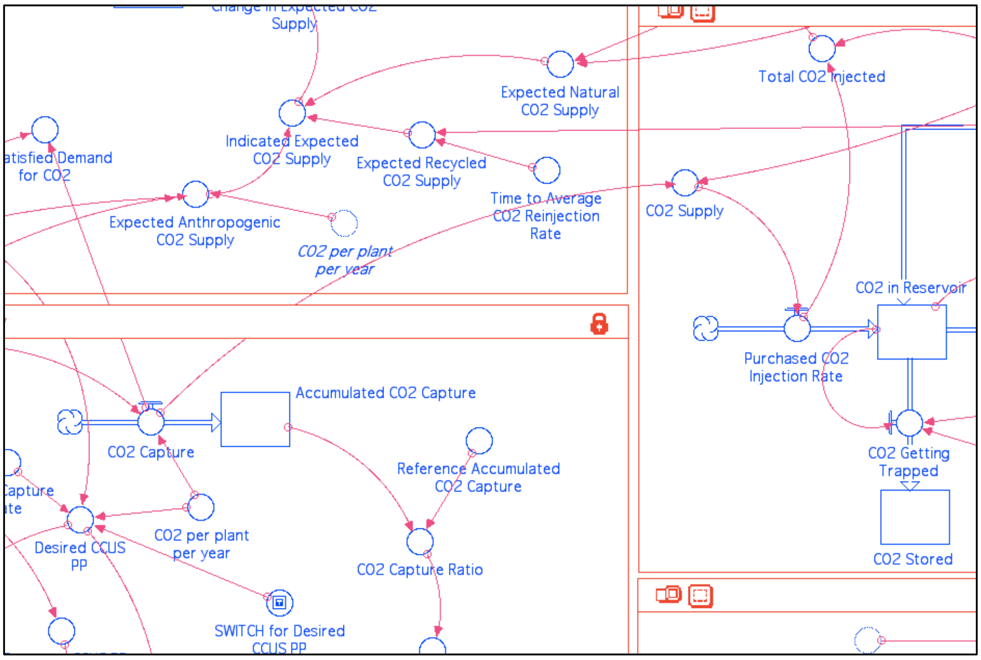


Figure 17. CO2 Supply Structure

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 client and the modeler working on the technical aspects of the issue (Jualian Andre Gil Garcia). 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 (the policy part will be described in Chapter 5) 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 (iThink and its function "Unit Consistency Check"). As Figure 18 proves, all the units in the model appear to be consistent.

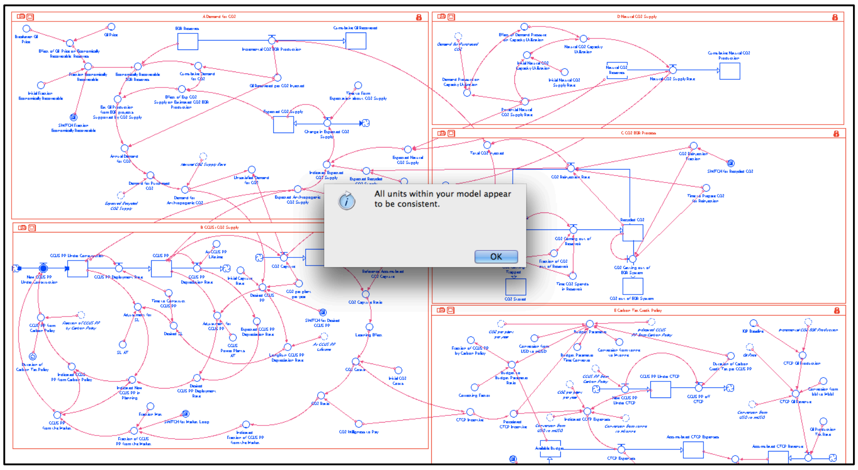


Figure 18. Unit Consistency Test

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 used 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.

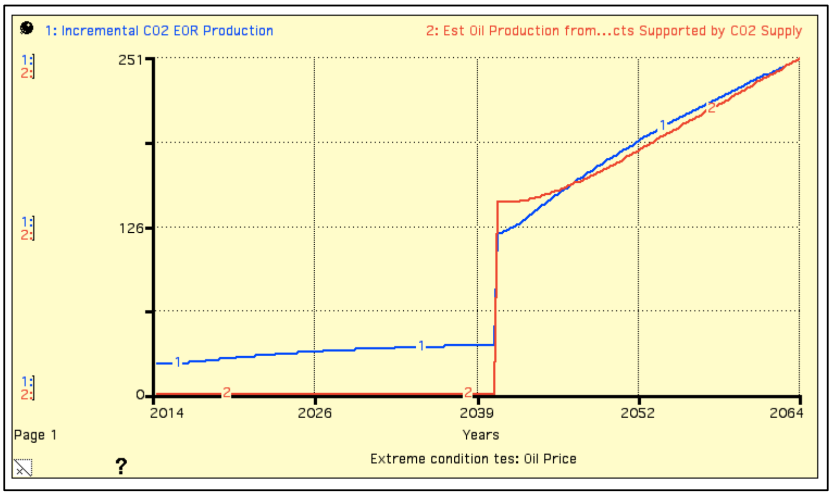


Figure 19. Extreme-condition test: Oil Price

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.

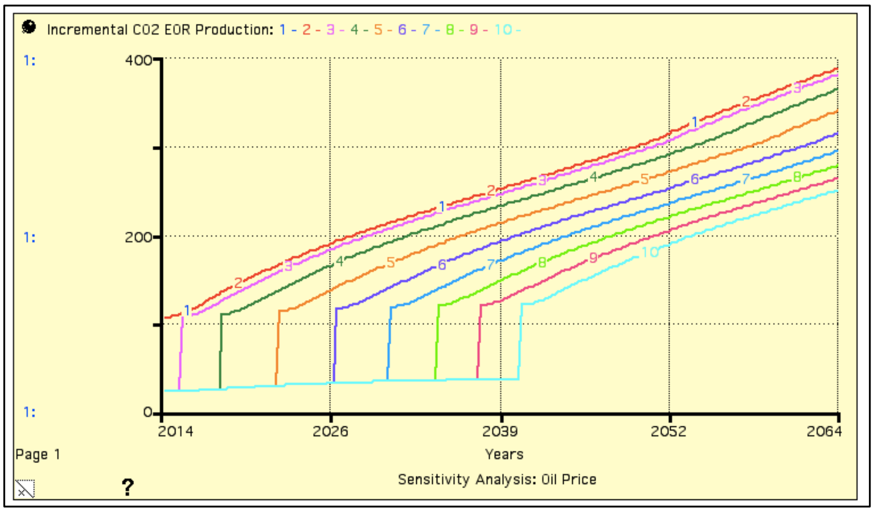


Figure 20. Sensitivity test: oil price

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).

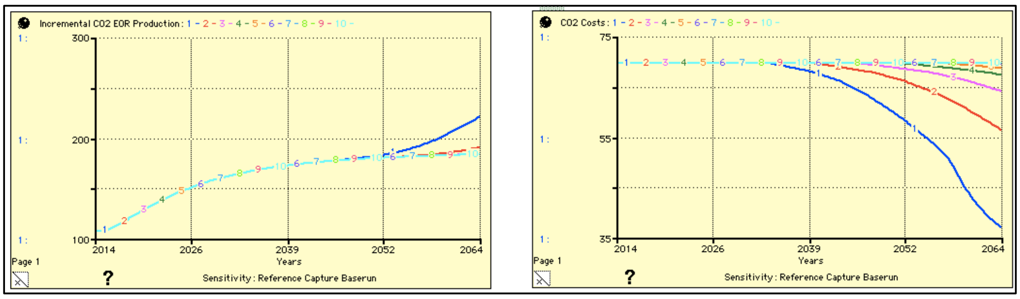


Figure 21. Sensitivity test: Reference Capture, Base run

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.

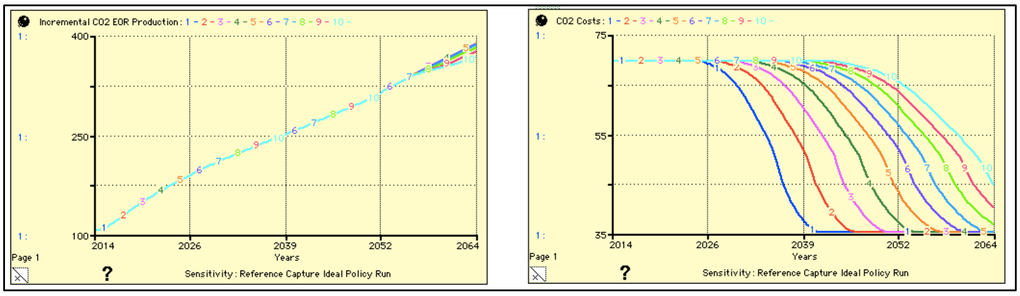


Figure 22. Sensitivity test: Reference Capture, Unconstrained Policy run

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.

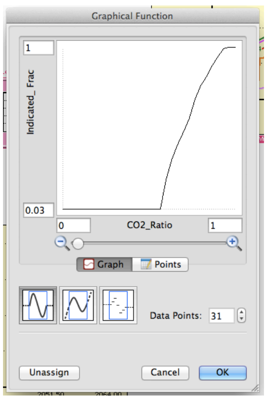


Figure 23. Concave LE

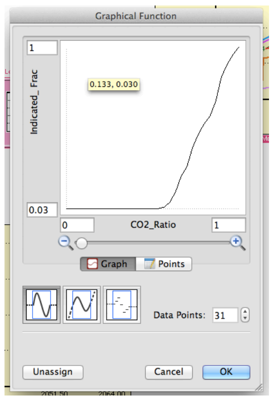


Figure 24. Close to Linear LE

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.

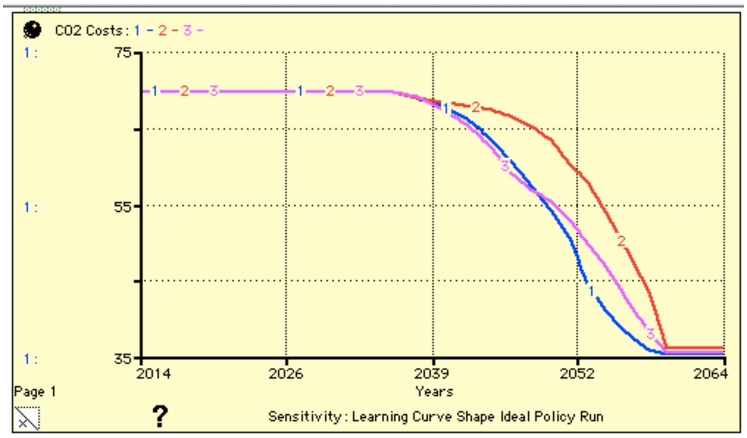


Figure 25. Sensitivity test: Learning Curve, CO2 costs

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.

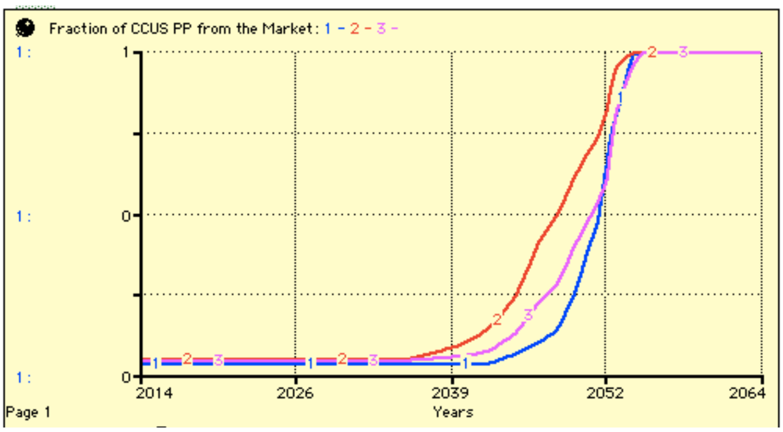


Figure 26. Sensitivity test: Market Fraction

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. This is the model that advocates for the carbon tax credit policy. Since the policy employed by our model in chapter 5 is also carbon credit tax, comparing the behavior of the two models at least gives a chance to get an idea about how reasonable the model results are based on other studies. This is covered in validation section of chapter 5.

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. Policy Analysis

5.1 Policy Choice

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.

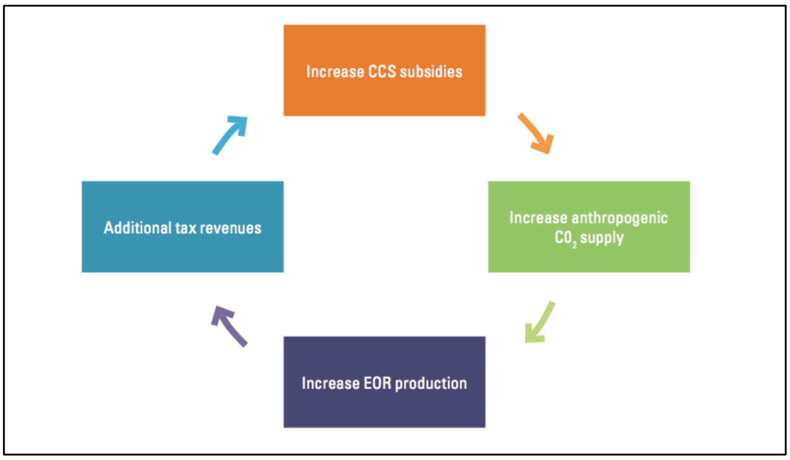


Figure 27. Reinforcing mechanism of carbon policy. Source: NEORI (2012)

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.

5.2 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.

5.3 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.

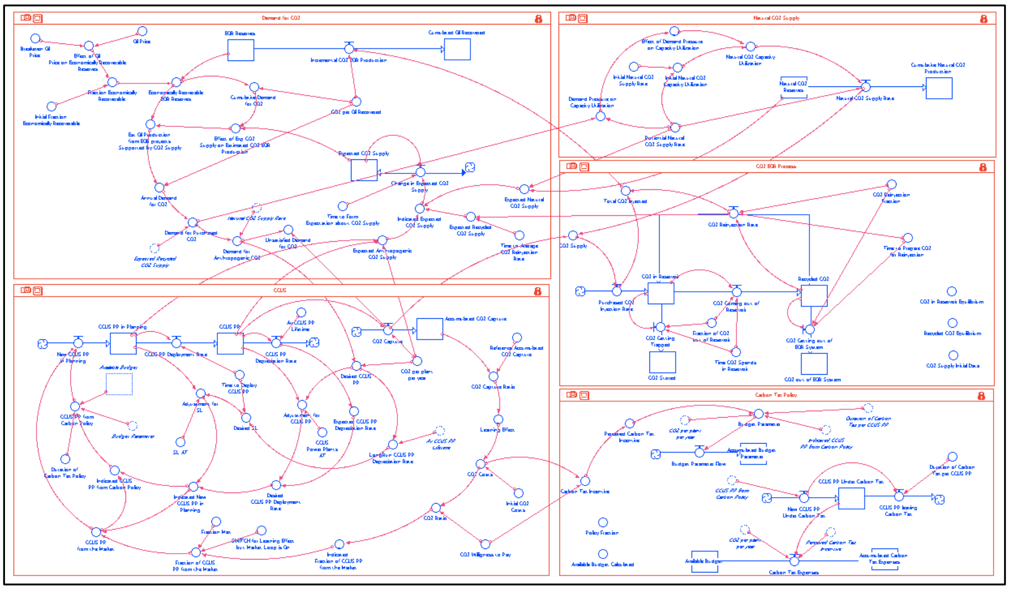


Figure 28. Model Overview with Carbon Policy

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.

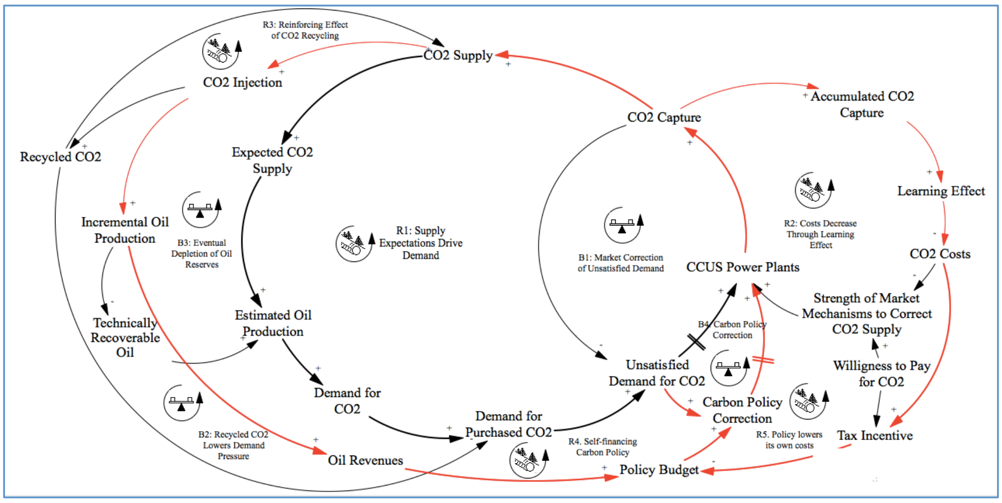


Figure 29. CLD for the Model with Carbon Policy.

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.

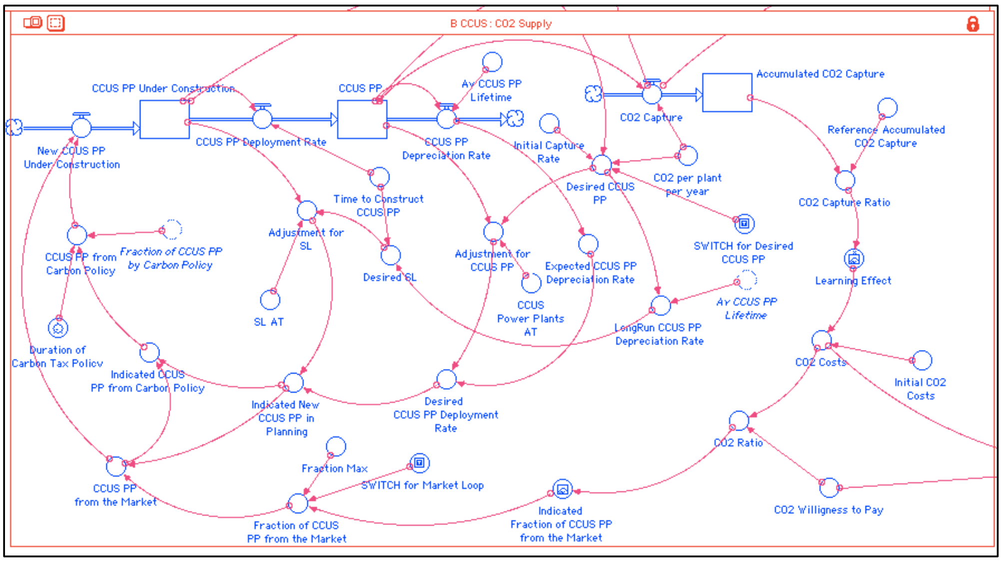


Figure 30. CCUS Sector with Carbon Policy

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.

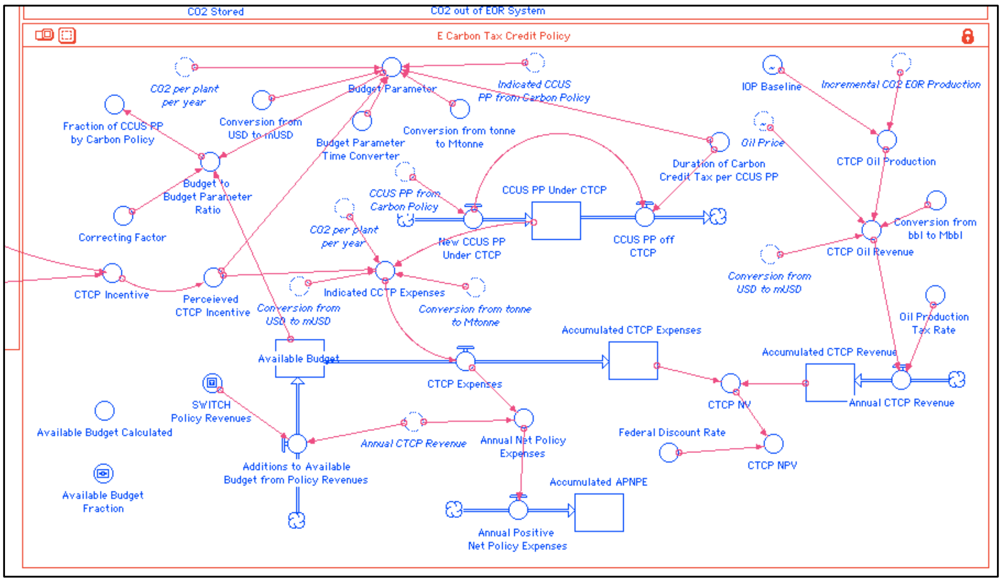


Figure 31. CTCP Sector

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.

5.4 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.

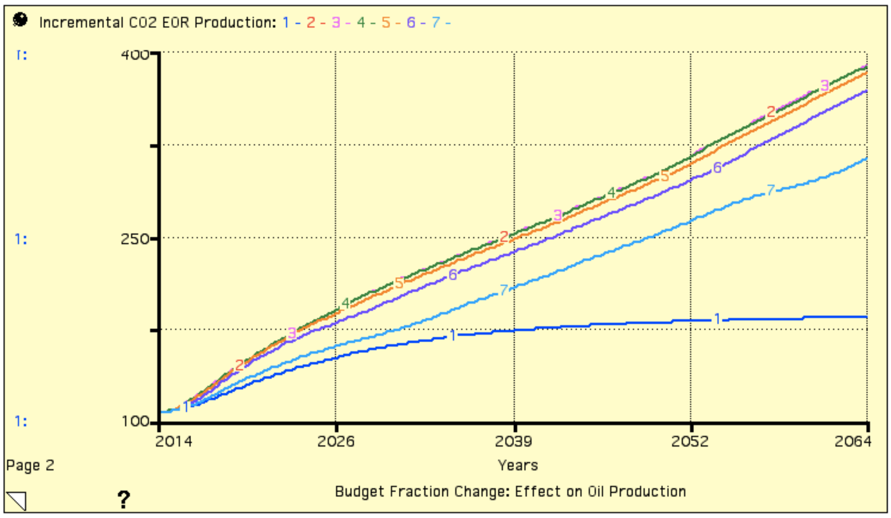


Figure 32. Budget Fraction Change: Oil Production

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.

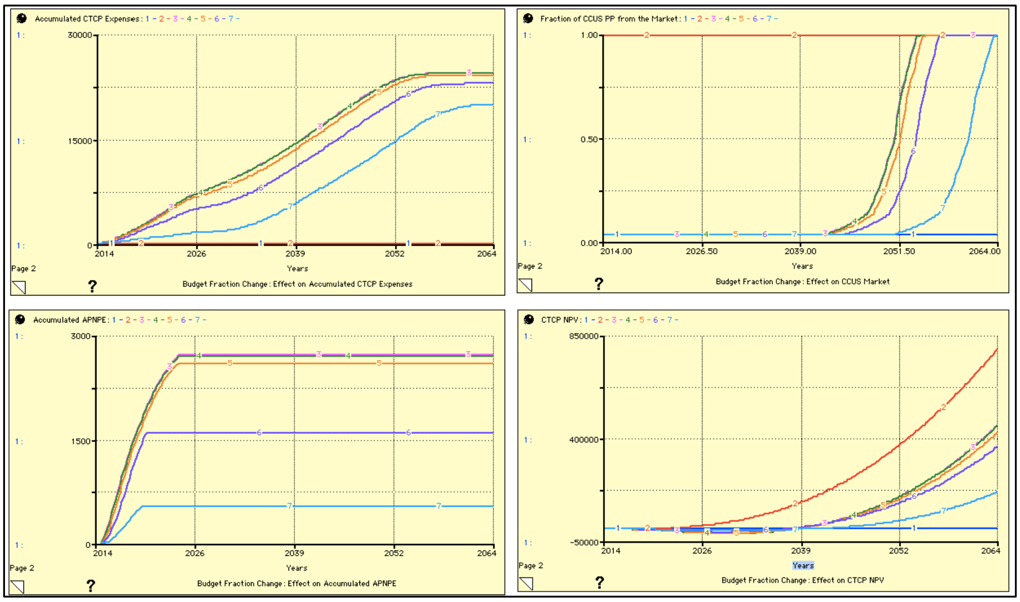


Figure 33. Budget Fraction Change: reinforcing mechanisms

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.

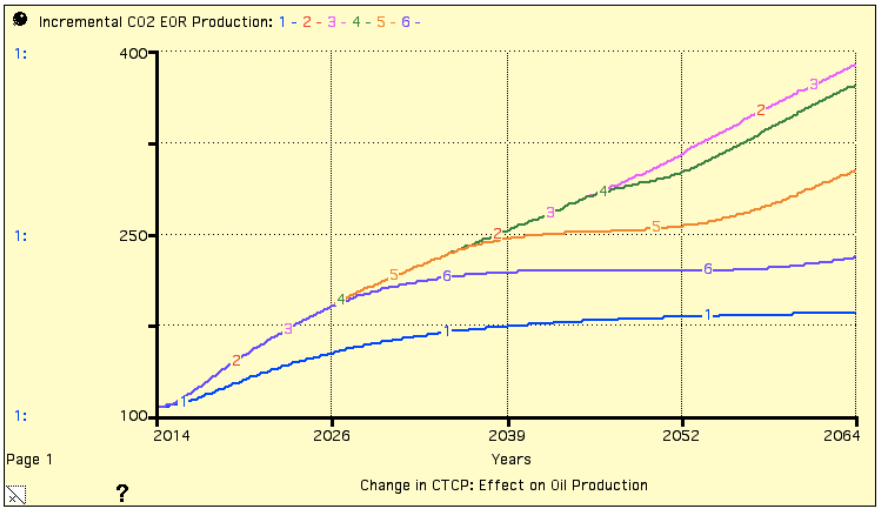


Figure 34. Change in CTCP Duration: Oil Production

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.

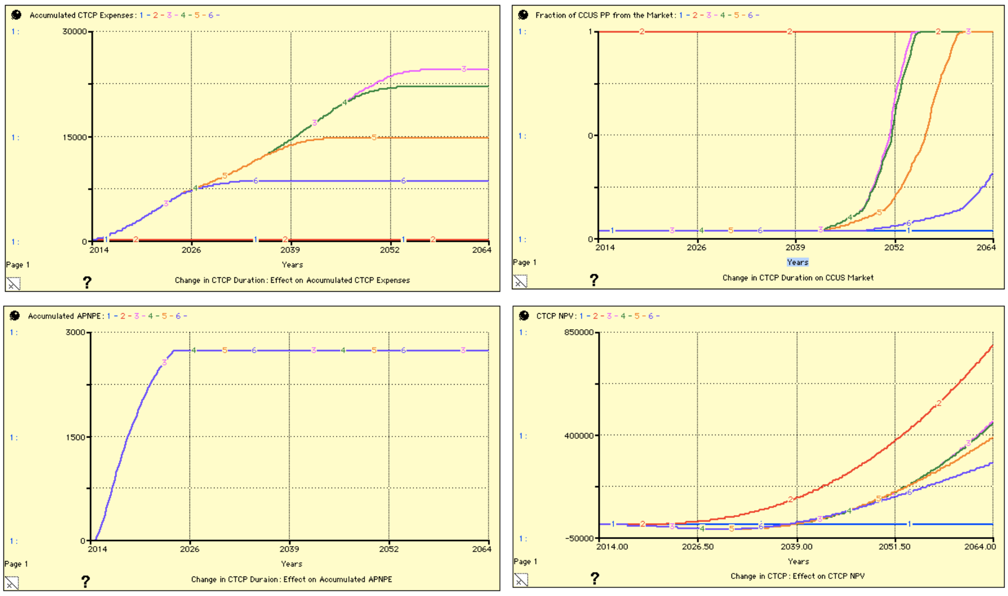


Figure 35. Change in CTCP Duration: Reinforcing Mechanisms

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.

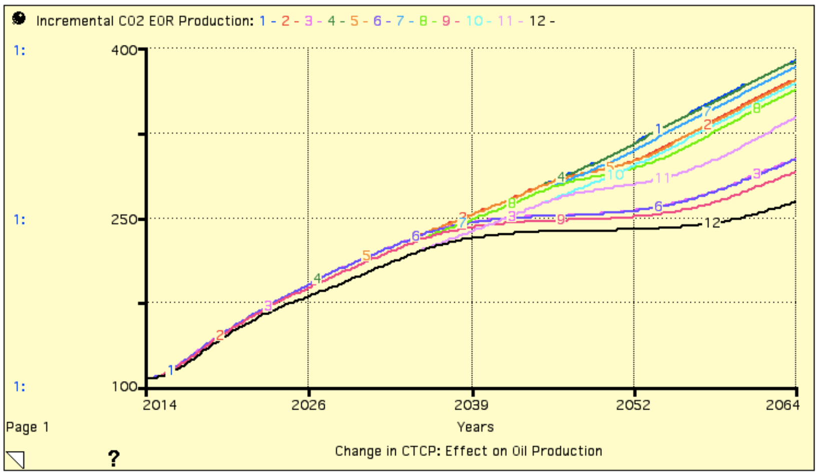


Figure 36. 12 Hybrid Policies

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.

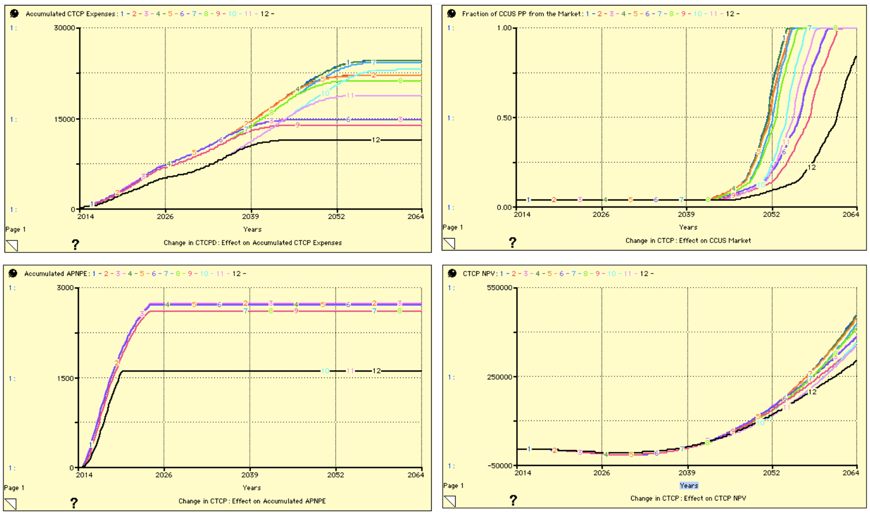


Figure 37. 12 Hybrid Policies: Dynamic Assessment

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:

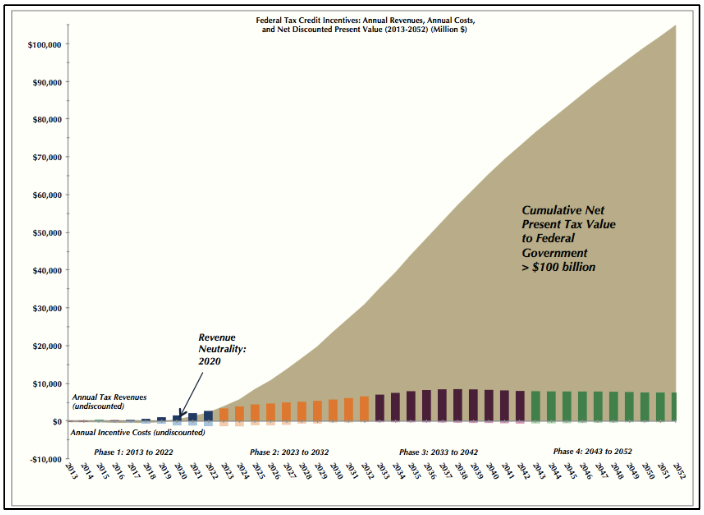
1. A complex integrated system such as the CO_2-EOR generates a number of key variables reflecting multiple objectives followed by different stakeholders. In the CO_2-EOR system these are at least the growth in oil production and more oil recovered (reflected by the variable Incremental Oil Produced) 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).

5.5 Comparison with the NEORI model result

As noted in Chapter 4 the availability of the model documentation and generated behavior up till 2052 provides for a chance to have at least some benchmark for comparison of the behavior of our system dynamics model. This is particularly crucial since there is no reference mode due to the nature of the problem issue. The comparison, however, can only be treated as indicative due to the difference in the underlying assumptions between the models. E.g., the NEORI model differentiates between three sources of CCUS, while our model assumes only one source. In principle, this would lead to different levels of generated CO_2.

Two points should be noted upon the performed comparison of the two models. First, the models arrive at a similar payback period of around 10 years.

Second, a number of key variables in the model exhibit a similar dynamics with the comparable values. Figure 38 illustrates the dynamics of the program's costs, revenues and NPV.



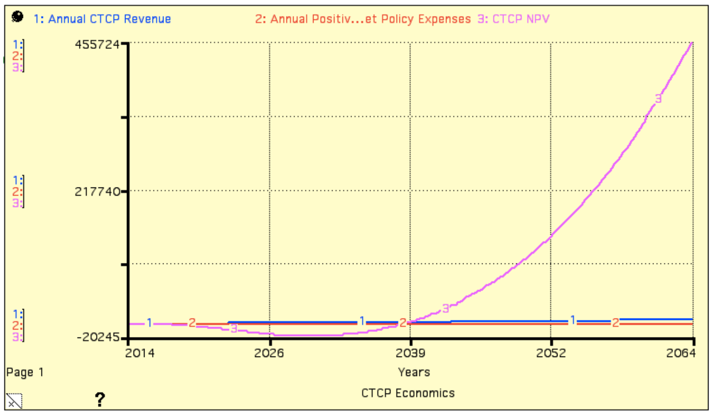


Figure 38. Policy Costs, Revenues and NPV as compared to NEORI (2012)

If we compare these results with the same variables generated by the system dynamics model (Figure 38), we will find a similar dynamic pattern at close to each other scales.

The comparison does not prove the validity of the model but indicates that the generate variables are operating within the reasonable ranges. This may increase our confidence in the obtained model and policy results.

Conclusions

Results

Chapter 1 established the context for the thesis project, described the client engagement and formulated the problem definition. Based on that the research objectives and research questions were stated.

If to reformulate the problem definition in a simplified way, the problem question will be why a complex integrated system of CO_2-EOR and CCUS industries with the related CO_2 market is not generating the growth behavior?

Then the first research objective would call investing an effort into our understanding of potential forces that may provide such growth (research question 1), how those forces function (research question 2) and, consequently, why they do not produce the desired growth at the present moment (research question 3).

Chapter 2 and 3 provide the answers to those questions.

Chapter 2 gives a detailed description of the model. By investigating the underlying feedback mechanisms the model makes explicit the key interconnections between the elements of the complex integrated CO_2-EOR-CCUS system. According to the feedback structure, the key reinforcing mechanisms are operating through the expectations about future CO_2 supplies (loop R1) and the learning effect (loop R2). The feedback structure provided the hypothesis for the current lack of growth dynamics in the system. The present weakness of the CCUS market mechanisms keeps the correcting B1 loop weak, which (a) does not allow loop R2 to get stronger through the ultimate activation of the learning effect and (b) keeps loop R1 practically dormant and thus does not generate the global growth in the system. The three core loops are linked by a complex interconnection, which at the moment is not active.

Chapter 3 tested the feedback hypothesis by means of simulation. The base run reproduced the current stabilizing dynamics in the key variables, namely incremental oil production and CO_2 capture. The ideal run indicated the potential development of the system under ideal work of loops B1, R1 and R2. The conducted analysis suggested the need for the policy so that the scenario indicated by the ideal run could be achieved.

Chapter 4 was devoted to establishing confidence in the model. While due to the nature of the problem and the absence of the reference mode, the ability to conduct the behavior tests was constrained, the structure and structure-related behavior tests indicated the validity of the model with regard to its purpose. The sensitivity analysis revealed that there is only one source of uncertainty to which the model is highly sensitive, which is the learning effect parameter (Reference Accumulated CO_2 Capture). However, in accordance with the model's purpose, this uncertainty can be tolerated.

Based on achieving the first research objective, the final Chapter 5 focused on addressing the second objective – how to generate the self-sustained growth in this complex dynamic system – and the corresponding two research questions: what are the uncertainties and associated policies robust to those uncertainties. Different policy designs were formulated and tested. The key challenge was revealed to be that in a highly dynamic complex system like CO_2-EOR-CCUS a policy maker is left uncertain about when exactly the non-linear interaction of various feedback loops would result into self-supporting mechanisms becoming active. There is a problem of overinvesting resources when the growth could have been relied on inherent reinforcing mechanisms or underinvesting and, thus, not giving the system enough momentum for activation of the growth-generating loops.

The tested Carbon Tax Credit policy itself introduces 2 more reinforcing mechanism in the system, based on the ultimate ability of the program to finance itself through the tax revenues from the incremental oil production. The policy testing led to two key insights. First, the additional reinforcing mechanisms brought by the policy allow achieving growth even with budgets less then required. Second, the key criterion for the robustness of a policy design in this system is whether after the program the self-sustained growth in the key variable of the system could be maintained. A number of generic policy designs satisfying this criterion were identified.

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.

The further work in this direction can continue along at least 2 dimensions.

First, the current model in its form can be calibrated to the case of North Dakota state to address the further needs of the Client of this project. The calibration is plausible and meaningful at the current stage as the assumptions underlying the model fit the specific of the ND case (e.g., one source of CCUS).

Second, the author of this thesis continues his system dynamics journey within the Ph.D. studies. Developing comprehensive models behind each sector of the current model is his target for the upcoming three years.

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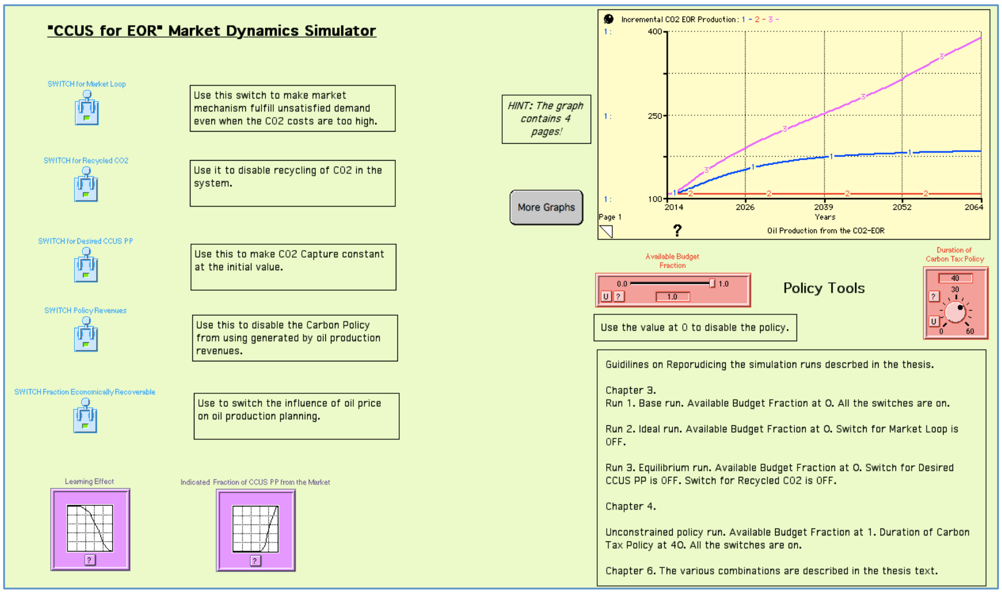
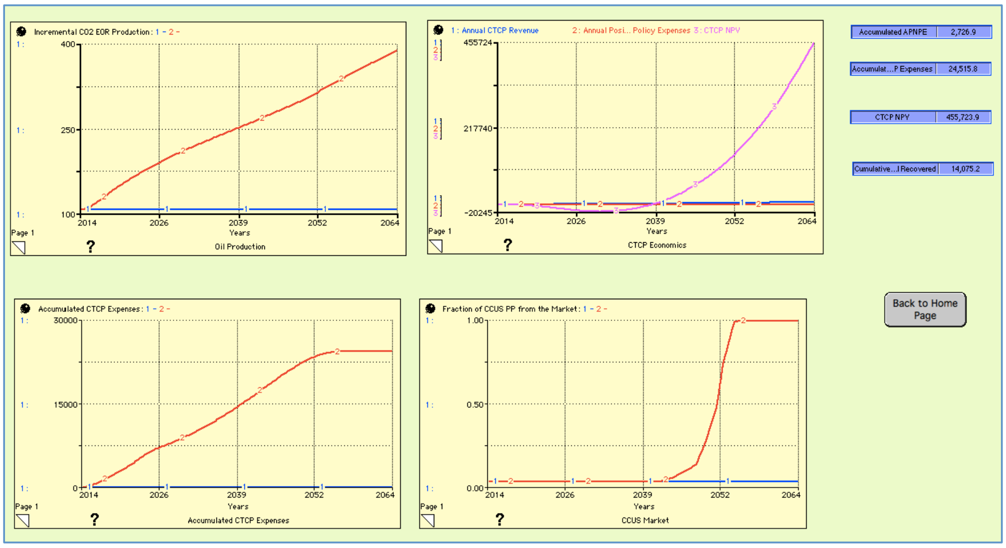
Appendix A. Model Interface



Model Interface: Page 1



Model Interface: Page 2

Appendix B. Model Documentation

The following pages provide the complete model documentation generated by the iThink 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.

A_Demand_for_CO2 =

Cumulative_Oil_Recovered(t) = Cumulative_Oil_Recovered(t - dt) + (Incremental_CO2_EOR_Production) * dt
INIT Cumulative_Oil_Recovered = 1500
UNITS: Mbbl

INFLOWS:

Incremental_CO2_EOR_Production = Oil_Recovered_per_CO2_Injected* Total_CO2_Injected
UNITS: mbbl/yr

EOR_Reserves(t) = EOR_Reserves(t - dt) + (-Incremental_CO2_EOR_Production) * dt
INIT EOR_Reserves = 61.5*1000
UNITS: Mbbl
DOCUMENT: According to AIR, 2011; based on the State of the Art EOR technology; this is one of the most conservative estimations.□□Mbbl stands for million barrels.

OUTFLOWS:

Incremental_CO2_EOR_Production = Oil_Recovered_per_CO2_Injected* Total_CO2_Injected
UNITS: mbbl/yr

Expected_CO2_Supply(t) = Expected_CO2_Supply(t - dt) + (Change_in_Expected_CO2_Supply) * dt
INIT Expected_CO2_Supply = Indicated_Expected_CO2_Supply
UNITS: mtonne/yr
DOCUMENT: Initialized in accordance with the initial level of oil production. Based on OGJ (2014).

INFLOWS:

Change_in_Expected_CO2_Supply = (Indicated_Expected_CO2_Supply-Expected_CO2_Supply)/Time_to_Form_Expectation_about_CO2_Supply
UNITS: mtonne/yr^2

Annual_Demand_for_CO2 = Est_Oil_Production_from_EOR_projects_Supported_by_CO2_Supply/ Oil_Recovered_per_CO2_Injected
UNITS: mtonne/yr

- Breakeven_Oil_Price = 85
UNITS: USD/bbl
DOCUMENT: according to NETL (2011); defined as the price that at $40 per metric tone of CO2 ensures 20% rate of return before tax

- CO2_per_plant_per_year = 0.0063
UNITS: Mtonne/Mwt-yr
DOCUMENT: According to NETL(2011); assuming 7MMmt/yr of CO2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity

- Correcting_Factor_for__Cum_Demand = 0.001
UNITS: Mtonne
DOCUMENT: Is used for technical purposes: to esnure that the Effect of Exp CO2 Supply which follows further does no include the division by zero

- Cumulative_Demand__for_CO2 = Economically_Recoverable_EOR_Reserves/ Oil_Recovered_per_CO2_Injected+Correcting_Factor_for__Cum_Demand
UNITS: Mtonne
DOCUMENT: Represents the idea of how much CO2 is required to recover of the economically recoverable reserves.

- Demand_for_Anthropogenic_CO2 = Demand_for_Purchased__CO2-Natural_CO2_Supply_Rate
UNITS: mtonne/yr

- Demand_for_Purchased__CO2 = Annual_Demand_for_CO2-Expected_Recycled_CO2_Supply
UNITS: mtonne/yr

- Economically_Recoverable_EOR_Reserves = EOR_Reserves* Fraction_Economically_Recoverable
UNITS: Mbbl

- Effect_of_Exp_CO2_Supply_on_Estimated_CO2_EOR_Production = Expected_CO2_Supply/(Cumulative_Demand__for_CO2)
UNITS: per year (1/yr)
DOCUMENT: A ver simple way to represent the idea of supply expectation as the key determinant of CO2 demand: only as much of economically recoverable reserves can be planned for annual production as supported by expectations about CO2 supplies.

- Est_Oil_Production_from_EOR_projects_Supported_by_CO2_Supply = Economically_Recoverable_EOR_Reserves* Effect_of_Exp_CO2_Supply_on_Estimated_CO2_EOR_Production
UNITS: mbbl/yr

- Expected_Anthropogenic_CO2_Supply = SMTH1((CCUS_PP_Under_Construction+ CCUS_PP)*CO2_per_plant_per_year,5)
  UNITS: mtonne/yr

- Expected_Natural_CO2_Supply = IF(Natural_CO2_Reserves>0) THEN(Potential_Natural_CO2_Supply_Rate) ELSE(0)
  UNITS: mtonne/yr

- Expected_Recycled_CO2_Supply = SMTH1(CO2_Reinjection_Rate,Time_to_Average_CO2_Reinjection_Rate)
  UNITS: mtonne/yr
  DOCUMENT: The expectation is formulated as the average of the actual CO2 re-injection rate accross the time to average the supply rate.

- Expected_Recycled_CO2_Supply = SMTH1(CO2_Reinjection_Rate,Time_to_Average_CO2_Reinjection_Rate)
  UNITS: mtonne/yr
  DOCUMENT: The expectation is formulated as the average of the actual CO2 re-injection rate accross the time to average the supply rate.

- Fraction_Economically_Recoverable = (Initial_Fraction_Economically_Recoverable* Effect_of_Oil__Price_on_Economically_Recoverable__Reserves)* SWITCH_Fraction_Economically_Recoverable+(1- SWITCH_Fraction_Economically_Recoverable)*Initial_Fraction_Economically_Recoverable
  UNITS: Unitless

- Indicated_Expected_CO2_Supply = Expected_Anthropogenic_CO2_Supply+ Expected_Recycled_CO2_Supply+Expected_Natural_CO2_Supply
  UNITS: mtonne/yr

- Initial_Fraction_Economically_Recoverable = 0.44
  UNITS: Unitless
  DOCUMENT: Initialized analytically to match the current oil production (NETL, 2011).

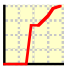
- Oil_Recovered_per_CO2_Injected = 1.6
  UNITS: Mbbl/Mtonne
  DOCUMENT: Represets the conversion factor from CO2 to Oil recovered due to EOR; the reverse of the CO2 Utilization factor. Estimated according to a number of sources: NETL (2010), AIR (2011), Melzer (2012).

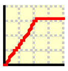
SWITCH_Fraction_Economically_Recoverable = 1
UNITS: Unitless
DOCUMENT: SWITCH ON (value 1) = the Fraction Economically Recoverable changes according to theoil price dynamics; SWITCH OFF (value 0) = the Fraction Economically Recoverable remains at its initial value. The sensitivity testing showed the effect of the dynamics in the fraction does not change the behaviour of Estimated Oil Production from EOR projects (as CO2 supplies still constitute a small portion of EOR reserves).

Time_to_Average_CO2_Reinjection_Rate = 5
UNITS: years (yr)

Time_to_Form_Expectation_about_CO2_Supply = 3
UNITS: years (yr)
DOCUMENT: Ausual time for adjusting supply expectations (OGJ, 2014)

Unsatisfied_Demand_for_CO2 = Max(Demand_for_Anthropogenic_CO2-CO2_Capture,0)
UNITS: mtonne/yr

Effect_of_Oil__Price_on_Economically_Recoverable__Reserves = GRAPH(Oil_Price/Breakeven_Oil_Price)

(0.00, 0.00), (0.2, 0.00), (0.4, 0.00), (0.6, 0.00), (0.8, 0.00), (1.00, 1.00), (1.20, 1.00), (1.40, 1.12), (1.60, 1.26), (1.80, 1.39), (2.00, 1.50)
UNITS: Unitless

Oil_Price = GRAPH(time)

(2014, 88.3), (2015, 88.2), (2016, 91.3), (2017, 96.1), (2018, 98.7), (2019, 101), (2020, 104), (2021, 106), (2022, 108), (2023, 110), (2024, 113), (2025, 115), (2026, 118), (2027, 120), (2028, 123), (2029, 126), (2030, 128), (2031, 131), (2032, 134), (2033, 137), (2034, 140), (2035, 143), (2036, 147), (2037, 150), (2038, 154), (2040, 157), (2041, 161), (2042, 161), (2043, 161), (2044, 161), (2045, 161), (2046, 161), (2047, 161), (2048, 161), (2049, 161), (2050, 161), (2051, 161), (2052, 161), (2053, 161), (2054, 161), (2055, 161), (2056, 161), (2057, 161), (2058, 161), (2059, 161), (2060, 161), (2061, 161), (2062, 161), (2063, 161), (2064, 161)
UNITS: USD/bbl
DOCUMENT: in 2011 USD (deflated); according to the forecast by the US EIA; http://www.eia.gov/forecasts/steo/

B_CCUS:_CO2_Supply =

Accumulated_CO2_Capture(t) = Accumulated_CO2_Capture(t - dt) + (CO2_Capture) * dt
INIT Accumulated_CO2_Capture = 0
UNITS: Mtonne
DOCUMENT: Mtonne stands for a million metric tonnes

INFLOWS:

CO2_Capture = (CO2_per_plant_per_year)*CCUS_PP
UNITS: mtonne/yr

CCUS_PP(t) = CCUS_PP(t - dt) + (CCUS_PP_Deployment_Rate - CCUS_PP_Depreciation_Rate) * dt
INIT CCUS_PP = 2200
UNITS: Mwt
DOCUMENT: CCUS power plants are measured in terms of the generating capacity

INFLOWS:

CCUS_PP_Deployment_Rate = CCUS_PP_Under_Construction/Time_to_Construct_CCUS_PP
UNITS: mwt/yr

OUTFLOWS:

CCUS_PP_Depreciation_Rate = CCUS_PP/Av_CCUS_PP_Lifetime
UNITS: mwt/yr

CCUS_PP_Under_Construction(t) = CCUS_PP_Under_Construction(t - dt) + (New_CCUS_PP_Under_Construction - CCUS_PP_Deployment_Rate) * dt
INIT CCUS_PP_Under_Construction = ((Initial_Capture_Rate/CO2_per_plant_per_year)/Av_CCUS_PP_Lifetime)*Time_to_Construct_CCUS_PP
UNITS: Mwt

INFLOWS:

New_CCUS_PP_Under_Construction = MAX(CCUS_PP_from_Carbon_Policy+CCUS_PP_from_the_Market,0)
UNITS: mwt/yr

OUTFLOWS:

CCUS_PP_Deployment_Rate = CCUS_PP_Under_Construction/Time_to_Construct_CCUS_PP
UNITS: mwt/yr

Adjustment_for_CCUS_PP = (Desired_CCUS_PP-CCUS_PP)/CCUS_Power_Plants_AT
UNITS: mwt/yr

Adjustment_for_SL = (Desired_SL-CCUS_PP_Under_Construction)/SL_AT
UNITS: mwt/yr

- Av_CCUS_PP_Lifetime = 30
UNITS: years (yr)
DOCUMENT: According to NETL(2010)

- Av_CCUS_PP_Lifetime = 30
UNITS: years (yr)
DOCUMENT: According to NETL(2010)

- CCUS_Power_Plants_AT = 1
UNITS: years (yr)

- CCUS_PP_from_the_Market = MAX(Indicated_New__CCUS_PP_in_Planning*Fraction_of_CCUS_PP_from_the_Market,2200/30)
UNITS: mwt/yr

- CCUS_PP_from_Carbon_Policy = IF(Time<=(STARTTIME+Duration_of_Carbon_Tax_Policy)) THEN(Indicated_CCUS_PP_from_Carbon_Policy*Fraction_of_CCUS_PP_by_Carbon_Policy) Else(0)
UNITS: mwt/yr
DOCUMENT: The model equation incorporates two constraints which are the policy variables in the model: the availability of the budegt and the duration of the policy.

- CO2_Capture_Ratio = Accumulated_CO2_Capture/Reference_Accumulated_CO2_Capture
UNITS: Unitless

- CO2_Costs = Learning_Effect*Initial_CO2__Costs
UNITS: USD per tonne (USD/tonne)

- CO2_per_plant_per_year = 0.0063
UNITS: Mtonne/Mwt-yr
DOCUMENT: According to NETL(2011); assuming 7MMmt/yr of CO2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity

- CO2_Ratio = CO2_Willigness_to_Pay/CO2_Costs
UNITS: Unitless

- CO2_Willigness_to_Pay = 40
UNITS: USD per tonne (USD/tonne)
DOCUMENT: NEORI, 2012

- Desired__CCUS_PP_Deployment_Rate = MAX(Adjustment_for_CCUS_PP+Expected_CCUS_PP_Depreciation_Rate,0)
UNITS: mwt/yr

- Desired_CCUS_PP = MAX(Demand_for_Anthropogenic_CO2/CO2_per_plant_per_year,0)*SWITCH_for_Desired_CCUS_PP+(Initial_Capture_Rate/CO2_per_plant_per_year)*(1-SWITCH_for_Desired_CCUS_PP)
  UNITS: Mwt

- Desired_SL = LongRun_CCUS_PP__Depreciation_Rate*Time_to_Construct_CCUS_PP
  UNITS: Mwt

- Duration_of_Carbon_Tax_Policy = 40
  UNITS: years (yr)
  DOCUMENT: Policy Variable

- Expected_CCUS_PP_Depreciation_Rate = SMTH1(CCUS_PP_Depreciation_Rate,5)
  UNITS: mwt/yr

- Fraction_Max = 1
  UNITS: Unitless

- Fraction_of_CCUS_PP_from_the_Market = Indicated__Fraction_of_CCUS_PP_from_the_Market*SWITCH_for_Market_Loop+Fraction_Max*(1-SWITCH_for_Market_Loop)
  UNITS: Unitless

- Fraction_of_CCUS_PP_by_Carbon_Policy = IF(Budget_to__Budget_Parameter_Ratio>=1) THEN(1) EISE(Budget_to__Budget_Parameter_Ratio)
  UNITS: Unitless
  DOCUMENT: The function of the variable is not to allow Carbon Policy work if the required coorrection is beyond the limits of the policy budget.

- Indicated_CCUS_PP_from_Carbon_Policy = Max(Indicated_New__CCUS_PP_in_Planning-CCUS_PP_from_the_Market,0)
  UNITS: mwt/yr

- Indicated_New__CCUS_PP_in_Planning = MAX((Adjustment_for_SL+Desired__CCUS_PP_Deployment_Rate),0)
  UNITS: mwt/yr

- Initial_Capture_Rate = 13.86
  UNITS: mtonne/yr

- Initial_CO2__Costs = 70
  UNITS: USD per tonne (USD/tonne)
  DOCUMENT: NEORI, 2012

LongRun_CCUS_PP__Depreciation_Rate = Desired_CCUS_PP/Av_CCUS_PP_Lifetime
UNITS: mwt/yr
DOCUMENT: Is the depreciation rate based on the target for the balancing loop; is introduced to determine the desired supply line (which should be aligned with the idea of along-run eqilibrium in the supply line in accordance with the demand target).

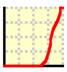
Reference_Accumulated_CO2_Capture = 700
UNITS: Mtonne
DOCUMENT: Is determined based on the estimation that in the absence of stimulating policies the learning effect will kick in only by the end of the 50 year period (SBC Energy Institute, 2012)

SL_AT = 1
UNITS: years (yr)

SWITCH_for_Desired_CCUS_PP = 0
UNITS: Unitless
DOCUMENT: SWITCH ON (value 1) = Desired CCUS PP is determined endogenously by the model;□□SWITCH OFF (value 0) = Desired CCUS PP are constant, set at the initial value of anthropogenic CO2 capture.

SWITCH_for_Market_Loop = 0
UNITS: Unitless
DOCUMENT: SWITCH ON (value 1): the market fraction is generate by the CO2 economics in the model;□□SWITCH OFF (value 0): a hypothetical scenario under which regardless the CO2 economics, the market mechanim works to the fullest (for validation testing).

Time_to_Construct_CCUS_PP = 5
UNITS: years (yr)
DOCUMENT: NETL(2010)

Indicated__Fraction_of_CCUS_PP_from_the_Market = GRAPH(CO2_Ratio)

(0.00, 0.03), (0.0333, 0.03), (0.0667, 0.03), (0.1, 0.03), (0.133, 0.03), (0.167, 0.03), (0.2, 0.03), (0.233, 0.03), (0.267, 0.03), (0.3, 0.03), (0.333, 0.03), (0.367, 0.03), (0.4, 0.03), (0.433, 0.03), (0.467, 0.03), (0.5, 0.03), (0.533, 0.03), (0.567, 0.03), (0.6, 0.03), (0.633, 0.0653), (0.667, 0.101), (0.7, 0.139), (0.733, 0.252), (0.767, 0.387), (0.8, 0.486), (0.833, 0.631), (0.867, 0.727), (0.9, 0.804), (0.933, 0.904), (0.967, 0.994), (1.00, 1.00)
UNITS: Unitless
DOCUMENT: based on the key assumptions from SBC Energy Institute (2012)

Learning_Effect = GRAPH(CO2_Capture_Ratio)
(0.00, 1.00), (0.15, 1.00), (0.3, 1.00), (0.45, 1.00), (0.6, 1.00), (0.75, 1.00), (0.9, 1.00), (1.05, 0.987), (1.20, 0.972), (1.35, 0.947), (1.50, 0.912), (1.65, 0.868), (1.80, 0.821), (1.95, 0.775), (2.10, 0.724), (2.25, 0.642), (2.40, 0.593), (2.55, 0.556), (2.70, 0.53), (2.85, 0.51), (3.00, 0.503)
UNITS: Unitless
DOCUMENT: Based on SBC Energy Institute (2012)

C_CO2_EOR_Process =

CO2_in_Reservoir(t) = CO2_in_Reservoir(t - dt) + (Purchased_CO2_Injection_Rate + CO2_Reinjection_Rate - CO2_Coming_out_of_Reservoir - CO2_Getting_Trapped) * dt
INIT CO2_in_Reservoir = 0
UNITS: Mtonne

INFLOWS:

Purchased_CO2_Injection_Rate = CO2_Supply
UNITS: mtonne/yr

CO2_Reinjection_Rate = (Recycled_CO2*CO2_Reinjection_Fraction)/ Time_to_Prepare_CO2_for_Reinjection
UNITS: mtonne/yr

OUTFLOWS:

CO2_Coming_out_of_Reservoir = (CO2_in_Reservoir* Fraction_of_CO2_out_of_Reservoir)/Time_CO2_Spends_in_Reservoir
UNITS: mtonne/yr

CO2_Getting_Trapped = (CO2_in_Reservoir*(1- Fraction_of_CO2_out_of_Reservoir))/Time_CO2_Spends_in_Reservoir
UNITS: mtonne/yr

CO2_out_of_EOR_System(t) = CO2_out_of_EOR_System(t - dt) + (CO2_Getting_out_of_EOR_System) * dt
INIT CO2_out_of_EOR_System = 0
UNITS: Mtonne

INFLOWS:

CO2_Getting_out_of_EOR_System = (Recycled_CO2*(1- CO2_Reinjection_Fraction))/Time_to_Prepare_CO2_for_Reinjection
UNITS: mtonne/yr

CO2_Stored(t) = CO2_Stored(t - dt) + (CO2_Getting_Trapped) * dt
INIT CO2_Stored = 0
UNITS: Mtonne

INFLOWS:

CO2_Getting_Trapped = (CO2_in_Reservoir*(1-Fraction_of_CO2_out_of_Reservoir))/Time_CO2_Spends_in_Reservoir
UNITS: mtonne/yr

Recycled_CO2(t) = Recycled_CO2(t - dt) + (CO2_Coming_out_of_Reservoir - CO2_Getting_out_of_EOR_System - CO2_Reinjection_Rate) * dt
INIT Recycled_CO2 = 0
UNITS: Mtonne

INFLOWS:

CO2_Coming_out_of_Reservoir = (CO2_in_Reservoir*Fraction_of_CO2_out_of_Reservoir)/Time_CO2_Spends_in_Reservoir
UNITS: mtonne/yr

OUTFLOWS:

CO2_Getting_out_of_EOR_System = (Recycled_CO2*(1-CO2_Reinjection_Fraction))/Time_to_Prepare_CO2_for_Reinjection
UNITS: mtonne/yr

CO2_Reinjection_Rate = (Recycled_CO2*CO2_Reinjection_Fraction)/Time_to_Prepare_CO2_for_Reinjection
UNITS: mtonne/yr

CO2_Reinjection_Fraction = 0.6*SWITCH_for_Recycled_CO2
UNITS: Unitless
DOCUMENT: Mezer (2012)

CO2_Supply = CO2_Capture+Natural_CO2_Supply_Rate
UNITS: mtonne/yr

Fraction_of_CO2_out_of_Reservoir = 0.7
UNITS: Unitless
DOCUMENT: Mezer (2012)

SWITCH_for_Recycled_CO2 = 0
UNITS: Unitless
DOCUMENT: SWITCH ON (value 1) = the model supports the CO2 recycling SWITCH OFF (value 0)= the model does not support CO2 recycling (for validation purposes)

○ Time_CO2_Spends_in_Reservoir = 5
UNITS: years (yr)
DOCUMENT: Based on Melzer (2012)

○ Time_to_Prepare_CO2_for_Reinjection = 3
UNITS: years (yr)
DOCUMENT: Mezer (2012)

○ Total_CO2_Injected = CO2_Reinjection_Rate+Purchased_CO2_Injection_Rate
UNITS: mtonne/yr

D_Natural_CO2_Supply =

□ Cumulative_Natural_CO2_Production(t) = Cumulative_Natural_CO2_Production(t - dt) + (Natural_CO2_Supply_Rate) * dt
INIT Cumulative_Natural_CO2_Production = 2300
UNITS: Mtonne

INFLOWS:

Natural_CO2_Supply_Rate = Natural_CO2_Capacity_Utilization* Potential_Natural_CO2_Supply_Rate
UNITS: mtonne/yr

□ Natural_CO2_Reserves(t) = Natural_CO2_Reserves(t - dt) + (-Natural_CO2_Supply_Rate) * dt
INIT Natural_CO2_Reserves = 3000
UNITS: Mtonne
DOCUMENT: Based on OGJ (2014)

OUTFLOWS:

Natural_CO2_Supply_Rate = Natural_CO2_Capacity_Utilization* Potential_Natural_CO2_Supply_Rate
UNITS: mtonne/yr

○ Demand_for_Purchased__CO2 = Annual_Demand_for_CO2-Expected_Recycled_CO2_Supply
UNITS: mtonne/yr

○ Demand_Pressure_on_Capacity_Utilization = Demand_for_Purchased__CO2/ Potential_Natural_CO2_Supply_Rate
UNITS: Unitless

○ Initial_Natural_CO2_Capacity_Utilization = Initial_Natural_CO2_Supply_Rate/ Potential_Natural_CO2_Supply_Rate
UNITS: Unitless

Initial_Natural_CO2_Supply_Rate = 2.8*19.42
UNITS: mtonne/yr
DOCUMENT: Based on OGJ (2014)

Natural_CO2_Capacity_Utilization = Initial_Natural_CO2_Capacity_Utilization*
Effect_of_Demand_Pressure__on_Capacity_Utilization
UNITS: Unitless

Potential_Natural_CO2_Supply_Rate = 3.4*19.42
UNITS: mtonne/yr
DOCUMENT: Based on OGJ (2014)

Effect_of_Demand_Pressure__on_Capacity_Utilization =
GRAPH(Demand_Pressure_on_Capacity_Utilization)
(0.00, 0.00), (0.5, 0.642), (1.00, 0.949), (1.50, 1.00), (2.00, 1.00), (2.50, 1.21), (3.00, 1.22), (3.50, 1.22), (4.00, 1.22), (4.50, 1.22), (5.00, 1.22), (5.50, 1.22), (6.00, 1.22), (6.50, 1.22), (7.00, 1.22), (7.50, 1.22), (8.00, 1.22), (8.50, 1.22), (9.00, 1.22), (9.50, 1.22), (10.0, 1.22)
UNITS: Unitless

E_Carbon_Tax_Credit_Policy =

Accumulated_APNPE(t) = Accumulated_APNPE(t - dt) +
(Annual_Positive__Net_Policy_Expenses) * dt
INIT Accumulated_APNPE = 0
UNITS: mUSD

INFLOWS:

Annual_Positive__Net_Policy_Expenses = IF(Annual_Net_Policy_Expenses>0)
THEN(Annual_Net_Policy_Expenses) ELSE(0)
UNITS: musd/yr

Accumulated_CTCP_Expenses(t) = Accumulated_CTCP_Expenses(t - dt) +
(CTCP_Expenses) * dt
INIT Accumulated_CTCP_Expenses = 0
UNITS: mUSD

INFLOWS:

CTCP_Expenses = Indicated_CCTP_Expenses
UNITS: musd/yr

Accumulated_CTCP_Revenue(t) = Accumulated_CTCP_Revenue(t - dt) + (Annual_CTCP_Revenue) * dt
INIT Accumulated_CTCP_Revenue = 0
UNITS: mUSD

INFLOWS:

Annual_CTCP_Revenue = CTCP_Oil_Revenue*Oil_Production_Tax_Rate
UNITS: musd/yr

Available_Budget(t) = Available_Budget(t - dt) + (Additions_to_Available_Budget_from_Policy_Revenues - CTCP_Expenses) * dt
INIT Available_Budget = Available_Budget_Calculated*Available_Budget__Fraction
UNITS: mUSD

INFLOWS:

Additions_to_Available_Budget_from_Policy_Revenues = Annual_CTCP_Revenue*SWITCH_Policy_Revenues
UNITS: musd/yr

OUTFLOWS:

CTCP_Expenses = Indicated_CCTP_Expenses
UNITS: musd/yr

CCUS_PP_Under_CTCP(t) = CCUS_PP_Under_CTCP(t - dt) + (New_CCUS_PP_Under_CTCP - CCUS_PP_off_CTCP) * dt
INIT CCUS_PP_Under_CTCP = 0
UNITS: Mwt

INFLOWS:

New_CCUS_PP_Under_CTCP = CCUS_PP_from_Carbon_Policy
UNITS: mwt/yr

OUTFLOWS:

CCUS_PP_off_CTCP = DELAY(New_CCUS_PP_Under_CTCP,Duration_of_Carbon_Credit_Tax_per_CCUS_PP,0)
UNITS: mwt/yr

Annual_Net_Policy_Expenses = CTCP_Expenses-Annual_CTCP_Revenue
UNITS: musd/yr

Available_Budget__Fraction = 1
UNITS: Unitless
DOCUMENT: Policy varibale in the model

- Available_Budget_Calculated = 5355
  UNITS: mUSD
- Budget_Parameter = (Duration_of_Carbon_Credit_Tax_per_CCUS_PP*
  Perceieved__CTCP_Incentive*CO2_per_plant_per_year*
  Indicated_CCUS_PP_from_Carbon_Policy)*Budget_Parameter_Time_Converter*
  Conversion_from_tonne_to_Mtonne*(1/Conversion_from_USD_to_mUSD)
  UNITS: mUSD
  DOCUMENT: mUSD stands for million USD
- Budget_Parameter_Time_Converter = 1
  UNITS: years (yr)
  DOCUMENT: Takes account of the fact that we calculate the accumulated policy expense over 10 years period for the current inflow of new CCUS PP. For the calculation of the budget parameter we are not thinking of those new CCUS PPs as plants per year but as plants that would capture a certain amount of CO2 during a 10 year period which multiplied by the tax incentive size gives the idea of the associated expense.
- Budget_to__Budget_Parameter_Ratio = Available_Budget/(Budget_Parameter+
  Correcting_Factor)
  UNITS: Unitless
- CCUS_PP_from_Carbon_Policy = IF(Time<=(STARTTIME+
  Duration_of_Carbon_Tax_Policy)) THEN(Indicated_CCUS_PP_from_Carbon_Policy*
  Fraction_of_CCUS_PP_by_Carbon_Policy) Else(0)
  UNITS: mwt/yr
  DOCUMENT: The model equation incorporates two constraints which are the policy variables in the model: the availability of the budegt and the duration of the policy.
- CO2_per_plant_per_year = 0.0063
  UNITS: Mtonne/Mwt-yr
  DOCUMENT: According to NETL(2011); assuming 7MMmt/yr of CO2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity
- CO2_per_plant_per_year = 0.0063
  UNITS: Mtonne/Mwt-yr
  DOCUMENT: According to NETL(2011); assuming 7MMmt/yr of CO2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity
- Conversion_from_bbl_to_Mbbl = 1000000
  UNITS: bbl/Mbbl
- Conversion_from_USD_to_mUSD = 1000000
  UNITS: USD/mUSD

- Conversion_from_USD_to_mUSD = 1000000
  UNITS: USD/mUSD
- Conversion_from_USD_to_mUSD = 1000000
  UNITS: USD/mUSD
- Conversion_from_tonne_to_Mtonne = 1000000
  UNITS: tonne/Mtonne
- Conversion_from_tonne_to_Mtonne = 1000000
  UNITS: tonne/Mtonne
- Correcting_Factor = 0.001
  UNITS: mUSD
  DOCUMENT: Is used for technical purposes to prevent the ratio being divided by zero at a very small values of the budget parameter.
- CTCP_Incentive = MAX(CO2_Costs-CO2_Willigness_to_Pay,0)
  UNITS: USD per tonne (USD/tonne)
- CTCP_NPV = NPV(CTCP_NV,Federal_Discount_Rate,0)
  UNITS: mUSD
- CTCP_NV = Accumulated_CTCP_Revenue-Accumulated_CTCP_Expenses
  UNITS: mUSD
- CTCP_Oil_Production = MAX(Incremental_CO2_EOR_Production-IOP_Baseline,0)
  UNITS: mbbl/yr
- CTCP_Oil_Revenue = (Oil_Price*CTCP_Oil_Production)*Conversion_from_bbl_to_Mbbl*(1/Conversion_from_USD_to_mUSD)
  UNITS: musd/yr
- Duration_of_Carbon_Credit_Tax_per_CCUS_PP = 10
  UNITS: years (yr)
  DOCUMENT: according to the design of the policy (NEORI, 2012)
- Federal_Discount_Rate = 0.024
  UNITS: Unitless
  DOCUMENT: Based on NEORI (2012)
- Fraction_of_CCUS_PP_by_Carbon_Policy = IF(Budget_to__Budget_Parameter_Ratio>=1) THEN(1) EISE(Budget_to__Budget_Parameter_Ratio)
  UNITS: Unitless
  DOCUMENT: The function of the variable is not to allow Carbon Policy work if the required coorrection is beyond the limits of the policy budget.

○ Indicated_CCTP_Expenses = CCUS_PP_Under_CTCP*CO2_per_plant_per_year*Perceieved__CTCP_Incentive*Conversion_from_tonne_to_Mtonne*(1/Conversion_from_USD_to_mUSD)
UNITS: musd/yr

○ Indicated_CCUS_PP_from_Carbon_Policy = Max(Indicated_New__CCUS_PP_in_Planning-CCUS_PP_from_the_Market,0)
UNITS: mwt/yr

○ Oil_Production_Tax_Rate = 0.2
UNITS: Unitless
DOCUMENT: represents the fraction of oil revenue that goes to the federal budegt; based on NEORI (2012)

○ Perceieved__CTCP_Incentive = SMTH1(CTCP_Incentive,2)
UNITS: USD per tonne (USD/tonne)

○ SWITCH_Policy_Revenues = 1
UNITS: Unitless

IOP_Baseline = GRAPH(TIME)
(2014, 107), (2015, 109), (2016, 112), (2017, 117), (2018, 121), (2019, 126), (2020, 130), (2021, 134), (2022, 138), (2023, 142), (2024, 145), (2025, 149), (2026, 152), (2027, 154), (2028, 157), (2029, 159), (2030, 162), (2031, 164), (2032, 165), (2033, 167), (2034, 169), (2035, 170), (2036, 171), (2037, 173), (2038, 174), (2040, 175), (2041, 176), (2042, 177), (2043, 178), (2044, 179), (2045, 180), (2046, 180), (2047, 181), (2048, 182), (2049, 182), (2050, 183), (2051, 184), (2052, 184), (2053, 185), (2054, 185), (2055, 186), (2056, 186), (2057, 187), (2058, 187), (2059, 187), (2060, 188), (2061, 188), (2062, 188), (2063, 188), (2064, 189)
UNITS: mbbl/yr
DOCUMENT: is the time series generated by the Base SImulation Run

Oil_Price = GRAPH(time)
(2014, 88.3), (2015, 88.2), (2016, 91.3), (2017, 96.1), (2018, 98.7), (2019, 101), (2020, 104), (2021, 106), (2022, 108), (2023, 110), (2024, 113), (2025, 115), (2026, 118), (2027, 120), (2028, 123), (2029, 126), (2030, 128), (2031, 131), (2032, 134), (2033, 137), (2034, 140), (2035, 143), (2036, 147), (2037, 150), (2038, 154), (2040, 157), (2041, 161), (2042, 161), (2043, 161), (2044, 161), (2045, 161), (2046, 161), (2047, 161), (2048, 161), (2049, 161), (2050, 161), (2051, 161), (2052, 161), (2053, 161), (2054, 161), (2055, 161), (2056, 161), (2057, 161), (2058, 161), (2059, 161), (2060, 161), (2061, 161), (2062, 161), (2063, 161), (2064, 161)
UNITS: USD/bbl
DOCUMENT: in 2011 USD (deflated); according to the forecast by the US EIA; http://www.eia.gov/forecasts/steo/