NATIONAL ENERGY TECHNOLOGY LABORATORY

NEMS CO_2 Market Model Development

Documentation Report

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1. PROJECT DESCRIPTION

1.1 PROJECT BACKGROUND INFORMATION

The types of fossil technologies that NETL supports via various R&D projects -- PC, IGCC, NGCC, and CTL -- can be adapted to capture, dry and compress flue gas CO_2 for transfer via pipeline (as a liquid) to a sequestration repository (e.g., saline aquifer) or oil/gas fields for enhanced recovery (EOR applications) applications. Since NETL is particularly interested in EOR applications (in addition to sequestration), which would both provide new revenue streams to power plant and CTL plant owners and help sequester a significant portion of the CO_2, NETL developed EOR-CO_2 oil supply and CO_2 demand curves by state and region. These relationships help quantify annual projected CO_2 demand for EOR projects and help value the economic potential of selling CO_2 to EOR operators. For a carbon-regulated environment, this also helps characterize residual CO_2 that will have to be sequestered in terrestrial repositories and must, therefore, bear a financial burden to pay for transport and injection of the CO_2.

EIA's National Energy Modeling System (NEMS) is a model that NETL relies on to establish the performance and economic benefits associated with R&D programs. The NEMS model can project potential supplies of CO_2 made available via regional power plant and fuel conversion plant capture to meet future climate change mitigation regulations. Directly matching this regional CO_2 supply with future EOR demand for CO_2 offers a significant economic opportunity for such facilities to accelerate adoption of capture technology. Greater regional diversity of CO_2 supplies can also offer the EOR operators the means for increased future production in different areas of the country and competitive CO_2 pricing. While EIA's latest version of NEMS currently accounts for EOR[1] and accounts for quantities sent to refineries for conversion to fuel products, it does not have the capability to integrate EOR production with the potential supply of CO_2 from power plant and CTL plant capture. Therefore, power generation economics, particularly under imposed carbon mitigation constraints, are not afforded the potential cost credits that can result from sales to EOR facilities; in general, NEMS does not interactively equilibrate CO_2 supply and demand for this purpose.[1] Thus, NETL staff deemed it highly desirable to develop a version of NEMS ("CO_2 Market Model") that links potential CO_2 supply sources with EOR demand specifications.

1.2 PROJECT GOAL

The goal of this project was to develop a modified version of EIA's NEMS model that directly represents potential CO_2 transfer between alternative supply sources and regional EOR-CO_2 production capability as represented by the NETL supply/demand curves; the CO_2 sources included in this project are existing and projected coal and gas-fired power plant capacity and projected CTL plants. Industrial and natural sources of CO_2 are also accounted for via specification as components of the NETL EOR-CO_2 database.

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[1] For AEO2008, EIA has established a preprocessing EOR production methodology based on: 1) projected annual CO_2 source availability by OGSM region and associated CO_2 cost; 2) potential EOR field/reservoir production based on COGAM data; 3) EOR economic model that accounts for a specified world oil price (WOP) profile and the CO_2 cost at the wellhead (based on CO2 capture and transport costs). The economic model establishes EOR production levels based on selection of the most economic CO_2 available in any given region subject to availability of CO_2 for the life cycle of the project, as well as the WOP profile and other economic assumptions (e.g., 15% ROR).

1.3 PROJECT EXECUTION, DOCUMENTATION, AND DELIVERABLES

1.3.1 Project Execution Summary

The project execution steps were as follows:

- Initially, NETL project goals were translated into a detailed design basis document (DBD) required by NEMS modelers. The DBD was completed in mid-February 2008, with modeling initiated thereafter.
- Based on the DBD specifications, the project effort changed focus to modifying the AEO2008 version of NEMS by adding a new module to NEMS (the CO_2 Market Module or CO2MM) as well as incorporating NETL's power plant retrofit code and modifying existing code in other NEMS' modules.
- The basic NEMS structural definition changes and module coding additions and modifications have been performed and tested.
- Model test cases have been executed successfully, the results of which are reported in this document.

A final summary of the project schedule is presented in **TABLE 1-1**.

1.3.2 Project Documentation and Deliverables

The purpose of this document and accompanying material is to comprehensively summarize the project execution, NEMS' model modifications, and additions, and specified model results.

The project deliverables include:

- This documentation report;
- Appendices (contained in separate document file);
  - CO2 Market Model (CO2MM) variables and definitions
  - CO2MM source code
  - CO2MM output report
  - CO2MM input file tables
- Spreadsheet file that contains all project results tables, CO2MM source code, and input and output files;
- All new and modified NEMS files on CD.

1.4 DOCUMENTATION REPORT OVERVIEW

This project documentation report provides the information required to understand the fundamental goals of the project, the necessary requirements and assumptions determined to help satisfy these goals, the modeling methodology utilized to modify NEMS, and the results of a test case that helps validate the coded methodology. The report also provides the essential documentation of the NEMS coding that is critical in future use and modification of this body of work. In order to assist the user in understanding the contents and easily maneuvering around the report, **TABLE 1-2** identifies each section, provides a brief description of the contents, and provides a direct link to jump to any section desired. Note, however, that the Appendix is provided as a separate file due to its large page size.

TABLE 1-1. PROJECT SCHEDULE AND ACTIVITIES RELATIVE TO SOW

SOW DELIVERABLES	SOW SCHEDULE	ACTUAL
A document describing the approach and methodology used to model CO_2 transfers	2 months from initiation	**Project initiated – Week of October 15, 2007** **1st Draft Design Basis Document (DBD) – November 28, 2007** **2nd Draft Design Basis Document – December 18, 2007** **DBD Project Review Meeting at NETL – December 19, 2007** **AEO2008 vs. AEO2007 Comparison – January 8, 2008** **Final Design Basis Document – February 18, 2008** **DBD Project Review Meeting at NETL – February 20, 2008**
Logic flow diagram	3 months from initiation	**1st Draft Logic Flow Diagram – November 28, 2007** **2nd Draft Logic Flow Diagram – December 18, 2007** **Final Logic Flow Diagram – February 18, 2007**
Draft version of the model	7 months from initiation	**Initiated Model Coding – Week of February 25, 2008** **Project Review Meeting (McLean, VA): April 9, 2008** **Plan: Draft Version of Coded Model – Mid-June 2008** **Actual: Late June**
Set of outputs from NEMS runs conducted to exercise the model and prove its functionality,	10 months from initiation	**Plan: Draft of Coded Model and Output – Mid-July 2008** **Actual: Mid-July (Operational in single-cycle mode only) and Mid-September (Operational in multiple-cycle mode)** **Refinement and modifications were made in August to October 2008** **Project update document provided on September 12, 2008** **Project Review Meeting: September 16, 2008**
Final version of the model and supporting document.	12 months from initiation	**Plan: Final Version of Model and Documentation –October 31, 2008** **Actual: Final Version of Model and Documentation –October 31, 2008**

TABLE 1-2. REPORT SUMMARY TABLE**

REPORT SECTION NUMBER	SECTION DESCRIPTION	SECTION LINK
1	Project description and background information	**Section 1**
2	Succinctly describes the project modeling requirements and assumptions.	**Section 2**
3	Discusses the overall methodology that has been implemented in NEMS to equilibrate EOR-CO_2 demand with potential natural and industrial sources, and large-scale power generation and coal-to-liquids (CTL) plant supplies of CO_2 to maximize EOR production over the NEMS projection period.	**Section 3**
4	Describes the CO_2 Market Module (CO2MM), a new module that has been added to the NEMS system to represent CO_2 transfer between different sources and already identified U.S. CO_2 EOR plays.	**Section 4**
5	Describes the modified NEMS structure developed to incorporate the CO2MM into NEMS.	**Section 5**
6	Describes the changes made to other NEMS modules.	**Section 6**
7	Describes the model test results. The CO2MM test case represents a fully integrated 50-cycle NEMS run. The test run results are compared to the two CO2MM reference cases, which are based on AEO2008 version of NEMS with few modifications.	**Section 7**
APPENDICES	CO_2 Market Model (CO2MM) variables and definitions; CO2MM source code; CO2MM output report; CO2MM input file tables	**Appendix File**

** To use the section link, depress the Ctrl key on the keyboard, scroll the mouse over the section link number, and then right click the mouse to go directly to the link.

2. SUMMARY OF KEY MODELING REQUIREMENTS AND ASSUMPTIONS

This section of the report succinctly describes the project modeling requirements and assumptions.

The overriding project modeling requirements, which have been significantly accomplished, were established as follows:

- Maintain compatibility with NEMS' modeling structure and proven execution/convergence methods. Modifications must work with or without imposition of carbon constraints in the model. Carbon constraints can be set either as a CO_2 cap or a tax.
- Replace NEMS' current OGSM accounting of unconventional EOR-CO_2 oil production with NETL's EOR oil production and CO_2 demand projections
- CO_2 demand for economically recoverable oil is assumed to be satisfied by industrial and natural sources, and existing and projected power plant and CTL plant sources
- EOR-CO_2 oil production curves include industrial and natural CO_2 sources (assumed satisfied)
- Market-based methodology is added to establish <u>net</u> EOR-CO_2 oil production and associated CO_2 demand
- Generally want to equilibrate regional CO_2 supply from major energy conversion sources with projected net EOR-CO^2 regional demand to solve for the total regional EOR oil production, CO_2 transfer capacity, and regional marginal CO_2 transfer price offered to CTL and power plants that employ CO_2 capture.
- Total EOR production sent to OGSM = EOR (Industrial & Natural) + EOR (CTL & Power Plant)
- Market-based methodology requires integration of a regional CO_2 transfer price into NEMS' regional calculation of capture-capable power plant and CTL plant levelized product costs (e.g., electricity and liquid fuel).
  - CO_2 transfer price must be established at a high-enough value to ensure suitable selection of capture-based technologies by NEMS to meet marginal CO_2 demand (net of industrial and natural sources assumed to have established long-term contracts with the regional EOR-CO_2 entities).
  - CO_2 transfer price and CO_2 allowance price are different, but mutually dependent
  - CO_2 transfer price will depend on CO_2 supply conditions (less than or in excess of EOR demand)

Based on the above goals, the following assumptions were used to modify NEMS.

2.1.1 EOR-CO_2 Production and CO_2 Demand Assumptions

The oil production and associated CO_2 demand assumptions used for this modeling effort are identified below.

- NETL has developed EOR-CO_2 supply and demand curves for applicable states (and NEMS EMM regions) as provided in a spreadsheet format. These relationships quantify aggregate 30-year CO_2 demand for EOR projects based on EOR oil production, competitive oil market price, and EOR project's IRR specification; they therefore help value the economic potential of selling CO_2 to EOR operators.

  - 30 year aggregate basis with no temporal production basis
  - *f* (IRR, location by state, 5-year average benchmark oil price, CO_2 transfer cost)
  - Spreadsheet data format

- The EOR-CO_2 demand that is matched with NEMS' CO_2 sources (power plants and CTL plants) is assumed to be net of the natural and industrial CO_2 demand that is also included in NETL's EOR-CO_2 database. At the minimum, EOR production is calculated based on the natural and industrial CO_2 supply in a region.
- All regional NETL EOR-CO_2 production and CO_2 demand data is read into NEMS using a spreadsheet format as supplied by NETL and modified by SAIC. It contains the following data:
  - Available internal rate of return (IRR) values
  - Available oil price values
  - Available CO_2 price values - maximum CO_2 price value defines the maximum transfer price that Power Plants and CTL plants can receive.
  - Demand curve tables for all the available states.
  - The demand curve table for each state contains the corresponding EMM and OGSM region ID, 30-year total CO_2 demand, corresponding EOR oil, natural CO_2, and industrial CO_2 for all available IRR values at the oil and CO_2 prices defined above.
- Overall IRR is specified by user and annual benchmark oil price is supplied by NEMS PMM over the projection period. The latter is used to calculate the moving 5-year crude oil price.
- Based on specified IRR and average oil price, 30-year aggregate EOR production and CO_2 demand, by state and EMM region, are calculated via specification of the CO_2 transfer cost. This is the **marginal transfer price** that also represents the sale value to the supplier (including some user-defined portion of the transport cost). It is the key variable that is quantified to equilibrate supply and demand.
- NETL production and demand projection curves are currently maximized at a zero cost CO_2 transfer price. The demand curves have not been adjusted to account for a negative transfer price (e.g., EOR facility is paid to take the CO_2) and associated added oil production capacity. The model assumes that CO_2 is sequestered if CO_2 demand is exceeded. The cost of sequestration is specified on a regional basis.
- NETL demand projections are based on a 30-year aggregate production basis. Use of the demand projections in NEMS requires disaggregation via specification of annual limits on the deployment of EOR-CO_2 production capacity. A deployment profile, based on percentage of total EOR production deployed per year, is a user input specification.

- NETL-based oil production and CO_2 demand curves are adjusted each year of the NEMS projection to account for EOR production capacity (active plays) that is already "married" with operating CO_2 supply sources.
- NETL-based EOR production projections replace EIA's current projection method.

2.1.2 CO_2 Supply Assumptions

The modeling assumptions used to account for CO_2 supply sources are listed below.

- CO_2 sources include 'coal power plants with CO_2 capture', 'natural gas power plants with CO_2 capture', 'CTL/CBTL deployments with CO_2 capture', regional natural supply sources, and regional industrial sources.
- Existing natural CO_2 sources (aggregate 30-year supply of 44.6 TCF) and industrial CO_2 supply sources (aggregate 30-year supply of 4.2 TCF) are uniquely included in the NETL EOR-CO_2 database. The new CO_2 Market Module (CO2MM) assumes that these sources are fully utilized for EOR production as a base level of CO_2 supply.
- For power plants and CTL plants, the CO_2 supply cost accounts for cost-of-capture, compression, and CO_2 trunk-line transport.
- NEMS must adjust the CO_2 transfer price paid to the plants in order to adjust the quantities of the CO_2 supplied by power plants and CTL plants based on annual total regional CO_2 demand requirements.
- Regional CO_2 source costs for the different fossil power technologies are calculated annually based (effectively) on the cost differential ($/ton CO_2) between plants with and without CO_2 capture, including the fuel cost, CO_2 sales credit, and CO_2 transport cost, to cover both carbon-constrained and non-carbon-constrained scenarios. Therefore, plants compete against each other for the "right" to sell their CO_2 into the limited regional EOR markets.

2.1.3 CO_2 Transport Assumptions

The modeling assumptions used for regional CO_2 transport are listed below.

- All CO_2 pipeline transfers are assumed to occur within each NEMS Electricity Market Model (EMM) region, with no transport between regions except the CO_2 transfer to EMM region 13 (California) from the adjacent regions 11 and 12.
- CO_2 pipelines are represented as distinct cost accounting entities in the CO_2 supply chain.
  - Financed and operated by independent organizations.
  - Independent regional pipeline operators buy CO_2 from various sources and sell the CO_2 to the EOR entities – they effectively represent the price negotiators between the buyers and sellers
  - Transport cost is economically represented as the cost differential between the source cost and the EOR buy price for CO_2 (nominally 5-10 $/mt CO_2).
  - Transfer price accounts for both the supply cost and transport cost.

- EOR-CO_2 production capacity is handled on an aggregate regional basis with assumed average pipeline distances from the various CO_2 sources that is directly associated with the user-specified regional transport costs.
- Average regional transport cost is specified by the user for each EMM region.

2.1.4 CO_2 Transfer Price Calculation Assumptions

- On a region-by-region basis, the model establishes the direct quantitative link between different large-source emissions of CO_2 (power plant and CTL plant sources that apply capture technology) and EOR entities based on NETL's regional CO_2 demand curves.
- In order to satisfy the regional, annual CO_2 demand, the most economical supply sources are selected by incorporating the transfer price into power plant and CTL plant investment calculations. The financial benefit of the CO_2 sales to a specific plant-type is factored into:
  - Power plant levelized cost-of electricity (LCOE) calculations used to quantify plant capacity additions;
  - Power plant the O&M cost used to dispatch available power plants; and
  - CTL plant levelized cost of liquid fuel products.
- CO_2 can be sold until the regional aggregate EOR-CO_2 production limit is satisfied based on NETL specifications. Once the annual aggregate regional constraint level is satisfied, then supply plants in the region will have to pay to transport and sequester <u>all</u> captured CO_2. The only reason that supply may exceed EOR demand is if a carbon cap constraint or carbon tax is implemented in the model; excess supply will likely mean that supply sources will have to pay EOR or other entities to take the CO_2.
- CO_2 supply sources, such as power plants, that exceed their demand requirement (e.g., continue to operate beyond the demand time-frame) will need to sequester the excess.
- The CO_2 transfer price (at pressure at the EOR plant gate) is calculated as the effective annual equilibrium price point obtained by matching the effective CO_2 supply curves and the regional EOR demand curve as provided by NETL. A key challenge of the model is to find the equilibrium price point by interpolation between the minimum and maximum transfer price values.
  - The transfer price low-cost limit is based on the cost of regional pipeline transport (e.g., \$5 to \$10/mt CO_2) + sequestration in saline formations (e.g., \$2 to \$10/mt CO_2); CO_2 sources needing to dispose of CO_2 in a regulated environment will pay no more than this aggregate cost. (Negative price means that the EOR operator is paid to take the CO_2 and a positive price means that the EOR facility pays the supplier for CO_2).
  - The revised NEMS model currently initiates the transfer price at this lower limit and raises its value until CO_2 supply at least meets demand or hits the maximum annual supply limit at the maximum transfer price specification. Upon satisfying regional demand (or reaching the production limit), the transfer price reverts back to low-cost limit, which means that regional CO_2 producers must pay to have their CO_2 piped and sequestered.

- The CO_2 Transfer Subsidy has been constrained not to exceed a unique regional calculated value. This value is currently calculated to be **\$54.75/tonne** CO_2, which corresponds to the upper limit of the CO_2 price (\$47.25) provided on the NETL demand curve specification. The value is based on the following definition:

  Transfer Subsidy = EOR Transfer Cost + CO_2 Sequestration Cost – EOR Transport Cost

  = \$47.25 + \$10 - \$2.50 **= \$54.75**

  Currently all regions are assigned the same sequestration and transport costs. If these values are changed by the user, the maximum Transfer Subsidy will be different and different for each region. The code handles this automatically.

- NEMS currently employs a reference case world oil price profile that starts high, decreases to a minimum value, and then increases again to values exceeding the initial level; this profile originally created inconsistencies in the model execution. This oil pricing has the potential to cause an over-supply of CO_2 production during the years of diminishing price.
  - In order to deal with this issue, it is assumed that the maximum allowable annual production will not grow before the year of the minimum oil price. This constraint prevents a conflict between the building of the new Power Plants with CCS and possible production decline associated with the declining oil price profile. The addition of this constraint has been relatively straightforward, since NEMS provides a perfect foresight of the world oil price.
- The regional supply and demand curves yield aggregate EOR production and associated CO_2 demand capacity a 30-year period based on CO_2 transfer price (constant \$2007), benchmark crude oil price (supplied by NEMS), and internal EOR rate-of-return (IRR) specification (supplied by the user). While the current projection time-frame of NEMS is only 22 years (2008 to 2030), the EOR production time-frame is assumed to extend at least 30 years beyond NEMS' projection period to 2060 in order to account for production capacity brought on-line in 2030.
- The projected regional aggregate oil production capacity and associated aggregate CO_2 demand are annualized by specifying yearly EOR production and CO_2 demand limits (annual percentage of total that is initiated in a year) based on a user-specified profile. Therefore, for each slice of the total CO_2 demand satisfied in each year of the projection, the CO_2 supply sources added in each year (e.g., power plant with CO_2 capture) are assumed to contractually supply this required quantity of CO_2. This capacity is "locked-up" for the remainder of the projection.
- In addition to the natural and industrial CO_2 sources, the total marginal supply capacity of CO_2 in each region is determined by the number, type, and size of fossil energy conversion plants with capture that NEMS deploys. They are deployed either because they are economically justified within both carbon-constrained and non-carbon-constrained scenarios or as a result of the requirement to meet specified CO_2 emission levels in a carbon-constrained scenario.

- Regardless of whether the CO_2 is used for EOR or sequestered in a geological sink (e.g., saline aquifer), the model accounts for the cost and parasitic load associated with CO_2 capture from coal power plants, natural gas power plants, and CTL plant deployments. This is accomplished for new and existing plants by including these costs in the plant data provided in the ecpdat file for IGCC with sequestration (IS) and NGCC with sequestration (CS), and CTL with sequestration (input data provided in a PMM input file). *The cost of transport and sequestration/monitoring is not be included in the plant capital and operating cost EMM/PMM input, but added independently to account for regional differences.*
- Once the aggregate EOR CO_2 demand capacity is exhausted, NEMS is required to account for the externality cost associated with transferring/sequestering a certain amount of CO_2 (but only when operating NEMS to constrain CO_2 emissions). Note that NEMS may build plants with CO_2 capture capability even if we're not constraining CO_2 emissions if the CO_2 transfer price yields a cost-effective choice for the capture technology. However, when constraining emissions, the model tracks both EOR-type emissions and required sequestered emissions that will ultimately satisfy the user's specified CO_2 control constraint.
- The user specifies the transport cost distribution (percentage basis) between the CO_2 sellers (e.g., power plants) and the CO_2 buyers (e.g., EOR-CO_2 operators), which ensures proper accounting in the power plant and CTL plant life-cycle cost calculations.
- The methodology used to calculate transfer price makes use of NEMS' perfect foresight[2], whereby the CO_2 transfer price used for calculating levelized product costs for investment decisions derives from the model's ability to use the results from each previous cycle for all components of the levelized cost calculation, including the previous cycle's valuation of the transfer price. This implies the use of long-term contractual vehicles, versus the use of short-term CO_2 contracts and an "early-movers-get-a-high-price-for-their-CO_2" approach. The model uses a first-come-first-serve approach, but the results inherently reflect the use of perfect foresight.
- Limits on the annual deployment rate of EOR-CO_2 plays are explicitly specified by the user.

[2] The perfect foresight approach is based on the theory of rational expectations. This approach generates an internally consistent scenario for which the formation of expectations is consistent with the projections realized in the model. In practice, perfect foresight describes the configuration and solution algorithm that achieves the convergence of expected values and realized solution values. Implementation of perfect foresight involves the iterative cycling of NEMS runs, with each cycle being a complete pass over the entire projection period. The objective is to have expected values and realized values converge between cycles, a state referred to as inter-cycle convergence, in addition to having convergence within the cycle for individual projection years, or intra-cycle convergence. The EMM is heavily dependent on expectations techniques. The EMM requires fuel price expectations for natural gas, oil, and coal for use in its capacity planning submodule. The capacity planning submodule also requires expectations for electricity demand.

2.1.5 NEMS Modification Assumptions

- The latest version of NEMS, AEO2008 – May version, has been used for this effort. All current legislation has been incorporated, as well as the capability to assess climate change legislation.
- This methodology utilized does not interfere with NEMS overriding goals of meeting projected energy demand while constraining pollutant and CO_2 emissions at specified levels.
- While crude oil demand is always satisfied by NEMS, increased and accelerated EOR-CO_2 production will displace imported crude oil consumption in the model, a key goal. This capability is inherently handled by the Petroleum Market Module (PMM).
- The NEMS modification applies to both new fossil energy conversion plants that incorporate CO_2 capture (IGCC, NGCC, CTL) and existing power plants (retrofit of NGCC and PC with CO_2 capture capability). For the latter, NETL developed a method by which to identify and retrofit existing PC power plants, which has successfully been incorporated into the modified NEMS model. The code developed by R. Geisbrecht was implemented.[3] The CO2MM output report file includes appropriate power plant retrofit results to properly track this
- The model includes a parameter to account for the lag-time between CO_2 injection & oil production
    - Baseline value = 1 year
- The code has been structured to enable ***sensitivities*** to be conducted with respect to:
    - Regional CO_2 demand curves,
    - Cost and parasitic load of CO_2 capture from coal power plants, natural gas power plants, and CTL deployments,
    - Cost and parasitic load from CO_2 transport within each region, and
    - Cost of CO_2 injection into a saline formation and MM&V.
    - Lag-time between CO_2 injection & oil production
- The financial benefit of the CO_2 sales to a plant-type have been factored into: 1) power plant levelized cost-of electricity (LCOE) and CTL fuel cost calculations used to quantify plant capacity additions, and 2) plant the O&M costs used to dispatch available plants.
- **TABLE 2-1** provides an overview of the NEMS modules that were added or modified.

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[3] NEMS does not come with a retrofit model for CO_2 capture and sequestration, so the only options for coal plants in carbon constrained scenarios the purchase of CO_2 emission allowances, replacement with more efficient fossil conversion technologies, or their retirement in favor of carbon neutral technologies. In order to provide for the option to retrofit existing coal-fired power plants, certain modification to NEMS code and input files were developed by NETL, and it was possible to stay within the existing modeling structures of NEMS. The modifications effectively extend the existing NEMS retrofit algorithm from a 3-P to a 4-P formulation by adapting an unused option ("spray cooling") originally intended for mercury control (retrofit for mercury control is actually addressed in NEMS by a separate "fabric filter" option).

TABLE 2-1. SUMMARY OF NEMS MODULES CODED

NEMS MODELS	MODEL DESCRIPTION
Integrating Module (IM) Modification	**Controls the NEMS solution algorithm**, executing the NEMS component modules iteratively in an attempt to achieve an energy market equilibrium in each projection year. Using the Energy Market Data portions of the NEMS Global Data Structure as its inputs, the IM tests whether convergence has occurred, and optionally adjusts the solution values to aid the convergence process. The IM also manages the storage of global data and the access to input and output files. Finally, the IM includes an **emission policy submodule** to calculate carbon dioxide emissions and implement some emissions control options that cut across all of NEMS.
$C0_2$ Market Module (CO2MM) Development and Addition	**This is a new NEMS module.** The model incorporates the **NETL regional demand curves** and regional **EOR supply curves** that are used to solve for the optimal regional CO_2 supply requirement and associated transfer price subject to specific constraints (e.g., individual supply source limits, contract supply requirements). The results of this model are passed to the EMM, OGSM, PMM, and IM for subsequent model processing and accounting purposes.
Electricity Market Module (EMM) Modification	**Represents generation, transmission, and pricing of electricity**, subject to delivered prices for coal, petroleum products, natural gas, and biofuels; costs of generation by all generation plants, including capital costs; macroeconomic variables for costs of capital and domestic investment; enforced environmental emissions laws and regulations; and electricity load shapes and demand. There are three primary submodules: **capacity planning**, **fuel dispatching**, and **finance and pricing**. **The EMM has been modified so that the capacity planning and dispatch account for CO_2 transfer cost.**
Petroleum Market Module (PMM) Modification	**Models petroleum refining activities**, the **marketing of petroleum products to consumption regions**, the **production of natural gas liquids in gas processing plants**, **domestic methanol and ethanol production**, and **gas-to-liquids** and **coal-to-liquids production**. The PMM projects petroleum product prices and sources of supply for meeting petroleum product demand. The sources of supply include domestic and imported crude oil; other inputs including alcohols, biodiesel, and ethers; domestic natural gas plant liquids production; petroleum product imports; unfinished oil imports. **The PMM has been modified such that CTL plant addition and operations account for the CO_2 transfer cost.**
Oil and Gas Supply Module (OGSM) Modification	**Represents domestic crude oil and natural gas supply** within an integrated framework that captures the interrelationships among the various sources of supply: **onshore, offshore, and Alaska by both conventional and unconventional techniques, including gas recovery from coal beds and low-permeability formations of sandstone and shale**. The framework analyzes cash flow and profitability to compute investment and drilling for each of the supply sources, based on the prices for crude oil and natural gas, the domestic recoverable resource base, and the state of technology. Oil and gas production functions are computed at a level of 12 supply regions, including 3 offshore and 3 Alaskan regions. This module also represents foreign sources of natural gas, including pipeline imports and exports to Canada and Mexico, and liquefied natural gas (LNG) imports and exports. **The OGSM has been modified such that NETL CO_2-EOR production in the EMM regions are mapped to OGSM regions for feed to the PMM PADDs.**

3. OVERVIEW OF CO_2 SUPPLY-DEMAND AND TRANSFER PRICE IMPLEMENTATION IN NEMS

The purpose of this section of the documentation report is to discuss the overall methodology that has been implemented in NEMS to equilibrate EOR-CO_2 demand with potential natural and industrial sources, and large-scale power generation and coal-to-liquids (CTL) plant supplies of CO_2 to maximize EOR production over the NEMS projection period. The goal of the methodology is to establish an annual cost of CO_2 paid by EOR production entities to the sources to provide sufficient economic incentive to capture, compress, and pump the CO_2 byproduct; increased availability of CO_2 commensurately increases total EOR output and output rate. This methodology has been applied so that it does not interfere with NEMS overriding goals of meeting projected energy demand and constraining pollutant and CO_2 emissions at specified levels. While crude oil demand will always be met by NEMS, increased and accelerated EOR production displaces imported crude oil consumption in the model.

CO_2 transfer between the CO_2 suppliers and EOR-CO_2 entities is effectively represented as long-term contracts in which the transfer price, CO_2 demand, and CO_2 availability vary (or over X number of years) based on the price of benchmark crude oil, availability and cost of alternative CO_2 supply sources, imposed carbon constraints, and other NEMS metrics and constraints that influence demand and supply options. Key factors are:

- Low sulfur light crude oil price projection through 2030 is an exogenous input to NEMS that translates into a price projection for U.S. benchmark crude supplies[4] – PADD III average price of crude (West Texas Intermediate) was used as the benchmark.
- Natural source supply data are incorporated into the model via the NETL supply curves by state and Electricity Market Module (EMM) region. These natural and industrial source supply curves are used as follows:
  - Natural and industrial supplies of CO_2 are assumed to be utilized fully.
- The natural and industrial CO_2-based EOR production is subtracted from NETL's gross EOR production data to yield a separate 30-year EOR production basis to be supplied by the power plant and CTL plant CO_2 supply sources.
- Total EOR production quantities are obtained by adding the annual natural and industrial resource-based EOR production to the calculated annual EOR production from the power plant and CTL plant CO_2 supply sources.
- 'CTL with capture' source availability will vary depending on NEMS' build decisions over the projection period, which are inherently linked to: 1) the price of oil since NEMS competes these products against those from other crude oil sources; 2) level of carbon constraints imposed; and 3) CO_2 transfer price that will be incorporated into the cost calculations. Since the opportunity to sell CO_2 will influence NEMS' plant build decisions, the CO_2 capacity and cost of this supply resource will be established by the model, which is a primary goal of this effort.

[4] NEMS' World Oil Market (WOM) model in the International Model forecasts world oil price on the basis of an exogenously specified OPEC output path.

- Power plant CO_2 supply availability and cost will depend on NEMS selection of 1) existing plant retrofits of capture technology, 2) new 'IGCC with capture' capacity, and 3) new 'NGCC with capture' capacity based on competition with each other and other electricity supply technologies. NEMS overriding goal is to meet projected regional electricity demand projections at least-cost while satisfying all environmental constraints, including carbon constraints. Since the opportunity to sell CO_2 to EOR entities will influence NEMS' plant build decisions, the CO_2 capacity of this supply resource will be calculated by the model, which is a primary goal of this effort.
  - Capacity planning decisions are based on perfect foresight for CO_2 transfer price projection;
  - Annual dispatch varies with the changing CO_2 transfer price profile.
  - For the capture-based technologies, capital and O&M cost input to NEMS account for the CO_2 capture and compression costs, which is part of the current structure. CO_2 "disposition cost" is also accounted for in the capacity planning LCOE calculations, but is included as O&M "externalities." This latter approach provides the flexibility to account for both CO_2 sequestration and CO_2 sales.
    - Transfer cost is defined as the cost that the utility must pay (or be paid) to transfer their CO_2 to some other entity (e.g., EOR or geological sequestration site) for long-time storage.
    - ***Transfer Cost = ±Disposition Cost ± Transport Cost***
    - If carbon constraints are not imposed and sequestration is not required,
    - ***Disposition Cost = + Cost of Capture/Compression***
    - If carbon constraints are imposed and sequestration is required, there are several possibilities:
    - ***Disposition Cost = - Sequestration Cost***; NEMS chooses more capture capacity than EOR demand based on imposed carbon constraint - since there is excess supply in the marketplace, EOR will be treated like any other repository and be paid the same amount to take the CO_2; it's assumed that the power plant bears the cost burden of capture and compression.
    - ***Disposition Cost = - Sequestration Cost* + Transfer Subsidy**; NEMS chooses less capture capacity than EOR demand based on imposed carbon constraint – since supply is less than demand, EOR will accept some amount less than the full sequestration cost to obtain the CO_2 (difference = Transfer Subsidy). In order to maximize supply, the Transfer Subsidy may exceed the sequestration cost, which means that the EOR entity pays the power plant for the CO_2.
    - 0 ≤ **Transfer Subsidy** ≤ user specified value; *e.g., upper limit = CO_2 allowance price*
- ***Transport Cost = user specification by region;*** CO_2 transport will be handled by a separate entity and average regional values will be a user input.
    - No carbon constraint imposed -- EOR facility pays the transport cost (positive value)

- Carbon constraint imposed – Energy plant pays the transport cost (negative value)

  - **Sign protocol:** positive value (+) means that the EOR entity pays the source; negative value (-) means that the source pays the EOR entity

- Projected regional, aggregate CO_2-EOR production levels (e.g., 30-years as provided by ARI) act as the ultimate constraint on regional demand for and sales of CO_2 over the projection time period. However, the model projects annual estimated regional limits on CO_2-EOR production to account for the practical limits of opening new EOR plays, building pipelines, and building supply plants. This also prevents NEMS from attempting to overbuild CO_2 capture-based capacity within too short a time frame.

3.1 CO_2 TRANSFER PRICE CALCULATION METHODOLOGY

3.1.1 No Carbon Constraints (Existing Operating Environment)

There is no incentive for base-load power plants (existing or new) and CTL plants to install CO_2 capture technology unless they can recover the full cost of their capital investment, increased O&M costs (including CO_2 transport), and make a profit. Unless the plant with CO_2 capture is cheaper than a conventional fossil-fired plant, NEMS won't select it for baseload capacity that can meet EOR demand. Thus, the transfer price must be large enough to cover the above cited cost elements (and possibly even higher) so that NEMS will select the technology versus other fossil plants without capture capability and non-fossil plants (e.g., nuclear).

3.1.1.1 Modeling Approach

NEMS calculates the marginal LCOE relative to uncontrolled plants and sells CO_2 at the price that makes up the difference plus profit. CO_2 capture will be specified (user input) at a percentage of maximum yield (e.g., 90%) that directly corresponds to input specification for capital investment and O&M costs (plant + capture + pipeline). A plant must be able to sell all of the CO_2 captured for the life of the plant.

Regional CO_2 demand for a given year is set via the demand curves based on the user-specified IRR value, calculated 5-year price of oil in that year, and the average transfer price of CO_2 (as calculated above). An annual constraint is placed on the CO_2 production capacity by EMM region based on maximum annual EOR demand by region. Once the annual demand is met, then CO_2 transfer value is set to $0/ton valuation. The model must run through multiple 30-year cycles until annual transfer prices are selected such that annual supply meets annual demand. Annual and cumulative CO_2 transfer is tracked by the integrating module.

3.1.1.2 Carbon Tax Case

NEMS responds to exogenous specification of a carbon tax by increasing the cost of fossil fuels to include the tax on a dollar-per-Btu basis. The demand and conversion models respond to the adjusted fossil fuel prices to induce CO_2 emissions reductions. Technologies that capture/sequester CO_2 are credited back the CO_2 tax value by reducing the CO_2-adjusted cost of fuel in proportion to the percentage of total fuel carbon removed. The CO_2-based fuel credit may or may not return the investment in CO_2 capture technology (depending on the technology) such that these technologies are selected. The tax threshold at which CO_2 capture technologies are selected by NEMS is when the tax is large enough to at least return the capital investment and O&M costs. If other technologies, such as nuclear, are still cheaper, they will be selected by NEMS.

The only difference between this and a cap case is that the latter chooses the CO_2 market-clearing price (carbon tax) to satisfy the user-specified cap constraint, while in the former the user directly specifies the carbon tax. The EOR transfer price needs to be set at a level such that NEMS selects at least enough capacity to satisfy marginal CO_2 demand. If the tax is set high enough, NEMS may select more capture-capable plant capacity than is required to meet the marginal EOR CO_2 demand, and any residual CO_2 must be sequestered.

3.2 CO_2 MARKET MODULE (CO2MM) DEVELOPMENT

The project has created a new CO_2 Market Module (CO2MM) in NEMS that attempts to equilibrate supply and demand and establish regional transfer prices. This model incorporates the NETL regional demand curves and regional CO_2 supply curves and program logic used to solve for the optimal regional CO_2 supply requirement and associated transfer price subject to specific constraints (e.g., individual supply source limits, contract supply requirements). The results of this model are then passed to the EMM, OGSM, and PMM for subsequent model processing and accounting purposes.

3.2.1 CO2MM General Logic Description

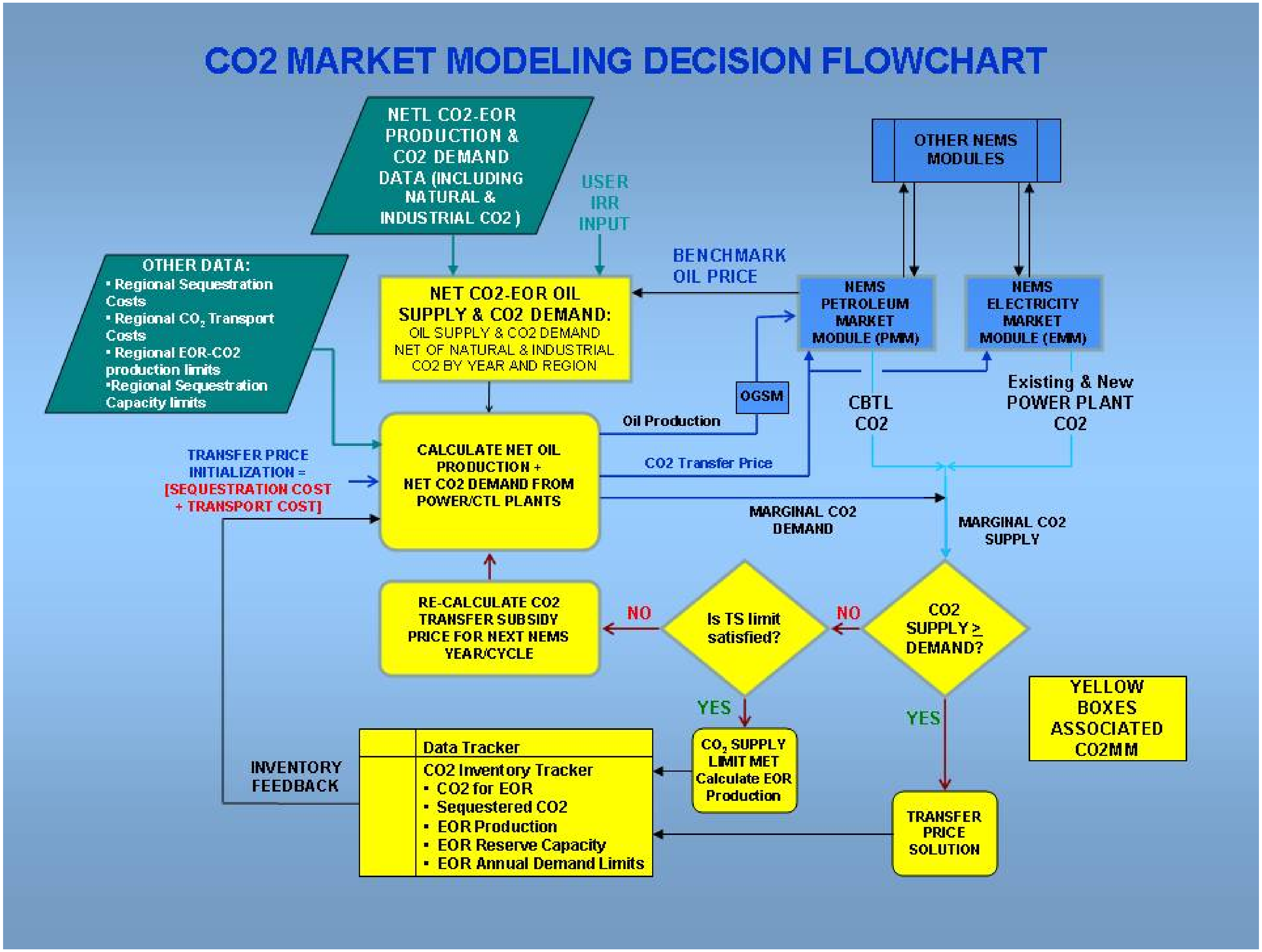
The CO2MM modeling decision flowchart is provided in **FIGURE** 3-1. The most important aspect of the module's logic is that it interactively works with the EMM, PMM, and Integrating Module to derive regional transfer pricing and in doing so positively influences technology selection within a region. However, the addition of this module does not interfere with NEMS' primary goal of satisfying energy demand within prescribed environmental limits.

The CO2MM has been designed to utilize CO_2 supplied by natural, industrial, and large-scale energy conversion plants as specified by the NETL data; these sources were described previously. The CO_2 analysis hierarchy currently assumes that natural and industrial sources are utilized fully, while the large-scale conversion plants are the marginal suppliers. This means that the first calculation priority of the CO2MM is to establish the regional marginal or net CO_2 demand.

The overall goal of the CO_2 Market Module (CO2MM) is to "marry" CO_2 supply from a number of different sources with CO_2 demand for EOR production. In doing so, we want to maximize EOR production by maximizing CO_2 supply while minimizing the CO_2 transfer cost. Assuming operation of NEMS within a carbon constraint scenario, a general execution description is provided below:

- Read in NETL data that quantify gross projected EOR production and associated CO_2 demand for EOR projects (aggregate production and demand covering 30-years) based on a 5-year (backward-looking) average benchmark oil price and the EOR project's IRR specification; this provides the capability to value the economic potential of selling CO_2 to EOR operators over a long-term contract period. See **Section 5.3** for more detail**.**
  - On a state-by-state basis, the natural and industrial CO_2 supply is subtracted from the state total CO_2 demand and the net state demand values are added to obtain the EMM regional CO_2 demand curves.

FIGURE 3-1. CO_2 MARKET MODELING DECISION FLOWCHART



- Read in other user-defined data required for the calculations as defined below in **Section 5.3.1**:
  - Start Year for the EOR production
  - Gross regional CO_2 sequestration storage capacities for deep saline formations
  - Regional CO_2 sequestration and transport costs
  - Regional Gross EOR reserve limit based on NETL data for 30-year capacity @ $70/bbl oil price and $0/metric ton CO_2 price and user-defined IRR value
  - Regional EOR maximum, annualized gross production profile
  - Regional EOR annualization production profile
  - EOR internal rate of return (IRR) - user specification by region (currently set to 30%)
- NEMS executes in the following order: *International Model, Macroeconomic Model, Coal Market Model, Residential Demand Model, Commercial Demand Model, Industrial Demand Model Transportation Demand Model, CO2MM, EMM, OGSM, NGTDM, PMM, Renewables*
- **CO2MM:** For EOR Start Year, C02MM initially performs the following functions by region:
  - Initialize Transfer Subsidy = Max Value
  - Initialize CO_2 transfer price = -sequestration cost + transfer subsidy $\pm$ Transport Cost
  - Calculate the gross EOR production and associated gross CO_2 demand from NETL data based on user-specified IRR, benchmark crude oil price passed from PMM, and initial transfer cost (**See Section 5.2.5.1**).
  - Annualize the gross production and CO_2 demand via user-specified annual production profile input specification
  - Pass the following data to other modules:
    - EOR annual production to OGSM
    - Initial CO_2 transfer cost to PMM and EMM
- EMM executes and calculates technology capacity addition, including PC plant retrofits, IS and CS capacity; power plant CO_2 capture quantity is calculated and passed back to CO2MM;
  - Until the annual gross EOR CO_2 demand is met (in each year), the transfer cost will exceed the cost of sequestration; added capacity is based on this transfer cost; EMM stores this transfer cost for this specific capacity addition (by type and region) and uses it for capacity dispatch
  - When the annual gross EOR CO_2 demand is met or exceeded in a particular year of the projection, the transfer cost equals the cost of sequestration; added capacity is based on this transfer cost (as adjusted for cost of CO_2 transport); EMM stores this transfer cost for this specific capacity addition (by type and region) and uses it for capacity dispatch.

    - Note that there is no need to add new EOR-only capture technologies to NEMS based on the above market-oriented logic.

- OGSM executes -- adds EOR production to conventional and unconventional production and passes total oil production to PMM

- PMM executes and calculates 'CTL with CO_2 capture'; total PMM CO_2 capture is passed back to CO2MM

- CO2MM compares current annual CO_2 demand with total annual CO_2 supply from EMM and PMM

    - **Logical comparison**: Is CO_2 supply $\geq$ EOR demand?

        - **Yes**: Transfer price solution has been found; CO2MM calculates CO_2 to be sequestered (total – EOR demand); CO2MM data tracker saves data

        - **No**: **Logical comparison**: Is Transfer Subsidy limit satisfied?

            - **Yes**: CO_2 supply limit has been satisfied; CO2MM calculates EOR production associated with CO_2 supply limit; No CO_2 sequestration is required; CO2MM data tracker saves data

            - **No**: **Logical comparison**: Is EOR CO_2 demand associated with annual EOR production limit satisfied?

                - **Yes**: CO_2 demand limit has been satisfied; CO2MM calculates EOR production associated with CO_2 supply limit; No CO_2 sequestration is required; CO2MM data tracker saves data

                - **No**: Since total CO_2 supply is less than the specified demand **and** the transfer subsidy limit isn't exceeded **and** CO_2 demand limit isn't exceeded, **then** CO2MM changes the transfer subsidy, to update the transfer cost; CO2MM recalculates the EOR production and associated CO_2 demand from NETL data based on user-specified IRR, the benchmark crude oil price passed from PMM, and the updated transfer cost.

- NEMS executes next year in the cycle and repeats its steps with some additional calculation specifications to correctly handle the NETL data.

- CO2MM executes

    - **Logical comparison**: Is the cumulative gross EOR production = Maximum gross EOR production?

        - **Yes**: CO2MM execution is complete and EOR production is maximized

        - **No**: CO2MM execution continues

            - Execution is same as described above, but the gross EOR production and associated gross CO_2 demand are calculated differently – by difference between the current year and the previous year. See **Section 5.2.5.1** for a description.

- The model must run through multiple 30-year cycles until annual transfer costs are selected such that the cumulative gross CO_2 demand meets cumulative gross CO_2 supply. Annual and cumulative CO_2 transfer to EOR facilities and sequestration facilities is tracked by the CO2MM. Of course, all of the other NEMS constraints must also be satisfied.

3.2.2 Definition of Key Design Parameters

Many of the key design parameters used in the CO2MM coding are defined in this section to provide insight into the approach taken to implement the previously described methodology and the level of control afforded to the user. A complete listing is provided in **Appendix A**.

- The following parameters are manually set (or obtained from data input) in the CO2MM (R = EMM region #; Y = Year; N = number):
  - **EORSTYR(R): Start year for EOR production** (user specified year); units = year
  - **CO2STG(R): Gross regional CO_2 sequestration storage capacity** for deep saline formations based on DOE Sequestration Program data (Billion metric Tons CO_2 total); CO2MM will track regional aquifer utilization based on captured CO_2 not applied to EOR; Units = Billion metric tons CO_2
  - **CO2STGCST(R): Regional deep saline formation sequestration costs** (escalated in subsequent years at user-defined rate); **\$2007;** Units = \$/metric ton CO_2
  - **CO2TRCST(R): Regional CO_2 transport costs** (escalated in subsequent years at user-defined rate)**; \$2007;** Units = \$/metric ton CO_2
  - **EORRES(R): Regional Gross EOR reserve limit** based on ARI data for 30-year capacity @ \$70/bbl oil price and \$0/mton CO_2 price and user-defined IRR value – establishes initial regional EOR reserve capacity as applied to the start of EOR production. This parameter represents an **upper bound on total EOR production by region** that cannot be exceeded; Units = Million bbls oil
  - **EORPRDLMT(N,R,Y): Initial regional, annualized maximum production profile** (for N =1) based on applicable constraints on production of the regional gross EOR supply (e.g., wells drilled, field production limits, pipeline construction, etc.). Regional annual production profile represents the maximum regional production limits <u>for all years in the projection</u> as initialized at the start year of EOR production. The maximum production profile will be reset in each subsequent year based on the actual levels of EOR production. This year-by-year profile will set as a percentage of the total gross regional supply and should add to 100%, which assumes that the gross capacity will be spoken for by 2030; Units = Millions bbls oil; N =1 for start year of EOR production
- The following parameters are initialized, calculated, and tracked in the CO2MM (R = EMM region #; Y = Year; T = technology type #; S = CO_2 source):
  - **TFRSUB(R,Y)**: CO_2 transfer subsidy paid by EOR facility to CO_2 supplier; initialized to zero value in each year of the projection; Units = \$/metric ton CO_2
  - **TFRCST(R,Y)**: CO_2 transfer cost; initialized in each projection year by setting Transfer Subsidy = 0; Units = \$/metric ton CO_2

- **SCO2CAP(T,R,Y)**: aggregate annual CO_2 captured by technology-type, region, and year; Units = Million metric tons CO_2
- **CO2CAP(R,Y): = ΣCO2CAP (T,R,Y)**; aggregate annual CO_2 captured by region, and year; Units = Million metric tons CO_2
- **CO2SEQ(R,Y):** aggregate annual CO_2 sequestered in deep saline formations by region, and year; Units = Million metric tons CO_2
- **EORPRODARI(R,Y):** Gross 30-year production of EOR estimated for year Y (e.g., 2010) in region R as directly calculated using ARI data; Units = Million bbls oil
- **EORPROD(R,Y):** Incremental 30-year production of EOR for each year in the projection; Units = Million bbls oil:
  - For the EOR start year (e.g., 2010), value = **EORPRODARI(R,Y);** if value **exceeds EORPRDLMT(R,Y), EORPROD(R,Y) = EORPRDLMT(R,Y)**
  - For subsequent years (e.g., 2011, 2012, etc.), value = **EORPRODARI(R,Y+1) - EORPROD(R,Y);** if value **exceeds EORPRDLMT(R,Y+1), EORPROD(R,Y+1) = EORPRDLMT(R,Y+1)**
- **EORRES(R,Y):** Remaining total EOR reserves by region and year; **for start year Y of EOR production, = EORRES(R)**; **for year Y+1 of EOR production, =EORRES(R) - EORPROD(R,Y);** Units = Million bbls oil
- **SEORAPROD(S,R,Y):** Annualized regional production of EOR in year Y (e.g., 2010) and by source of CO_2 (e.g., natural, industrial, energy); Units = Millions bbls oil
- **EORAPROD(R,Y): = ΣEORAPROD(S,R,Y)**; Annualized regional production of EOR in year Y (e.g., 2010); this annual production is required to feed the PMM; must be mapped to individual PADDs; Use **EORPRDLMT(N,R,Y)** values as the basis for annualizing **EORPROD(R,Y);** Units = Millions bbls oil
- **EORPRDLMT(N,R,Y): Regional, annualized maximum production profile** must be adjusted for year Y+1 based on the year Y value of **EORPROD(R,Y);** N = Y – EOR start year; Units = Million bbls oil
- **SEORCO2(S,R,Y):** Aggregate regional 30-year demand for CO_2 that begins in year Y (e.g., 2010) and by source of CO_2 (e.g., natural, industrial, energy); must directly correspond to value of **EORPROD(S,R,Y);** Units = Million metric tons CO_2
- **EORCO2(R,Y): =ΣEORCO2(S,R,Y)**; Aggregate 30-year demand for CO_2 that begins in year Y (e.g., 2010) in region R; for year Y+1 in the projection, subtract this value from **EORCO2(R,Y+1)** to calculate the aggregate 30-year CO_2 that begins in year Y+1 (e.g., 2011); Units = Million metric tons CO_2
- **EORACO2(R,Y): = ΣEORCO2(S,R,Y)**; Annualized regional demand for CO_2 in year Y (e.g., 2010) this annual demand must directly correspond to annual EOR production **EORAPROD(R,Y)**; Units = Million metric tons CO_2

4. CO_2 MARKET MODEL DOCUMENTATION

4.1 MODEL OBJECTIVES

The CO_2 Market Module (CO2MM) is a new module that has been added to the NEMS system to represent CO_2 transfer between different sources and already identified U.S. CO_2 EOR plays.

The purpose of CO2MM is to equilibrate CO_2 supply and demand and establish regional CO_2 transfer prices between CO_2 sources (e.g., power plant, natural supply) and EOR/sequestration entities.

4.2 RELATIONSHIP TO OTHER MODELS

Within the NEMS execution order, the CO2MM follows the Transportation Demand Model. The complete module execution order of NEMS is:

1. International Model
2. Macroeconomic Model
3. Coal Market Model
4. Residential Demand Model
5. Commercial Demand Model
6. Industrial Demand Model
7. Transportation Demand Model
8. **CO_2 Market Module (CO2MM)**
9. Electricity Market Model (EMM)
10. Oil and Gas Supply Model (OGSM)
11. Natural Gas Transmission and Distribution Model (NGTDM)
12. Petroleum Market Model (PMM)
13. Renewables

CO_2MM directly interacts with the EMM, PMM, and OGSM modules of NEMS. The NEMS inputs to CO2MM include:

- Quantities of captured CO_2;
- Coal and Natural Gas consumption levels by region and technology type;
- World Oil Price.

CO2MM also provides output to other NEMS modules. The CO2MM outputs include:

- CO_2 Transfer Price;
- EOR Oil Production.

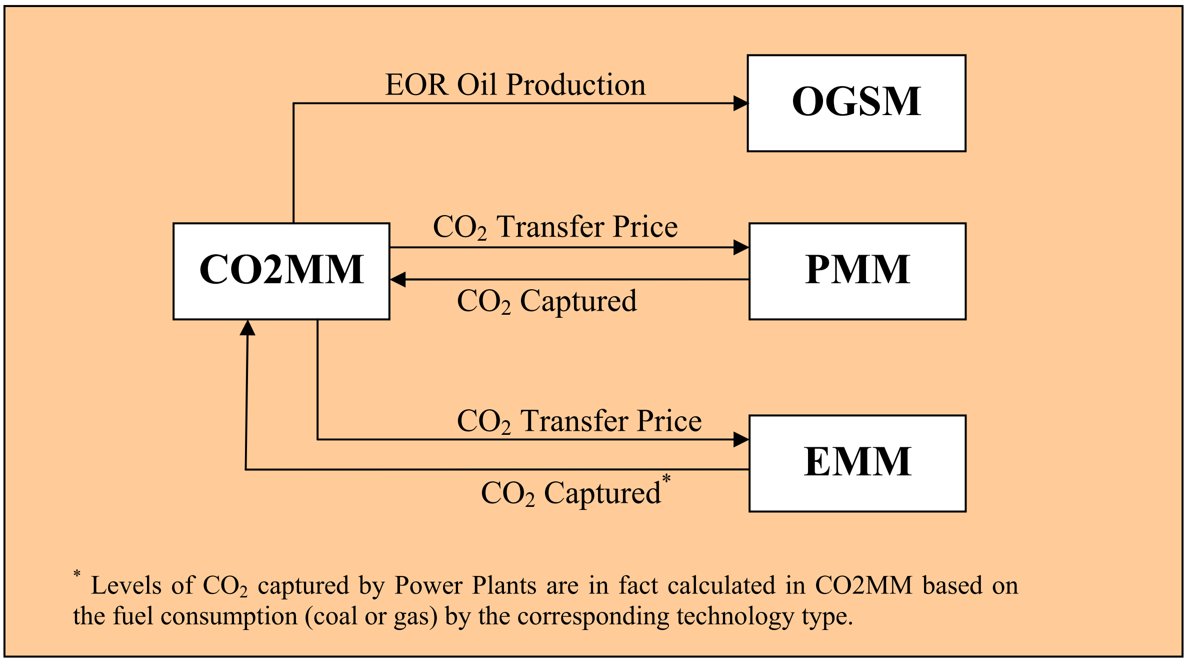
The data flow between CO2MM and these NEMS modules is shown in FIGURE 4-1.

CO2MM models CO_2 pipeline transfers within 15 EMM regions (FIGURE 4-2). However, all NEMS modules use their own module-specific region definitions:

- EMM coal power plant variables are dimensioned by Coal Demand Regions shown in FIGURE 4-3. Natural gas power plant variables are dimensioned by NGTDM/EMM regions which are presented in FIGURE 4-4.
- PMM CTL deployments are modeled in five Petroleum Administration for Defense Districts (PADD) regions. FIGURE 4-5 shows the map of PADD regions.
- OGSM regions are shown in FIGURE 4-6.

To pass information between the variables with different regional definition, the CO2MM utilizes regional mappings which will be discussed in detail later in Section 5.3.

FIGURE 4-1. CO2MM PRIMARY DATA FLOW DIAGRAM



4.3 CO2MM CONVERGENCE AND MAIN ALGORITHM

Due to the existing NEMS' structural constraints and EMM execution, the CO2MM solution convergence routine is based on a cycle-by-cycle approach (e.g., one cycle covers the full NEMS projection horizon through 2030) as opposed to all the other models of NEMS that converge on an iteration-by-iteration basis within one cycle year.

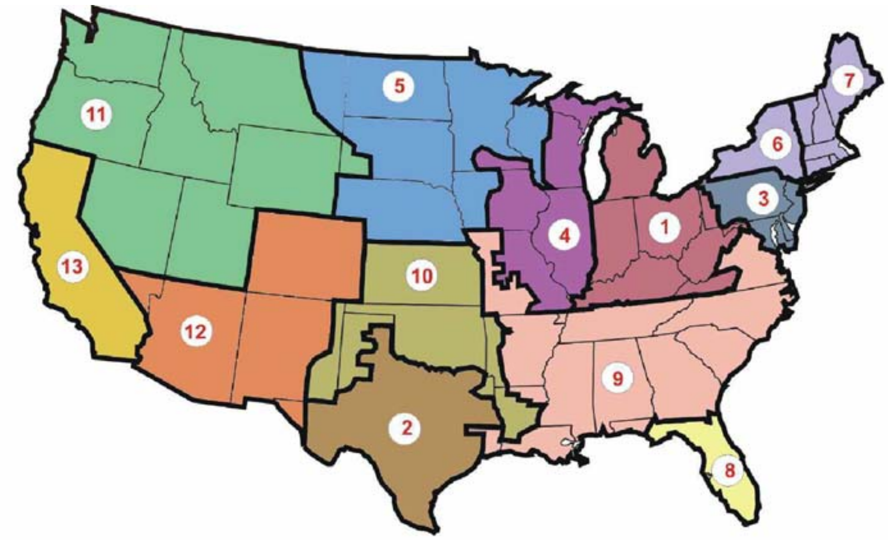
To comply with the NEMS convergence routine, the CO2MM turns off all the NEMS models and starts a new cycle at the second iteration of a given year unless the CO2MM solution for that year is established. Then the CO2MM, along with the rest of NEMS, proceeds to the next cycle year.

The following describes the cyclical algorithm of the CO2MM:

NEMS Model Cycle 1

a. The model starts with the Maximum Transfer Subsidy (currently $54.75) for all allowed regions – can't go higher than this. Note that the CO2MM start year for each cycle is the EOR start year (e.g., 2012) defined in the CO2MM input file.

FIGURE 4-2. EMM REGIONS



1 East Central Area Reliability Coordination Agreement (ECAR)
2 Electric Reliability Council of Texas (ERCOT)
3 Mid-Atlantic Area Council (MAAC)
4 Mid-America Interconnected Network (MAIN)
5 Mid-Continent Area Power Pool (MAPP)
6. New York (NY)
7. New England (NE)
8. Florida Reliability Coordinating Council (FL)
9. Southeastern Electric Reliability Council (SERC)
10. Southwest Power Pool (SPP)
11. Northwest Power Pool (NWP)
12. Rocky Mountain Power Area, Arizona, New Mexico, and Southern Nevada (RA)
13. California (CA)

FIGURE 4-3. COAL DEMAND REGIONS

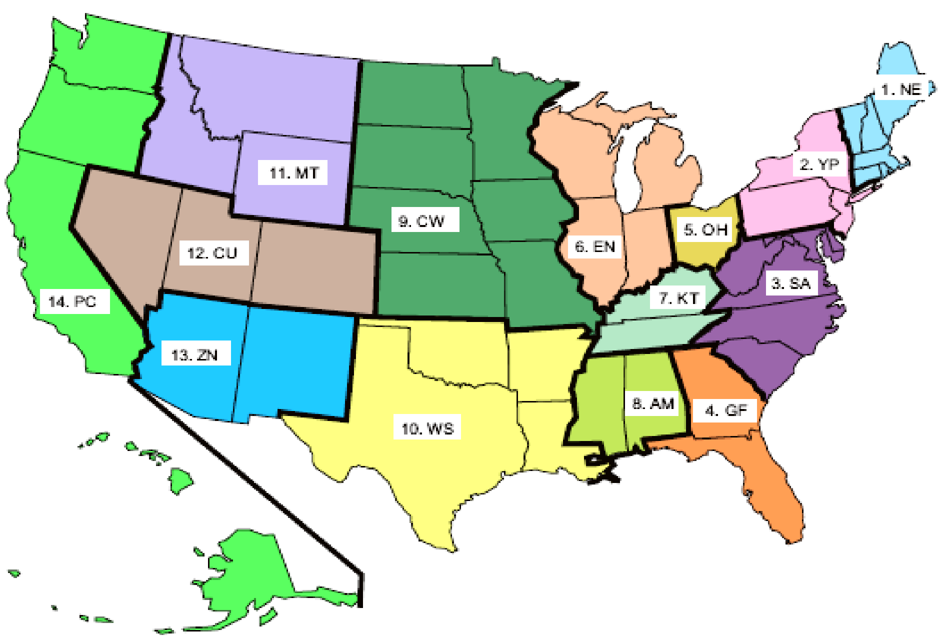


FIGURE 4-4. NGTDM/EMM REGIONS

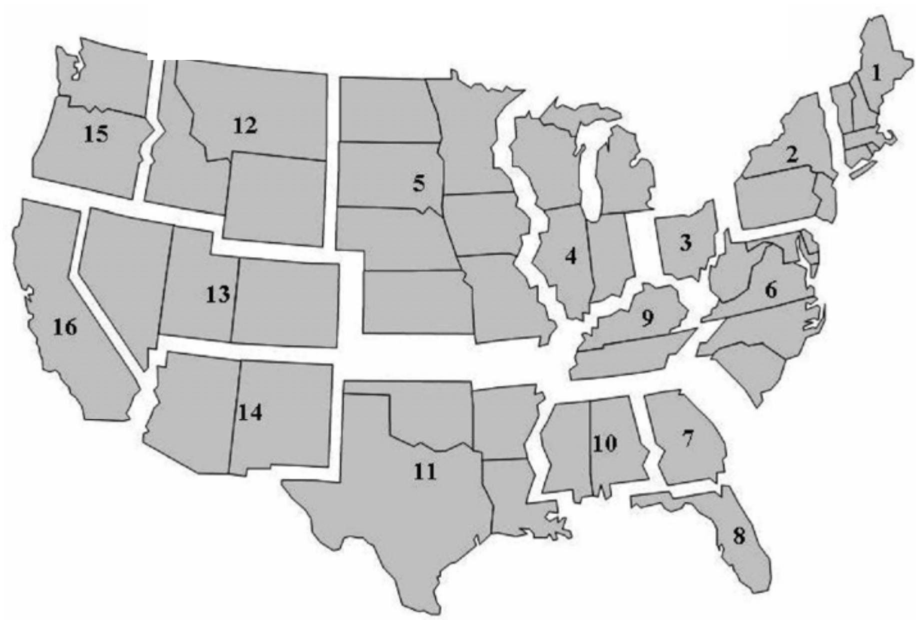


FIGURE 4-5. PETROLEUM ADMINISTRATION FOR DEFENSE DISTRICTS

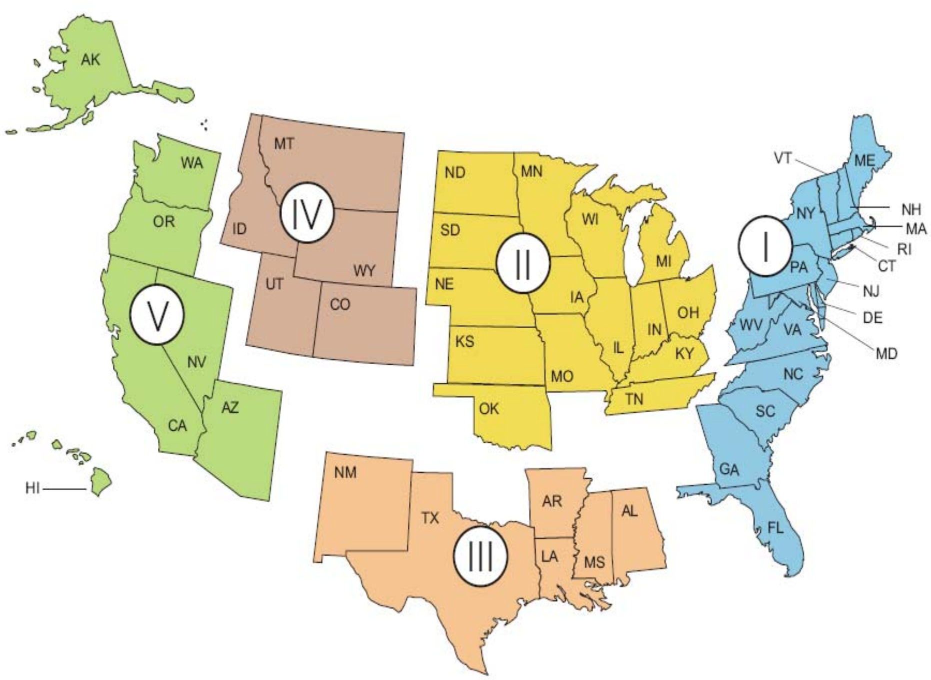
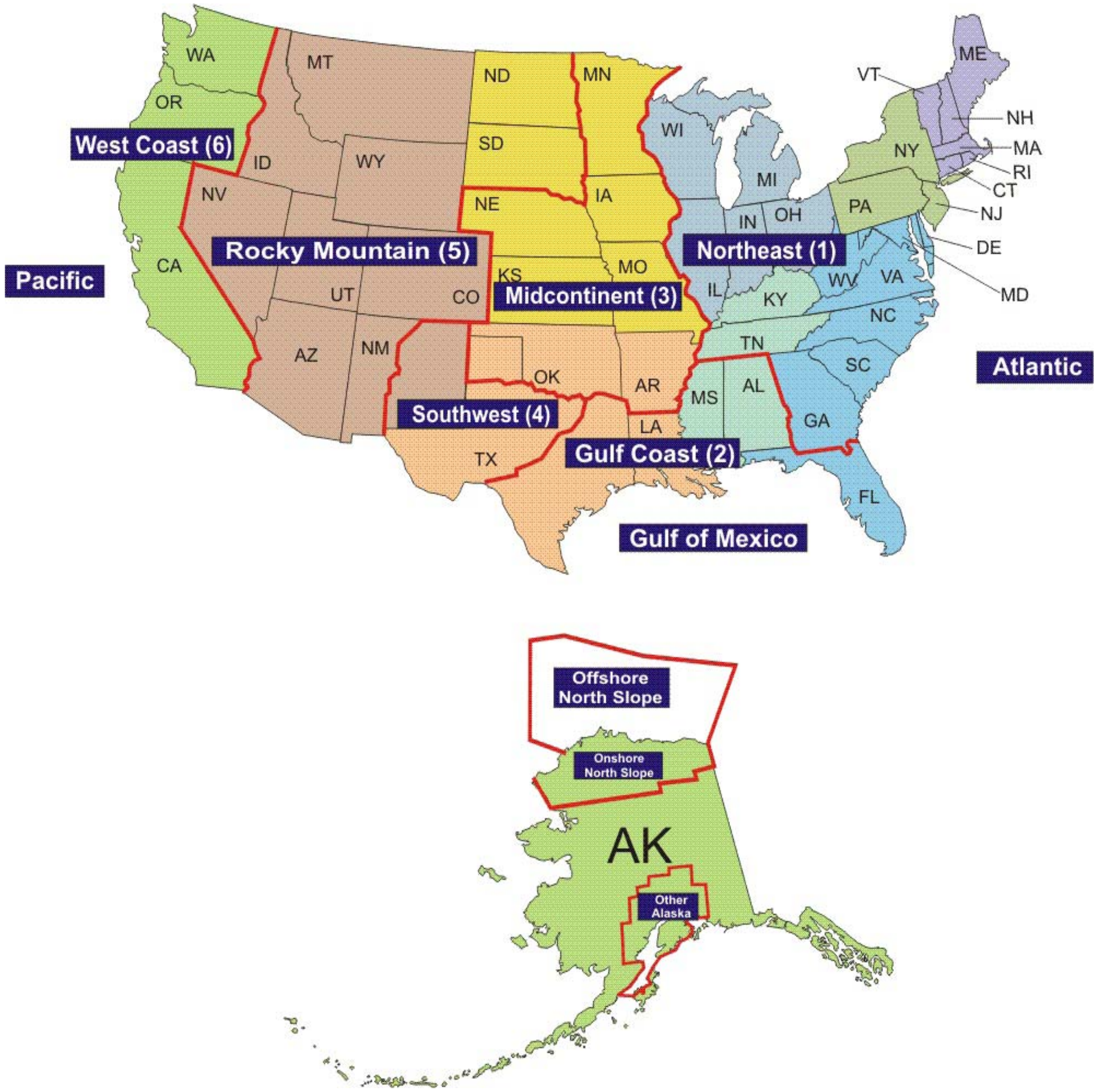


FIGURE 4-6. OIL AND GAS SUPPLY MODEL REGIONS



b. The CO_2 demand and the corresponding oil production are calculated on the first iteration of the current year of the run from the NETL demand curves using the specified model assumptions and constraints.

c. The net CO_2 supply is derived from the solution of the EMM and PMM in the next iteration (excludes CO_2 already provided by natural and industrial sources).

d. The model performs a check to determine if the solution has been found **<u>for each region</u>** (See Cycle 2.c for these solution assumptions). If the solution has been found for all the regions, the model proceeds to the next year (e.g., 2013). Otherwise all the NEMS modules are shut down and the model starts a new cycle starting again from the NEMS start year. *The* *advantage of this approach is to prevent the model from executing any additional years before obtaining a full solution for the current year.*

NEMS Model Cycle 2

a. Unless a solution was found in the previous cycle, the Transfer Subsidy is set to a zero value and the same procedure used in the first cycle is repeated.

b. The cycle stops and proceeds to the next model cycle unless a solution has been found for **all** regions. If a solution is found for all regions, then the model proceeds to the next year within this cycle.

c. The regional solution is assumed to be found if the following is true:

If supply equals demand within the modeler-specified tolerance level

-OR-

The model undersupplies at the maximum transfer subsidy possible

-OR-

The model oversupplies at zero transfer subsidy

To avoid unnecessary cycling, the following additional conditions are introduced to establish the converged solution:

The difference between supply and demand is negligible in absolute terms

-OR-

The supply and demand levels have stabilized between the cycles

The model will also stop equilibrating if *the modeler-specified maximum allowable number of cycles per year has been exceeded.*

NEMS Model Cycle N

a. The Transfer Subsidy is increased or decreased based on how much the model under- or oversupplies CO_2 versus demand.

b. The model converges when the solution is found for all the regions in all the years of a cycle.

4.4 MODEL ASSUMPTIONS

4.4.1 EOR Production and CO_2 Demand Assumptions

NETL developed EOR-based CO_2 demand curves for applicable states (and NEMS EMM regions) as provided in a spreadsheet format. These relationships quantify aggregate 30-year CO_2 demand for EOR projects based on EOR oil production, competitive crude oil market price, and EOR project's IRR specification; they therefore help value the economic potential of selling CO_2 to EOR operators.

- When using the NETL data, the competitive market price of crude oil establishes the application curve to be used by CO2MM; CO2MM uses a default 5-year moving average of world oil price (WOP) as the oil decision price, but this is adjustable via user input. NEMS/AEO2008 currently employs a reference case world oil price profile that starts high, decreases to a minimum value, and then increases again to values exceeding the initial level;

this profile originally created inconsistencies in the model execution. This oil pricing has the potential to cause an over-supply of CO_2 production during the years of diminishing price.

In order to deal with this issue, it is assumed that the maximum allowable annual production will not grow before the year of the minimum oil price. This constraint prevents a conflict between the building of new 'power plants with CCS' and the possible EOR production decline associated with the declining oil price portion of the profile.

- NETL demand projections are based on a 30-year aggregate production basis. Use of the demand projections in NEMS will require disaggregating via specification of annual limits on the deployment of CO_2-EOR. A deployment profile, based on percentage of total EOR production deployed per year, is user input specification (See Section 5.3.2). The annual limit profile currently used is shown in Table 5-1.
- In addition to the deployment profile, an annual deployment cap is specified via user input (See Section 5.3.2). The total annual increase in CO_2-EOR production is currently limited to 100 million barrels per year for all regions.

4.4.2 CO_2 Pricing Assumptions

- The CO_2 Transfer Subsidy has been constrained not to exceed a unique regional "calculated value." This value is currently calculated to be **\$54.75/tonne** CO_2, which corresponds to the upper limit of the CO_2 price (\$47.25) provided by the NETL CO_2 demand curve specification. The value is based on the following definition:

  Transfer Subsidy = EOR Transfer Cost + CO_2 Sequestration Cost – EOR Transport Cost

  = \$47.25 + \$10 - \$2.50 = **\$54.75**

- Currently all regions are assigned the same sequestration and transport costs. If these values are changed by the user, the maximum Transfer Subsidy will be different from the above value and may be different for each region. The code handles this automatically.
- CO_2 can be sold until the regional aggregate capacity limit is satisfied based on NETL specifications. Once the annual aggregate regional constraint level is satisfied, then supply plants in the region (other than natural sources) will have to pay to transport and sequester all captured CO_2. Regardless of whether the CO_2 is used for EOR or sequestered in a saline aquifer, the cost and parasitic load associated with CO_2 capture from coal power plants, natural gas power plants, and CTL and ethanol deployments is accounted for. For new power plants this is accomplished by including such costs in the plant data provided in the ecpdat.txt file for IGCC with sequestration (IS) and NGCC with sequestration (CS), and CTL with sequestration (input data provided in a PMM input file). The new NETL method developed for PC plant retrofits will incorporate this data into the retrofitted plant costs. The cost of transport and sequestration/monitoring is not included in the plant capital and operating cost EMM input, but added independently to account for regional differences.
- All CO_2 pipeline transfers are assumed to occur within each NEMS region, with no transport between regions[5]. Independent regional pipeline operators buy CO_2 from various sources

[5] The only interregional CO_2 transfer currently modeled in CO2MM is from regions 11 and 12 to region 13 (California). The modeling approach is described in Section 5.2.11.

and sell the CO_2 to the EOR entities – they effectively represent the price negotiators between the buyers and sellers. Transport cost is economically represented as the cost differential between the source cost and the EOR buy price for CO_2 (nominally 5-10 $/mt CO_2).

5. MODEL STRUCTURE

Like all other NEMS modules, the CO2MM is a FORTRAN-based model which consists of the source code *co2mm.f*, include files *co2mmout* and *co2mminc*, and *aridmd.txt* and *co2dat.txt* input files. The CO2MM variable names and definitions with cross-references to the corresponding include files are listed in **Appendix A**. A copy of the *co2mm.f* source code is provided in **Appendix B**. The detailed description of the CO2MM input files is provided in Section 5.3. The output report file generated by the model is called *CO2MMREP.txt* and is described in Section 5.4. The report and input files are attached in **Appendix C** and **Appendix D** respectively. The directions on how to setup a NEMS run with CO2MM and a sample scedes file are provided in **Appendix E**.

The CO2MM subroutine (called by NEMS) is the main controlling subroutine for the CO_2 Market Module. Through subroutine calls, it initializes variables, reads in data, establishes solution and processes results, sets up solution flags, and generates reports.

During the first year and first iteration of a NEMS run, the CO2MM subroutine reads fixed data from the input files. The subroutine also identifies the year of the minimum WOP 5-year moving average during the first year and first iteration to impose the maximum annual oil production growth constraint as described in Section 4.4.1.

The CO2MM subroutine establishes the flag identifying whether the solution has converged for a given year and region. The solution flag is updated every year and every cycle.

The flow process of CO2MM is described in Section 5.1 and is illustrated by the flow diagram in **FIGURE 5-1**. The flow diagram refers to the FORTRAN subroutine names, the detailed description of which is provided in Section 5.2.

5.1 CO2MM FLOW PROCESS

Depending on the type of NEMS iteration, the CO2MM subroutine follows one of the following branches:

- **First Year, First Iteration –** If it is the first year and first iteration, the input data files are read, demand curves are loaded, and variables are initialized.
- **No EOR Year –** If it is a year before the specified EOR production start year, the CO2MM performs no operations and simply returns to the NEMS.
- **First Iteration of EOR Production Year**[6] **–** If it is the first iteration of an EOR production year, the transfer subsidy is updated; the transfer price and annual demand values are re-estimated according to the methodology described in Section 5.2.5.
- **Second Iteration of EOR Production Year –** In the second iteration of an EOR production year, the quantities of CO_2 captured by power plants and CTL plants are retrieved from the EMM and PMM, and the CO2MM input variables are updated. The actual EOR oil production corresponding to the quantity of CO_2 sold by each available source is estimated and the total actual EOR oil production variable is updated and then is passed to OGSM.

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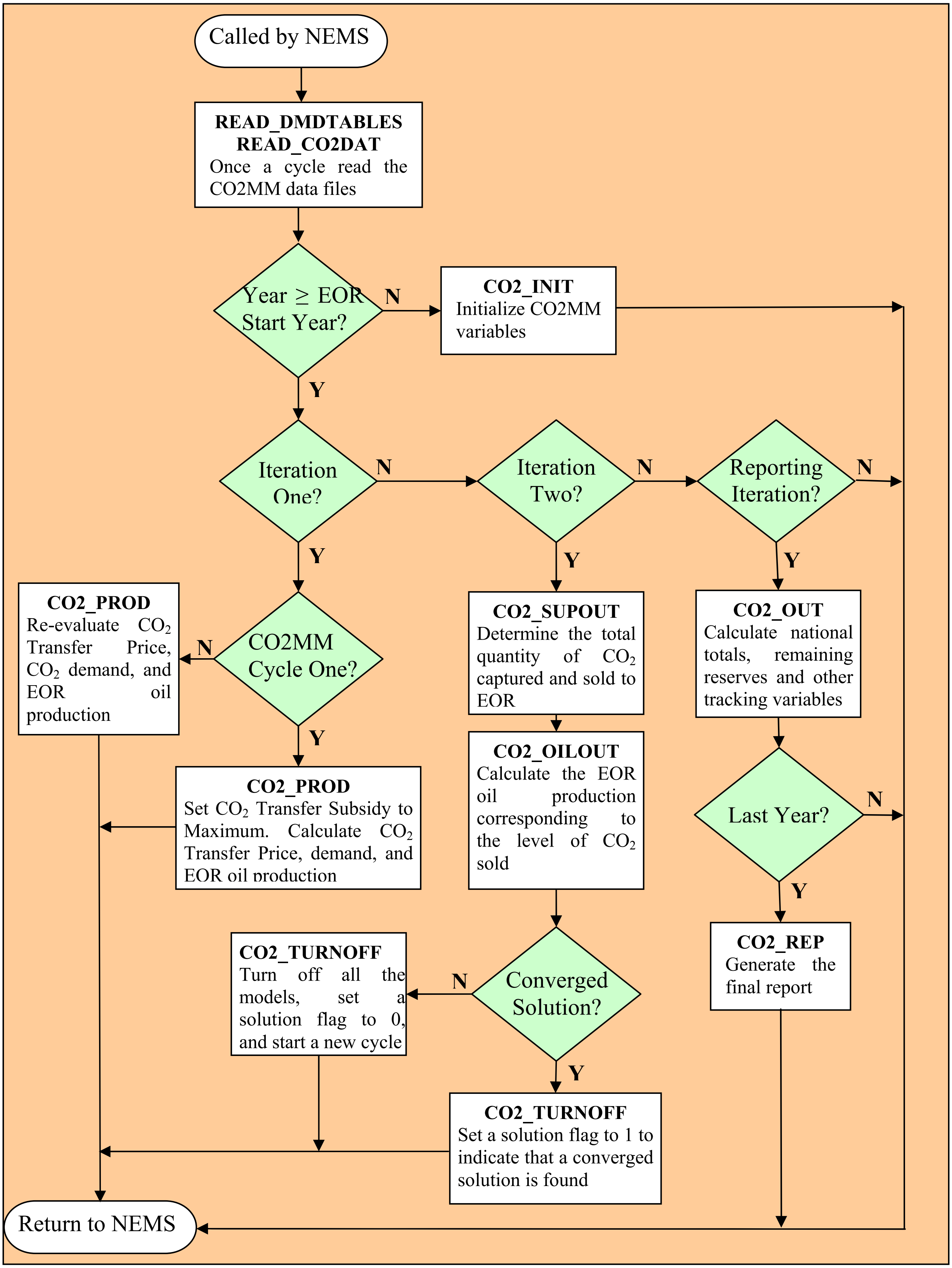
[6] The EOR production year is considered to be the user-specified EOR production start year and any year in the projection horizon after it.

FIGURE 5-1. CO2MM PROCESS DIAGRAM



Then the convergence test is performed and if the solution has been found for every region, the solution flag is set to 1. If the solution has not converged, all the modules are turned off and the solution flag is set to 0. The CO2MM returns to NEMS and a new NEMS cycle begins.

- **Reporting Iteration of EOR Production Year –** If it is a reporting iteration of an EOR production year and the CO2MM solution has converged for all the regions in the current year, the input variables (the quantity of captured CO_2 and the corresponding oil production) are updated. The quantity of CO_2 sequestered is established as a difference between CO_2 captured and demanded if capture exceeds demand. Other variable that are calculated at this stage include national totals for CO_2 capture, sequestration and oil production, remaining end-of-year CO_2 reserves, and revenues to pipeline company, EOR fields and CO_2 sources based on the levels of CO_2 sold.
- **Reporting Iteration of Last Year –** In the reporting iteration of the last year of the NEMS projection horizon the final report of CO2MM is generated.

5.2 CO2MM MAIN SUBROUTINES

5.2.1 CO2MM

CO2MM is the main subroutine of the CO_2 Market Module. It defines the subroutine calling order, initializes the *CO2MMOUT[c][7].txt* and *CO2MMDBG[c].txt* output and debug files and initializes solution flags.

The following subroutines are called by CO2MM:

READ_DMDTABLES

READ_CO2DAT

CO2_INIT

CO2_PROD

CO2_OILOUT

CO2_TURNOFF

CO2_OUT

CO2_REP

5.2.2 READ_DMDTABLES

Subroutine READ_DMDTABLES reads the aridmd.txt input file which contains the NETL CO_2 demand and EOR supply curve data tables.

5.2.3 READ_CO2DAT

Subroutine READ_CO2DAT reads the co2dat.txt input file. This input files contains fixed price information, model assumptions, and various miscellaneous data required by the model. The content of input files is discussed in detail in Section 5.3.

[7] [c]- is the cycle number

5.2.4 CO2_INIT

Subroutine CO_2_INIT initializes all the input and output variables at zero. It runs only during the years before the EOR production start year.

5.2.5 CO2_PROD

Subroutine CO_2_PROD is called on the first iteration of every EOR production year.

5.2.5.1 EOR Production and Corresponding CO_2 Demand Calculation

The 30-year gross EOR oil production and corresponding CO_2 demand is estimated from the input NETL supply and demand curves at the calculated Transfer Price and WOP 5-year moving average. The CO_2 demand curve implementation approach is discussed in Sections 5.2.5.1.1 and 5.2.5.1.2 below. A function, **EOR_DMDCRV**, is used to interpolate oil production and CO_2 demand between the steps of the curve. The 30-year CO_2 demand from Industrial and Natural sources is also estimated here. The minimum 5-year moving average oil price is used to constrain the growth of the maximum allowable annual EOR production during the declining world oil price interval. See Section 4.4 for the model assumption.

5.2.5.1.1 Basic Methodology for CO_2 demand curve implementation approach

This section describes the basic approach for using NETL's EOR production and associated CO_2 demand data. The curves are used as gross production curves that cover a 30-year production period. For specified IRR and benchmark oil price, gross EOR production is only dependent on the average purchase price of CO_2. As an example, refer to FIGURE 5-2 (in constant $2007). Maximum 30-year production for region 2 can be represented by the intersection of $70/bbl oil and $0.00/mcf CO_2 purchase price; 18,116 MM bbls. Assuming an average cost of $1/mcf CO_2 purchase price and an average benchmark oil price of $60/bbl, this region will be expected to produce a 30-year total of 15,490 MM bbls of oil.

The equivalent CO_2 demand curves for the above oil production are shown in FIGURE 5-3 (in constant $2007). Maximum 30-year CO_2 demand for region 2 can be represented by the intersection of $70/bbl oil and $0.00/mcf CO_2 purchase price; 4,918 MM metric tons. Assuming an average cost of $1/mcf CO_2 purchase price and an average benchmark oil price of $60/bbl, this region will be expected to demand a 30-year CO_2 total of 4,189 MM metric tons.

FIGURE 5-2. TOTAL REGION 2 EOR PRODUCTION CURVES FOR 15% IRR

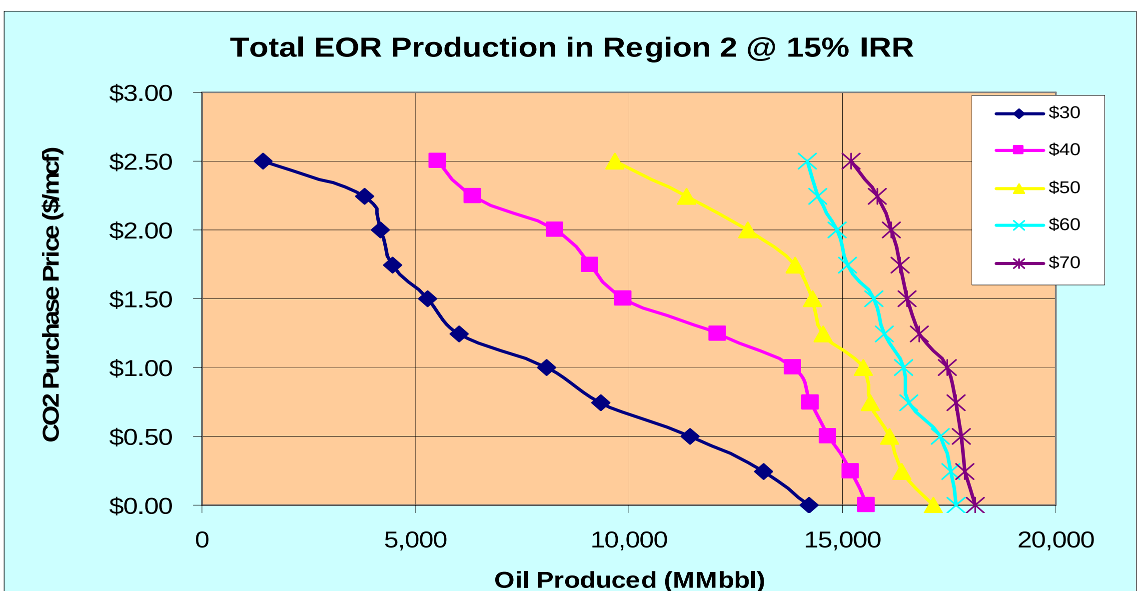
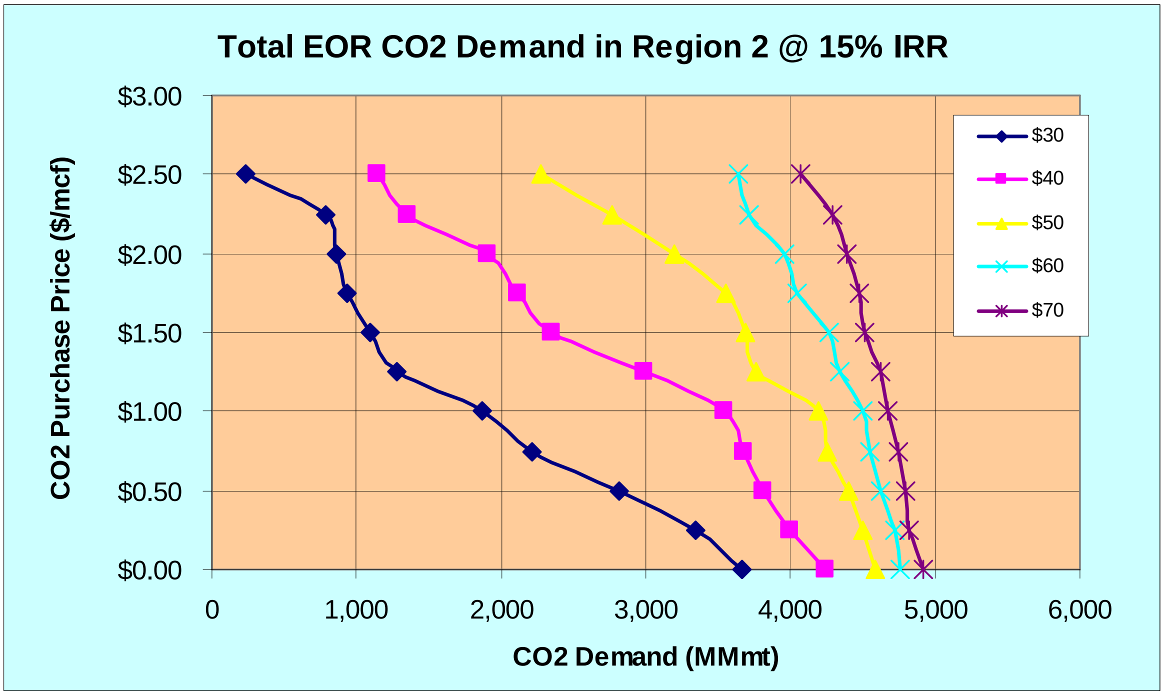


FIGURE 5-3. TOTAL CO_2 DEMAND IN REGION 2 FOR 15% IRR



A key characteristic of these curves is that they do not provide any temporally-based characterization regarding EOR production and CO_2 demand levels – they always predict gross regional EOR and associated CO_2 demand based on oil price and CO_2 purchase price. When project conditions change, it is the difference between estimates that must be used to reflect the impact of the changes. The following is an explicit example of how to use the curves – note that the oil price change values are exaggerated for illustration purposes.

The example demonstrates the impact of changing market conditions in Region 2 as we move through the NEMS projection. Based on the market conditions of 2012 and the equilibrated transport price of CO_2 (via NEMS' equilibrium calculations), the EOR facilities in Region 2 are financially limited to gross production of 9.655 billion bbls of oil – **EORPROD(2,2012)** – and contract to purchase 2.277 billion mt (gross) of CO_2 – **EORCO2(2,2012)**. The key conservative assumption is that average oil price over the long-term will not fall below the calculated 5-year moving average and that it's financially sound to commit to the "negotiated" CO_2 transfer price for the long-term. See the text box below titled "*Basic Methodology for Use of EOR Production and CO_2 Demand Curves*."

However, with changed market conditions in 2013 the EOR facilities have new information that permits modifications to the previous year's decision-making. Since the average oil price is now much higher and the equilibrated CO_2 transfer price somewhat lower (based on NEMS' equilibrium calculations), the EOR facilities in Region 2 can afford to purchase more CO_2 to expand production. They now project gross EOR production of 14.861 billion bbls – **EORPROD(2,2013)**. Therefore, the incremental expansion is represented by the difference between the gross production estimates (2013 minus 2012 estimates) or 5.206 billion barrels; an incremental 1.687 billion mt of CO_2 is required to support the production expansion.[8]

This basic methodology continues for the remainder of the NEMS projection period, continuing to calculate incremental changes to EOR production and CO_2 demand and effectively removing them from the "game" as they are married off with long-term CO_2 supply sources. The methodology is self-limiting in that only positive incremental production changes (from one year to the next) alter the gross production levels and the total EOR production will never exceed the maximum regional production limit found at \$70/bbl oil and \$0/mt CO_2.

BASIC METHODOLOGY FOR USE OF EOR PRODUCTION AND CO_2 DEMAND CURVES

ASSUMPTIONS FOR NEMS EOR START YEAR = 2012:

2012 oil price (5-year moving average) = \$50

2012 average CO_2 purchase price = \$2.50/mcf

Gross EOR production and CO_2 demand are calculated to be:

EOR gross production = 9,655 MM bbls

CO_2 gross demand = 2,277 MMmt

This quantity of EOR production is now "married" to a long-term contract for CO_2 supply and is "out of the game."

ASSUMPTIONS FOR NEMS PROJECTION YEAR = 2013:

2013 oil price (5-year moving average) = \$60

2013 average CO_2 purchase price = \$2.00/mcf

Gross EOR production and CO_2 demand are calculated to be:

EOR gross production = 14,861 MM bbls

CO_2 gross demand = 3,964 MMmt

By difference with the previous year, incremental EOR production and CO_2 demand are:

EOR incremental production = 5,206 MM bbls

CO_2 incremental demand = 1,687 MMmt

This incremental quantity of EOR production is now "married" to a long-term contract for the associated CO_2 supply and is "out of the game." Total committed production and demand through 2013 are: 14,861 MM bbls & 3,964 MMmt

[8] By definition, the described methodology assumes that each year's incremental EOR production level covers 30 years of operation and 30 years of contracted CO_2 supply. Because the model is not necessarily providing all of the CO_2 at once in the EOR start year, EOR production is assumed to extend beyond a base 30-year production schedule. For example, if the model still establishes incremental EOR production and demand in 2030, then that level of production is assumed to extend through 2060. Only the calculated annual production level and CO_2 demand in 2030 will impact the NEMS projection.

5.2.5.1.2 Basic Methodology with EOR Production Limits (Modified Methodology)

The same methodology is used for an EOR production constraint profile, **EORPRDLMT(N,R,Y)**, that sets temporal limits based on applicable constraints on production of regional gross EOR supply (e.g., wells drilled, field production limits, pipeline construction, etc.). Regional annual production profile represents the maximum regional production limits for all years in the projection as initialized at the start year of EOR production.

The maximum production profile is reset in each subsequent year based on the actual levels of EOR production and proportional increases to the limits in the remaining years. This year-by-year profile will be set as a percentage of the total gross regional supply and should add to 100%, which assumes that the gross capacity will be spoken for by 2030. The box below adds this feature based on the previous example.

The methodology described in this section yields incremental aggregate EOR production and CO_2 demand quantities for each year beginning with the EOR start year. Based on the previous example, the year 2012 EOR production value (5,000 million bbls) represents 30 years of aggregate production beginning in 2012. Likewise, the year 2013 EOR production value (9,861 million bbls) represents 30 years of aggregate production beginning in 2013. (In other words, each year characterizes new contracts between EOR entities and CO_2 suppliers in each region.) The cumulative summation of these values for each year of the projection provides the gross EOR production and CO_2 demand quantities through that year: 14,861 million bbls oil & 3,964 million mt CO_2. However, these results do not represent annual production and demand values, which are required by NEMS to satisfy PMM requirements and tracking of annual CO_2 utilized for EOR and that sequestered. The next section discusses their disaggregation to provide annual production and demand quantities.

5.2.5.1.3 Disaggregation of EOR Production and CO_2 Demand Projections into Annual Quantities

Each year's aggregate EOR production and CO_2 demand quantities must be disaggregated independently; the NETL data provides no temporal information in this regard. Industry production estimates will be required to accurately establish an annual production profile based on historical production levels. In lieu of such profile data, the model has been set up to provide a generic approach whereby annual independent production profiles can be established by the user for each projection year and region. Each profile quantifies the yearly percentage of the total production, **EORPROD(R,Y)**, beginning in the year when that production starts. A sample annual production profile table is provided below in **Table 5-1**. This approach provides the user with full control over the annual rate at which the total aggregate production total (assumed to be 30-years) is developed. The most simplistic assumption can be that the production is disaggregated on the basis of equal annual production levels; therefore, for EOR production that starts in year 2012, each year yields 3.3% of the total; years 2013 through 2030 are set up the same way. If desired the annual production levels can be set up such that total EOR production occurs within the NEMS projection.

Initial regional, annualized maximum production profile (Table 5-1) is used to calculate the incremental annual EOR oil production and CO_2 demand for the current year. These values are used to derive the cumulative annual maximum potential EOR oil production and corresponding CO_2 demand.

MODIFIED METHODOLOGY FOR USE OF EOR PRODUCTION AND CO_2 DEMAND CURVES

ASSUMPTIONS FOR NEMS EOR START YEAR = 2012:

2012 oil price (5-year moving average) = $50

2012 average CO_2 purchase price = $2.50/mcf

Gross EOR production and CO_2 demand are calculated to be:

EOR gross production = 9,655 MM bbls

CO_2 gross demand = 2,277 MMmt

Gross EOR production limit for year 2012:

EOR gross production limit (2012) = 5,000 MM bbls

Since calculated EOR production level exceeds the production limit, the production limit value and associated CO_2 demand are substituted. This quantity of EOR production is now "married" to a long-term contract for CO_2 supply and is "out of the game."

ASSUMPTIONS FOR NEMS PROJECTION YEAR = 2013:

2013 oil price (5-year moving average) = $60

2013 average CO_2 purchase price = $2.00/mcf

Gross EOR production and CO_2 demand are calculated to be:

EOR gross production = 14,861 MM bbls

CO_2 gross demand = 3,964 MMmt

By difference with the previous year, incremental EOR production and CO_2 demand are calculated to be:

EOR incremental production = 9,861 MM bbls

CO_2 incremental demand = 2,785 MMmt

Gross EOR production limit for year 2013:

EOR gross production limit (2013) = 10,000 MM bbls

Since calculated EOR incremental production level is less than the production limit, the calculated incremental production and associated CO_2 demand are used. The incremental quantity of EOR production is now "married" to a long-term contract for the associated CO_2 supply and is "out of the game." Total committed production and demand through 2013 are: 14,861 MM bbls & 3,964 MMmt

5.2.5.1.4 Basic Methodology to Apply Deployment Cap to Annual EOR Production and CO_2 Demand Projections

In addition to disaggregating the EOR production, the total annual production increase must not exceed the specified deployment cap **EORPRODCAP**. This cap is applied after calculating the regional maximum potential annual production with no limit. If total increment exceeds cap, then the increment equals the cap. The cap is then regionalized by prorating the regional production by the relative weighting.

5.2.6 EOR_DMDCRV

Function EOR_DMDCRV uses demand curves to interpolate oil production and CO_2 demand between the steps of the curve corresponding to the calculated current transfer price and oil price. Based on the input requirements, it returns the values for oil production and total CO_2 demand, CO_2 demand from Industrial and Natural sources, or CO_2 demand net of Industrial and Natural. It is also capable of returning values by EMM or OGSM regions as needed.

5.2.7 CO2_OILOUT

Subroutine CO2_OILOUT is called on the second iteration of every EOR production year. It calculates the actual EOR oil production corresponding to the quantity of CO_2 sold by each available source. The total actual EOR oil production from all the sources is passed to OGSM.

Subroutine CO2SUP_OUT is called by CO2_OILOUT.

In addition, the output report CO2MMOUT[c].txt for every cycle is generated in this subroutine at the end of cycle [c].

5.2.8 CO2SUP_OUT

Subroutine CO2SUP_OUT is called by CO2_OILOUT on the second iteration of every EOR production year.

It calculates the quantities of CO_2 captured by Power Plants based on the fuel consumption and capture/emissions coefficients provided by the EPM module and fills out the CO2MM input variables accordingly. The CO_2 capture from the CTL plants is provided directly by PMM.

5.2.9 CO2_TURNOFF

Subroutine CO2_TURNOFF checks if the solution has been found for every region and sets the corresponding flag: 1 if solution converged; 0 if it did not. If the model has not converged for any region all the NEMS modules are turned off and NEMS starts a new run (cycle).

TABLE 5-1. ANNUAL EOR PRODUCTION PROFILE FOR ALL REGIONS BY AGGREGATE PRODUCTION YEAR START AND ANNUAL PRODUCTION YEAR

EORPROD(R,Y)	PRODUCTION YEAR/ANNUAL PERCENTAGE																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
2,2012	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2013	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2014	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2015	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2016	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2017	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2018	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2019	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2020	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2021	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2022	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2023	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2024	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2025	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2026	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2027	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2028	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2029	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
2,2030	0.9	2	2.5	3.2	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52

5.2.10 CO2_TRFCOST

Subroutine CO2_TRFCOST is called by CO2_TURNOFF. CO2_TRFCOST updates the transfer price for the next iteration.

5.2.10.1 Transfer Subsidy Calculation

If it is the first CO2MM cycle of a NEMS year, the transfer subsidy is initialized at the maximum which corresponds to the upper limit of the CO_2 price provided on the CO_2 demand curve specification.

The CO2MM cycle is defined as the solution iteration for the CO2MM and is reset to 1 at the beginning of every subsequent year. The maximum number of CO2MM cycles is specified by the modeler, and currently equals 6.

If it is not the first CO2MM cycle of the NEMS year and the solution has not converged, the transfer subsidy is re-calculated.

If the model overproduced at the maximum transfer subsidy, the transfer subsidy is set to 0. Otherwise, the transfer subsidy will be increased or decreased based on how much the model under- or overproduced.

The **secant method**[9] of finding a root (zero) of a function is used to calculate the new transfer subsidy. The function of the CO_2 transfer price in this case is considered to be [CO_2 demand – CO_2 supply].

5.2.10.2 Transfer Price Calculation

The transfer price for each region is calculated as follows.

For EOR entities:

> **TRANSFER COST = - SEQUESTRATION COST + PORTION OF TRANSPORT COST PAID BY EOR + TRANSFER SUBSIDY**

For the CO_2 Supply Sources:

> **TRANSFER COST = SEQUESTRATION COST + PORTION OF TRANSPORT COST PAID BY SOURCE - TRANSFER SUBSIDY**

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9 In numerical analysis, the secant method is a root-finding algorithm that uses a succession of roots of secant lines to better approximate a root of a function *f*.

The secant method is defined by the recurrence relation

$$x_{n+1} = x_n - \frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} f(x_n)$$

As can be seen from the recurrence relation, the secant method requires two initial values, x_0 and x_1, which should ideally be chosen to lie close to the root. The method has a superlinear convergence with the order of convergence ≈ 1.618. It is faster than the bisection method which repeatedly divides an interval in half and then selects the subinterval in which a root exists, and is more efficient than Newton's method which requires the evaluation of both *f* and its derivative at every step, while the secant method only requires the evaluation of *f*.

5.2.11 CO2_INTERREG_ADJ

Subroutine CO2_INTERREG_ADJ re-allocates region 13 (California) CO_2 demand and determines the CO_2 transfers from regions 11 and 12 based on relative excess CO_2 supply in these regions. The transfer price for regions 11 and 12 is adjusted in this subroutine based on relative CO_2 demand levels.

CO2_INTERREG_ADJ is called by CO2_OILOUT and CO2_TRFCOST.

5.2.12 CO2_OUT

Subroutine CO2_OUT is called only on the reporting iteration of every EOR production year.

If the model has converged for all the regions for the current year, the final quantities of captured CO_2 are calculated along with the corresponding oil production. The quantity of CO_2 sequestered is established as a difference between CO_2 captured and demanded if the capture exceeds demand. Other variables that are calculated in this subroutine include national totals for CO_2 capture, sequestration and oil production, remaining end of year reserves, and revenues to pipeline companies, EOR fields, and CO_2 sources based on the levels of CO_2 sold.

5.2.13 CO2_REP

Subroutine CO2_REP is called on the reporting iteration of the last NEMS year. It writes out the final detailed report of the CO2MM solution to the output file CO2MMREP.txt. The tables created in this report and their corresponding descriptions are listed in Section 5.4.

5.3 CO2MM INPUT DATA

The CO2MM input data is stored in the following input files: ***aridmd.txt*** and ***co2dat.txt***

5.3.1 ARIDMD.txt

NETL has developed EOR-based CO_2 demand curves for applicable states (and NEMS EMM regions) as provided in a spreadsheet format. These relationships quantify aggregate 30-year CO_2 demand for EOR projects based on EOR oil production, competitive oil market price, and EOR project's IRR specification; they therefore help value the economic potential of selling CO_2 to EOR operators.

A new spreadsheet, ARIDMD.xls, has been developed based on the slightly modified and reformatted NETL "CO_2 Demand Rollup" spreadsheet. ARIDMD.xls then has been converted into the text input file which contains the following data:

- Available IRR values
- Available oil price step values
- Available CO_2 price step values - maximum CO_2 price value defines the maximum transfer subsidy that Power Plants and CTL plants can receive.
- Step EOR production/CO_2 demand curve tables for all the available states.

The production/demand curve table for each state contains the corresponding EMM and OGSM region ID, 30-year total CO_2 demand, corresponding EOR oil, natural CO_2, and industrial CO_2 for all available IRR values at the oil and CO_2 price steps defined above.

The EMM to OGSM region mapping is estimated during the run execution. This weighted mapping matrix is based on the EOR production levels by EMM and OGSM regions which are provided with the production curve definitions.

5.3.2 CO2DAT.txt

CO2DAT.txt data file is created from co2dat.xls spreadsheet. It contains the following user inputs and assumptions:

- IRR value – IRR value is specified by user and identifies a specific set of the demand curves to be used in the run;
- Start year for EOR production (user specified year) by EMM region;
- Gross regional CO_2 sequestration storage capacity for deep saline formations based on DOE Sequestration Program data. Currently, the sequestration storage capacity is assumed to be unlimited;
- Regional deep saline formation sequestration costs – currently, the sequestration costs are set to \$10/mtCO_2 for all regions;
- Regional CO_2 transport costs – transport costs are assumed to be \$5/mtCO_2;
- The portion of transport cost paid by EOR and the source. This fraction allows user to define who will be paying the incurred transportation costs. Currently the weight is distributed evenly between EOR facilities and the suppliers;
- Regional CO_2 capture and compression costs. The intended use of these costs is to replace the sequestration costs when the model is run in the environment with no carbon constraints imposed. However, currently these serve as a placeholder and are not used;
- Initial regional, annualized maximum production profile (for N =1) based on applicable constraints on production of the regional gross EOR supply. The current profile gradually increases over the first 5 years, and evenly distributes the incremental oil production over the remaining period of 25 years for each year in the NEMS projection horizon.
- NGTDM/EMM region (1-16) mapping into EMM region (1-13) – this mapping is imported from the NGTDM input file ngmap.txt. The EMM region and NGTDM/EMM region map are shown in **FIGURE 4-2** and **FIGURE 4-4**, respectively. **Table 5-2** below shows the mapping matrix used by the model.

TABLE 5-2. NGTDM/EMM REGION MAPPING INTO EMM REGION

NGTDM/EMM Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
EMM Region	7	6	1	4	5	3	9	8	9	10	2	11	12	12	11	13

- Coal Demand region (1-14) into EMM region (1-15) weighted mapping matrix. These weights are calculated offline based on the 2007 coal consumption data by Coal Demand Regions and EMM regions. The Coal Demand region map is shown in **FIGURE 4-3**. The mapping matrix used by the model is shown in

- TABLE **5-3** below.

TABLE 5-3. COAL DEMAND REGION MAPPING INTO EMM REGION

Coal Demand Region \ EMM Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	**1.000**	0	0	0	0	0	0	0	0
2	**0.248**	0	**0.613**	0	0	**0.122**	**0.017**	0	0	0	0	0	0	0	0
3	**0.301**	0	**0.147**	0	0	0	0	0	**0.552**	0	0	0	0	0	0
4	0	0	0	0	0	0	0	**0.417**	**0.583**	0	0	0	0	0	0
5	**1.000**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	**0.571**	0	0	**0.410**	**0.019**	0	0	0	0	0	0	0	0	0	0
7	**0.465**	0	0	0	0	0	0	0	**0.535**	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	**1.000**	0	0	0	0	0	0
9	0	0	0	**0.194**	**0.494**	0	0	0	**0.063**	**0.248**	0	**0.001**	0	0	0
10	0	**0.519**	0	0	0	0	0	0	**0.118**	**0.363**	0	0	0	0	0
11	0	0	0	0	**0.014**	0	0	0	0	0	**0.757**	**0.229**	0	0	0
12	0	0	0	0	0	0	0	0	0	0	**0.296**	**0.526**	**0.178**	0	0
13	0	0	0	0	0	0	0	0	0	0	0	**0.898**	**0.102**	0	0
14	0	0	0	0	0	0	0	0	0	0	**0.748**	0	**0.129**	**0.033**	**0.089**

- PADD region (1-5) into EMM region (1-15) weighted mapping matrix. The weights are estimated offline based on the refinery total operating capacity by state.[10] The PADD region map is shown in **FIGURE 4-5**. See the mapping matrix used by the model in **TABLE 5-4** below.

TABLE 5-4. PADD REGION MAPPING INTO EMM REGION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	**0.350**	**0.099**	0	**0.250**	**0.025**	0	0	0	**0.049**	**0.226**	0	0	0	0	0
3	0	**0.368**	0	0	0	0	0	0	**0.551**	**0.062**	0	**0.019**	0	0	0
4	0 **0.012**	0 0	0 **0.935**	0 0	0 0	0 0	0 0	0 0	0 **0.053**	0 0	**0.844** 0	**0.156** 0	0 0	0 0	0 0
5	0	0	0	0	0	0	0	0	0	0	**0.207**	0	**0.670**	**0.123**	0

[10] Source: EIA, Refinery Capacity Data by individual refinery as of January 1, 2008

- The total annual deployment cap for all regions. The total annual CO_2-EOR production can increase by no more than specified limit over the previous year. The limit is assumed to be 100 million barrels a year.

5.4 CO2MM OUTPUT REPORT

For the reporting iteration of last year of a cycle, the CO2MM generates the detailed output report CO2MMREP.txt. All the data in the report are shown by year and EMM region unless stated otherwise. CO2MMREP.txt output of CO2MM test run is included in **APPENDIX C**.

The list of tables printed in the report is provided below.

- **TABLE 1. ANNUALIZED EOR MAXIMUM PRODUCTION LIMIT PROFILE BY EMM REGION, MMbbl**

  Prints the initial production profile calculated as described in **Section 5.2.5.1**. It shows the maximum incremental annual EOR oil production. It corresponds to the maximum incremental gross production distributed over 30 years of EOR project life according to the profile specified in the co2dat.txt input file for every year in the NEMS projection horizon.

- **TABLE 2. ANNUAL MAXIMUM POTENTIAL EOR PRODUCTION BY EMM REGION, MMbbl**

  The annual maximum potential EOR production in year N equals the sum of maximum incremental annual production projected in years 1 through N. For details see **Section 5.2.5.1**.

- **TABLE 3. END-OF-YEAR EOR RESERVES BY EMM REGION, MMbbl**

  The end-of-year EOR reserves are the beginning-of-year reserves less the annual EOR production as determined by the model. The maximum EOR reserves are assumed to be the maximum aggregate 30-year production which is represented by the intersection of $70/bbl oil and $0.00/mcf CO_2 purchase price on the 30-year gross production curve.

- **TABLE 4. ANNUAL CO_2 DEMAND, SUPPLY, CO_2 SEQUESTERED, MMmt**

  Table 4 lists:

  - Total annual CO_2 purchased by EOR,
  - CO_2 demand from the Industrial and Natural sources,
  - CO_2 demand net of Industrial and Natural sources,
  - Captured CO_2 as solved by the model,
  - Sequestered CO_2 as a difference between CO_2 captured and demanded.

  The values presented are cumulative by year.

- **TABLE 5. ANNUAL CO_2 SUPPLY BY SOURCE, MMmt**

  Table 5 represents the annual CO_2 supply by EMM region and by four sources of capture which include retrofitted plants, IGCC with sequestration, NGCC with sequestration, and CTL plants.

- **TABLE 6. CO_2 TRANSFER PRICE, TRANSFER SUBSIDY, SEQUESTRATION COST, TRANSPORT PRICE, $/mt**

The solution CO_2 transfer price and transfer subsidy by EMM region is shown in Table 6, along with the user-defined CO_2 sequestration cost and transport price. The negative number represents the credit received, whereas the positive is the price paid.

- **TABLE 6a. REVENUES TO EOR, POWER PLANTS, CTL PLANTS AND TRANSPORTATION COMPANIES**

  Table 6a holds the revenues of EOR fields, Power Plants, CTL plants and Pipeline companies computed as the corresponding CO_2 price times quantity of CO_2 sold/transported. The negative number represents expenses (negative revenue).

- **TABLE 7. DEMAND CURVE VALUES**

  The solution from the demand curves is represented in Table 7. It includes the oil price 5-year moving average, the WOP, CO_2 transfer price to EOR, 30-year gross EOR production, corresponding 30-year gross CO_2 demand net of industrial and natural sources, and 30-year gross CO_2 purchased from industrial and natural sources.

- **TABLE 8. CO_2 SUPPLY BY EMM REGION AND PLANT TYPE, MMmt**

  Table 8 disaggregates the CO_2 supply by the EMM technology type with capture capability.

- **TABLE 9. EOR OIL PRODUCTION FROM CTL AND POWER PLANTS BY EMM REGION, MMbbl**

  Table 9 shows the EOR production corresponding to the CO_2 quantity received from CTL and Power Plants. This is calculated based on the oil production -to-CO_2 injected ratio.

- **TABLE 9a. EOR OIL PRODUCTION FROM NATURAL AND INDUSTRIAL SOURCES BY EMM REGION, MMbbl**

  Table 9a shows the EOR production corresponding to the CO_2 quantity received from the Natural and Industrial sources.

- **TABLE 10. TOTAL ANNUAL EOR OIL PRODUCTION BY EMM REGION, MMbbl**

  Table 10 represents total annual EOR oil production of all available sources by EMM region.

- **TABLE 10a. TOTAL ANNUAL EOR PRODUCTION BY OGSM REGION, MMbbl**

  The total annual EOR oil production of all available sources by OGSM region is shown in Table 10a.

- **TABLE 11. ELECTRICITY GENERATION CAPACITY BY PLANT TYPE, TECHNOLOGY, GW**

  This table replicates the Table 59 of FTAB representing the Electricity Generating Capacity by Plant Type and Technology. The purpose of this table was to create a backup table when the FTAB was not working correctly.

- **TABLE 12. EOR OIL PRODUCTION CAP ADJUSTMENT, MMBBL**

  Table 12 shows EOR oil production deployment cap adjustment by EMM region.

- **TABLE 12a. EOR CO_2 DEMAND CAP ADJUSTMENT, MMmt**

Table 12a represents the corresponding CO_2 demand cap adjustment by EMM region.

- **TABLE 13. EOR OIL TO CO_2 PRODUCTION RATIO, Fraction**

  EOR oil production to CO_2 production ratio for each EMM region and each NEMS year is shown in Table 13.

- **TABLE 14. EOR ADJUSTMENTS TO REG 13 (CALIFORNIA), MMmt**

  All adjustments and CO_2 transfers to region 13 (California) from the adjacent regions 11 and 12 are shown in Table 14.

6. MODIFICATIONS TO OTHER NEMS MODELS

6.1 INTEGRATING MODULE (IM) MODIFICATIONS

Integrating Module controls the NEMS solution algorithm, executing the NEMS component modules iteratively in an attempt to achieve energy market equilibrium in each projection year. Using the Energy Market Data portions of the NEMS Global Data Structure as its inputs, the IM tests whether convergence has occurred, and optionally adjusts the solution values to aid the convergence process. The IM also manages the storage of global data and the access to input and output files. Finally, the IM includes an emission policy submodule to calculate carbon dioxide emissions and implement some emissions control options that cut across all of NEMS.

The following modifications have been done to the IM and general NEMS structure:

- The NEMS run submitter has been modified to include the new CO2MM submodule
  - CO2MM module has been added as an option at runtime by adding a new "varkey" and corresponding code to **qnems.shell**
  - Code has been added to select the correct version of CO2MM and link with NEMS
  - Code has been added to qnems.shell to save the CO2MM report for each cycle
- A call has been added to CO2MM in main.f to specify CO2MM execution order
  - The CO2MM will be called after the demand modules and before the EMM and PMM.
- New source, includes and input files have been added into the Revision Control System (RCS)
  - After initial development, this system keeps track of modifications made to the submodule with comments and unique version numbers
  - This is required for the run submission system
- New output and debug reports have been designed and coded to present results from the CO2MM
- Global variables and report variables have been added to the RESTART file
  - All variables passed between the CO2MM and other submodules have been added to the common variable list and to the restart file. This insures that the variables are being passed properly, and gives ftab access to the data needed for reporting.

Full consistency has been maintained with the current NEMS structure.

6.2 ELECTRICITY MARKET MODULE (EMM) MODIFICATIONS

The EMM represents generation, transmission, and pricing of electricity, subject to delivered prices for coal, petroleum products, natural gas, and biofuels; costs of generation by all generation plants, including capital costs; macroeconomic variables for costs of capital and domestic investment; enforced environmental emissions laws and regulations; and electricity load shapes and demand. There are three primary submodules: capacity planning, fuel dispatching, and finance and pricing.

6.2.1 CO2MM Related Modifications

Regional Transfer Costs (TFRCST) are passed from the CO2MM to the EMM's Electricity Capacity Planning (ECP) and Electricity Fuel Dispatch Submodule (EFD) submodules – currently uses the externality cost variable (EPEXT) as a component of the levelized cost-of-electricity calculation. This applies to the levelized COE calculations for **IGCC/CCS (IS), NGCC/CCS (CS), and existing PC plant technologies chosen for CCS retrofit**.

The TFRCST variable is dimensioned by **EMM region and year** and is also mapped to the PMM by **PADD region and year.**

For IGCC/CCS (IS), NGCC/CCS (CS), and existing PC/CCS: Only cost values representing plants that account for integrated capture and compression technology are assumed to be included in the EMM input file (ecpdat file) for capital, fixed and variable O&M. Cost components do **not** include the cost of CO_2 transport and the cost of sequestration. **These are replaced by TFRCST as converted to $/MWh.**

New CO2MM common block *co2mmout* has been be added to NEMS and includes TFRCST and the variables that directly account for captured CO_2.

The subroutine **ECPCO2_TFRCST** has been added to the uecp.f EMM FORTRAN code to convert TFRCST to $/MWh and assign it to EPEXT variable.

Use of NEMS' calculated CO_2 allowance prices is not altered.

No other EMM changes have been made.

6.2.2 Retrofit Model for CO_2 Capture and Sequestration Modifications

NEMS does not utilize a retrofit model for CO_2 capture and sequestration, so the only options for coal plants in carbon constrained scenarios the purchase of CO_2 emission allowances, replacement with more efficient fossil conversion technologies, or their retirement in favor of carbon neutral technologies.

In order to provide for the option to retrofit existing coal-fired power plants, NETL has developed a method by which to identify and retrofit existing PC power plants. To integrate this method with the EMM module and stay within the existing modeling structure of NEMS, certain modifications have been developed and incorporated into the EMM uecp.f code, ecpdat.txt and emmcntl.txt input files. These modifications effectively extend the existing NEMS retrofit algorithm from a 3-P to a 4-P formulation by adapting an unused option ("spray cooling") originally intended for mercury control (retrofit for mercury control is actually addressed in NEMS by a separate "fabric filter" option).

6.3 PETROLEUM MARKET MODULE (PMM) MODIFICATIONS

The PMM models petroleum refining activities, the marketing of petroleum products to consumption regions, the production of natural gas liquids in gas processing plants, domestic methanol and ethanol production, and gas-to-liquids and coal-to-liquids production. The PMM projects petroleum product prices and sources of supply for meeting petroleum product demand. The sources of supply include domestic and imported crude oil; other inputs including alcohols, biodiesel, and ethers; domestic natural gas plant liquids production; petroleum product imports; unfinished oil imports.

6.3.1 PMM AND COAL/BIOMASS-TO-LIQUIDS ENHANCEMENT

PMM modifications are focused <u>only</u> on Coal-to-Liquids (CTL) technology.

The CTL model currently includes a CO_2 production stream (SCS, 1000 ston/cd). This stream has the option (in the LP) to go to a unit (CTS) that represents capture and sequestration, or to be released in the air via a 5-step cost curve. The EIA intent is to have the cost curve represent carbon tax penalty or some sort of trading.

The NETL methodology has enhanced EIA's approach so that CTL-only directly competes with CTL+CTS. **FIGURE 6-1** illustrates the CBTL model in the PMM. These enhancements include:

- Regional Transfer Costs (as mapped from EMM regions to the PADDs) are passed from the CO2MM to the PMM and used to calculate the CTL+CTS product cost. A new variable (**TRCST**) has been added to the cost calculations for CTL+CTS to account for the regional CO_2 Transfer Cost;
- CTL+CTS product cost calculation also accounts for a credit based on the quantity of CO_2 captured and NEMS' calculated CO2 allowance price. This credit accounts for the higher delivered cost of coal as impacted by the CO2 allowance cost. Since CTL-only does not receive this credit, CTL+CTS cost competitiveness is enhanced;
- CTS capital and O&M costs only account for integrated capture and compression technology and do **not** include the cost of CO_2 transport and the cost of sequestration. These are represented by TRCST;
- CO_2 captured in each PADD is mapped to EMM regions for use by CO2MM; and
- New CO2MM common block has been added to NEMS and includes TRCST and variables that directly account for captured CO_2 from CTL+CTS.

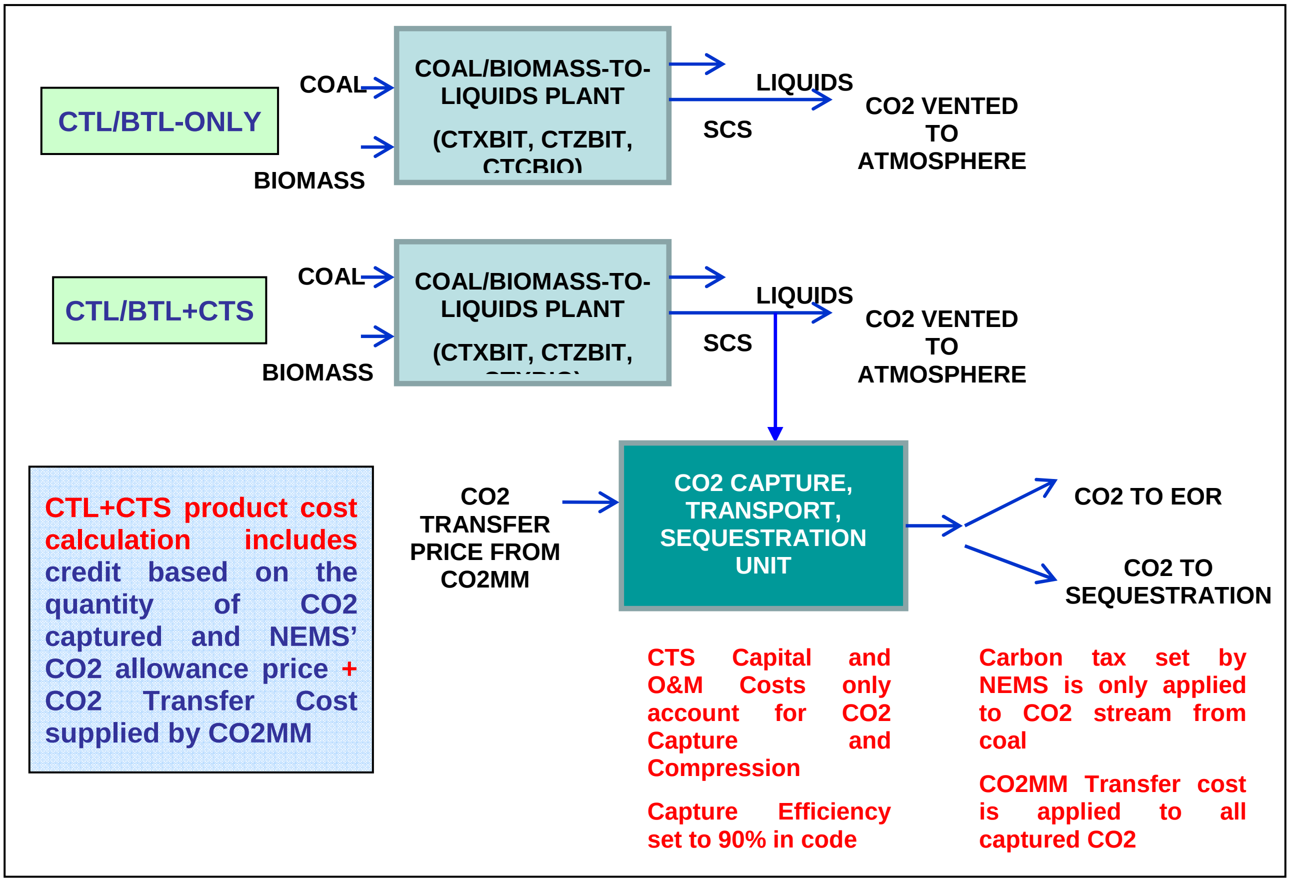
6.3.2 PMM CODE UPDATES

The PMM LP model representation and code were updated (and tested) to better represent the CTL CO_2 emissions and sequestration options. Changes were made to the files used by EIA to produce the AEO2008 (released in March 2008).

- CO_2 from CTL and from BTL were combined into a single pool. This needed to be tracked separately because of the carbon penalty being applied to the carbon in the coal (as opposed to the carbon being emitted as CO_2).
- Carbon capture/compression unit (CTS) did not include capture efficiency less than 100%, thus a link needed to be designed to properly account for the CO_2 quantity being emitted from this unit do to incomplete capture.
- Accounting variables were added in order to apply the carbon capture credit, and to report both capture and emission results.
- The subroutine **RPT_CO2CAPTR** was added to retrieve the solution results related to: Quantity of CO_2 released to the atmosphere (RFATMCO2Q, by PADD).

Quantity of CO_2 captured for sequestration or sale (RFCTLCO2Q, by PADD and CTLCO2Q, estimated split into NERC region). This represents the TOTAL CO_2 captured, not just from CTL.

FIGURE 6-1. COAL/BIOMASS-TO-LIQUIDS (CBTL) TECHNOLOGY REPRESENTATION



The subroutine **CTL_CARBON** was added to update the cost coefficients for added vectors. The regional CO_2 transfer costs, made available from the CO2MM module, are contained in the variable CO2TRCST which is reallocated from NERC region to PADD. This is used to update the LP vector T(r)CCTOT. The carbon tax adjustment is calculated from the emissions variables JCLIN and ECLIN, and used to update the LP vector N(r)CO2CCO.

New variables were added to the pmmcom1 include file. All of these variable have been put into a global include and passed between NEMS modules.

RFATMCO2Q(MNUMPR,MNUMYR)	! Refinery total qty CO_2 released, M ton CO_2/cd
RFCTLCO2Q(MNUMPR,MNUMYR)	! Refinery total qty CO_2 captured, M ton CO_2/cd
RFCO2TRCST(MNUMPR,MNUMYR)	! Refinery CO_2 capture + transfer cost, 87$/ton CO_2
CTLCO2Q(MNUMNR,MNUMYR)	! Total qty CO_2 captured, M ton CO_2/cd
TFRCST(MNUMNR,MNUMYR)	! CO_2 transfer cost, 87$/ton CO_2

6.4 OIL AND GAS SUPPLY MODULE (OGSM) MODIFICATIONS

OGSM represents domestic crude oil and natural gas supply within an integrated framework that captures the interrelationships among the various sources of supply: onshore, offshore, and Alaska by both conventional and unconventional techniques, including gas recovery from coal beds and low-permeability formations of sandstone and shale. The framework analyzes cash flow and profitability to compute investment and drilling for each of the supply sources, based on the prices for crude oil and natural gas, the domestic recoverable resource base, and the state of technology. Oil and gas production functions are computed at a level of 12 supply regions, including 3 offshore and 3 Alaskan regions. This module also represents foreign sources of natural gas, including pipeline imports and exports to Canada and Mexico, and liquefied natural gas (LNG) imports and exports.

CO_2-EOR production (OGEORAPROD) is passed from CO2MM to OGSM for inclusion with other unconventional crude oil sources that are made available to the PMM.

OGEORAPROD is dimensioned by OGSM regions. It is calculated in the co2mm.f code using EMM to OGSM region mapping.

7. CO_2 MARKET MODEL TEST CASE ANALYSIS

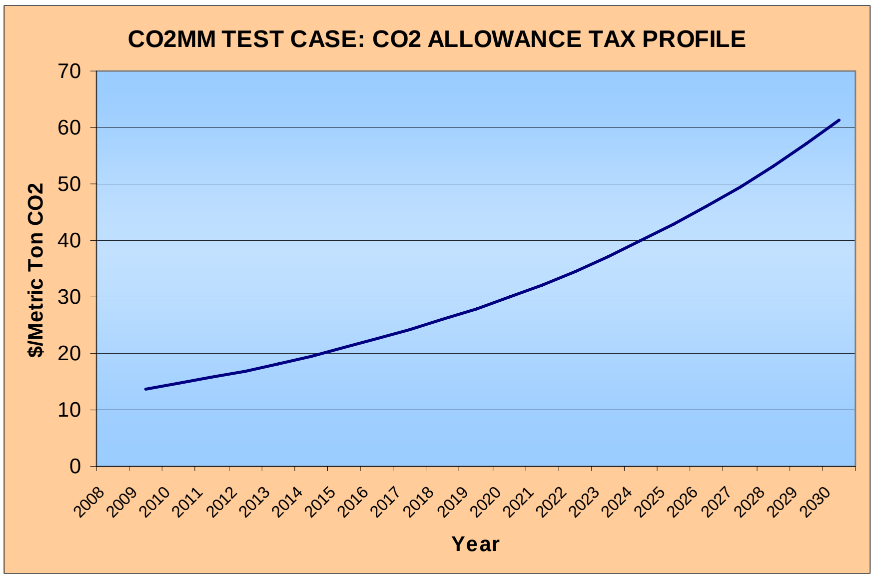
The CO2MM test cases represent a fully integrated 90-cycle NEMS run. The comparison of three test runs results is presented in this document. All cases are based on AEO2008 version of NEMS with few modifications. The input assumptions for all three cases are discussed below.

7.1 CO2MM TEST CASE INPUT ASSUMPTIONS

The following are the input assumptions used in the CO2MM Test Case run:

- Tax case input profile – based on EIA's S. 2191 Core Case output results

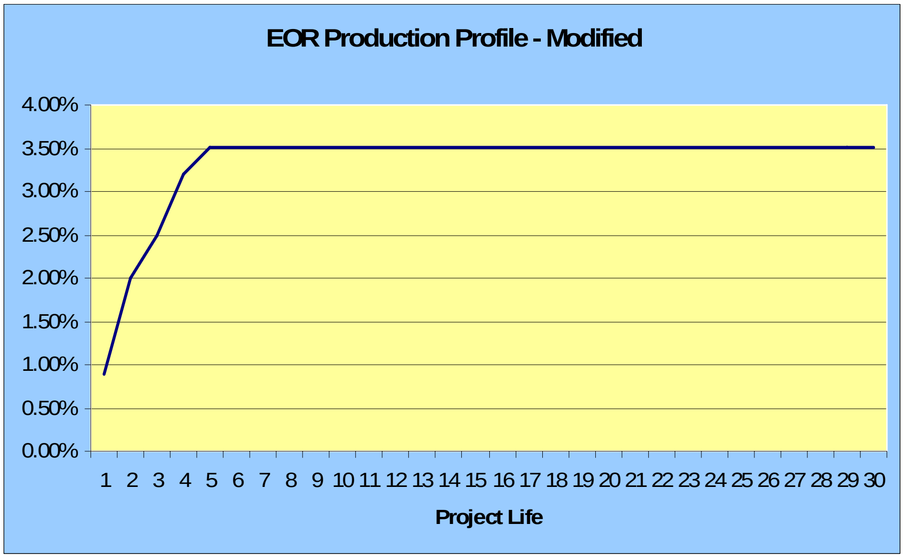
FIGURE 7-1. CO_2 ALLOWANCE TAX PROFILE



- Advanced Nuclear Capital Cost, used to control excessive nuclear capacity additions due to the imposition of the carbon tax
  - Overnight Capital Cost Input: **\$2,767/kW in 2008 Dollars**
  - Loaded Capital Cost Calculated by NEMS: **\$3,500/kW in 2008 Dollars**
- CO_2 Sequestration Cost (Same value used in all regions): **\$10/ton CO_2**
- CO_2 Transport Cost (Same value used in all regions): **\$5/Ton CO_2**
- Transport Cost Share (Same value used in all regions): **50%** EOR, **50%** power plant
- Maximum CO_2 Transfer Subsidy (Same value used in all regions): **\$54.75/tonne CO_2**
- This value corresponds to the upper limit of the CO_2 price (\$47.25) provided on the CO_2 demand curve specification. The value is based on the following definition:
- Transfer Subsidy = EOR Transfer Cost + CO_2 Sequestration Cost – EOR Transport Cost

  = \$47.25 + \$10 - \$2.50 = \$54.75
- Minimum CO_2 Transfer Subsidy (Same value used in all regions): **\$0.00/tonne CO_2**

- Demand curve assumptions:
  - IRR value(Same value used in all regions): **30%**
  - Deployment cap: 100 million barrels increase in production per year for all regions
  - Annual disaggregation profile:

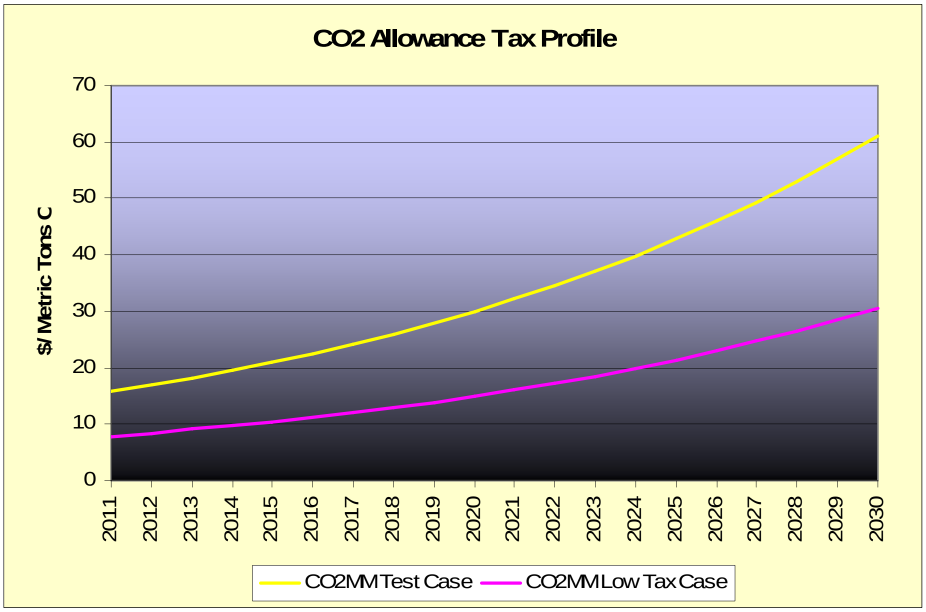


7.2 CO2MM TEST CASE I (LOW NUCLEAR COST) INPUT ASSUMPTIONS

CO2MM Test Case I uses the same input assumptions as the CO2MM Test Case, but utilizes lower Advanced Nuclear Capital Cost.

7.3 CO2MM TEST CASE II (LOW TAX) INPUT ASSUMPTIONS

CO2MM Test Case II uses the same input assumptions as the CO2MM Test Case, but utilizes lower CO_2 allowance tax profile.



7.4 CO2MM TEST CASE RESULTS AND DISCUSSION

This section presents and discusses the comparison of the Test Cases results.

7.4.1 CO2 EMISSIONS AND CAPTURE

FIGURE 7-2 compares the total energy-based CO_2 emissions for the three runs. The output is directly correlated with CO_2 allowance tax profile yielding the highest CO_2 emissions in the CO2MM Low Tax Case.

FIGURE 7-3 and **FIGURE 7-4** compare the CO_2 capture from coal-based and gas-based generation respectively. Both coal and gas-fired generation with CCS are significantly impacted by the regional CO_2 transfer subsidies, CO_2 tax profile and advanced nuclear cost, as expected.

The total annual CO_2 capture by technology type and by region for the three CO2MM Test Cases are, respectively, shown in **FIGURES 7-5 a-c** and **FIGURE 7-6 a-c.** **FIGURE 7-7 a-c** provides annual levels of CO_2 demand and CO_2 sequestered for the three CO2MM Test Cases. For the latter, the results indicate that the combination of high CO_2 tax and the calculated transfer costs yield a much greater IGCC with CCS build level. The EOR CO_2 demand results in much earlier introduction of the technology, which significantly impacts NEMS' learning feature and helps compound capacity growth, particularly in later years when the carbon tax becomes larger.

FIGURE 7-2. TOTAL ENERGY CONVERSION CO_2 EMISSIONS

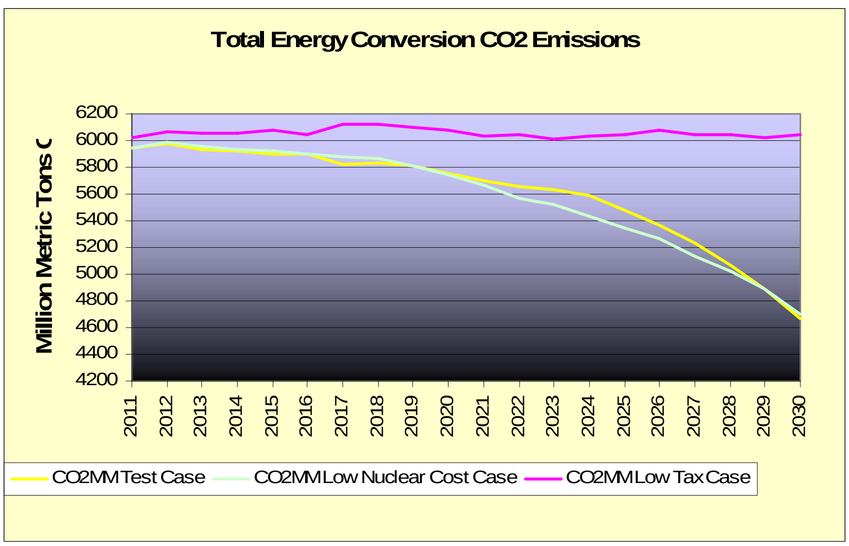


FIGURE 7-3. CO2 CAPTURED FROM COAL-BASED GENERATION

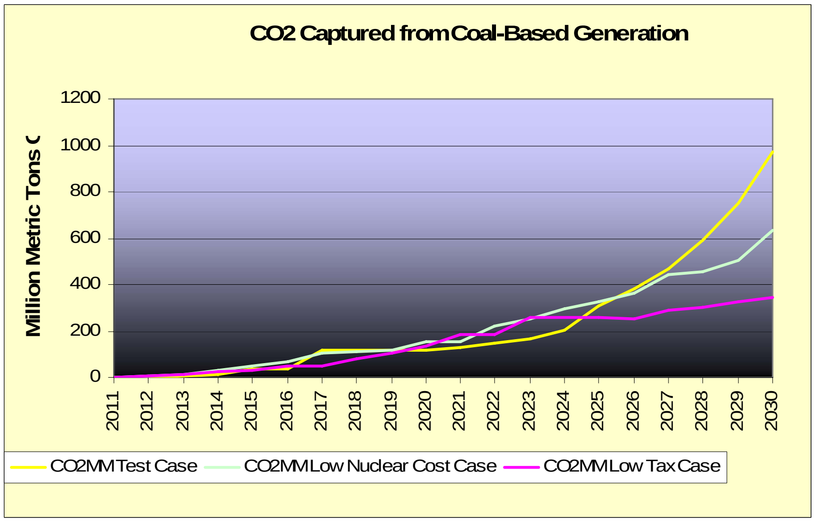
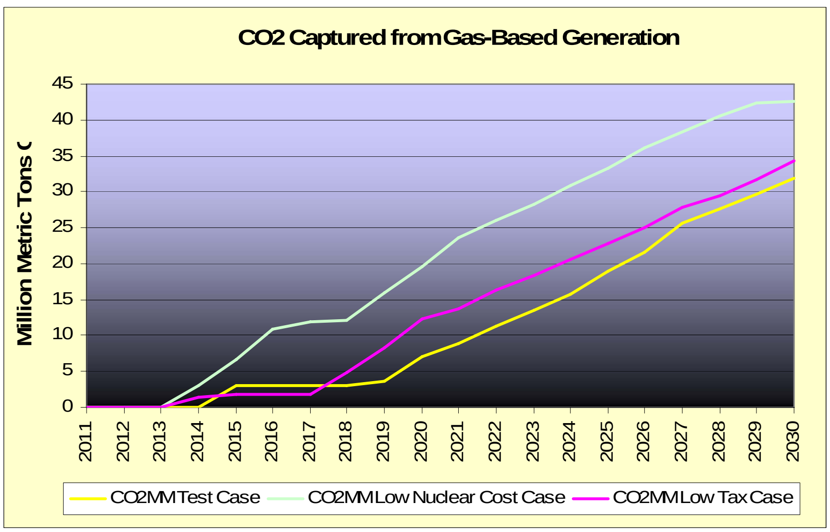
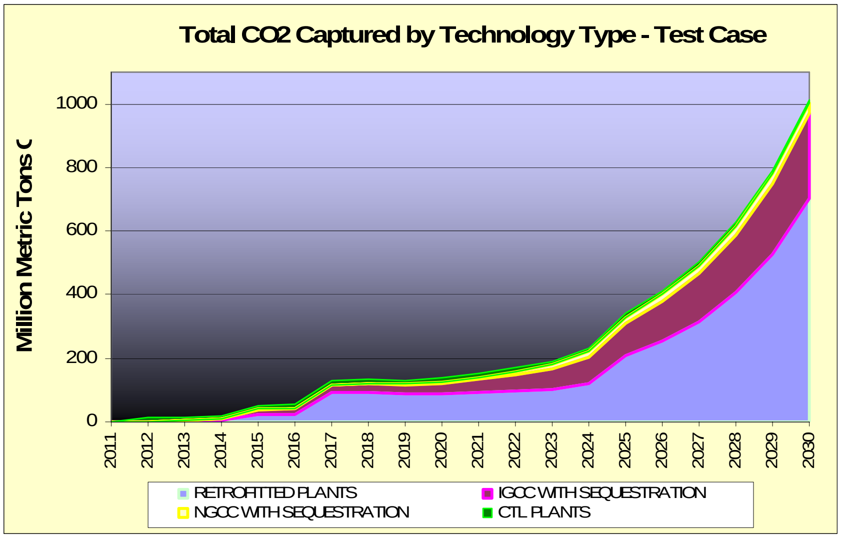
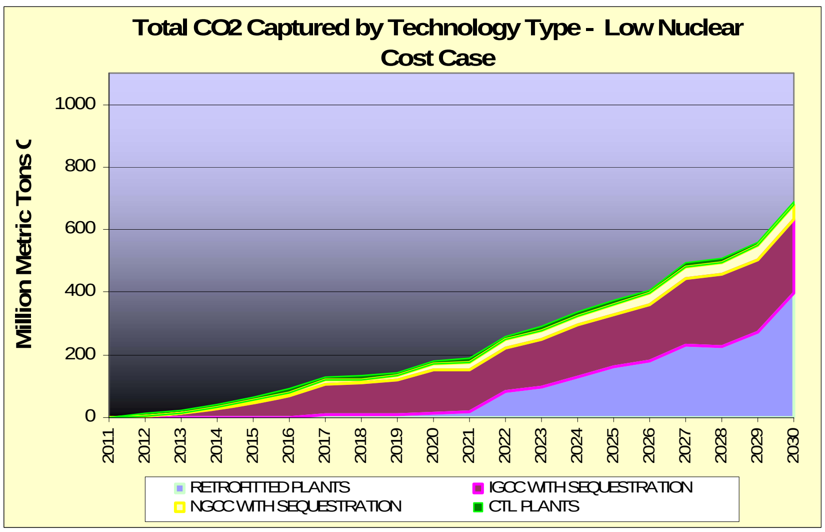


FIGURE 7-4. CO_2 CAPTURED FROM GAS-BASED GENERATION



FIGURES 7-5 A-C. TOTAL CO_2 CAPTURED BY TECHNOLOGY TYPE





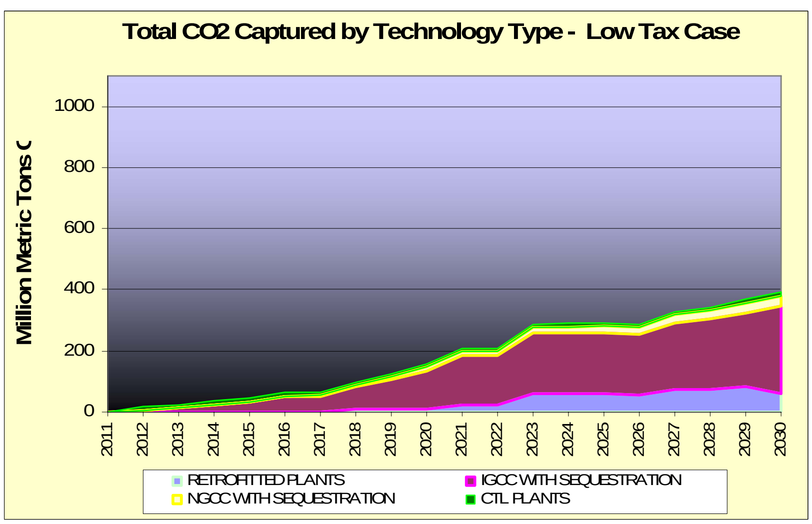
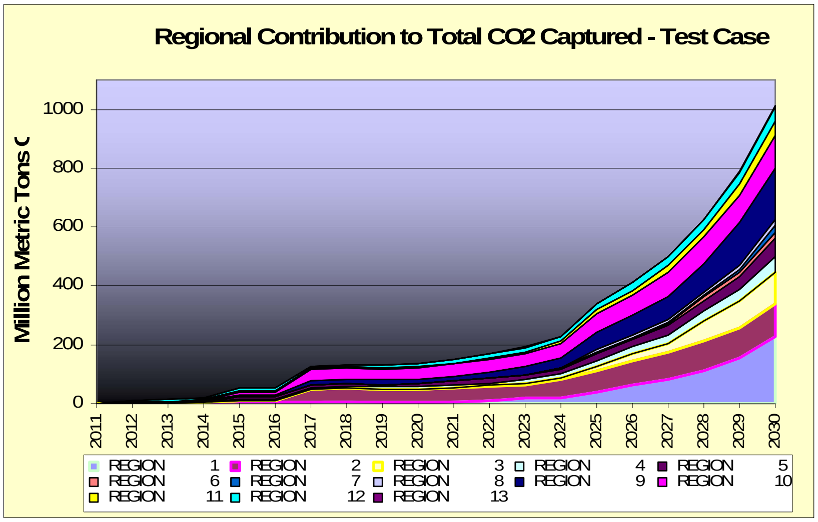
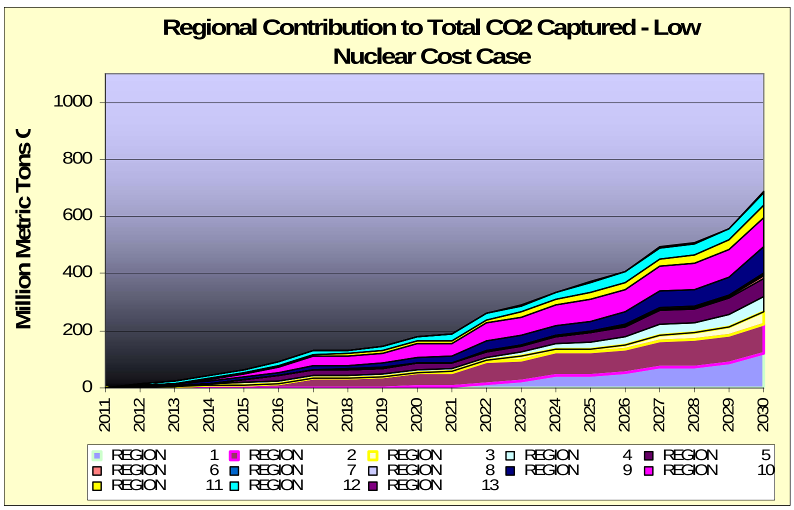


FIGURE 7-6 A-C. TOTAL CO_2 CAPTURED BY REGION





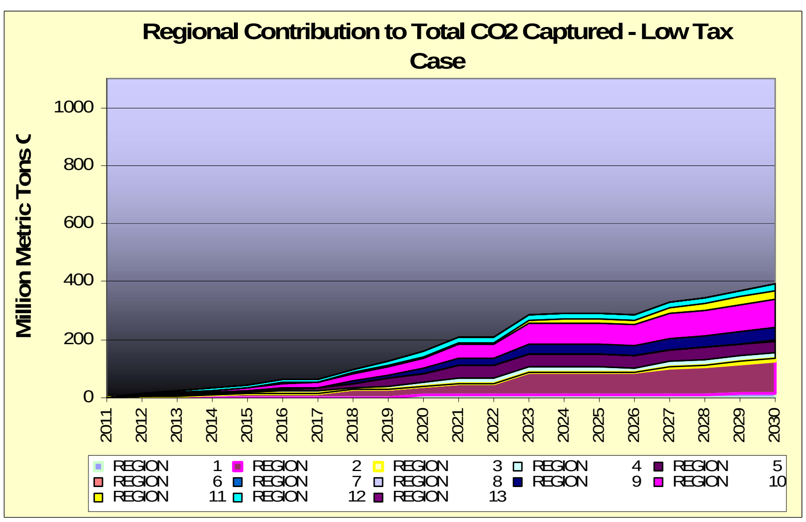
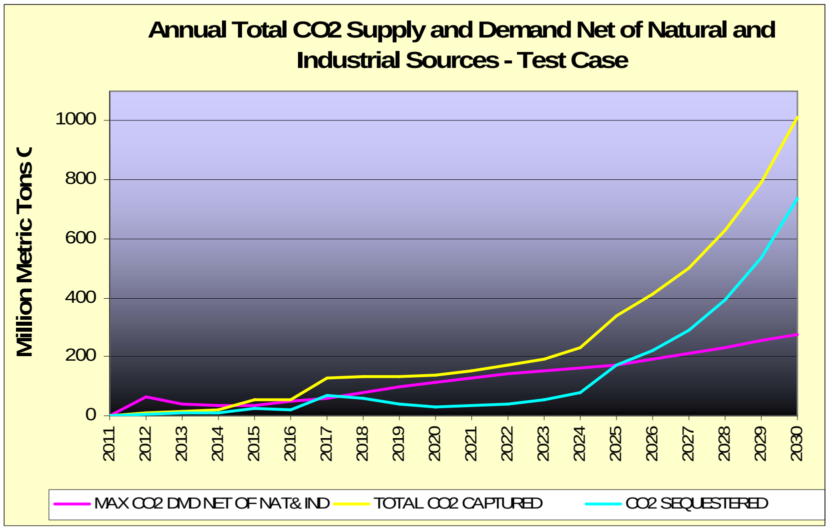
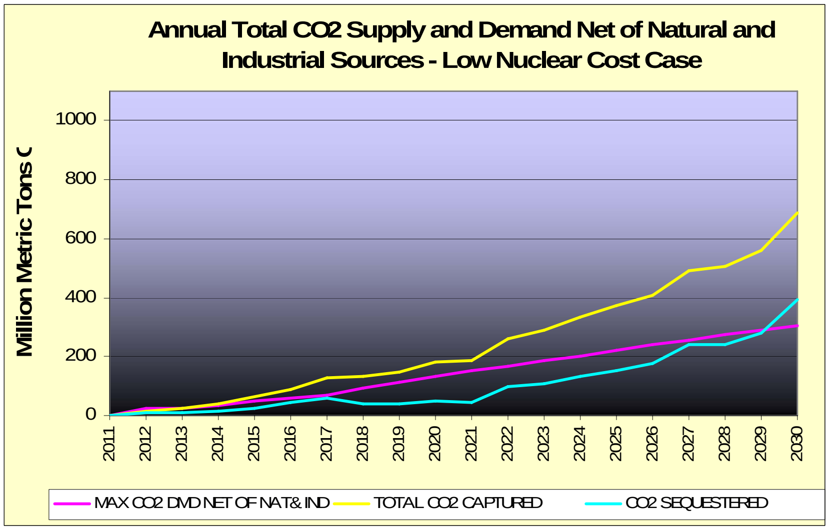
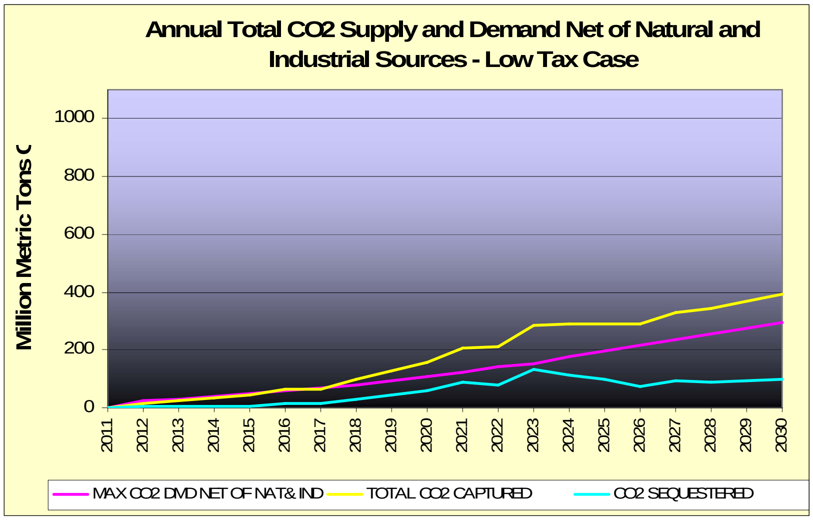


FIGURE 7-7 A-C. ANNUAL TOTAL CO_2 SUPPLY AND DEMAND







7.4.2 CRUDE OIL PRODUCTION

In this section, **FIGURE 7-8** through **FIGURE 7-11** show total and domestic oil supply, net imports, and CO_2-EOR production for the three cases. These charts generally show the favorable impact on total and domestic crude oil supplies and net reduction in crude oil imports. Domestic production increases through the NEMS projection horizon for all three cases. The impact of the lower tax or lower nuclear cost on the crude oil production or imports is not significant. Note, that EOR production is close to the maximum in all three cases.

FIGURE 7-8. TOTAL CRUDE OIL SUPPLY

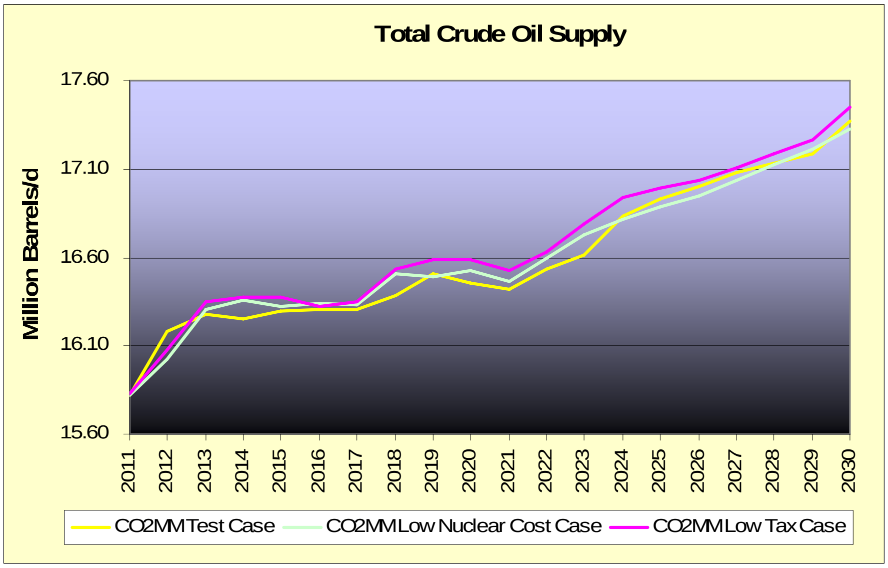


FIGURE 7-9. DOMESTIC CRUDE OIL PRODUCTION

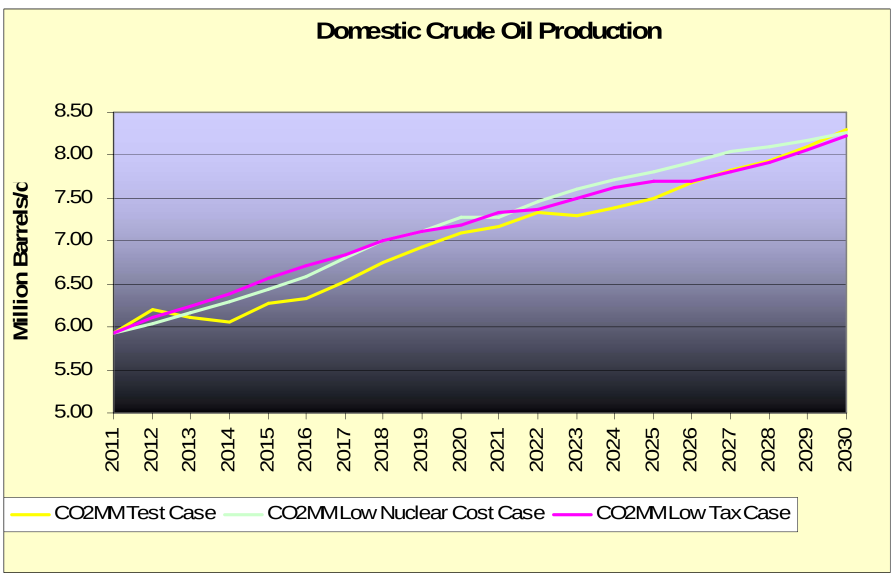


FIGURE 7-10. CRUDE OIL NET IMPORTS

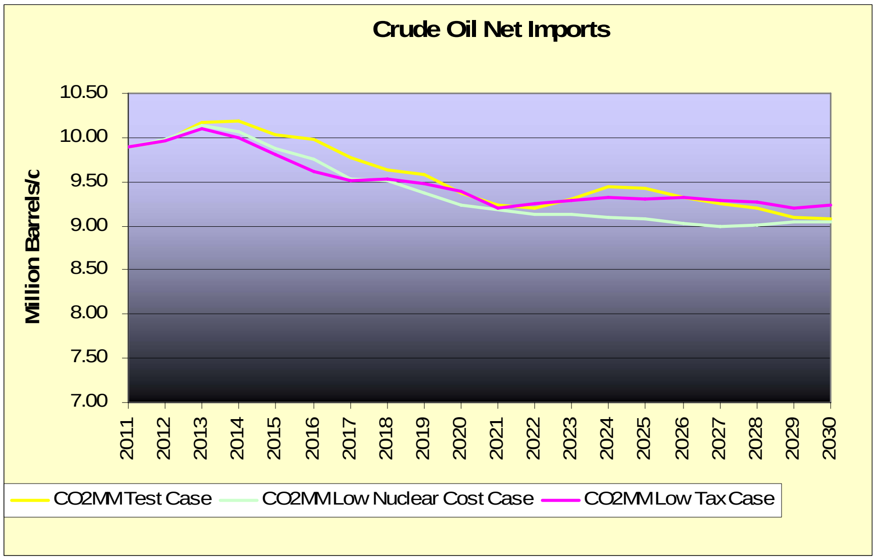
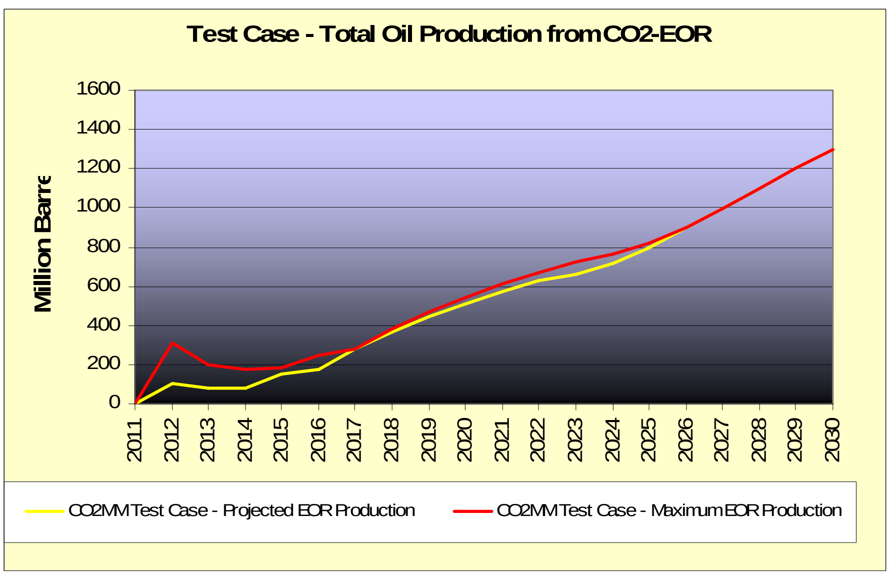
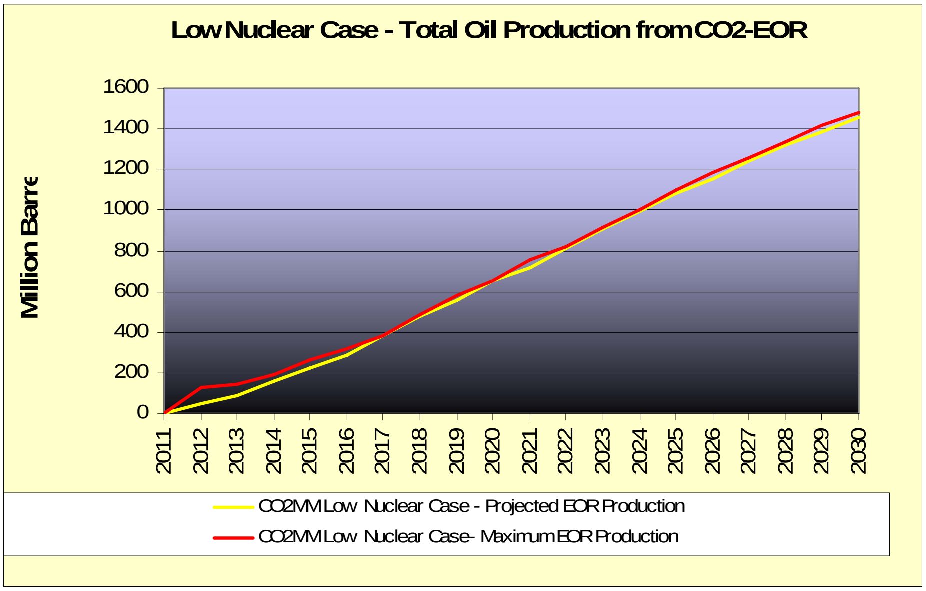
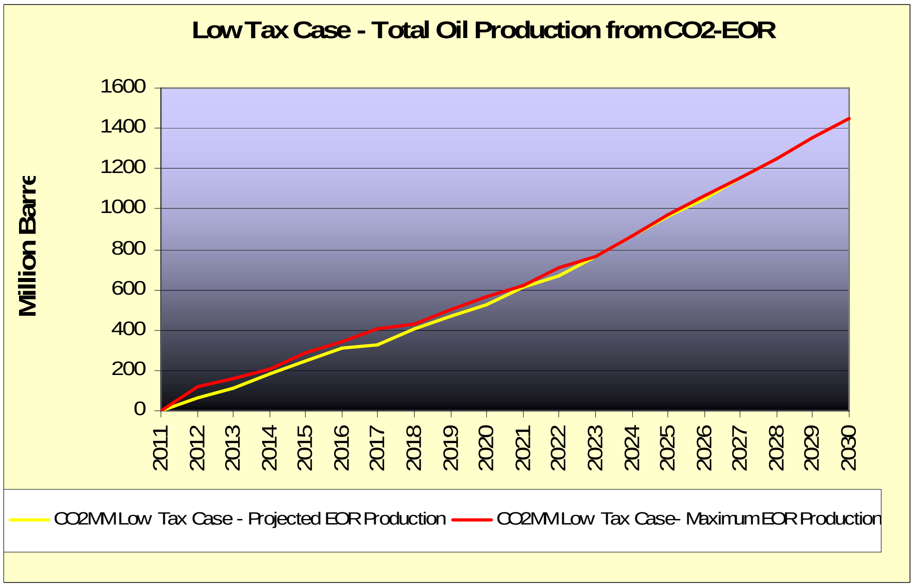


FIGURE 7-11 A-C. EOR OIL PRODUCTION





Low Nuclear Case - Total Oil Production from CO2-EOR
Million Barre
1600
1400
1200
1000
800
600
400
200
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
CO2MM Low Nuclear Case - Projected EOR Production
CO2MM Low Nuclear Case- Maximum EOR Production



Low Tax Case - Total Oil Production from CO2-EOR
Million Barre
1600
1400
1200
1000
800
600
400
200
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
CO2MM Low Tax Case - Projected EOR Production
CO2MM Low Tax Case- Maximum EOR Production

7.4.3 ELECTRIC POWER GENERATION AND BUILD CAPACITY

This section presents the NEMS EMM results with respect to power generation technology builds and retirements and electricity production. **FIGURE 7-12** through **FIGURE 7-18** represent build capacities for different technologies. As discussed previously, 'IGCC with CCS' technology is the prime beneficiary of the CO_2 purchases for transfer to EOR facilities. 'NGCC with CCS' also is initiated much earlier and capacity grows fast in the cases with higher nuclear cost. IGCC without sequestration technology builds are less and conventional PC plants are retired earlier and at a faster rate in the high tax cases because they aren't able to compete with the IGCC plants as depicted in **FIGURE 7-19** through **FIGURE 7-20**. Advanced Nuclear technology builds are much higher in the Low Nuclear Cost Case as expected.

FIGURE 7-12. IGCC WITH SEQUESTRATION BUILD CAPACITY

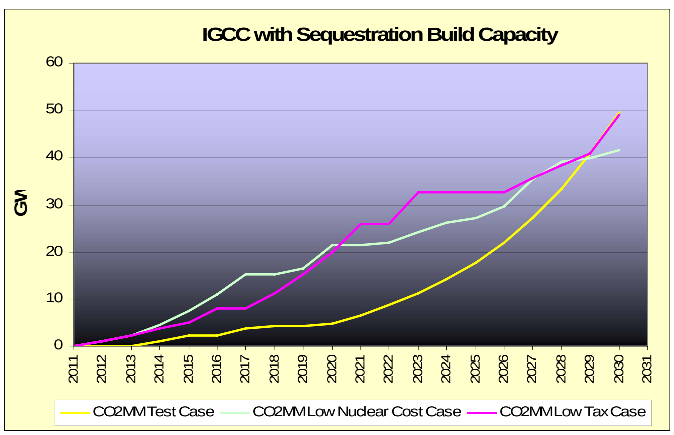


FIGURE 7-13. IGCC WITHOUT SEQUESTRATION BUILD CAPACITY

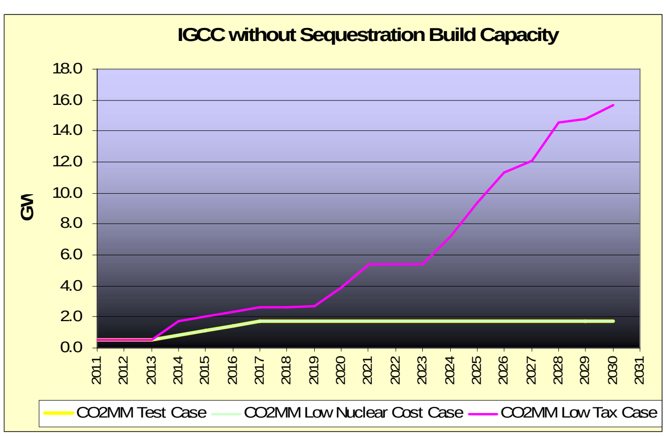


FIGURE 7-14. NGCC WITH SEQUESTRATION BUILD CAPACITY

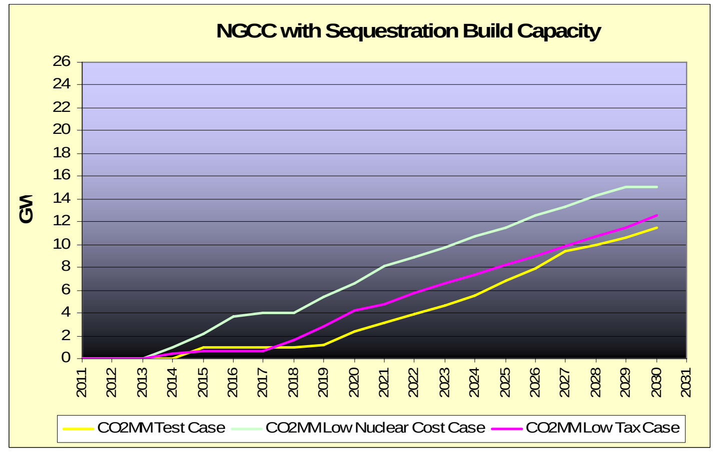


FIGURE 7-15. NGCC WITHOUT SEQUESTRATION BUILD CAPACITY

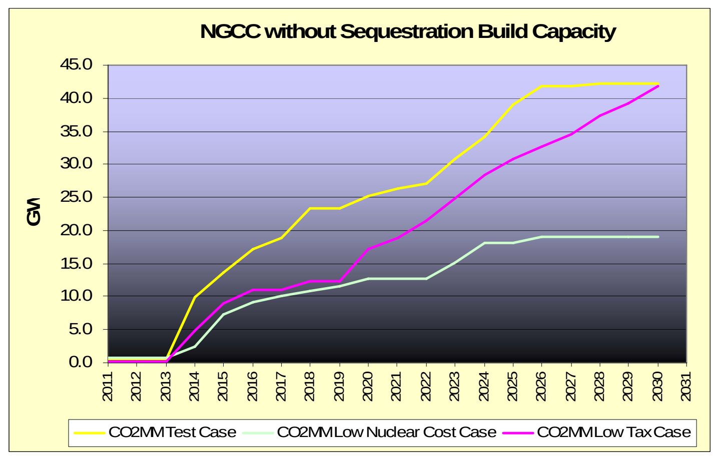


FIGURE 7-16. CONVENTIONAL COAL BUILD CAPACITY

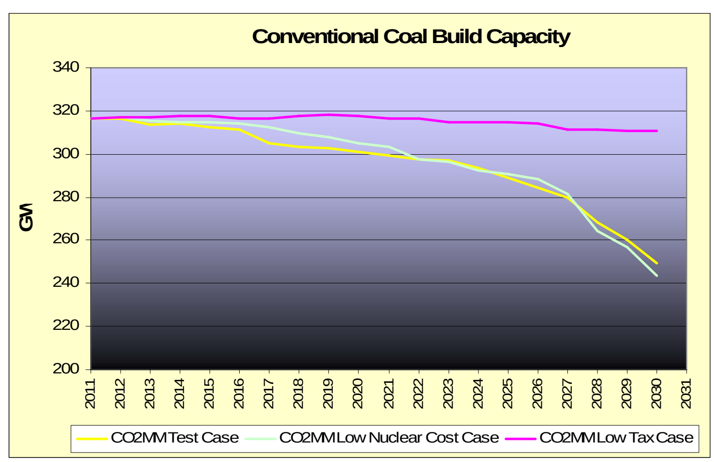


FIGURE 7-17. ADVANCED NUCLEAR BUILD CAPACITY

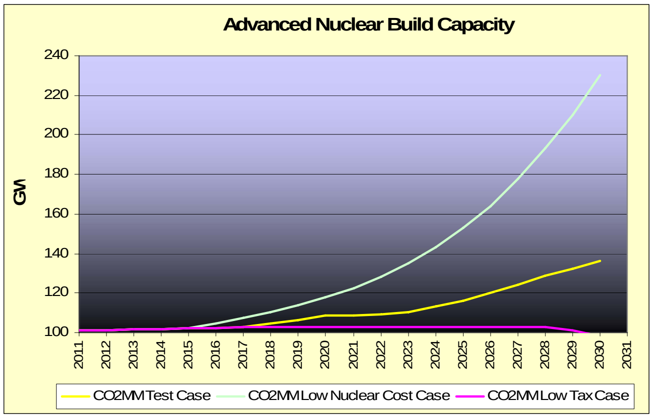


FIGURE 7-18. RENEWABALES BUILD CAPACITY

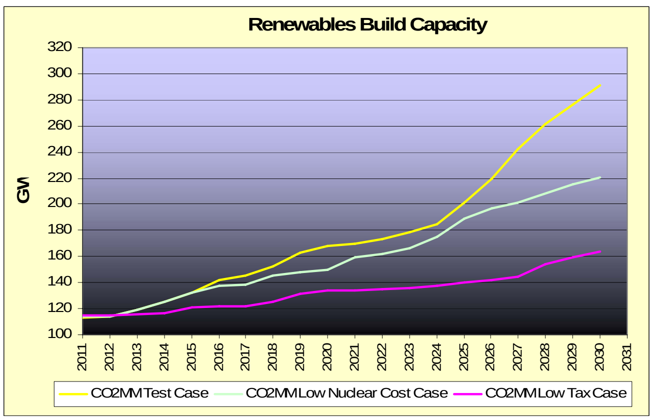


FIGURE 7-19. TOTAL CUMULATIVE UNPLANNED ADDITIONS

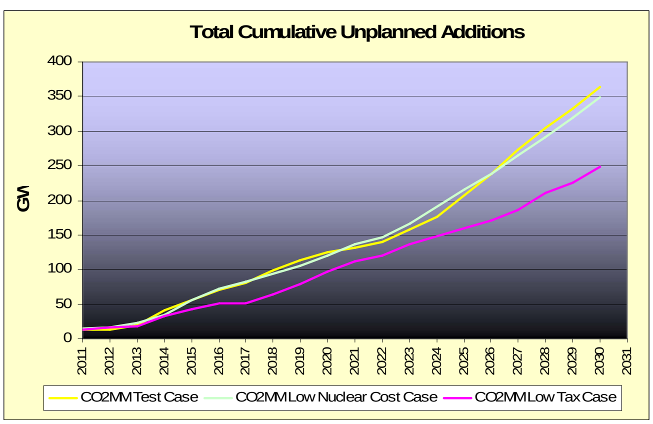


FIGURE 7-20. TOTAL CUMULATIVE PLANNED ADDITIONS

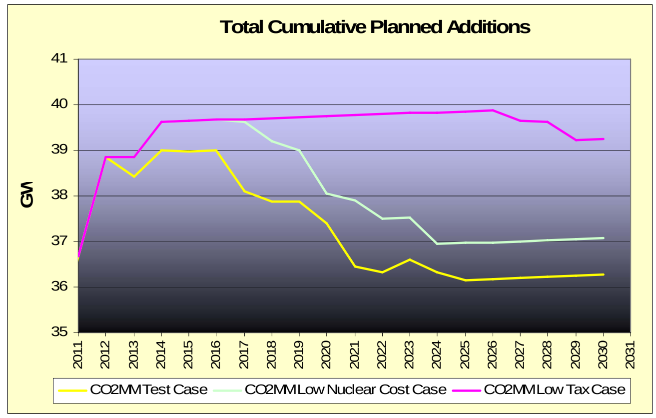
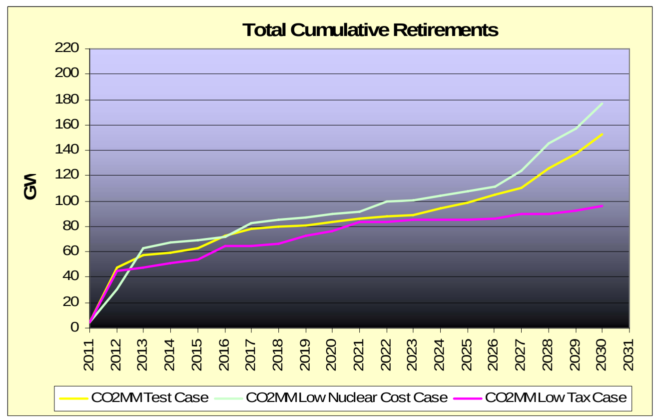


FIGURE 7-21. TOTAL CUMULATIVE RETIREMENTS



Electric power generation is shown in **FIGURE 7-22** through **FIGURE7-24**. Total generation is highest in the CO2MM Low Tax Case, due to significantly lower electricity price, as expected. The, coal-based power generation decreases in the two high tax case and increases in the Low Tax Case. This is the result of the significant increase in the coal capacity due to the lower tax.

FIGURE 7-22. TOTAL ELECTRIC POWER GENERATION

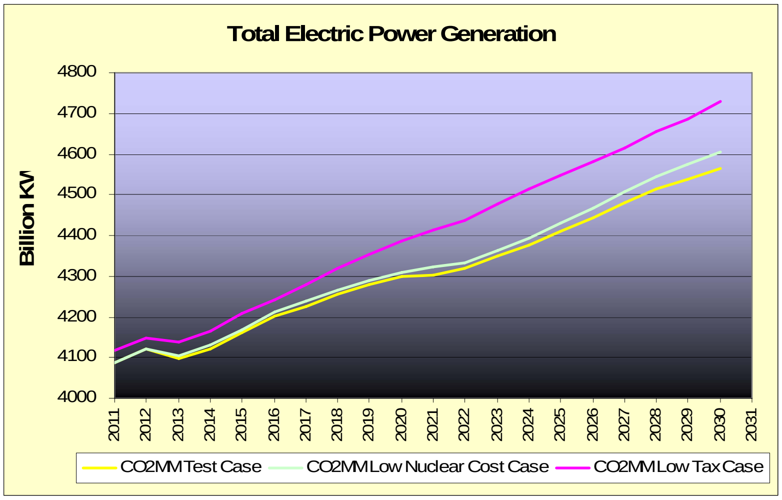


FIGURE 7-23. ELECTRIC POWER GENERATION - COAL

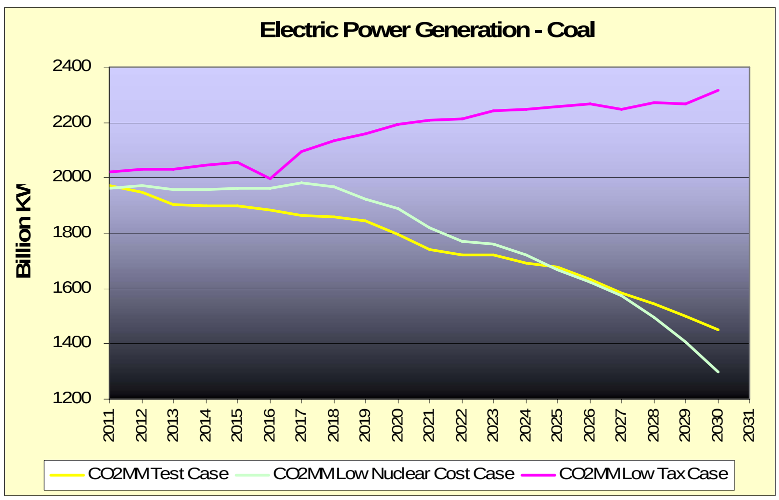
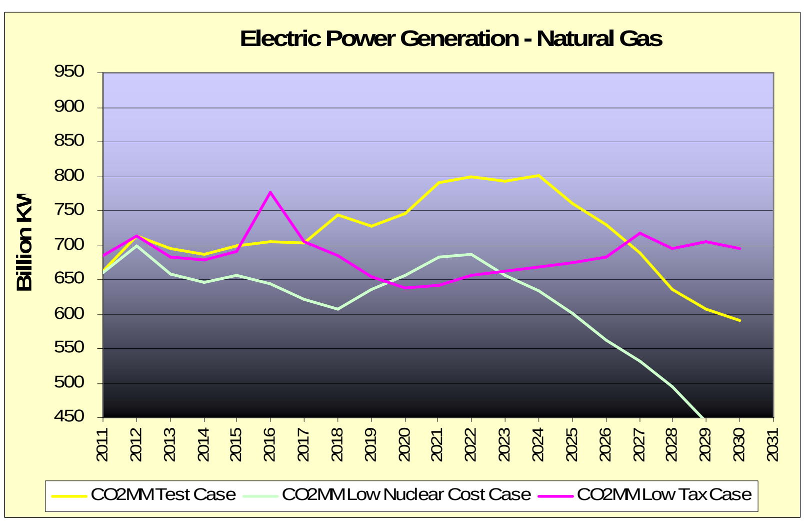


FIGURE7-24. ELECTRIC POWER GENERATION – NATURAL GAS



7.4.4 REGIONAL CO_2 SUPPLY, DEMAND AND EOR PRODUCTION

This section provides regional results for the CO2MM Test Case. Results for regions *1, 2, 4, 5, 8, 9, 10, 11, 12 and 13* include:

- CO_2 captured by technology type
- CO_2 sequestered
- CO_2 supply and demand
- CO_2 Transfer Price
- Annual EOR oil production

All of the regional results presented are done so in a consistent manner. The table below identifies the unique group of charts associated with each region. (Press 'Ctrl' on to keyboard and move the mouse over the figure numbers to link directly with the associated charts.)

TABLE 7-1. REGIONAL RESULTS CHARTS

EMM REGION Number	1	2	4	5	8	9	10	11	12	13
CHART Numbers	FIGURE 7-25 to FIGURE 7-28	FIGURE 7-37 to FIGURE 7-40	FIGURE 7-49 to FIGURE 7-52	FIGURE 7-61 to FIGURE 7-64	FIGURE 7-73 to FIGURE 7-76	FIGURE 7-85 to FIGURE 7-88	FIGURE 7-97 to FIGURE 7-100	FIGURE 7-109 to FIGURE 7-112	FIGURE 7-121 to FIGURE 7-124	FIGURE 7-133 to FIGURE 7-136

Each category is described below with examples from EMM Region 2 (Texas).

7.4.4.1 CO_2 Captured by Technology Type

Aggregate CO_2 capture is presented as a stacked bar chart for: 1) Retrofit PC plants with CCS, 2) IGCC with CCS, and 3) NGCC with CCS. As shown in **FIGURE 7-37**, IGCC with CCS yields the greatest portion of the CO_2 captured as "encouraged" by the sale of CO_2 to EOR entities in EMM Region 2.

7.4.4.2 CO_2 Supply and Demand and CO_2 Sequestration

This chart, as represented by **FIGURE 7-38**, compares the total CO_2 captured (yellow line - identical to the total presented in the previous chart) with maximum CO_2 demand (net of natural and industrial sources, pink line) by the EOR entities in the region <u>and</u> the total CO_2 that must be sequestered in the region (blue line).

In the early years, it is the EOR demand for CO_2 that results in the addition of capture technologies in region 2. It is expected, therefore, that the pink and yellow lines should be the same, with the blue line being zero (no sequestration required). Note, that in CO2MM Test, the total demand exceeds total supply; therefore the demand was not satisfied.

As the projection progresses from 2015 to 2020, the net demand and total captured lines merge. In the CO2MM Test Case beyond 2020, when the carbon tax increases beyond \$30/ton CO_2, the EMM starts to increase the capacities of the IGCC/CCS and NGCC/CCS and yields more CO_2 supply than the EOR demand. Therefore, we see the CO_2 sequestration requirement increase through 2030. However, in CO2MM Test Cases I and II the demand equals supply for the most part, and no sequestration is required.

7.4.4.3 CO_2 Transfer Price

This chart, as represented by **FIGURE 7-39**, depicts the outcome of the calculation of the transfer price negotiated between the power plant by the EOR entities (or the lack of a "deal" and the need to pay for transport and sequestration). Note that a negative $/Ton value connotes payment from the EOR facilities to the power plants. A positive value indicates that the power plants must pay for CO_2 transport and sequestration.

For region 2, the simulation indicates that the EOR entities start out by paying the maximum value allowed to obtain needed CO_2 with a gradual reduction of the transfer price payment as more captured CO_2 enters the market as a result of the increasing carbon tax. This is a good example of the influence that the tax has on the transfer cost.

In 2018, the simulation sees more CO_2 supply than demand and therefore, shuts off the demand by eliminating the purchase of CO_2 in 2023, requiring the power plants to pay for transport and sequestration. However, the following year the model appears to see the exact opposite situation and "negotiates" the full transfer cost with the CCS type of power plants that are being added. This model behavior would appear to be incorrect based on the oversupply of CO_2 shown in FIGURE 7-40. This is the result of the non-convergence of the model for the region for the specific year. By 2027, the model stabilizes and eliminates the EOR payments to the power plants in order to bring supply and demand closer to equilibrium.

The oscillating pattern of the transfer price is caused by the CO2MM transfer prices solution algorithm, which searches for the solution by oscillating between the two extreme points.

7.4.4.4 Annual EOR Oil Production

This chart, as represented by **FIGURE 7-40**, shows the EOR production (Million barrels per year) by source of CO_2: 1) CTL and power plants and 2) natural and industrial sources. Also shown is the maximum annual EOR production established by CO2MM, as well as the total CO_2 purchased for EOR production (note different units -- Million metric tons CO_2 per year).

This chart for region 2 shows that, through 2020, the simulation did a good job producing EOR at the maximum allows profile.

REGION 1 - CO2MM TEST CASE

FIGURE 7-25A. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 1

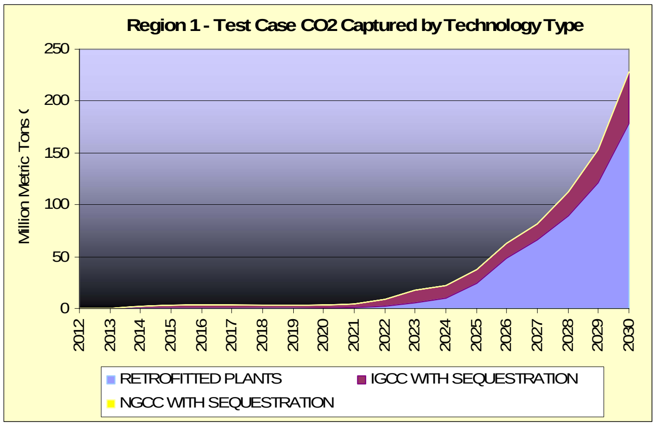


FIGURE 7-27A. TRANSFER PRICE – REGION 1

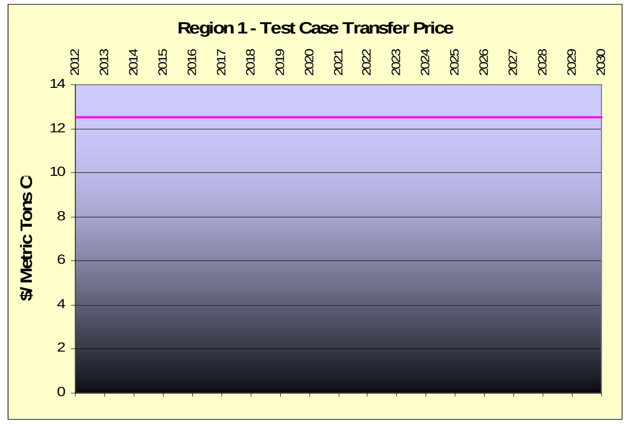


FIGURE 7-26A. CO2 SUPPLY AND DEMAND – REGION 1

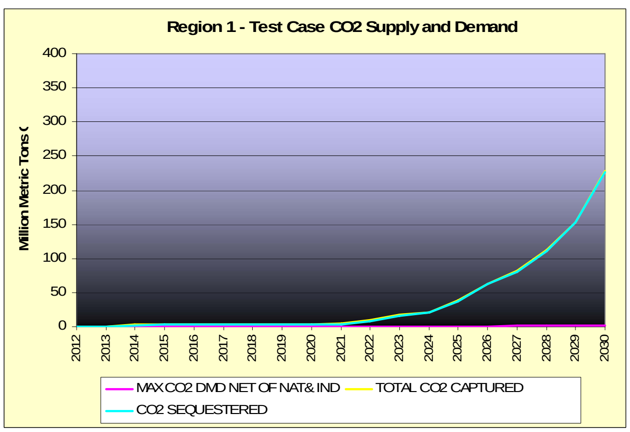
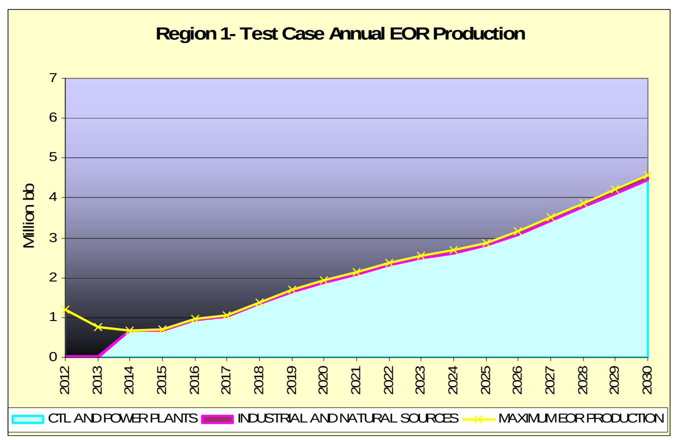


FIGURE 7-28A. ANNUAL EOR PRODUCTION – REGION 1



REGION 1- CO2MM TEST CASE I

FIGURE 7-29B. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 1

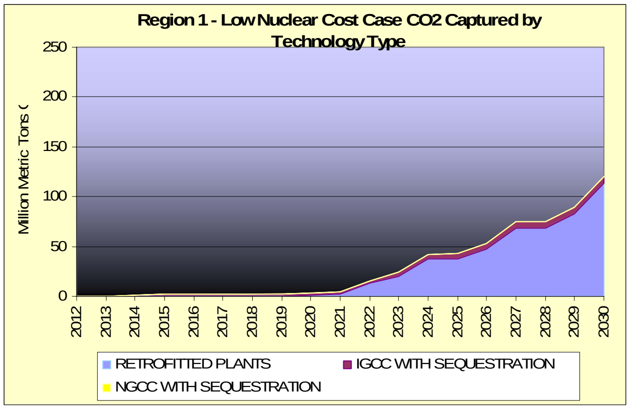


FIGURE 7-31B. TRANSFER PRICE – REGION 1

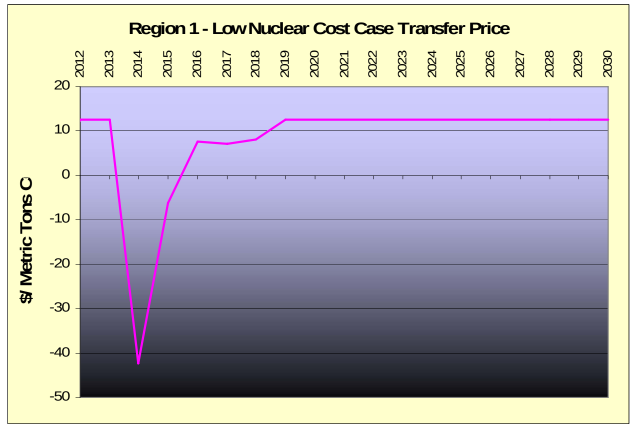


FIGURE 7-30B. CO2 SUPPLY AND DEMAND – REGION 1

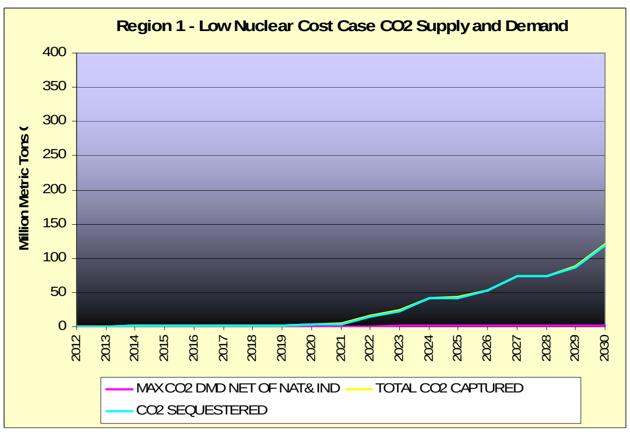
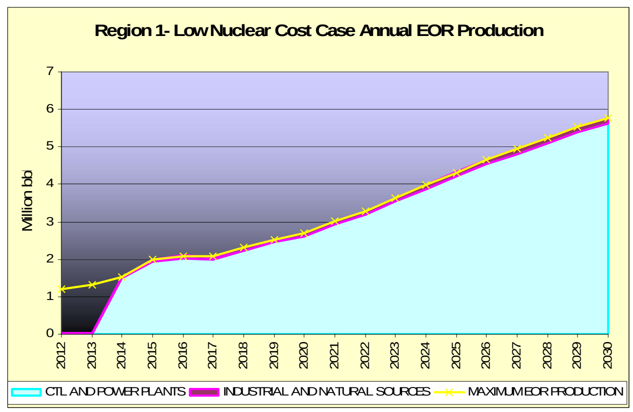


FIGURE 7-32B. ANNUAL EOR PRODUCTION – REGION 1



REGION 1- CO2MM TEST CASE II

FIGURE 7-33C. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 1

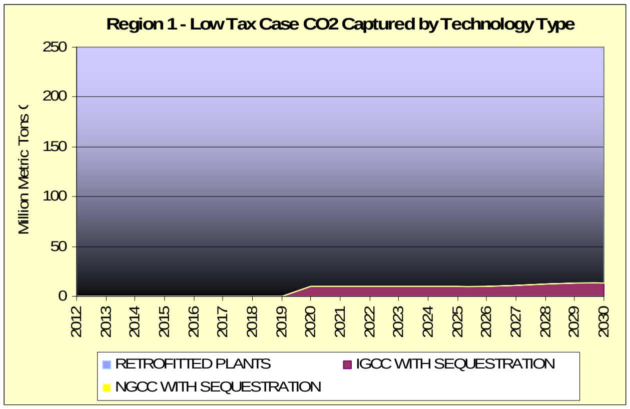


FIGURE 7-35C. TRANSFER PRICE – REGION 1

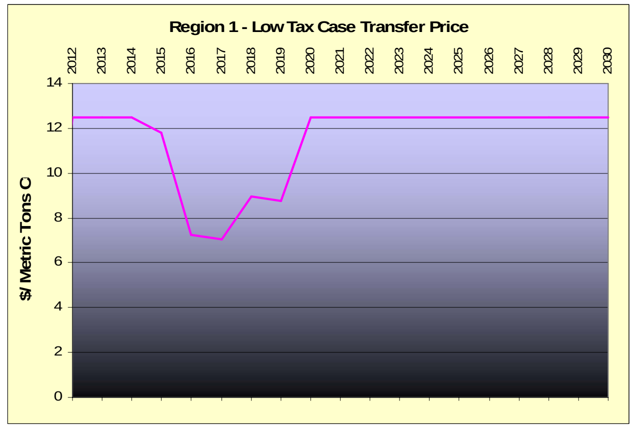


FIGURE 7-34C. CO2 SUPPLY AND DEMAND – REGION 1

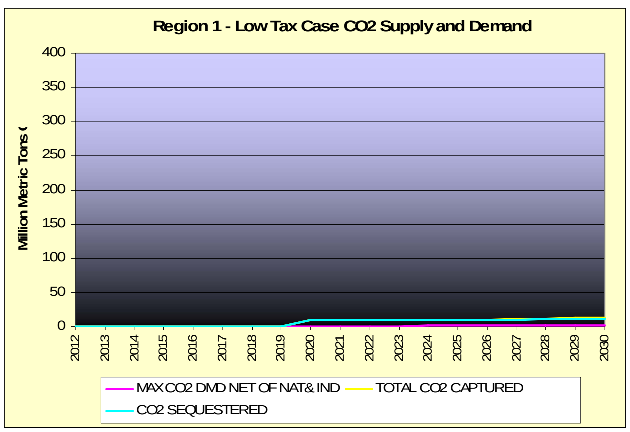
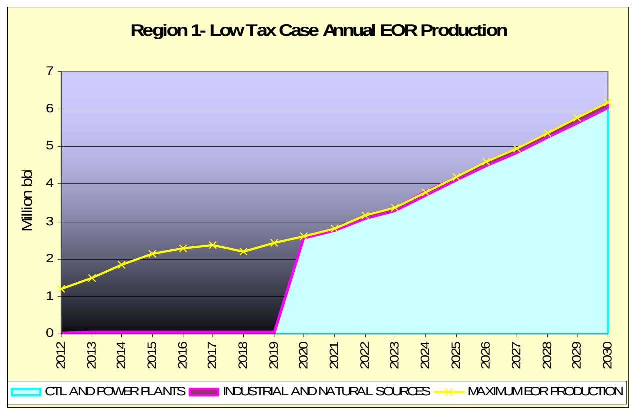


FIGURE 7-36C. ANNUAL EOR PRODUCTION – REGION 1



REGION 2- CO2MM TEST CASE

FIGURE 7-37. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 2

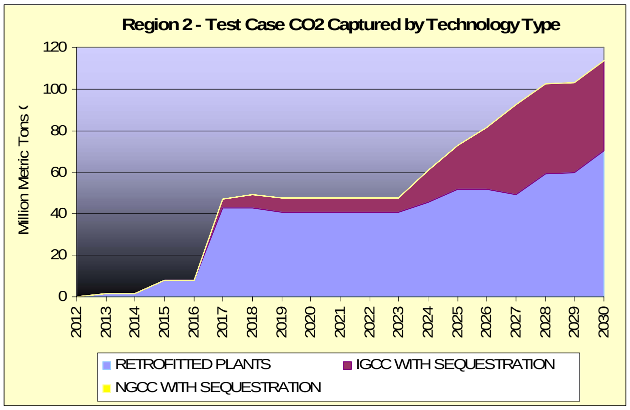


FIGURE 7-39. TRANSFER PRICE – REGION 2

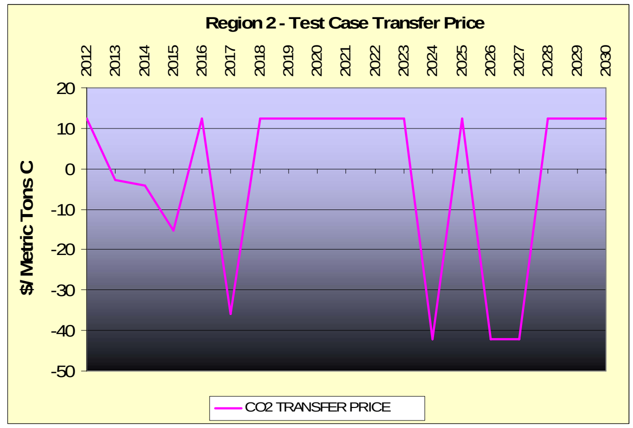


FIGURE 7-38. CO2 SUPPLY AND DEMAND – REGION 2

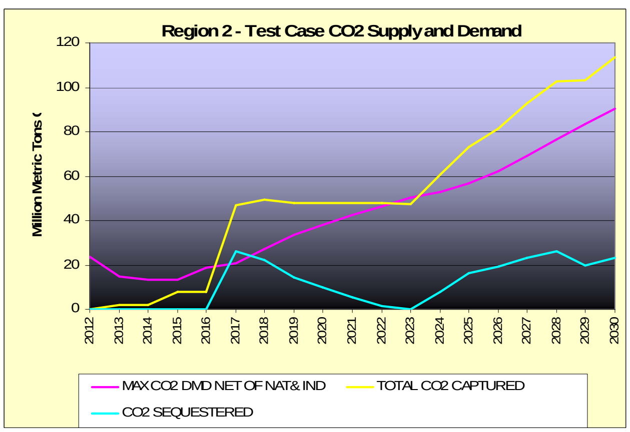
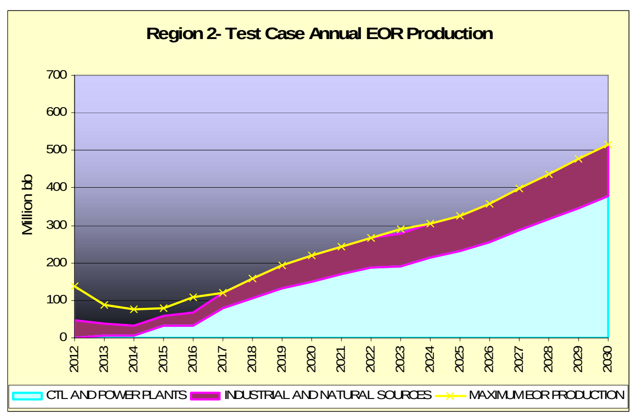


FIGURE 7-40. ANNUAL EOR PRODUCTION – REGION 2



REGION 2- CO2MM TEST CASE I

FIGURE 7-41. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 2

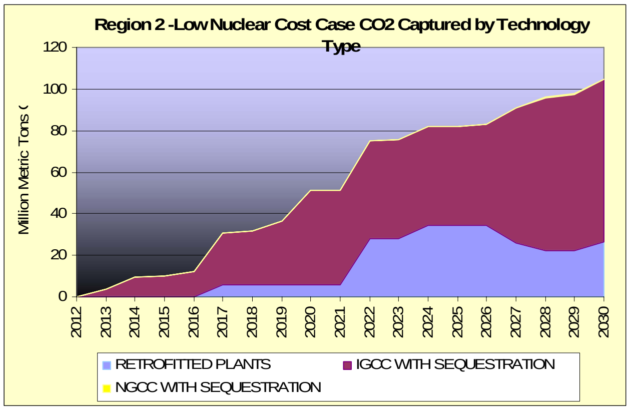


FIGURE 7-43. TRANSFER PRICE – REGION 2

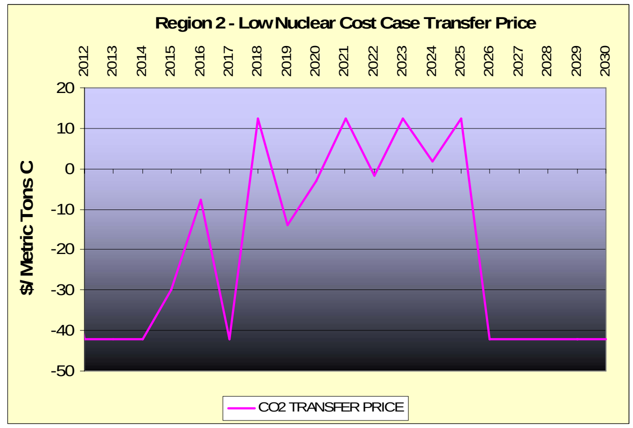


FIGURE 7-42. CO_2 SUPPLY AND DEMAND – REGION 2

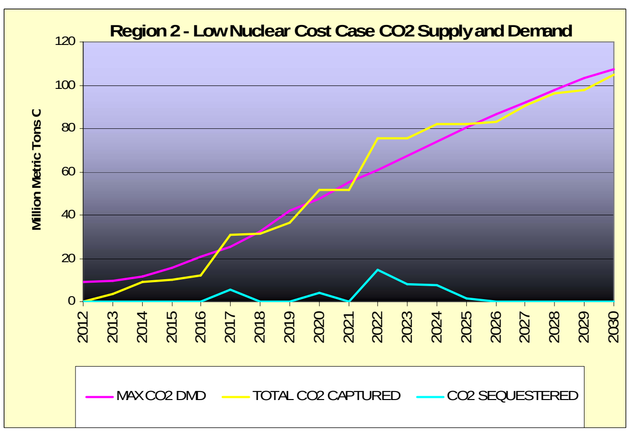
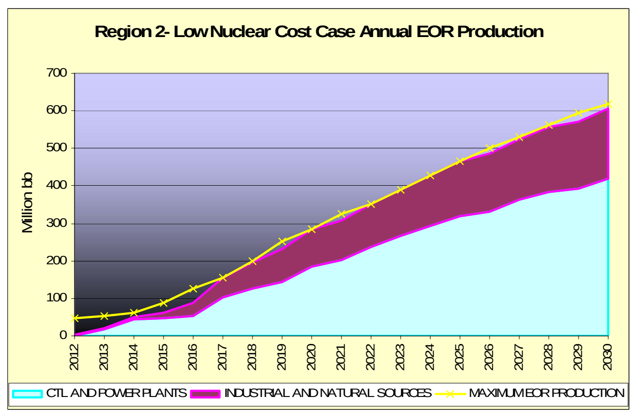


FIGURE 7-44. ANNUAL EOR PRODUCTION – REGION 2



REGION 2- CO2MM TEST CASE II

FIGURE 7-45. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 2

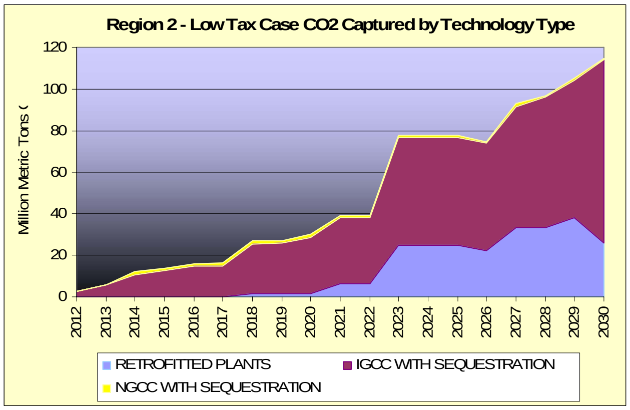


FIGURE 7-47. TRANSFER PRICE – REGION 2

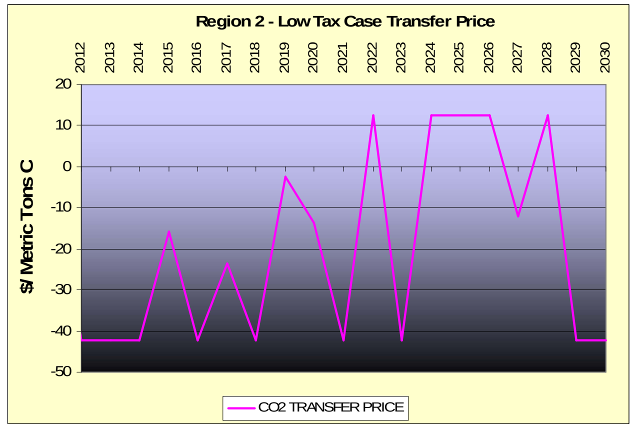


FIGURE 7-46. CO_2 SUPPLY AND DEMAND – REGION 2

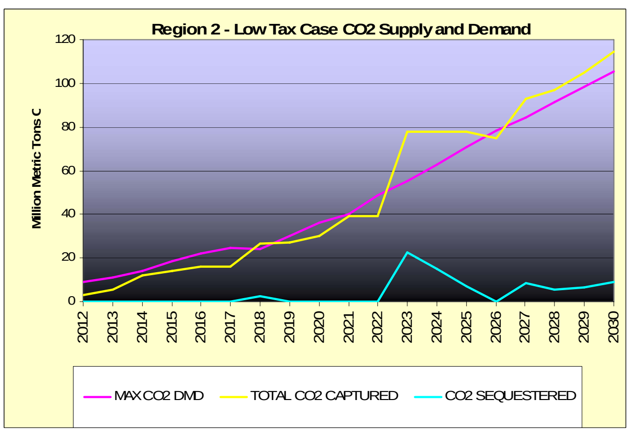
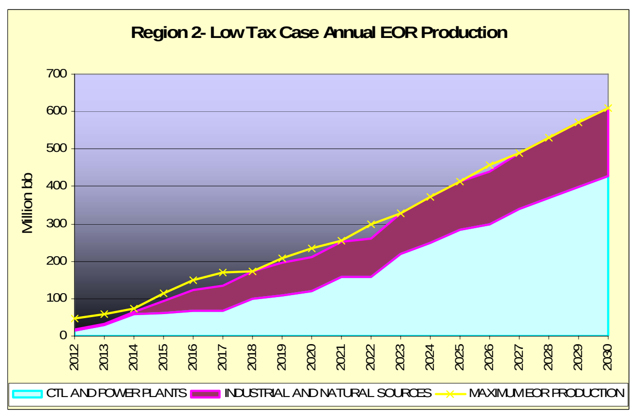


FIGURE 7-48. ANNUAL EOR PRODUCTION – REGION 2



REGION 4- CO2MM TEST CASE

FIGURE 7-49. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 4

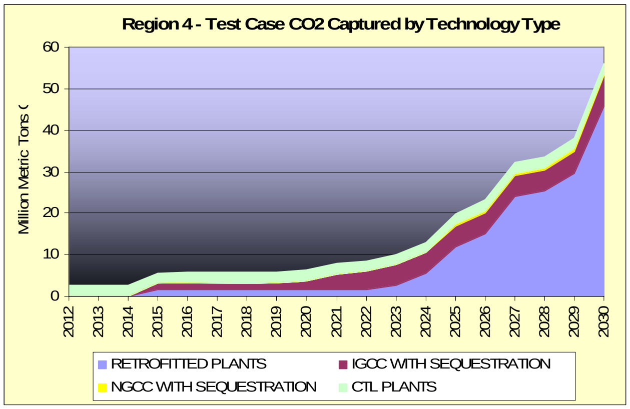


FIGURE 7-51. TRANSFER PRICE – REGION 4

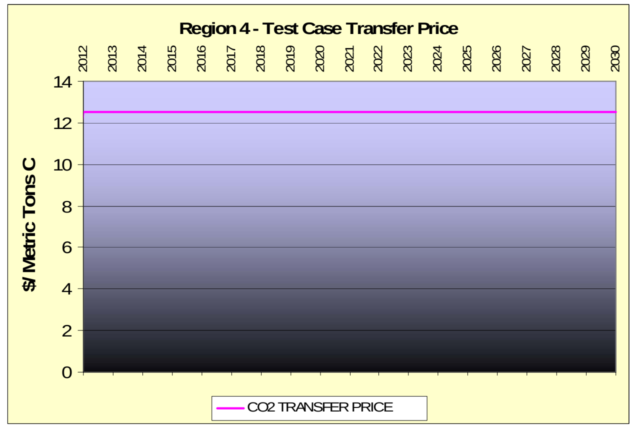


FIGURE 7-50. CO_2 SUPPLY AND DEMAND – REGION 4

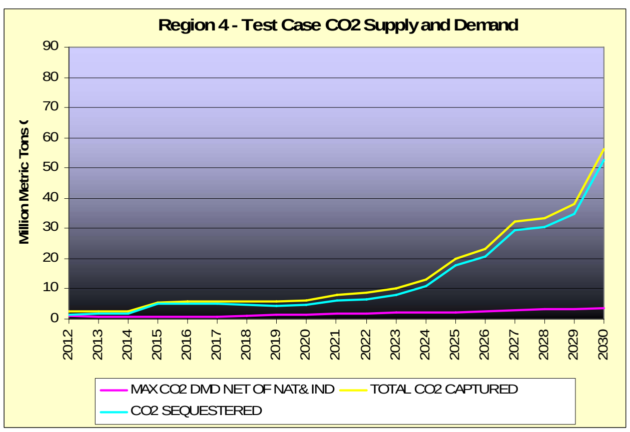
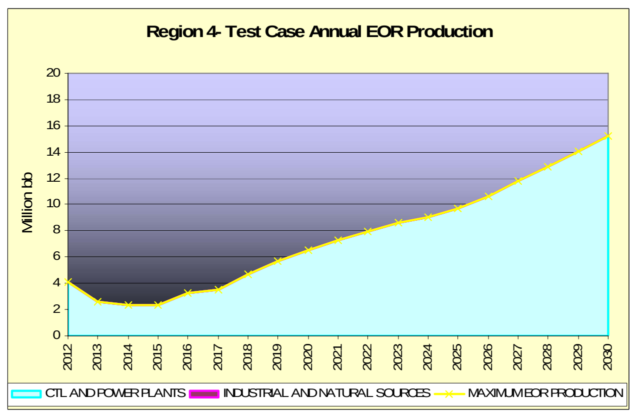


FIGURE 7-52. ANNUAL EOR PRODUCTION – REGION 4



REGION 4- CO2MM TEST CASE I

FIGURE 7-53. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 4

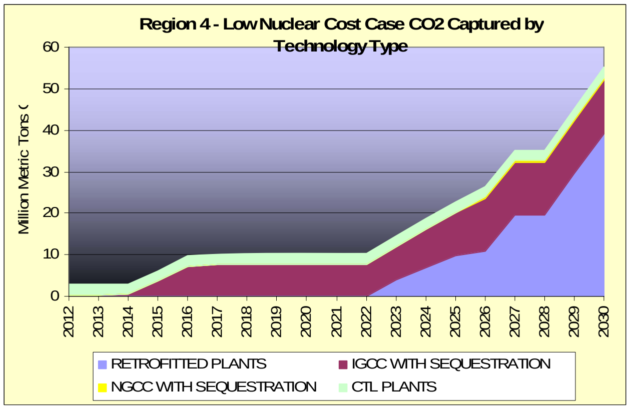


FIGURE 7-55. TRANSFER PRICE – REGION 4

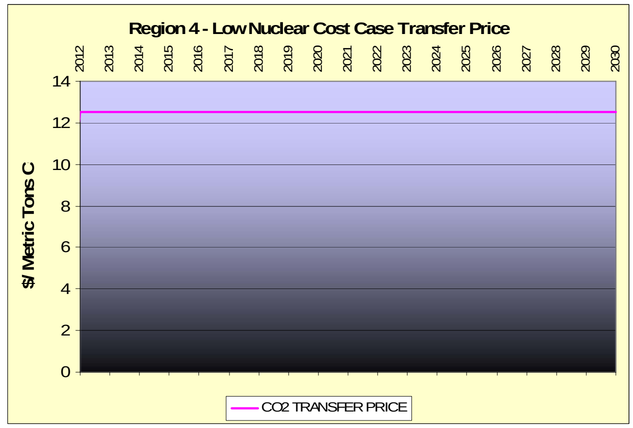


FIGURE 7-54. CO_2 SUPPLY AND DEMAND – REGION 4

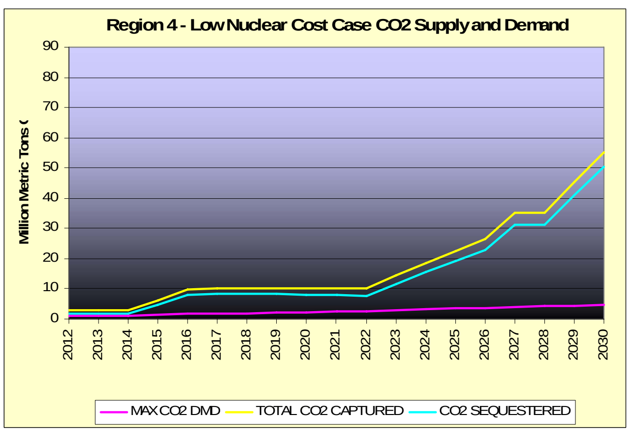
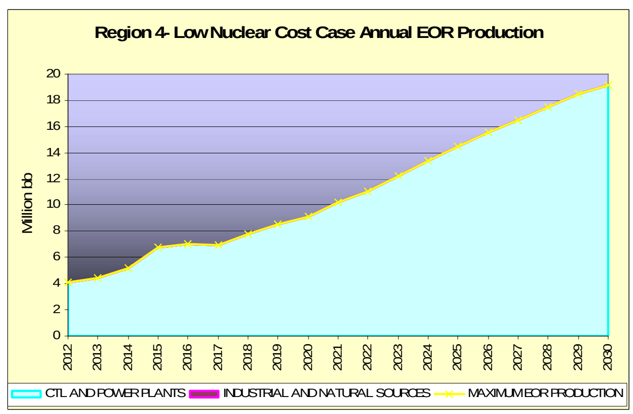


FIGURE 7-56. ANNUAL EOR PRODUCTION – REGION 4



REGION 4- CO2MM TEST CASE II

FIGURE 7-57. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 4

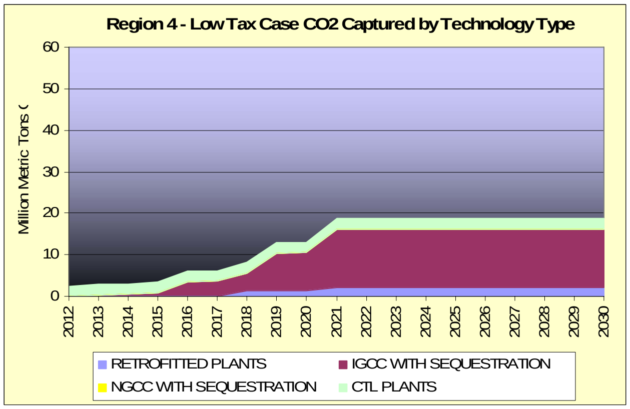


FIGURE 7-59. TRANSFER PRICE – REGION 4

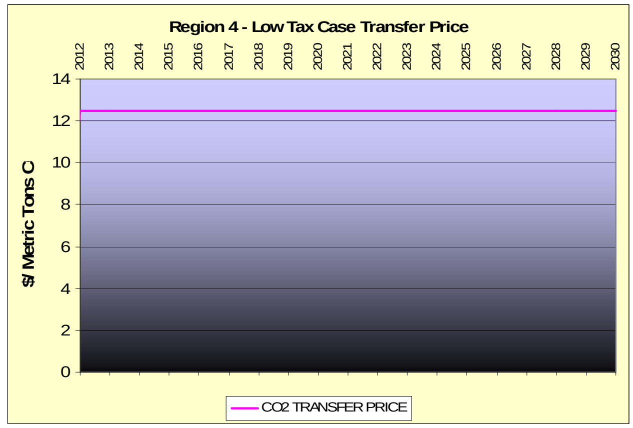


FIGURE 7-58. CO_2 SUPPLY AND DEMAND – REGION 4

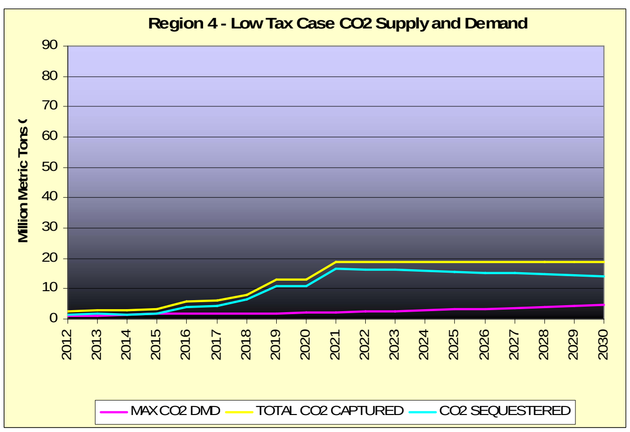
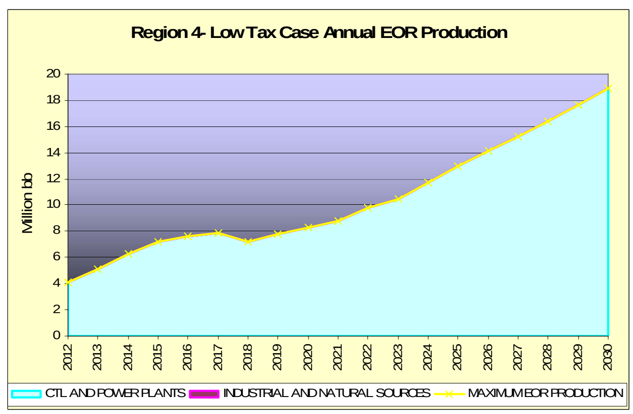


FIGURE 7-60. ANNUAL EOR PRODUCTION – REGION 4



REGION 5 - CO2MM TEST CASE

FIGURE 7-61. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 5

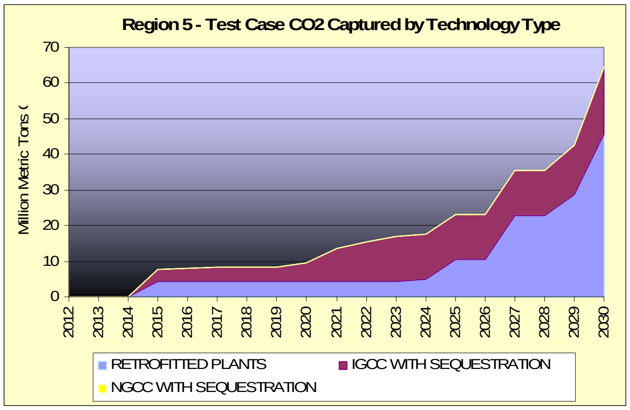


FIGURE 7-63. TRANSFER PRICE – REGION 5

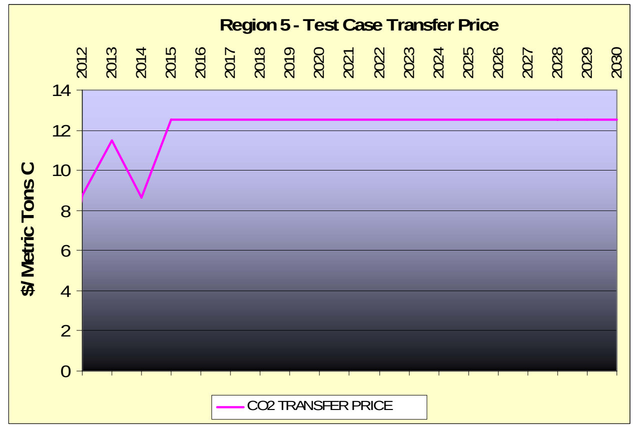


FIGURE 7-62. CO_2 SUPPLY AND DEMAND – REGION 5

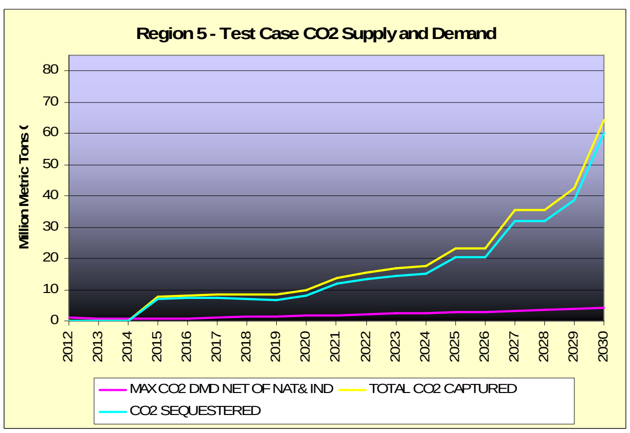
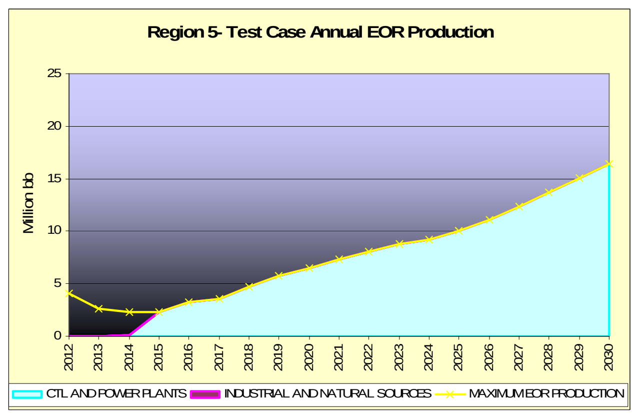


FIGURE 7-64. ANNUAL EOR PRODUCTION – REGION 5



REGION 5- CO2MM TEST CASE I

FIGURE 7-65. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 5

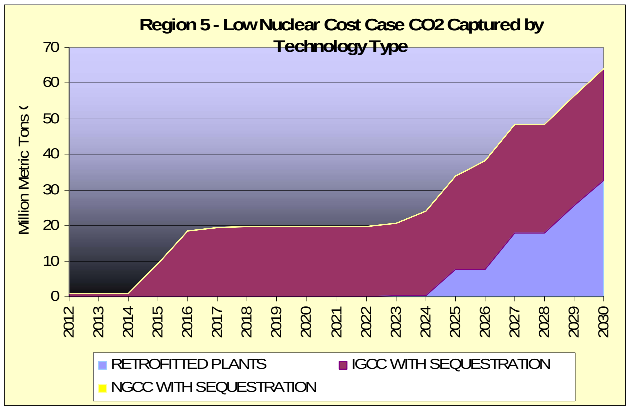


FIGURE 7-67. TRANSFER PRICE – REGION 5

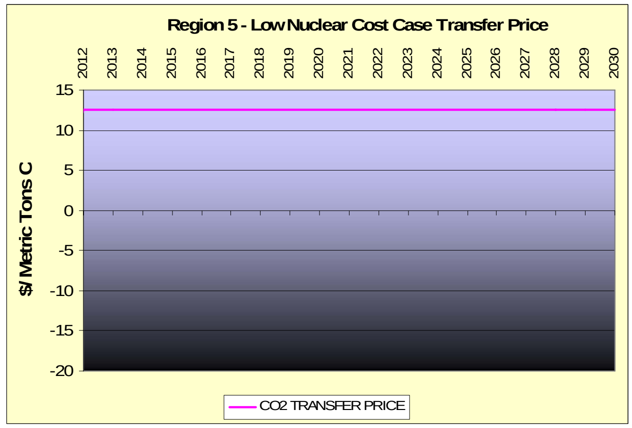


FIGURE 7-66. CO2 SUPPLY AND DEMAND – REGION 5

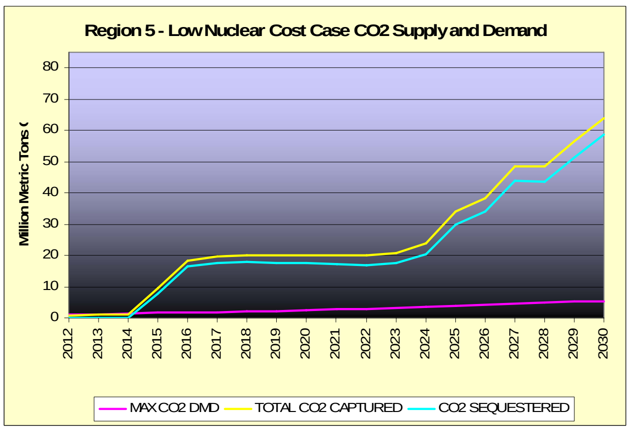
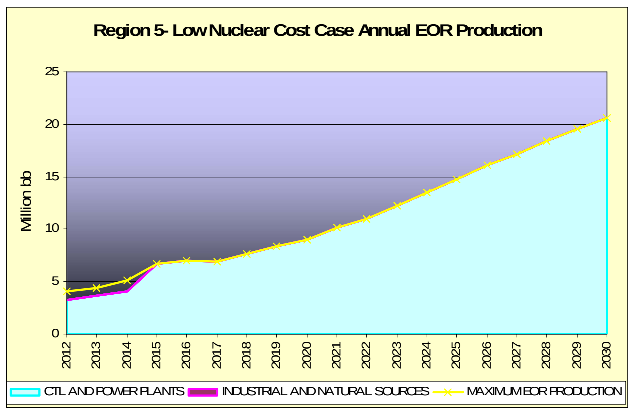


FIGURE 7-68. ANNUAL EOR PRODUCTION – REGION 5



REGION 5- CO2MM TEST CASE II

FIGURE 7-69. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 5

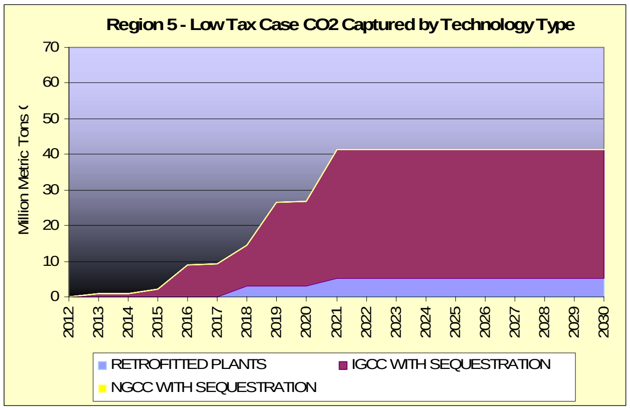


FIGURE 7-70. CO_2 SUPPLY AND DEMAND – REGION 5

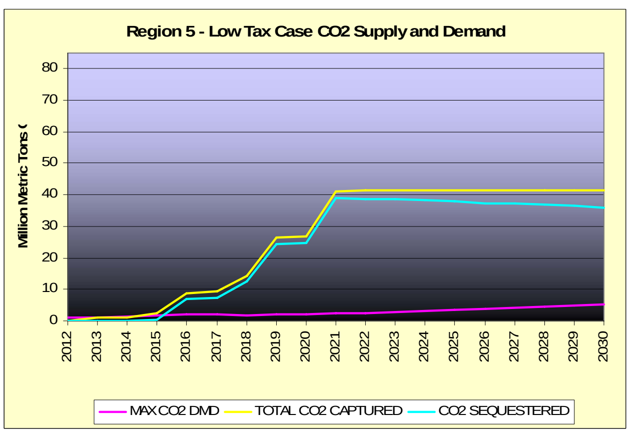


FIGURE 7-71. TRANSFER PRICE – REGION 5

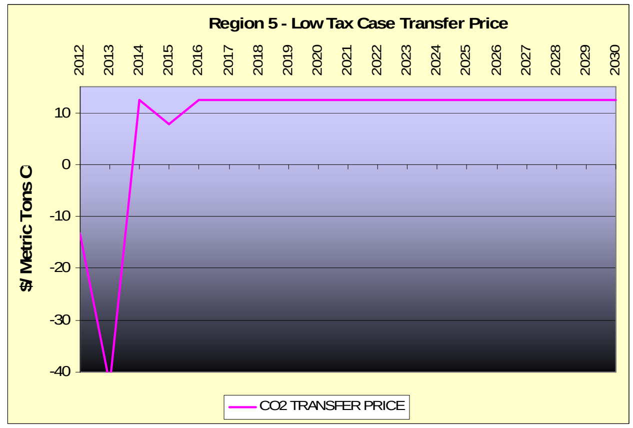
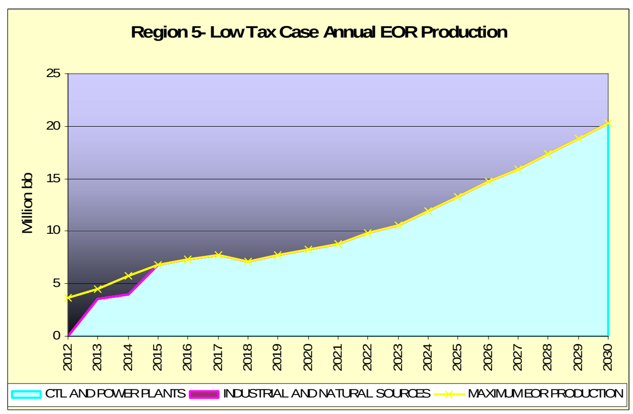


FIGURE 7-72. ANNUAL EOR PRODUCTION – REGION 5



REGION 8- CO2MM TEST CASE

FIGURE 7-73. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 8

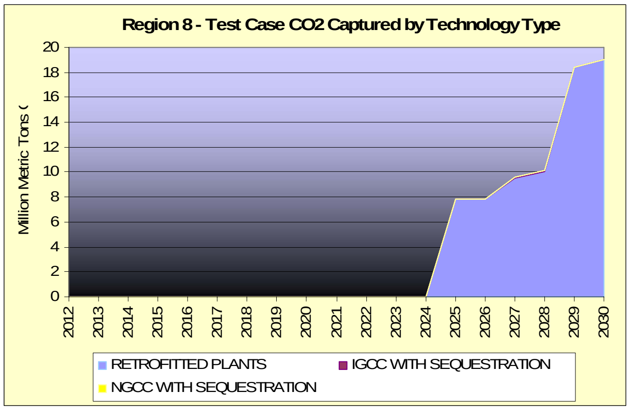


FIGURE 7-75. TRANSFER PRICE – REGION 8

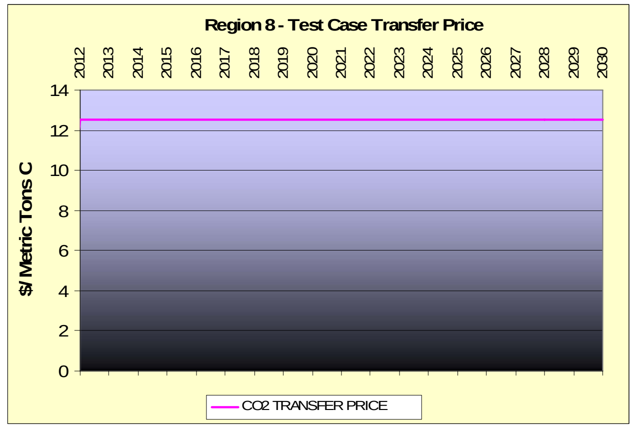


FIGURE 7-74. CO_2 SUPPLY AND DEMAND – REGION 8

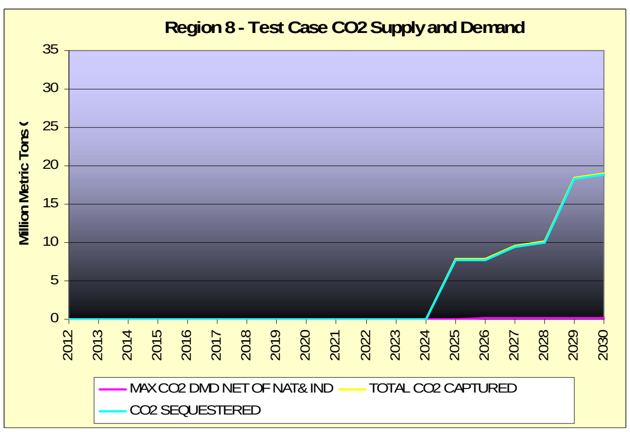
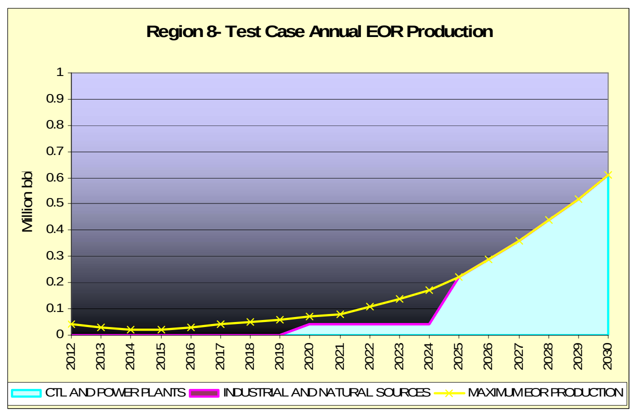


FIGURE 7-76. ANNUAL EOR PRODUCTION – REGION 8



REGION 8- CO2MM TEST CASE I

FIGURE 7-77. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 8

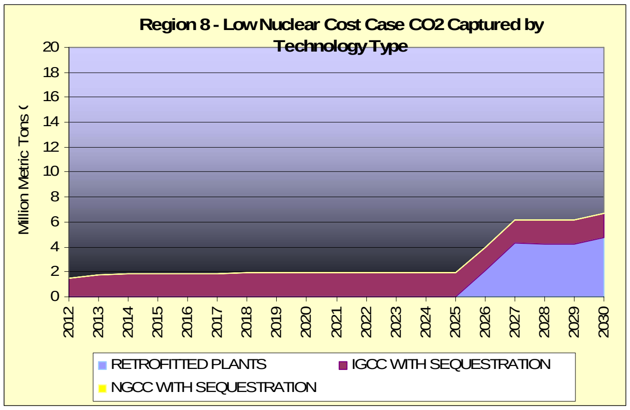


FIGURE 7-79. TRANSFER PRICE – REGION 8

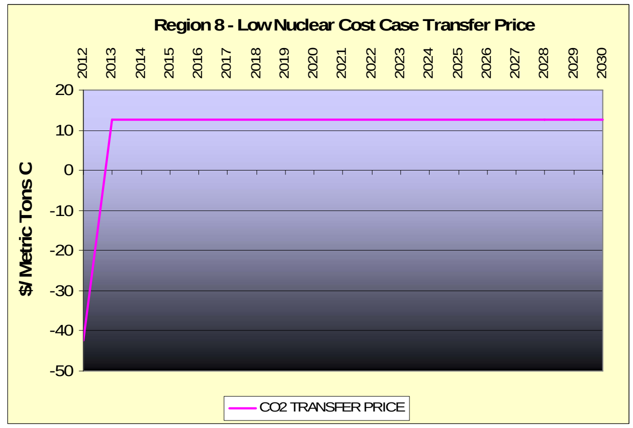


FIGURE 7-78. CO_2 SUPPLY AND DEMAND – REGION 8

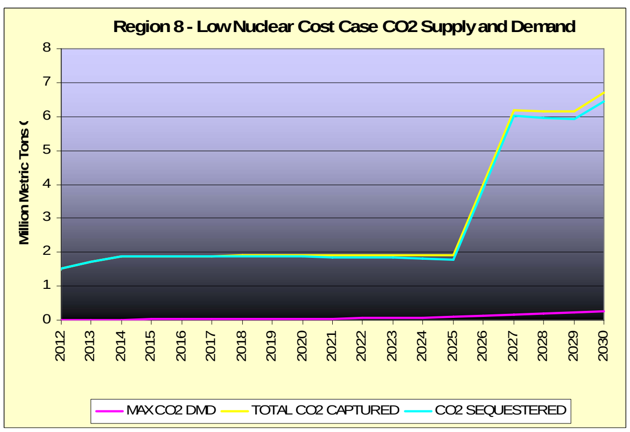
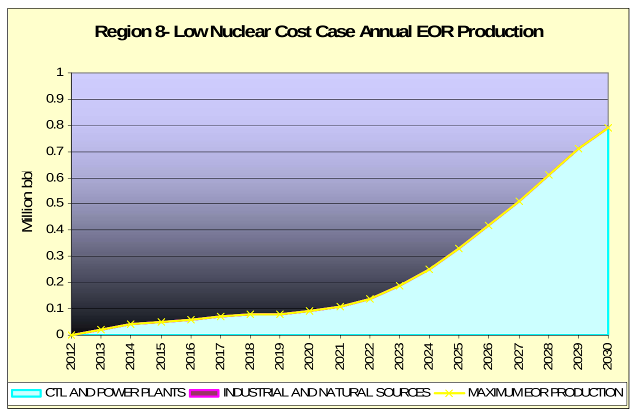


FIGURE 7-80. ANNUAL EOR PRODUCTION – REGION 8



REGION 8- CO2MM TEST CASE II

FIGURE 7-81. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 8

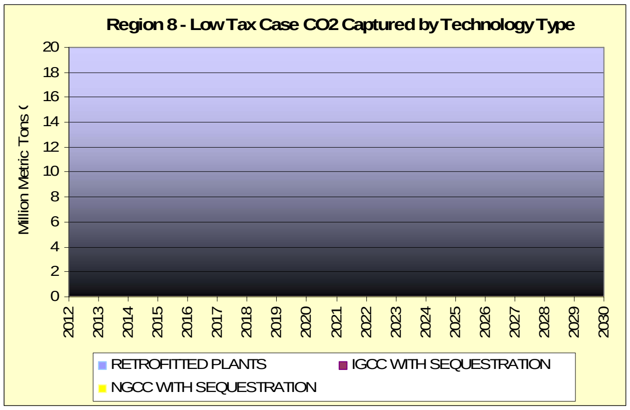


FIGURE 7-83. TRANSFER PRICE – REGION 8

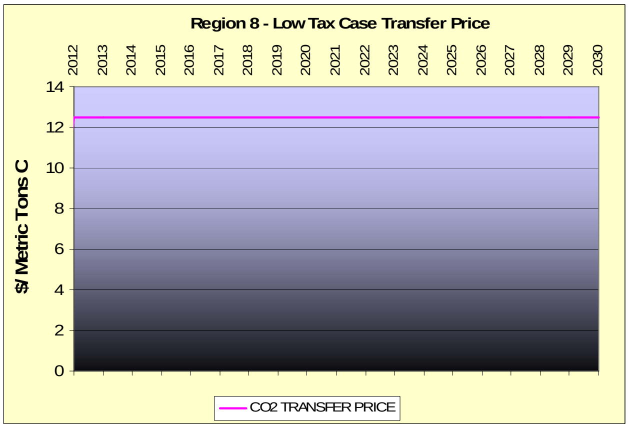


FIGURE 7-82. CO_2 SUPPLY AND DEMAND – REGION 8

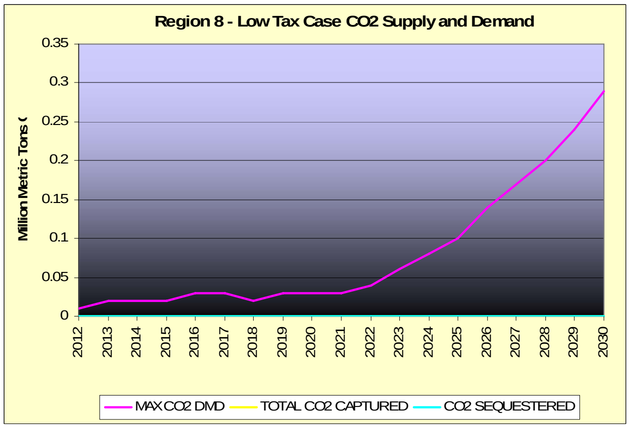
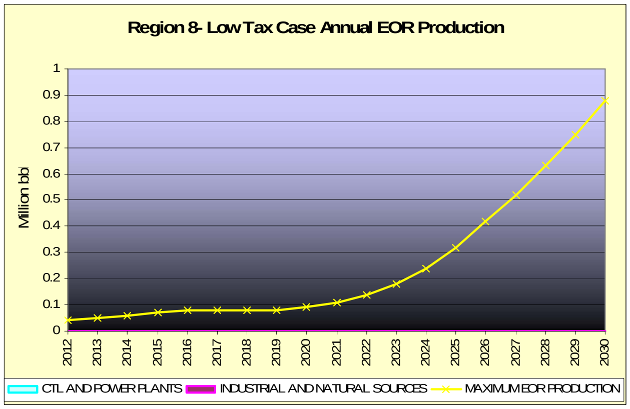


FIGURE 7-84. ANNUAL EOR PRODUCTION – REGION 8



REGION 9- CO2MM TEST CASE

FIGURE 7-85. CO2 CAPTURED BY TECHNOLOGY TYPE – REGION 9

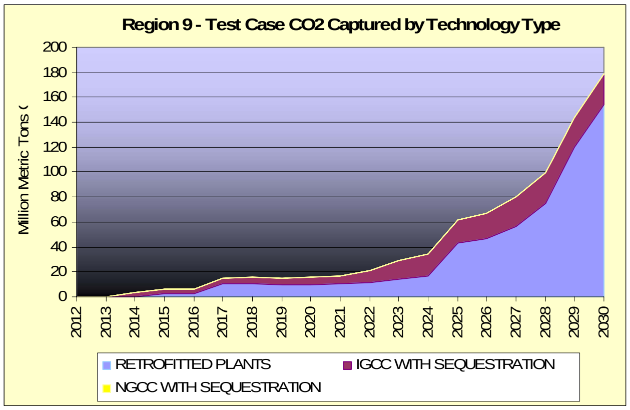


FIGURE 7-86. CO_2 SUPPLY AND DEMAND – REGION 9

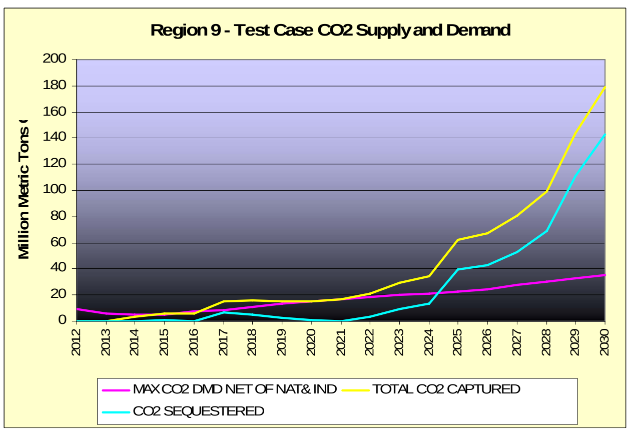


FIGURE 7-87. TRANSFER PRICE – REGION 9

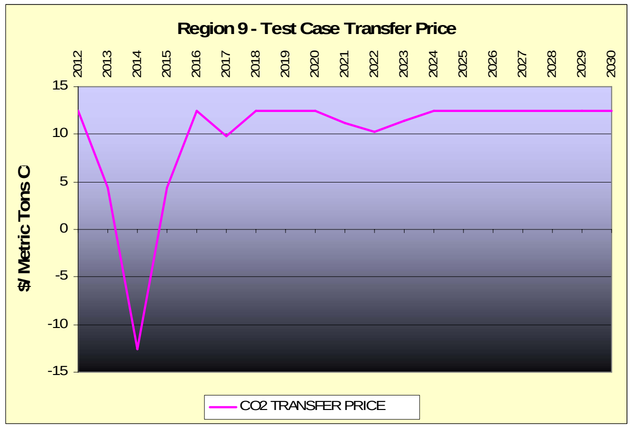
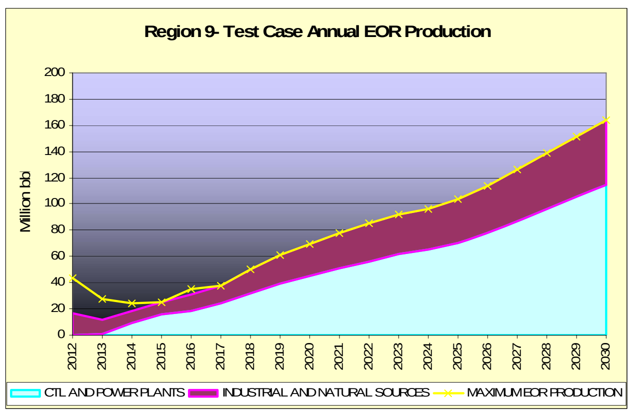


FIGURE 7-88. ANNUAL EOR PRODUCTION – REGION 9



REGION 9- CO2MM TEST CASE I

FIGURE 7-89. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 9

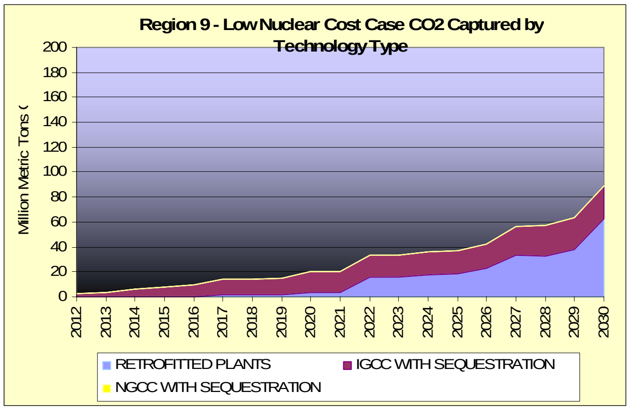


FIGURE 7-90. CO_2 SUPPLY AND DEMAND – REGION 9

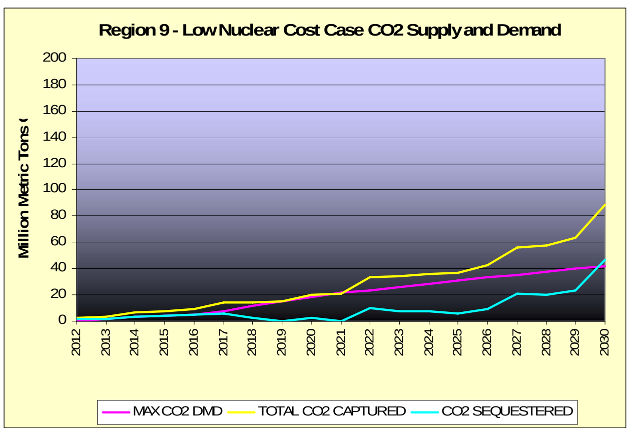


FIGURE 7-91. TRANSFER PRICE – REGION 9

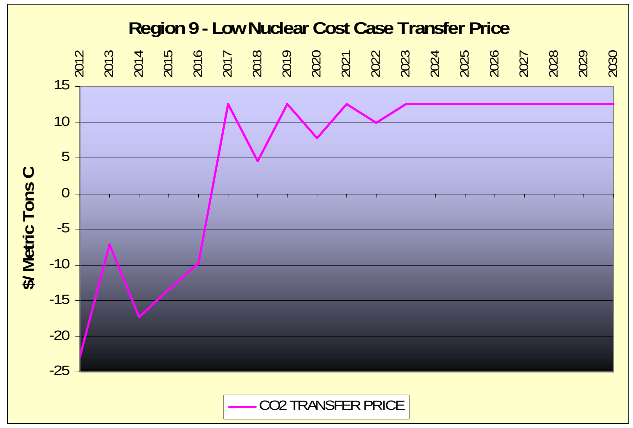
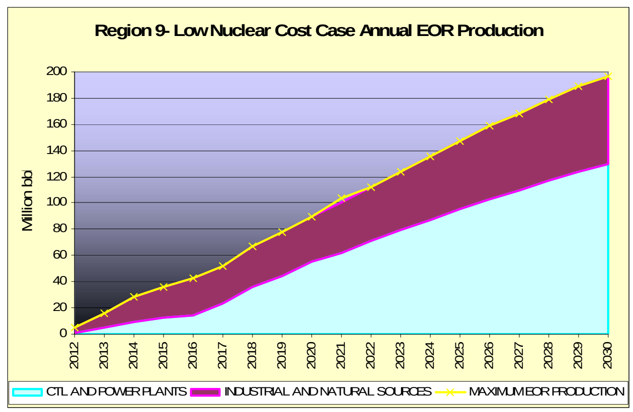


FIGURE 7-92. ANNUAL EOR PRODUCTION – REGION 9



REGION 9- CO2MM TEST CASE II

FIGURE 7-93. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 9

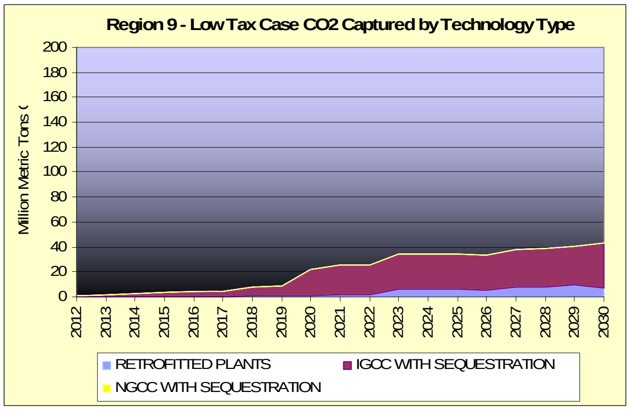


FIGURE 7-95. TRANSFER PRICE – REGION 9

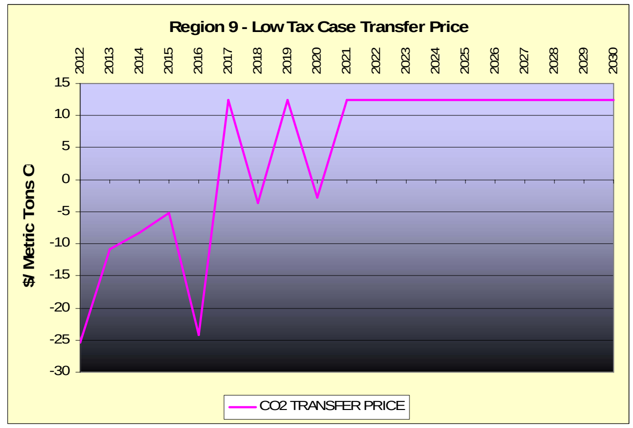


FIGURE 7-94. CO_2 SUPPLY AND DEMAND – REGION 9

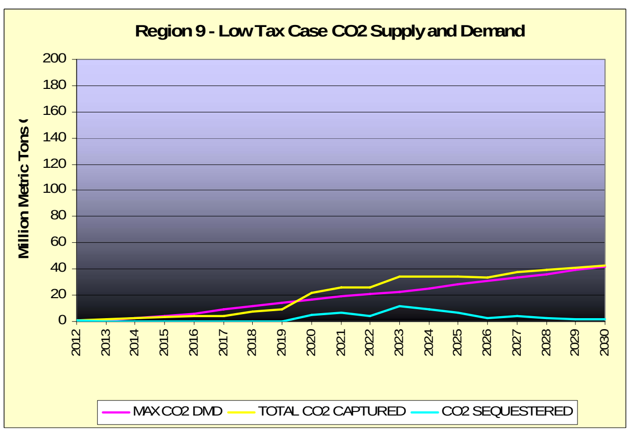
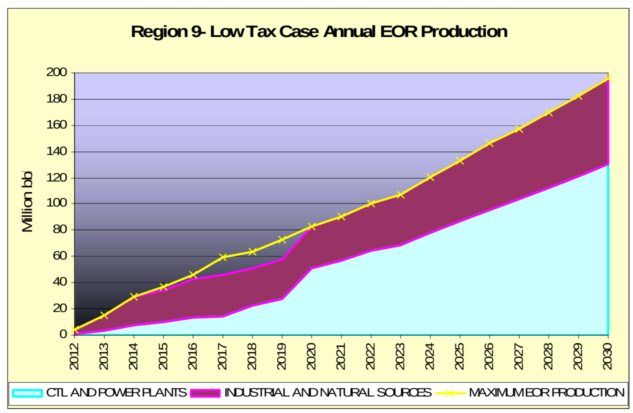


FIGURE 7-96. ANNUAL EOR PRODUCTION – REGION 9



REGION 10- CO2MM TEST CASE

FIGURE 7-97. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 10

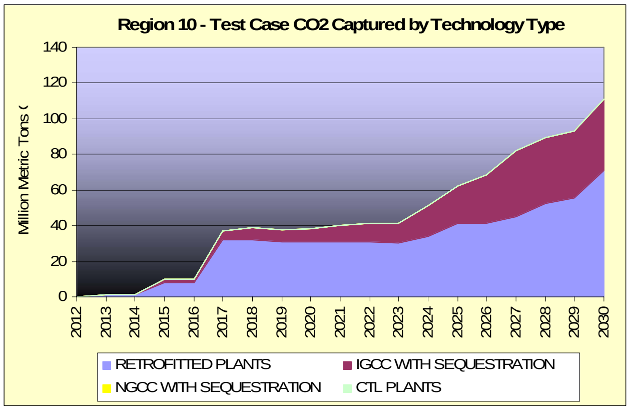


FIGURE 7-99. TRANSFER PRICE – REGION 10

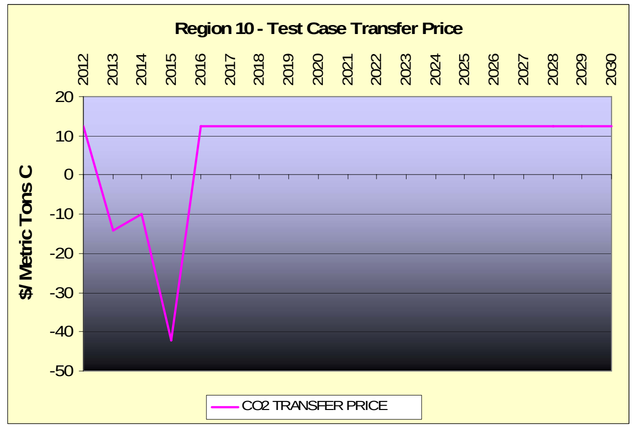


FIGURE 7-98. CO_2 SUPPLY AND DEMAND – REGION 10

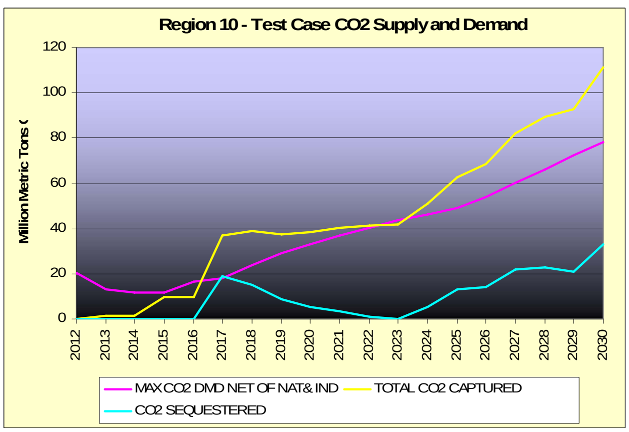
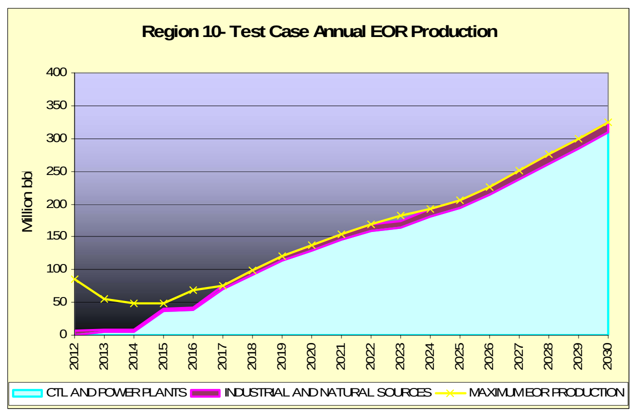


FIGURE 7-100. ANNUAL EOR PRODUCTION – REGION 10



REGION 10- CO2MM TEST CASE I

FIGURE 7-101. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 10

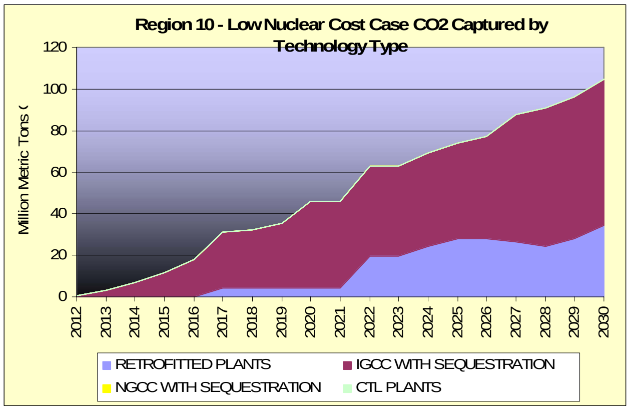


FIGURE 7-103. TRANSFER PRICE – REGION 10

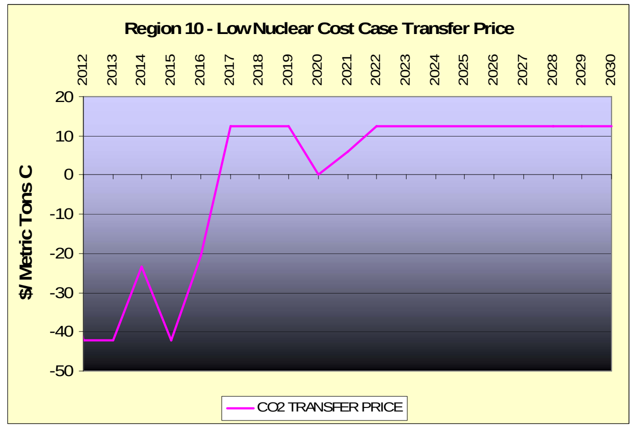


FIGURE 7-102. CO_2 SUPPLY AND DEMAND – REGION 10

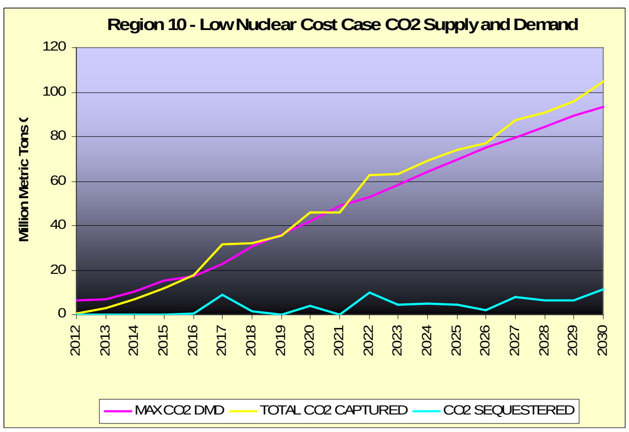
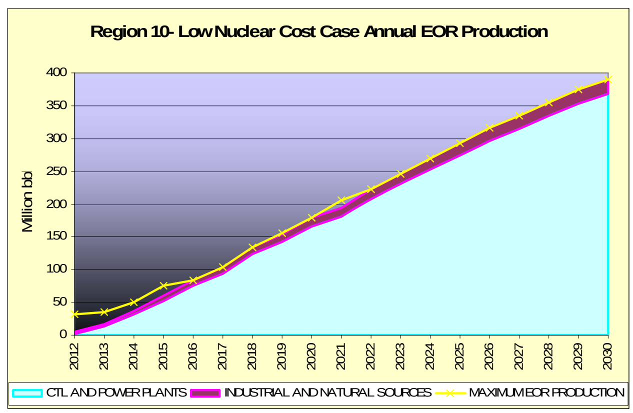


FIGURE 7-104. ANNUAL EOR PRODUCTION – REGION 10



REGION 10- CO2MM TEST CASE II

FIGURE 7-105. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 10

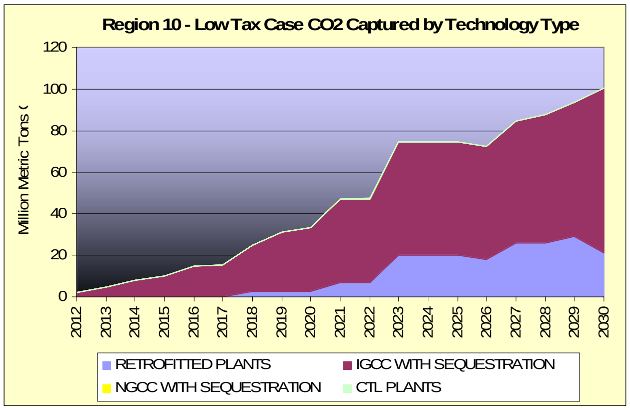


FIGURE 7-106. CO_2 SUPPLY AND DEMAND – REGION 10

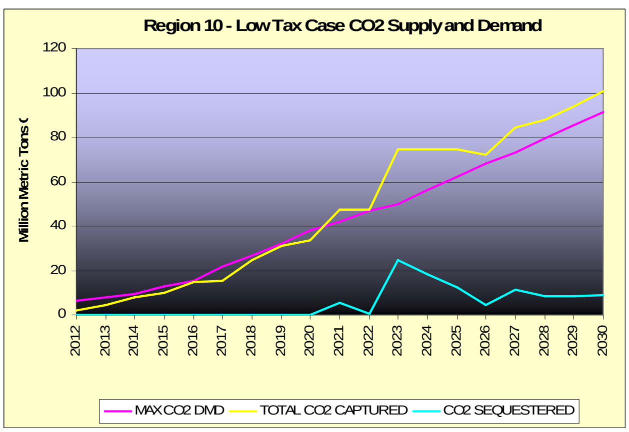


FIGURE 7-107. TRANSFER PRICE – REGION 10

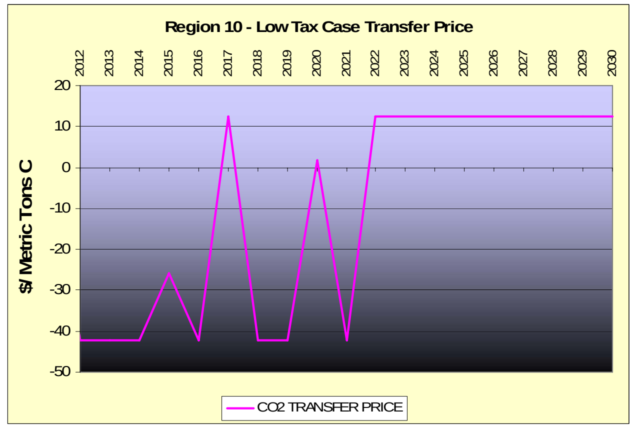
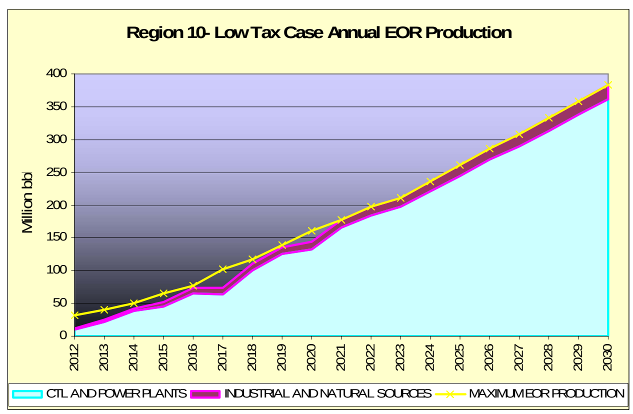


FIGURE 7-108. ANNUAL EOR PRODUCTION – REGION 10



REGION 11. - CO2MM TEST CASE

FIGURE 7-109. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 11

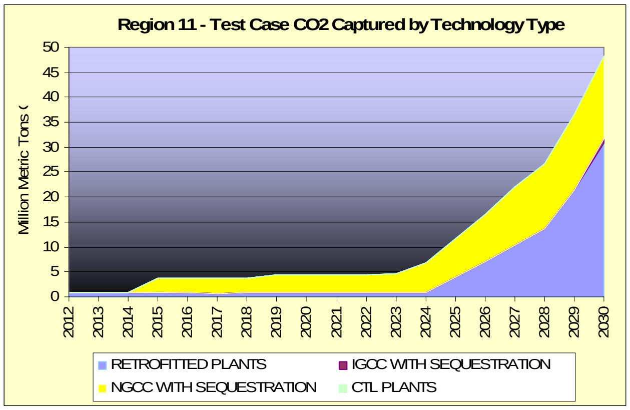


FIGURE 7-111. TRANSFER PRICE – REGION 11

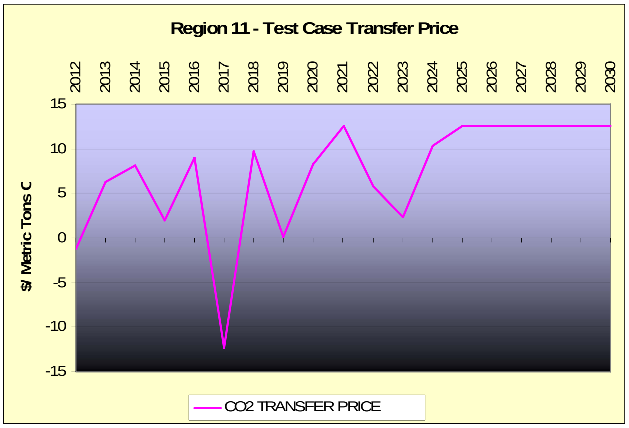


FIGURE 7-110. CO_2 SUPPLY AND DEMAND – REGION 11

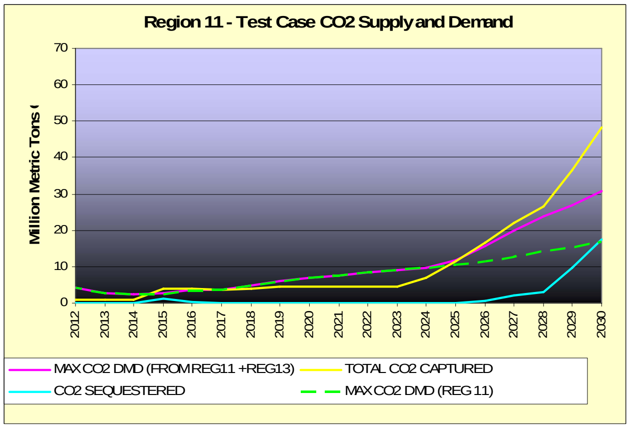
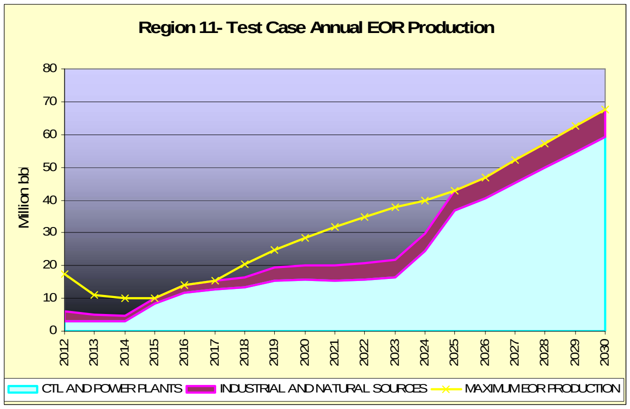


FIGURE 7-112. ANNUAL EOR PRODUCTION – REGION 11



REGION 11- CO2MM TEST CASE I

FIGURE 7-113. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 11

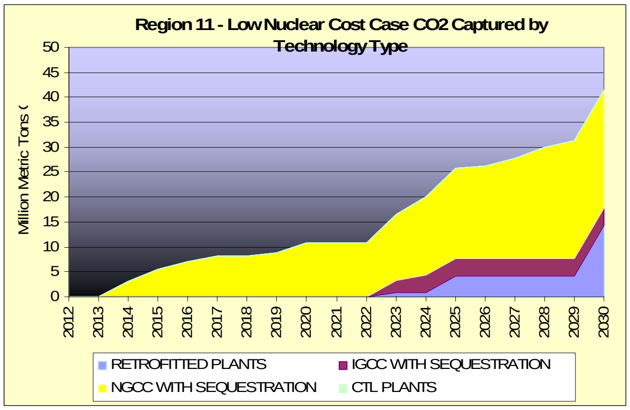


FIGURE 7-115. TRANSFER PRICE – REGION 11

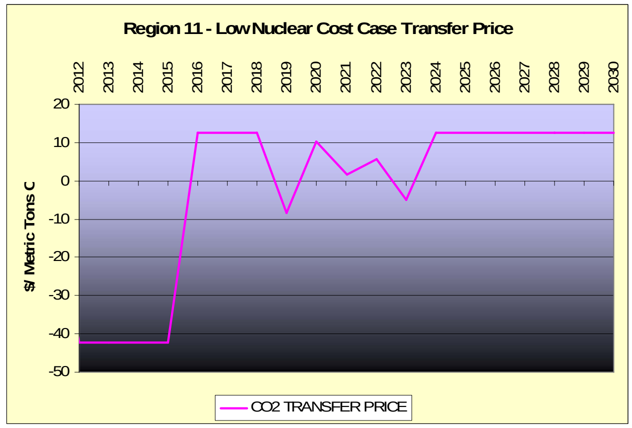


FIGURE 7-114. CO_2 SUPPLY AND DEMAND – REGION 11

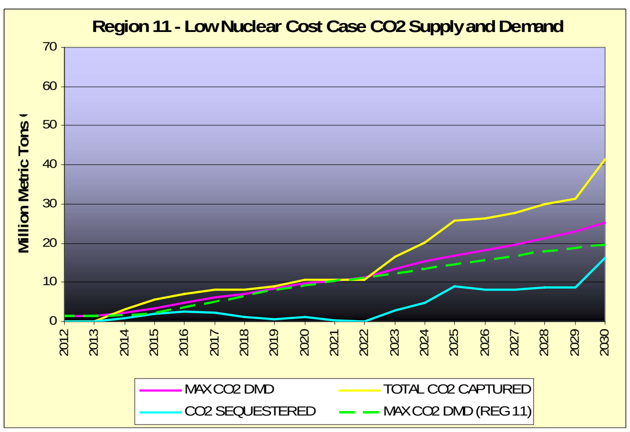
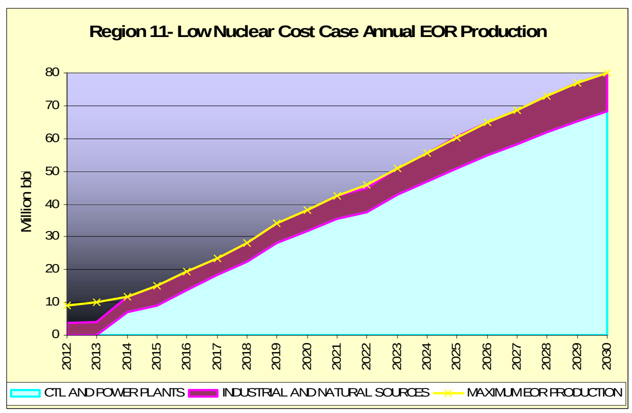


FIGURE 7-116. ANNUAL EOR PRODUCTION – REGION 11



REGION 11- CO2MM TEST CASE II

FIGURE 7-117. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 11

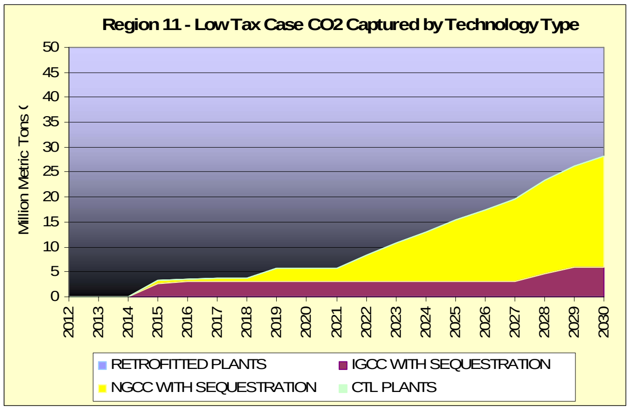


FIGURE 7-119. TRANSFER PRICE – REGION 11

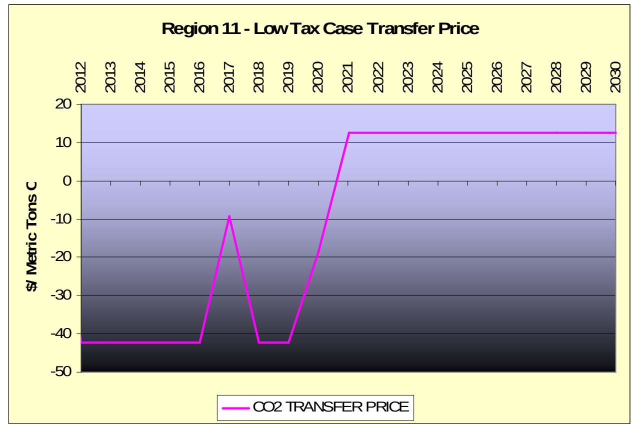


FIGURE 7-118. CO_2 SUPPLY AND DEMAND – REGION 11

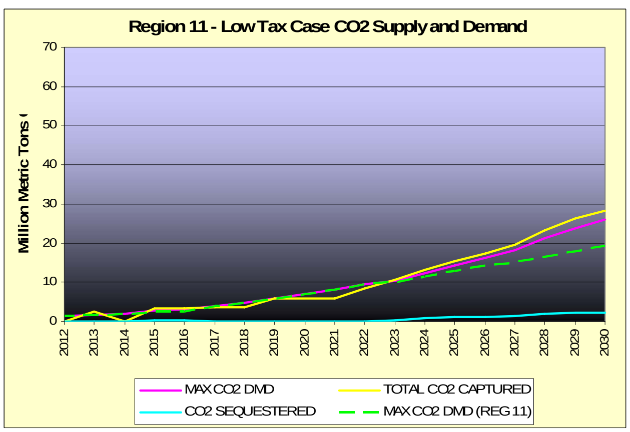
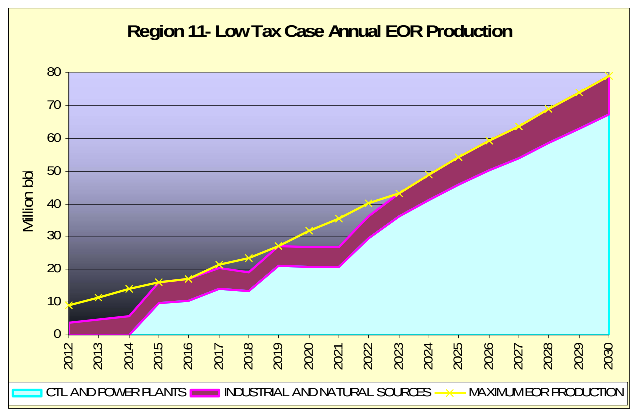


FIGURE 7-120. ANNUAL EOR PRODUCTION – REGION 11



REGION 12- CO2MM TEST CASE

FIGURE 7-121. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 12

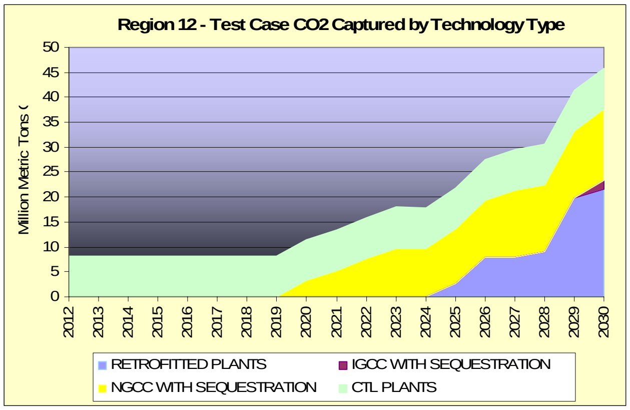


FIGURE 7-123. TRANSFER PRICE – REGION 12

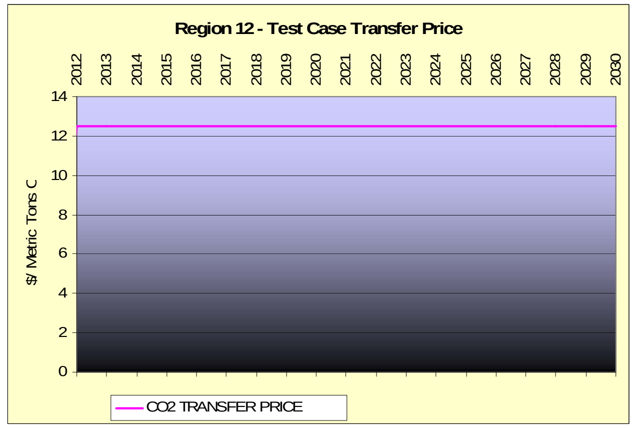


FIGURE 7-122. CO_2 SUPPLY AND DEMAND – REGION 12

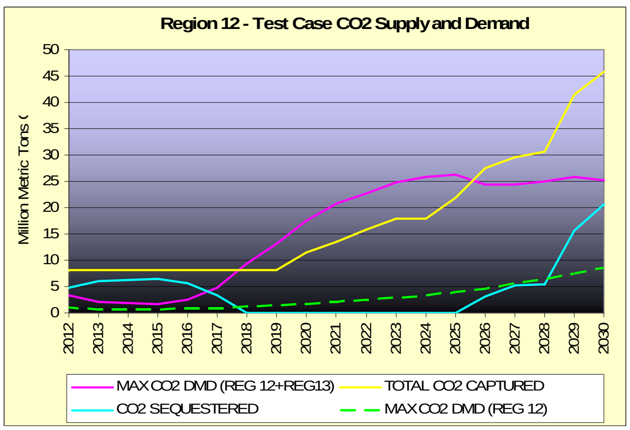
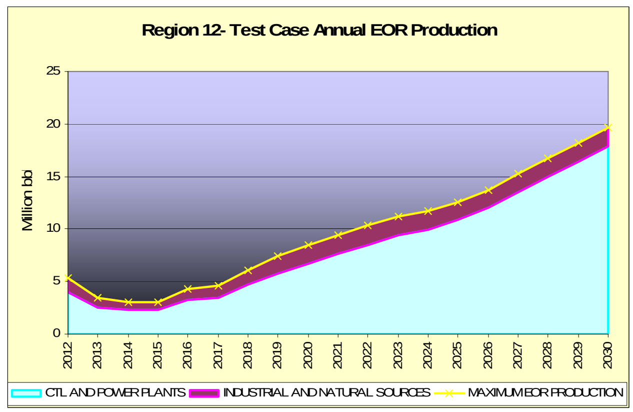


FIGURE 7-124. ANNUAL EOR PRODUCTION – REGION 12



REGION 12- CO2MM TEST CASE I

FIGURE 7-125. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 12

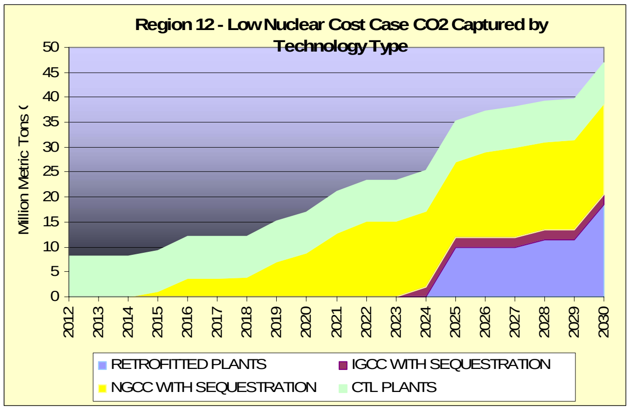


FIGURE 7-127. TRANSFER PRICE – REGION 12

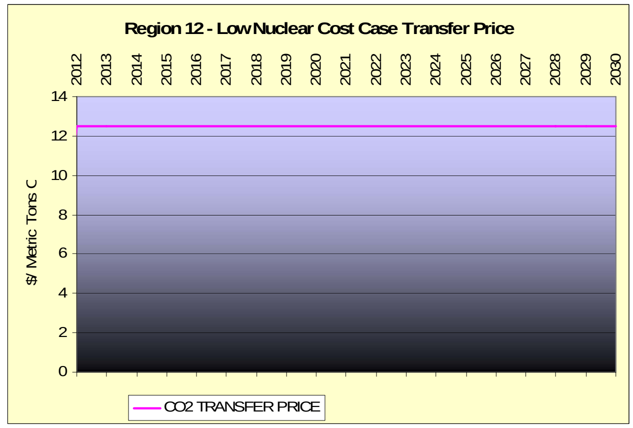


FIGURE 7-126. CO_2 SUPPLY AND DEMAND – REGION 12

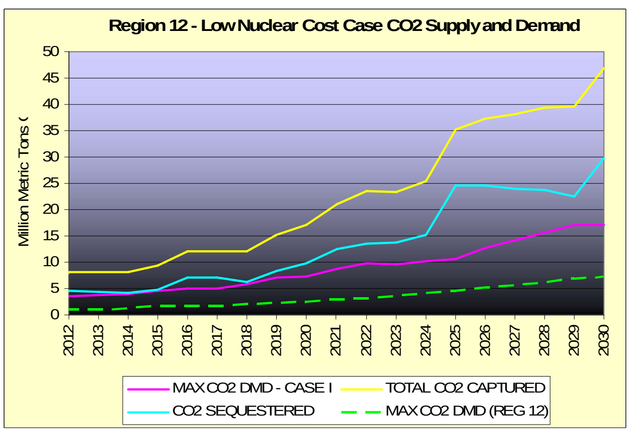
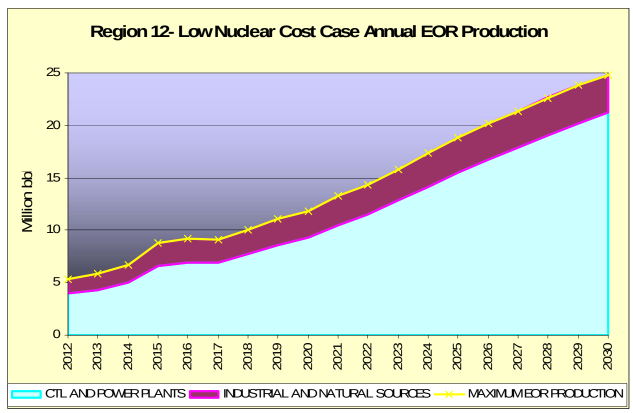


FIGURE 7-128. ANNUAL EOR PRODUCTION – REGION 12



<u>REGION 12</u>- CO2MM TEST CASE II

FIGURE 7-129. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 12

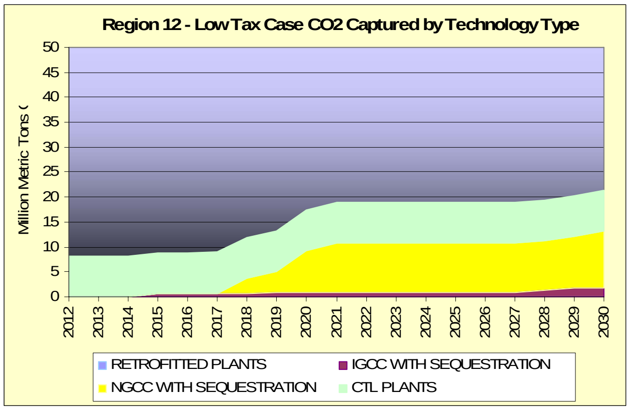


FIGURE 7-131. TRANSFER PRICE – REGION 12

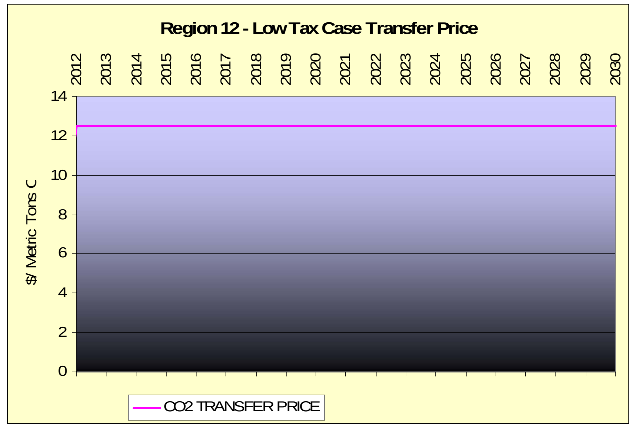


FIGURE 7-130. CO2 SUPPLY AND DEMAND – REGION 12

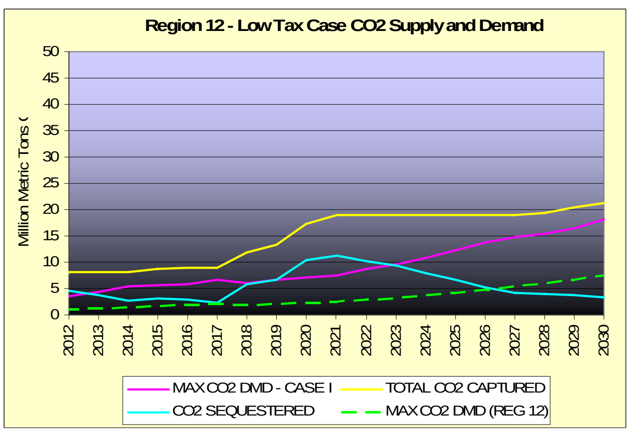
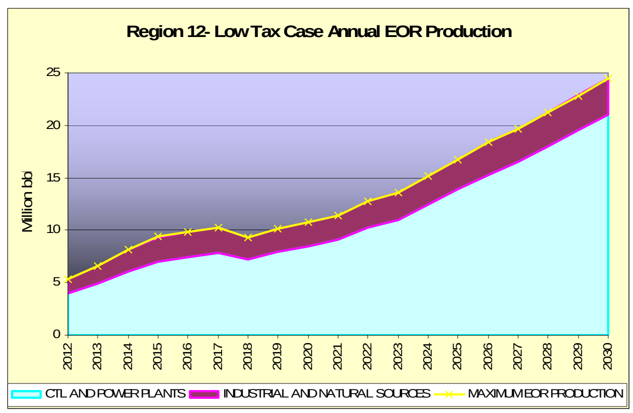


FIGURE 7-132. ANNUAL EOR PRODUCTION – REGION 12



REGION 13- CO2MM TEST CASE

FIGURE 7-133. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 13

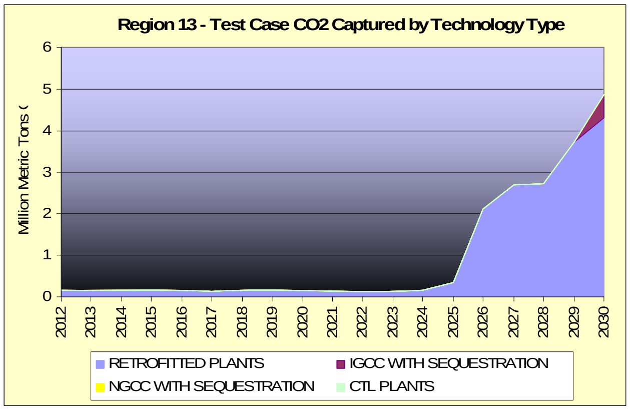


FIGURE 7-134. CO_2 SUPPLY AND DEMAND – REGION 13

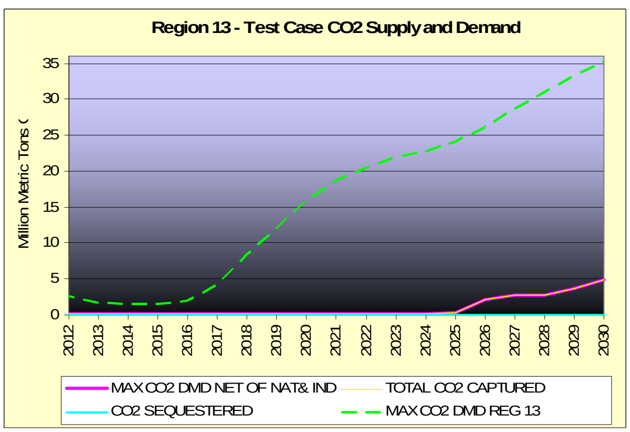


FIGURE 7-135. TRANSFER PRICE – REGION 13

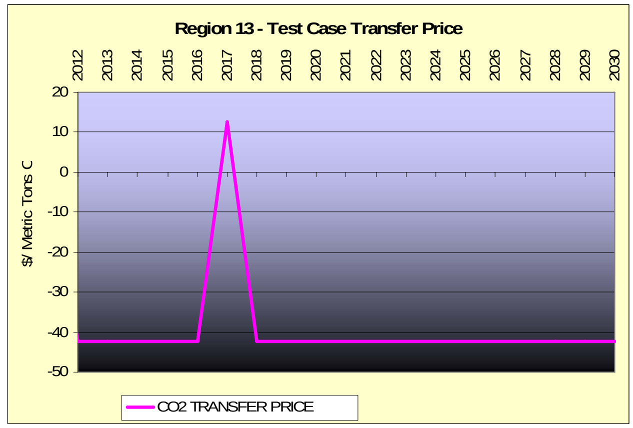
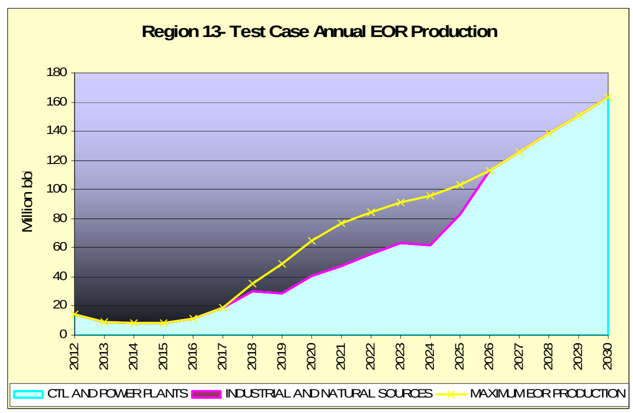


FIGURE 7-136. ANNUAL EOR PRODUCTION – REGION 13



REGION 13- CO2MM TEST CASE I

FIGURE 7-137. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 13

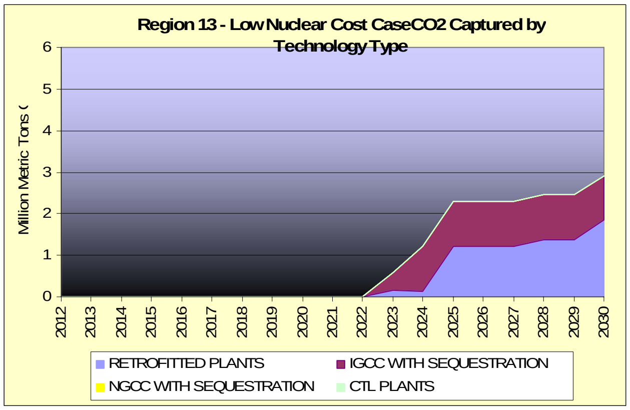


FIGURE 7-138. CO_2 SUPPLY AND DEMAND – REGION 13

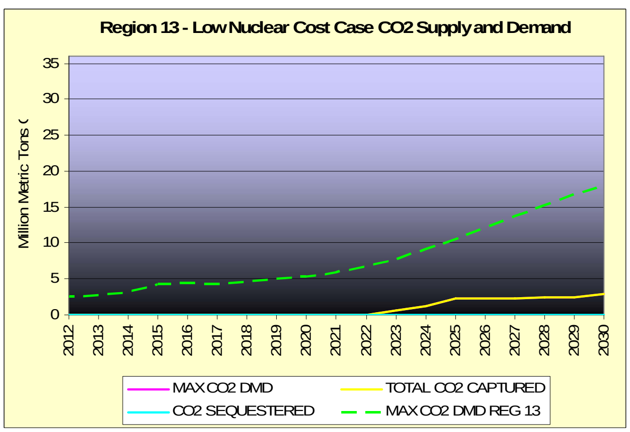


FIGURE 7-139. TRANSFER PRICE – REGION 13

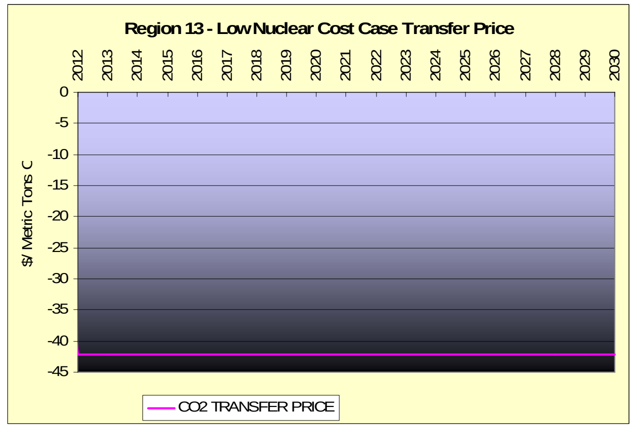
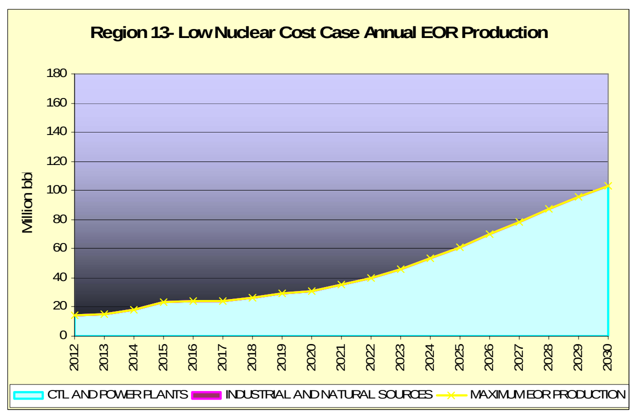


FIGURE 7-140. ANNUAL EOR PRODUCTION – REGION 13



REGION 13- CO2MM TEST CASE II

FIGURE 7-141. CO_2 CAPTURED BY TECHNOLOGY TYPE – REGION 13

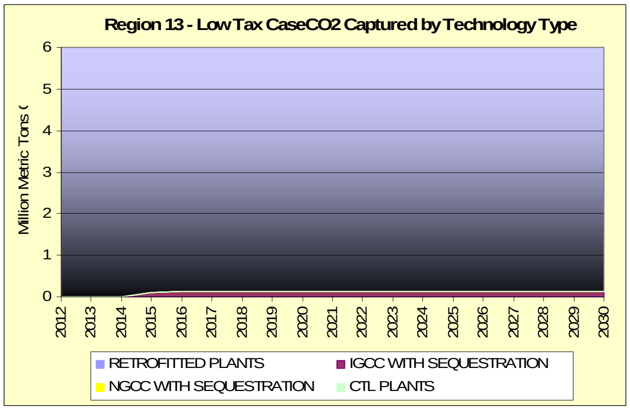


FIGURE 7-143. TRANSFER PRICE – REGION 13

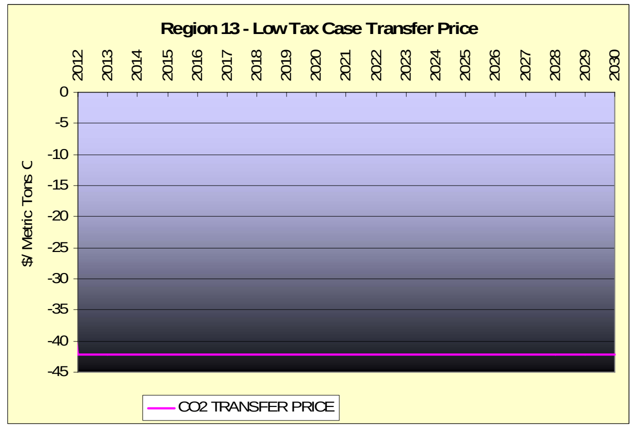


FIGURE 7-142. CO_2 SUPPLY AND DEMAND – REGION 13

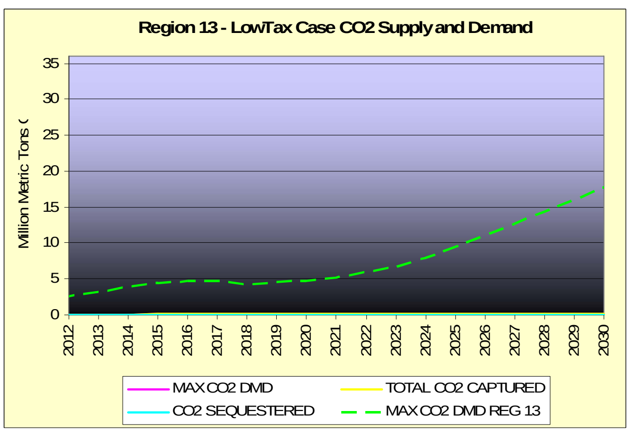
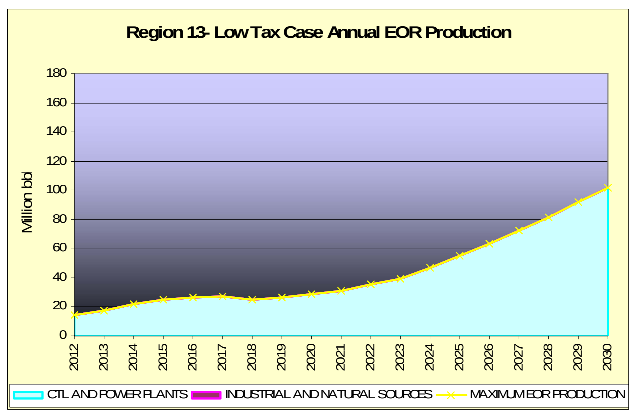


FIGURE 7-144. ANNUAL EOR PRODUCTION – REGION 13



INTERREGIONAL TRANSFERS TO REGION 13

FIGURE 7-145. CO2MM TEST CASE

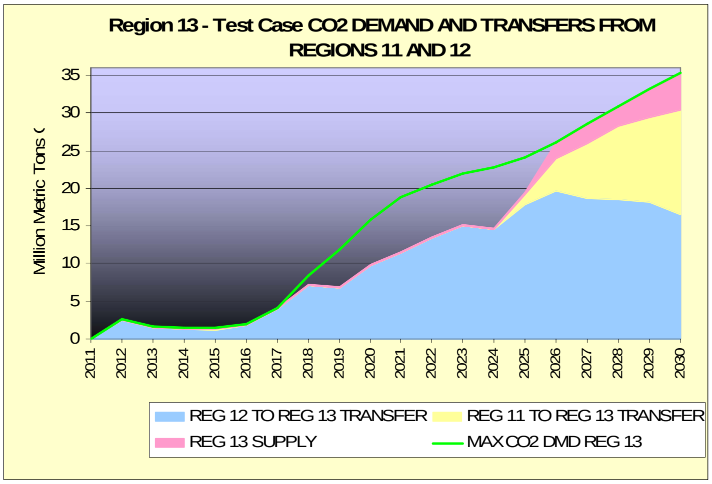


FIGURE 7-146. CO2MM TEST CASE I

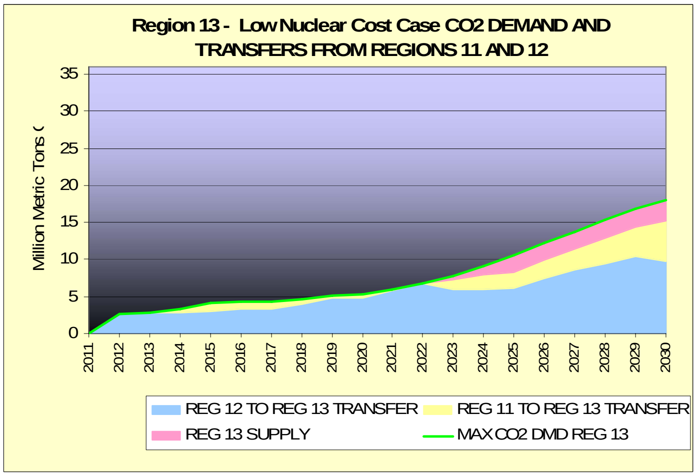


FIGURE 7-147. CO2MM TEST CASE II