

Modelling Greenhouse Gases in a General Equilibrium Model

by

Wing Chi Leung

Submitted to the Department of Electrical Engineering and
Computer Science

in partial fulfillment of the requirements for the degrees of

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Author
Department of Electrical Engineering and Computer Science
Dec 18, 1996

Certified by
Richard S. Eckaus
Professor of Economics
Thesis Supervisor

Accepted by
Frederic R. Morgenthaler
Chairman, Department Committee on Graduate Theses

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Abstract

Greenhouse effects, partially due to the increase in the abundance of atmospheric carbon dioxide (CO_2) released by fossil fuel combustion, has been a global concern. This research explores the feasibility of CO_2 reduction through various capture and disposal technologies. The new technologies are incorporated into an existing framework, the EPPA model, which is a general equilibrium model spanning from 1985 to 2100. Analysis is done to investigate various representations and cost effectiveness of the new technologies.

Thesis Supervisor: Richard S. Eckaus

Title: Professor of Economics

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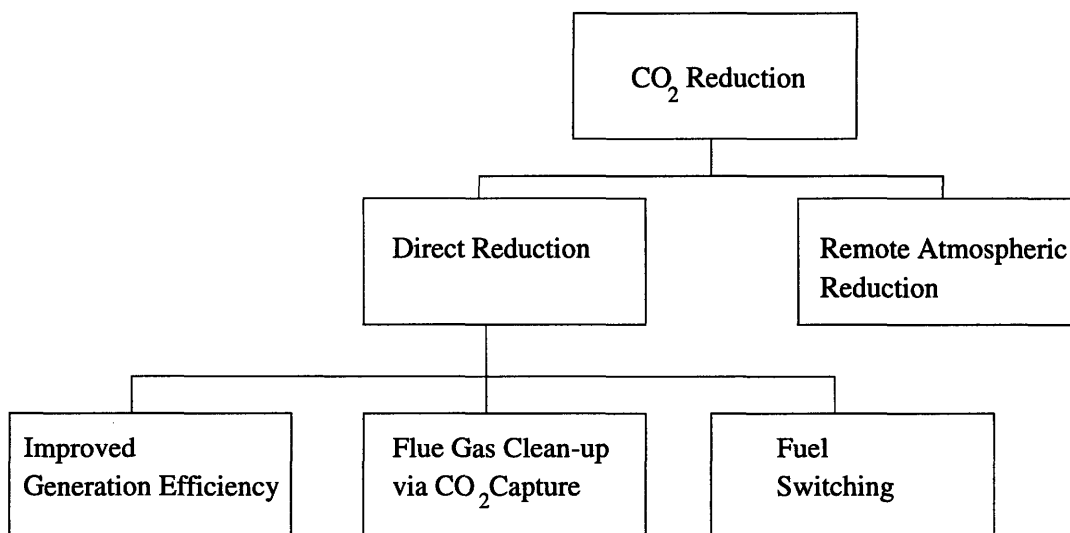
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Chapter 1

Introduction

In light of greenhouse effects and potential global warming, researchers have investigated many ways of reducing greenhouse gas emissions (Figure 1-1). Methods like complete fuel switching to nuclear or renewable sources seem unlikely in the near future. This research focuses on greenhouse gas reduction through capture and disposal of CO_2 from fossil fuel power plants. Direct capture of CO_2 from the atmosphere, fuel switching and conservation are beyond our scope of study.

Figure 1-1: Ways of Greenhouse Gas Reduction



This research investigates the feasibility of various capture and disposal tech-

nologies, and compares their cost effectiveness with respect to other CO_2 reduction schemes. The capacity and flexibility of capture and disposal are explored, in situations where constraints on CO_2 emission are imposed.

Chapter 2 presents some background and the research approach for this study. Chapter 3 introduces the currently available CO_2 capture and disposal technologies. Chapter 4 describes in details the EPPA Model. Chapter 5 explains the technical background of this study and suggests several alternative implementations. Chapter 6 provides details on the actual implementation and coding. Lastly, Chapter 7 presents the results and analysis of the model, and concludes the study.

Chapter 2

Background

Since Marchetti (1977) proposed the idea of capturing CO_2 and disposing it into deep ocean, many researchers have examined a spectrum of possibilities for CO_2 capture and disposal technologies applied to electric power generation plants.

U.S. electric power plants¹ alone account for 7% of the world's CO_2 emissions. Direct capture technologies inevitably incur costs for electric power plants. Studies have found that, in the case of retrofitting current coal-fired power plants, cost of electricity can go up by a factor of 2 or more, whereas for the case of advanced, high efficiency power plants that are designed integratively with capture and disposal technologies, a 50% or more increase is possible.

2.1 Research Approach

Using the Emissions Prediction and Policy Analysis model (the EPPA model in Chapter 4) as a foundation, the following researches are performed:

2.1.1 Alternative Implementations

Alternative representations of capture and disposal technologies are presented, and incorporated into the EPPA model. Results from various representations are compared

¹approximately 1.7 Gt CO_2 , over one-third of the U.S. emissions

and analyzed.

2.1.2 Cost Effectiveness

The boundary cost-effectiveness, at which CO_2 capture and disposal technology will come into the market, is investigated under the following scenarios:

- when backstop technologies² are not available, and there is an emission constraint policy but no trading of permits³.
- when backstop technologies are available, and there is an emission constraint policy but no trading of permits.
- when backstop technologies are available, and there is no emission constraint policy.

The boundary cost-effectiveness gives researchers insights on a target cost, at which CO_2 capture and disposal will become practical.

²details in chapter 4

³permits are CO_2 emission quota allocated to regions under an emission constraint policy

Chapter 3

CO_2 Capture and Disposal Technologies

3.1 CO_2 Capture

Fossil fuel power plants produce flue gas streams of carbon dioxide, nitrogen, oxygen, water and trace impurities. The CO_2 can be captured through chemical stripping, cryogenic fractionation, membrane separation, and molecular sieve adsorption.

Since power plants have long operating lives, existing plants can be retrofitted to incorporate the CO_2 capture technologies. On the other hand, new power plants are expected to have higher energy efficiencies and allow easier integration of CO_2 capture technologies. Therefore, new power plants with capture facilities are less costly to run than existing power plants that are retrofitted.

Table 3.1 summarizes the costs and effectiveness of various CO_2 capture technologies. These estimates are embedded with uncertainties, because the technologies are not commercialized on a large scale yet.

3.1.1 Chemical Stripping

Chemical stripping involves reversible reactions between CO_2 and another solvent material, e.g. monoethanol amine (MEA), to produce liquid or solid species, that

Table 3.1: Various CO_2 Capture Technologies

<i>Process</i>	<i>Energy Penalty in %</i>	<i>Capture Cost in \$/ton of CO_2</i>	<i>Net CO_2 Emission Reduction in %</i>
Base Case – No CO_2 Capture	0	0	0
MEA Stripping	35	37	84.6
Cryogenic Fractionation	75	24	60
Membrane Separation	63	Unknown	46
Molecular Sieve Adsorption	80	44	50

Sources: [11, Vol 1, page 29]

liberate CO_2 and the solvent upon heating.

Due to the low capacity (in terms of CO_2 absorbed per unit mass), a huge amount of liquid has to be heated in order to release a small amount of CO_2 , and energy is required for pumping the solvent and for compressing the flue gas.

Future energy savings might be attained by exploiting a solvent with a higher absorption capacity, such that less solvent needs to be pumped and cooled.

3.1.2 Cryogenic Fractionation

Cryogenic fractionation involves compression and cooling of gas stream containing CO_2 to low temperatures, leading to phase change in CO_2 , thereby making it possible to extract the CO_2 . Any water vapor present in the flue gas *must* be removed prior to the cooling process, to avoid formation of CO_2 clathrates and solid ice crystals.

The low partial pressure of CO_2 in the flue gas and the possibility of solid formation are the major obstacles to cryogenic fractionation. One solution is to compress the flue gas stream to high pressures, so as to raise the partial pressures of *all* of the combustion products, and to use high temperatures to suppress solid formation.

Nonetheless, compression and heating consumes energy.

3.1.3 Membrane Separation

Membranes are porous or semi-porous, solid structures, through which some species in a mixture would permeate much faster than other species.

High selectivity and high permeability would make an excellent membrane separator. But in the real world, these two attributes are inversely co-related. Each of the many species in the flue gas has its own concentration, solubility and diffusivity through a particular membrane material. Consequently, it is difficult to separate CO_2 exclusively from the rest through only one membrane. Mutli-stage separation is needed.

When it is not necessary to attain a pressure gradient across the membrane, membrane systems can be very energy efficient.

3.1.4 Physical Adsorption

Physical adsorption of CO_2 on solid adsorbents such as molecular sieve Zeolites holds the adsorbed CO_2 on the adsorbent surface by weak surface forces, and not by chemical bonding. The CO_2 adsorbed will be desorbed upon heating or depressurization.

The key performance measure for physical adsorption is the adsorbent's surface area per unit mass or volume, which is a function of temperature and pressure. The operation and regeneration of physical adsorbents are simple and energy efficient.

Unfortunately, physical adsorption is limited to small and medium applications, and its modular nature makes it hard to take advantage of the economies of scale.

3.2 CO_2 Disposal

The captured CO_2 must be sequestered so as to avoid prompt release to the atmosphere. Possible CO_2 disposal processes are shown in Figure 3-1.

Some disposal costs are estimated in Table 3.2. As with the capture costs in

Figure 3-1: CO_2 Disposal Options

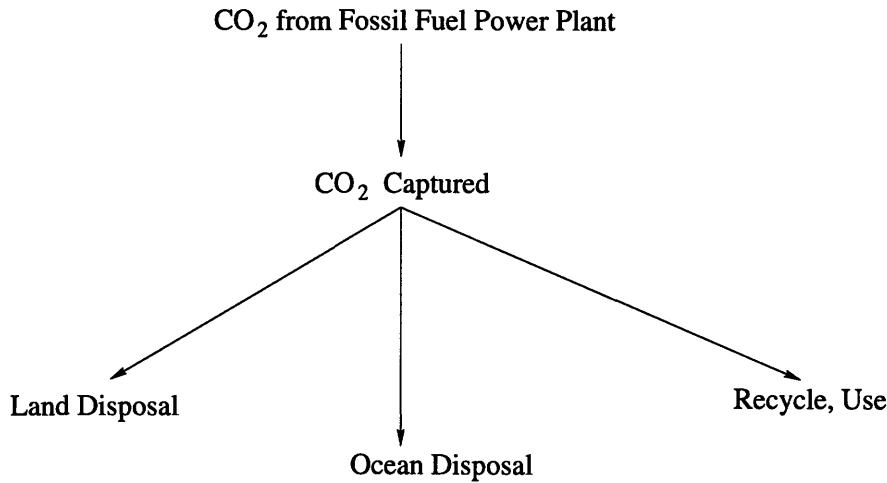


Table 3.1, the disposal costs are highly uncertain.

3.2.1 Land Disposal

Land disposal options include storing captured CO_2 in active or depleted gas and oil wells, aquifers, and salt and rock cavities.

Active or Depleted Gas and Oil Wells

Gas pressure, temperature, and density of a specific well determine its CO_2 storage capacity. Operating costs include capital costs for the wells, pumps, and distribution systems, as well as injection of CO_2 into the wells.

Aquifers

Aquifers are porous formations that are permeable, and can be saturated with water. Underground aquifers, that bear saline or brackish water, are possible storage sites for CO_2 via injection.

Table 3.2: Various CO_2 Disposal Technologies

<i>Process</i>	<i>Disposal cost in \$/tonne CO_2</i>
Active Oil Reservoir	15 to 31
Depleted Oil Reservoir	15 to 40
Microalgae CO_2 Utilization	about 67

Sources: [11, Vol 2, 3-14]

Salt and Rock Cavities

Cavities for storing CO_2 can be excavated in any zone of competent rock underlying the U.S., e.g. basement crystalline rocks and stable limestones. However, storing CO_2 in salt and rock cavities requires large-scale engineering efforts to access to and to create the storage volume.

3.2.2 Ocean Disposal

CO_2 can be released into and stored in the deep ocean:

- as dissolved in seawater,
- as a liquid,
- as a solid, and
- as a gas.

The ocean has an ample capacity for carbon; it contains approximately 38,000 Gt of carbon, in the form of bicarbonates and carbonates, which is ten times of the total carbon stored in all recoverable fossil fuels (about 4000 Gt) or sixty times of carbon that the atmosphere contains (about 750 Gt). Consequently, the ocean is more *adaptable* to CO_2 wastes than the atmosphere is. [11, Vol 1, page 10] states that

adding the amount of CO_2 that would double atmospheric concentration to the ocean would only increase the ocean's carbon level by less than 2%. Nonetheless, there are concerns about the duration of CO_2 storage because the deep ocean recirculates on the order of one thousand years. Moreover, there are questions about the depths and conditions of CO_2 disposal into the ocean.

Dissolved in Seawater

The captured, compressed CO_2 is dissolved in seawater, and the resulting solution is disposed into the ocean. Because the density of concentrated CO_2 solution is higher than that of seawater, the dissolved CO_2 will sink to a greater depth than from where it is released.

Liquid Release

CO_2 , that is compressed to liquid, can be transported directly from the power plants to the disposal site via pipelines or tankers for ocean release through a diffuser.

Solid Release

Because solid CO_2 is much denser than seawater, disposed CO_2 blocks sink rapidly to the deep ocean. Nonetheless, the formation of dry ice (frozen CO_2) is very energy-intensive, and the transportation costs are also higher than those for liquid CO_2 .

Gas Release

Gaseous CO_2 can be compressed so that its pressure is equal to or higher than the hydrostatic pressure at its release depth. To release CO_2 between 500-1000m deep, the CO_2 has to be compressed to 50-100atm, at which CO_2 is completely liquefied. Therefore, gaseous releases cannot be deeper than 500m, at which the CO_2 residence time is relatively short because of the shallow depth.

3.2.3 Other Disposal Methods

Other disposal options include utilization of captured CO_2 through food industry and enhanced oil recovery (EOR) that are just short-term CO_2 storage.

3.2.4 Environmental Impact

Land disposal of CO_2 may lead to dangers from CO_2 leakage and contamination of groundwater. On a global scale, because of the ocean's ample capacity for carbon, the effects of CO_2 disposal into the ocean seem negligible. On a local scale, nevertheless, the biological impacts can raise concerns. For instance, lowering of seawater pH as a result of dissolved CO_2 can upset biological processes of underwater organisms.

Chapter 4

The EPPA Model

Developed by the MIT Joint Program on the Science and Policy of Global Change, the Emissions Prediction and Policy Analysis (EPPA) model is a component of an Integrated Framework of natural and social science models. The EPPA model originates from the General Regional Emissions and ENergy (GREEN) model, which was developed by the OECD¹.

4.1 Model Structure

The EPPA model is a global, computable general equilibrium (CGE) model with a long time horizon, and regional and sectoral details, from 1985 through 2100.

The world is divided into twelve regions, as shown in Table 4.1, each of which consists of eight production sectors and four consumption sectors, plus one government and investment sector, as shown in Table 4.2.

In addition, there are two future types of energy supply:

- carbon backstop as a perfect substitute for refined oil (available only in USA, OOE and EEX)

¹ Organisation for *Economic Co-operation and Development*. It provides economic analysis of its member states. Its 24 member states are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United States and the United Kingdom. Source: International Financial Encyclopedia

Table 4.1: Regions in the EPPA Model

	<i>Regions</i>	<i>Abbreviations</i>
1	United States	USA
2	Japan	JPN
3	European Community	EEC
4	Other OECD	OOE
5	Central and Eastern Europe	EET
6	The former Soviet Union	FSU
7	Energy-exporting LDCs	EEX
8	China	CHN
9	India	IND
10	Dynamic Asian Economies	DAE
11	Brazil	BRA
12	Rest of the world	ROW

Total: 12 regions

- carbon-free backstop generation of electricity (available in all regions)

Each of the eight production sectors X is represented by a multi-layer constant elasticity of substitution (CES) structure, as in Figure 4-1. The sectors employ primary factors: labor L , capital K and fixed factors FF , in addition to the intermediate goods: material or energy inputs E_a from other sectors. Depletable natural resources (represented as fixed factors FF) are used up by five of the eight production sectors. These five production sectors are agriculture, crude oil, natural gas, coal, and electricity, gas and water. The fixed factor therefore represents land, reserves, nuclear and hydropower capacity etc... Both of the backstop energy production sectors have a linear Leontief structure² taking in capital K and labor L inputs, as shown in Figure 4-2.

Consumption in each region is modelled as if there is a representative consumer,

²Leontief structure reduces the solution of a linear programming problem to finding the optimum values (largest or smallest depending on the problem) of the linear expression $f = c_1x_1 + \dots + c_nx_n$, subject to a set of constraints $a_{m1}x_1 + \dots + a_{mn}x_n \leq b_m$.

The a_{mn} , b_m and c_n are determined by the costs, profits, and other restrictions of the problems.

Source: *Britannica Online / Merriam-Webster's Collegiate Dictionary*. <http://www.eb.com:180/>

Table 4.2: Production, Consumers and Primary Sectors in the EPPA Model

<i>Production Sectors</i>
Non-Energy
1. Agriculture
2. Energy-intensive industries
3. Other industries and services
Energy
4. Crude oil
5. Natural gas
6. Refined oil
7. Coal
8. Electricity, gas and water
Future Supply Technology
9. Carbon liquids backstop
10. Carbon-free electric backstop

<i>Consumer Sectors</i>	<i>Primary Sectors</i>
Food and beverages	Labor
Fuel and power	Capital (by vintage)
Transport and communication	Energy (sector-specific fixed factor)
Other good and services	Fixed factor (agricultural land, reserves)

Figure 4-1: CES Nesting of Production Sectors

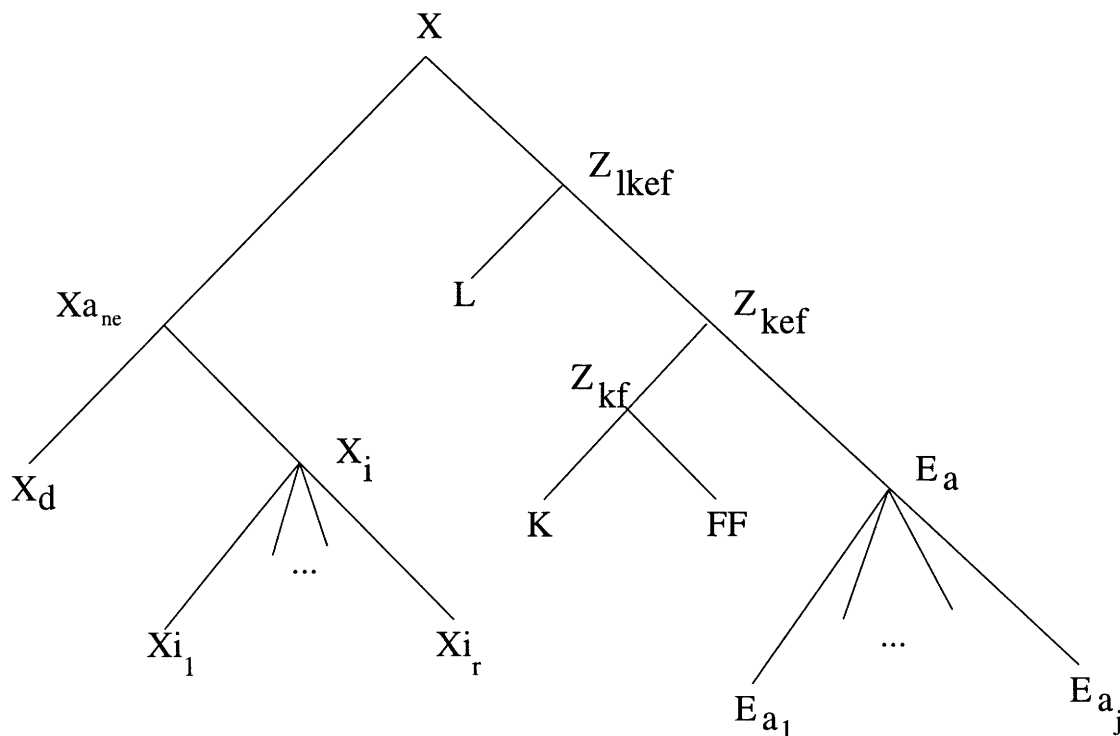
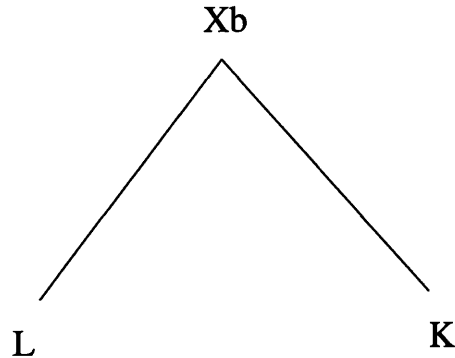


Table 4.3: Variables in the Production Sectors of the EPPA Model

Variable	Definition
X_i	Gross output of sector i
Xa_i	Armington output of sector i
Xd_i	Gross domestic output of sector i
Xi_i	Imported output of sector i
Z_{lkef}	Aggregate of labor, capital, energy and fixed factor bundle
Z_{kef}	Aggregate of capital, energy and fixed factor bundle
Z_{kf}	Aggregate of capital and fixed factor bundle
E_i	Aggregate of energy bundle
FF_i	Demand for fixed factor in sector i
K_i	Demand for capital in sector i
L_i	Demand for labor in sector i

Figure 4-2: Leontief Structure for Backstop Technologies



whose utility function is maximized, while subject to the constraint of disposable income. The consumer's disposable income is the sum of all factor returns and government transfers, less savings and household taxes.

The EPPA model is calibrated on a 1985 data set, which consists of Social Accounting Matrices (SAMs) for each of the twelve regions, and a multi-lateral trade matrix. This data set was originally developed by the OECD in 1993.

There is no forward-looking mechanism in the myopic EPPA model. Unlike a forward-looking dynamic model, the EPPA model solves an equilibrium for each period independently of future periods. For instance, when solving for a certain period, there is no consideration of future depletion of reserves. A general equilibrium is solved for each of the twenty-four five-year periods³, with endogenous changes in capital stocks and fixed factor supplies, but subject to exogenous rates of population growth, labor productivity growth and technology change.

4.2 Greenhouse Gas Emissions

In the EPPA model, the greenhouse gases carbon dioxide CO_2 , methane, nitrous oxide, nitrogen oxides, chlorofluorocarbons, carbon monoxide and sulfur oxides are identified.

³from year 1985 to year 2000

CO_2 gas emissions are calculated directly from levels of energy sector activities for each region in each period. All CO_2 emissions are ascribed to the region in which they are generated.

For each region, CO_2 emissions in each period are calculated as:

$$EE_t = \sum_e X a_{e,t} T J 85_e \varepsilon_e + X_{b,t} \lambda T J 85_{refined\ oil} \varepsilon_{refined\ oil}, \quad (4.1)$$

where

EE_t = emissions in period t , and

e = natural gas, refined oil, coal, and

b = carbon liquids backstop, and

t = indexing time period, and

X = gross output, and

Xa = Armington output.

Finally,

$TJ85_e$ represents the coefficients of energy contents and is measured in exajoule per million 1985 US\$, and

ε_e is the coefficient of carbon content in various energy resources, and is measured in million ton of carbon per exajoule of energy released.

Chapter 5

Technical Background

5.1 CO_2 Emission Accounting

Assuming all the CO_2 captured are subsequently disposed, the CO_2 reduction percentage is the same as the CO_2 capture percentage κ in the electricity generation process.

The amount of CO_2 captured and subsequently disposed is subtracted from the CO_2 emission accounting Equation 4.2:

$$EE_t = \sum_e X a_{e,t} T J85_e \varepsilon_e + X_{b,t} \lambda T J85_{refined\ oil} \varepsilon_{refined\ oil} - \underbrace{\sum_c \kappa_c X a_{coal\ in\ capture, t} T J85_{coal} \varepsilon_{coal}}_{CO_2\ captured\ and\ disposed}$$

where

c = different capture technologies, and

κ_c = CO_2 capture percentage associated with capture technology c .

This research assumes κ_c to be 90% for all capture technologies. Sources: [7, page 47]

5.2 The Economics of CO_2 Capture and Disposal

The electricity output from capture technology competes with conventional electricity and backstop electricity to satisfy total electricity demand.

Since all currently available capture and disposal technologies consume more power than conventional power plants, more CO_2 per kWh is produced in the process of generating electricity.

For instance, assume that for conventional power plants, to produce one unit of electricity, one unit of coal is used, and one unit of CO_2 is released. If CO_2 capture leads to an energy penalty of $x\%$, then to generate one unit of electricity, the power plant will now consume $\frac{1}{1-\frac{x}{100}}$ times the amount of coal used in conventional generation, and create $\frac{1}{1-\frac{x}{100}}$ times the amount of CO_2 released by conventional generation.

When κ of the CO_2 created is *captured*, the amount released will be $e^{\frac{1}{1-\frac{x}{100}}}(1-\kappa)$ units. Subsequently, $1 - \frac{1}{1-\frac{x}{100}}(1-\kappa)$ units of CO_2 are actually *avoided*.

If there is no CO_2 emission constraint, then capture and disposal of CO_2 would not be economically beneficial, due to the extra costs and energy consumed. Nonetheless, when CO_2 emission constraints are enforced, regions affected would start capturing and disposing CO_2 , only if the total costs of electricity generation with CO_2 capture and disposal are *less than* the sum of the electricity price and the carbon quota price. The carbon quota price measures the *value* of lowering CO_2 emission, as a result of the emission constraints.

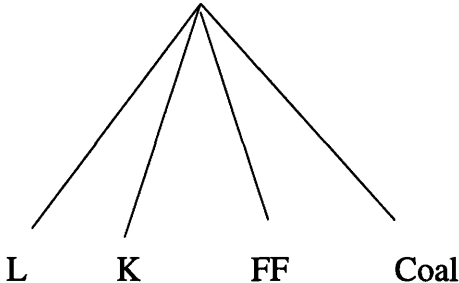
5.3 Alternative Implementations

5.3.1 Leontief Structure

The Leontief structure (Figure 5-1) is similar to the one for backstop technologies (Figure 4-2), but has fixed factor FF and coal as inputs, in addition to capital K and labor L .

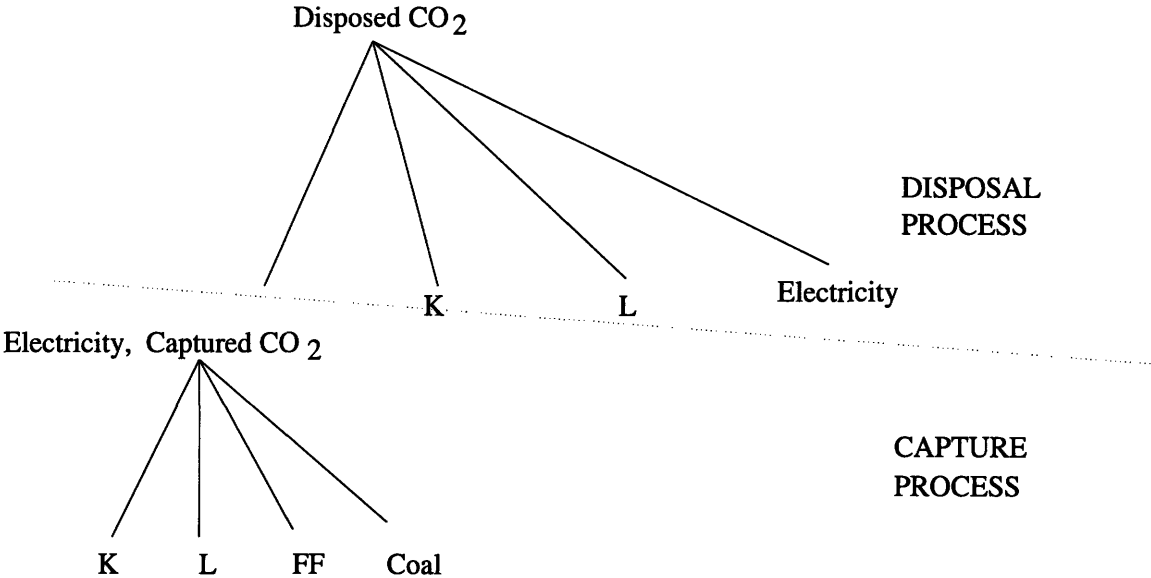
Figure 5-1: Leontief Structure for CO_2 Capture and Disposal

Electricity, Captured and Disposed CO_2



5.3.2 Two-Layer Structure

Figure 5-2: Two-Layer CO_2 Capture and Disposal Technology



The two-layer structure shown in Figure 5-2 mimics the Leontief structure for backstop technologies in Figure 4-2. The bottom layer represents the capture process, that takes in capital K , labor L , coal, and a fixed factor FF . Two co-products, electricity and captured CO_2 , are produced during the capture process. The captured CO_2 enters the disposal process, which consumes capital K , labor L , and electricity as energy input.

CAPCOST represents the costs of capturing a ton of CO_2 during the capture

process, whereas *DISCOST* represents the costs of disposing a ton of CO_2 during the disposal process. The capture and disposal costs per ton of carbon are calculated as:

$$\begin{aligned} \text{capture cost / ton carbon} &= \text{CAPCOST} * \frac{m_c + 2m_o}{m_c}, \text{ and} \\ \text{disposal cost / ton carbon} &= \text{DISCOST} * \frac{m_c + 2m_o}{m_c}. \end{aligned}$$

where m_c and m_o are the atomic masses of carbon and oxygen and $m_c + 2m_o$ is the molecular mass of CO_2 . Since *CAPCOST* and *DISCOST* are in units of \$/ton of CO_2 , the scaling factor $\frac{m_c + 2m_o}{m_c}$ translates the unit into \$/ton of carbon.

5.3.3 CES Structure

The CES representation is more complex. As shown in Figure 5-3 (definitions of variables as defined in Table 4.1), the CES structure for capture and disposal technology is similar to the one for conventional electricity in Figure 4-1, except now, there are premiums **a** on the labor L , capital K and fixed factor FF , and premium **b** on the energy bundle E_a .

The additional labor, capital and fixed factor incurred as a result of the capture and disposal process is represented by **a** as a premium over costs by conventional power plants.

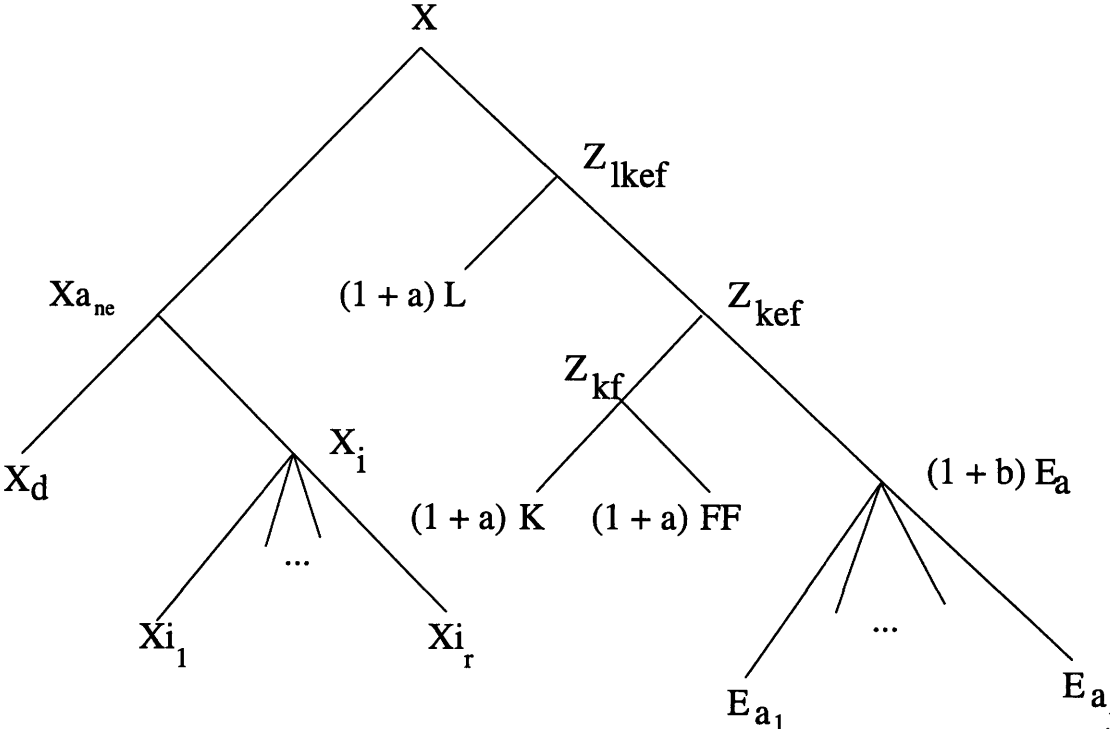
The fuel efficiency of a power plant equipped with CO_2 capture technology will be lower than that of a conventional plant. Denoting such efficiency loss by EL , energy penalty **b** is calculated as $b = (\frac{1.0}{1.0 - EL} - 1.0)$. The magnitude of EL varies from technology to technology.

a and **b** represent the extra costs and energy consumed by the capture and disposal processes. Both **a** and **b** are technology-dependent.

5.4 Environment

The modelling and programming environment employed is the Mathematical Programming System for General Equilibrium analysis (MPSGE), which is a subset of the Generalized Algebraic Modelling System (GAMS). GAMS makes concise algebraic

Figure 5-3: CES Structure for CO_2 Capture and Disposal Technology



statements of models in a language that is easily read by modelers.

MPSGE allows a compact, non-algebraic representation of the EPPA model's nonlinear equations, such as the CES representations. For instance, the complex equation that models the energy bundle for each region R:

$$E_{I,R} = \left[\sum_E X a_{E,I,R}^{\rho_I} \right]^{\frac{1}{\rho_I}} \quad (5.1)$$

is easily coded in MPSGE as:

```

$PROD:EN(I,R)  s: $\rho_I$ 
  O:PE(I,R)  Q:EN0(I,R)
  I:xa(E,R)  Q:EUUSE(E,R),

```

where ρ_I is the elasticity of substitution between energy inputs for the energy bundle in production sector I.

\$PROD block describes the single sector of production activities. O and I represent output and input for the production sector. Q symbols a *quantity field* as a reference input or output level of the commodity. s: ρ_I indicates the substitution elasticity for inputs to the production is ρ_I . For instance, a Leontief structure would have zero substitution elasticity, i.e. s:0.

Chapter 6

Implementation

6.1 Program Organization

Figure 6-1: Program Organization

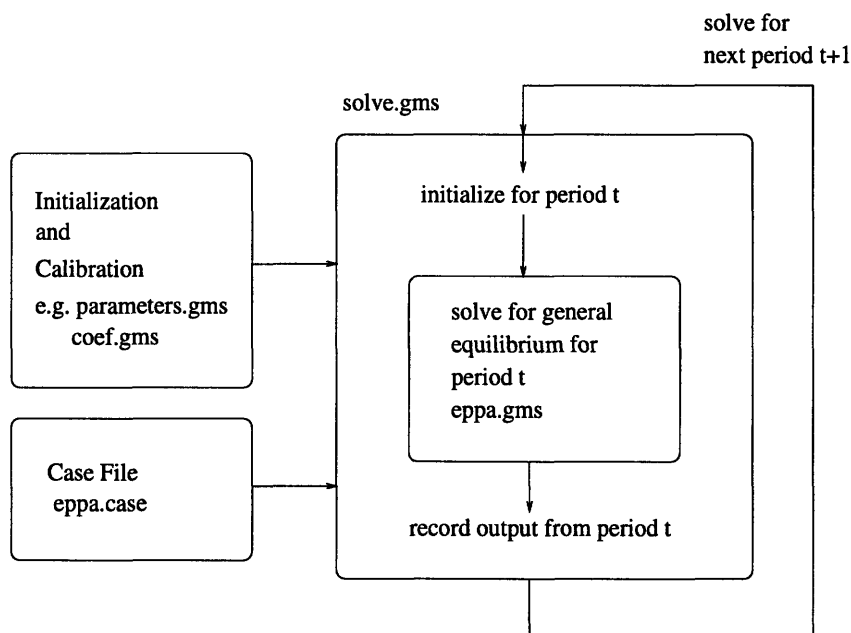


Figure 6-1 shows the program structure for the EPPA model. At the beginning of the simulation, the model is calibrated using base year (1985) data, coefficients and parameters. Before solving each period, results from previous period are incorporated into the current period. The model solves iteratively for an equilibrium over twenty-four periods, using assumptions from the case file. The case file specifies assumptions

on backstop availability, CO_2 emission constraints, and permit trading ...etc.

6.2 Parameters.gms

/jake/d10/vinci/capture/parameters.gms
 Written by Wing Chi Leung

PARAMETER CAPCOST(TECH) CAPTURE COST IN DOLLARS PER TON OF CO₂;
 CAPCOST("MEA") = 37;
 CAPCOST("CRYO") = 24;
 CAPCOST("ADSORP") = 44;

PARAMETER CAP_MKUP(R,TECH);

CAP_MKUP(R,TECH) = TJ_85D(R,"COAL")*EPSLON("COAL")/1000
 *(12+16*2)/12*CAPCOST(TECH) + 1;

10

TABLE CAP_BSTECH(TECH, *, *)

	INPUT.K	INPUT.L	INPUT.COAL	INPUT.FF	OUTPUT.CAPCO2	OUTPUT.ELEC
MEA	.35	.15	.43	.07	1	1
CRYO	.6	.18	.15	.07	1	1
ADSORP	.25	.15	.53	.07	1	1;

TABLE DIS_BSTECH(TECH, *, *)

	INPUT.K	INPUT.L	INPUT.ELEC	INPUT.CAPCO2
MEA	.5	.4	.1	1
CRYO	.5	.4	.1	1
ADSORP	.5	.4	.1	1;

20

PARAMETER GEN_PTG PERCENT OF TOTAL ELEC COST DUE TO GENERATION;
 GEN_PTG = 1;

PARAMETER TRN_PTG PERCENT OF TOTAL ELEC COST DUE TO TRANSMISSION;
 TRN_PTG = 1-GEN_PTG;

30

PARAMETER DISCOST(TECH) DISPOSAL COST IN DOLLARS PER TON OF CO₂;
 DISCOST(TECH) = 50;

PARAMETER DIS_MKUP(R,TECH);

DIS_MKUP(R,TECH) =
 CAP_BSTECH(TECH,"INPUT","COAL")*(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH))*
 TJ_85D(R,"COAL")*EPSLON("COAL")*DISCOST(TECH)/1000*(12+16*2)/12;

40

Parameters.gms takes in cost structure assumptions for CO₂ capture and disposal technologies.

CAPCOST(TECH) and DISCOST(TECH) are the costs of capture and disposal technology TECH per ton of CO₂.

CAP_MKUP(R,TECH) and DIS_MKUP(R,TECH) are the corresponding markup coefficients for technology TECH per ton of carbon, taking into consideration the different carbon contents of coal and generation efficiencies in different region R.

CAP_BSTECH(TECH,*,*) and DIS_BSTECH(TECH,*,*) describe the factor coefficients of various inputs for capture and disposal technology.

6.3 Eppa.gms

extracts from /jake/d10/vinci/capture/eppa.gms

Originally written by Zili Yang

Modified by Wing Chi Leung

...

SET TECH /MEA, CRYO, ADSORP/;

...

\$MODEL:EPPA

10

\$SECTORS:

...

EB(BT,R,TECH)\$ACTIVE(BT,R);

\$COMMODITIES:

...

PCC(R)\$ACTIVE("CO2-CAP",R) ! PRICE FOR CAPTURED CO2

\$CONSUMERS:

RA(R)

20

...

\$PROD:EB("CO2-CAP", R, TECH)\$ACTIVE("CO2-CAP",R)

O:PD(G,R) Q:CAP_BSTECH(TECH,"OUTPUT",G)

O:PCC(R) Q:CAP_BSTECH(TECH,"OUTPUT","CAPCO2")

I:PA(G,R) Q:(CAP_BSTECH(TECH,"INPUT",G)*(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH)))

I:PL(R) Q:(CAP_BSTECH(TECH,"INPUT","L")*(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH)))

I:PK(R) Q:(CAP_BSTECH(TECH,"INPUT","K")*(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH)))

I:PF("ELEC",R) Q:CAP_BSTECH(TECH,"INPUT","FF")

30

\$PROD:EB("CO2-DIS", R, TECH)\$ACTIVE("CO2-DIS",R)

**O:PCARB(R)\$CO2C(R) Q:(CAP_BSTECH(TECH,"INPUT","COAL")*
(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH))*0.9*TJ_85D(R,"COAL")*
EPSLON("COAL")*DIS_BSTECH(TECH,"INPUT","CAPCO2"))**

**O:PTCARB\$TCO2C(R) Q:(CAP_BSTECH(TECH,"INPUT","COAL")*
(TRN_PTG+GEN_PTG*CAP_MKUP(R,TECH))*0.9*TJ_85D(R,"COAL")*
EPSLON("COAL")*DIS_BSTECH(TECH,"INPUT","CAPCO2"))**

I:PCC(R) Q:(DIS_BSTECH(TECH,"INPUT","CAPCO2"))

I:PA(G,R) Q:(DIS_BSTECH(TECH,"INPUT",G)*DIS_MKUP(R,TECH))

40

I:PL(R) Q:(DIS_BSTECH(TECH,"INPUT","L")*DIS_MKUP(R,TECH))

I:PK(R) Q:(DIS_BSTECH(TECH,"INPUT","K")*DIS_MKUP(R,TECH))

...

...

In addition to the existing ten production sectors in Table 4.2, two additional sectors, namely CO_2 capture $EB(CO2-CAP,R,TECH)$ and CO_2 disposal $EB(CO2-DIS,R,TECH)$

are created. A new commodity, namely captured CO_2 $PCC(R)$, is produced by the capture sector, and consumed by the disposal sector. Any amount of captured CO_2 consumed/removed by the disposal sector in region R is credited to the region's carbon emission rights $PCARB(R)$.

6.4 Solve.gms

extracts from /jake/d10/vinci/capture/solve.gms

Originally written by Zili Yang

Modified by Wing Chi Leung

...

IF(BACKSTOP(T),

* **ACTIVE**("SOLAR",R) = **YES**;

* **ACTIVE**("SYNF-OIL","USA") = **YES**;

* **ACTIVE**("SYNF-OIL","OOE") = **YES**;

* **ACTIVE**("SYNF-OIL","EEX") = **YES**;

10

* **ACTIVE**("SYNF-OIL","FSU") = **YES**;

ACTIVE("CO2-CAP","USA") = **YES**;

ACTIVE("CO2-DIS","USA") = **YES**;

ACTIVE("CO2-CAP","JPN") = **YES**;

ACTIVE("CO2-DIS","JPN") = **YES**;

ACTIVE("CO2-CAP","OOE") = **YES**;

ACTIVE("CO2-DIS","OOE") = **YES**;

ACTIVE("CO2-CAP","EEX") = **YES**;

ACTIVE("CO2-DIS","EEX") = **YES**;

ELSE

20

ACTIVE(BT,R) = **NO**);

...

...

* keep track of coal used in cap that are actually disposed

* amount of CO2 disposed in million tons

BB2OUT(R,TECH,T) = **B2OUT.L**(R,TECH)***TJ_85D**(R,"COAL")

***CAP_BSTECH**(TECH,"INPUT","COAL")

*(**TRN_PTG**+**GEN_PTG*****CAP_MKUP**(R,TECH))***EPSLON**("COAL")*0.9;

30

* amount of CO2 captured

BB3OUT(R,TECH,T) = **B3OUT.L**(R,TECH)***TJ_85D**(R,"COAL")

***CAP_BSTECH**(TECH,"INPUT","COAL")

*(**TRN_PTG**+**GEN_PTG*****CAP_MKUP**(R,TECH))***EPSLON**("COAL")*0.9;

* amount of elec from cap technology

BB4OUT(E,R,TECH,T) = **TJ_85D**(R,E)***B4OUT.L**(E,R,TECH);

...

40

* **TOTAL CO2 EMISSIONS INCLUDE PRIMARY EMISSIONS FROM "SYNF-OIL".**

TOTCO2(R,T) = **SUM**(E, **CO2F**(R,E,T))+**BB1OUT**("REFOIL",R,T)***EPSLON**("OIL")*0.8
- **SUM**(TECH, **BB2OUT**(R,TECH,T));

...

For each period, solve.gms performs parameter initialization and output recording.

ACTIVE(BT,R) activates the availability of backstop BT in region R.

BB2OUT(R,TECH,T) records the amount of CO_2 captured and disposed by technology TECH in region R during period T. BB2OUT(R,TECH,T) is deducted from the total CO_2 emissions TOTCO2(R,T) from region R in period T.

Chapter 7

Results and Analysis

7.1 Reference Runs

The reference outputs from the EPPA model, without any CO_2 capture and disposal technology, are presented in Figures 7-1 and 7-2.

Figure 7-1 shows the global CO_2 emissions from year 1985 to year 2100. The four scenarios presented are with and without AOSIS, and with and without backstops. AOSIS, the Alliance of Oceanic and Small Island States, is a CO_2 emissions constraint protocol, in which OECD regions start reducing their CO_2 emissions in 1990, and stabilize their CO_2 emissions at 80% of 1990 levels from 2010 onwards.

As illustrated by Figure 7-1, global CO_2 emissions are reduced by the AOSIS policy constraint, regardless of the backstop availability assumptions. Meanwhile, the availability of backstop energies can further reduce global CO_2 emissions, by providing a clean fuel alternative, the carbon-free electric backstop.

Figure 7-2 shows the price of carbon quota under AOSIS, when there is no permit trading allowed among OECD regions. The carbon price for Japan nearly doubles those of other OECD regions, because the Japanese economy operates at higher energy and carbon efficiency levels, leading to more stringent CO_2 emission constraints as AOSIS kicks in.

Under AOSIS, OECD regions' CO_2 emissions cannot exceed a certain quota per period. If these regions engage in CO_2 capture and disposal, they reduce their carbon

Figure 7-1: Global CO_2 Emissions from Reference Runs

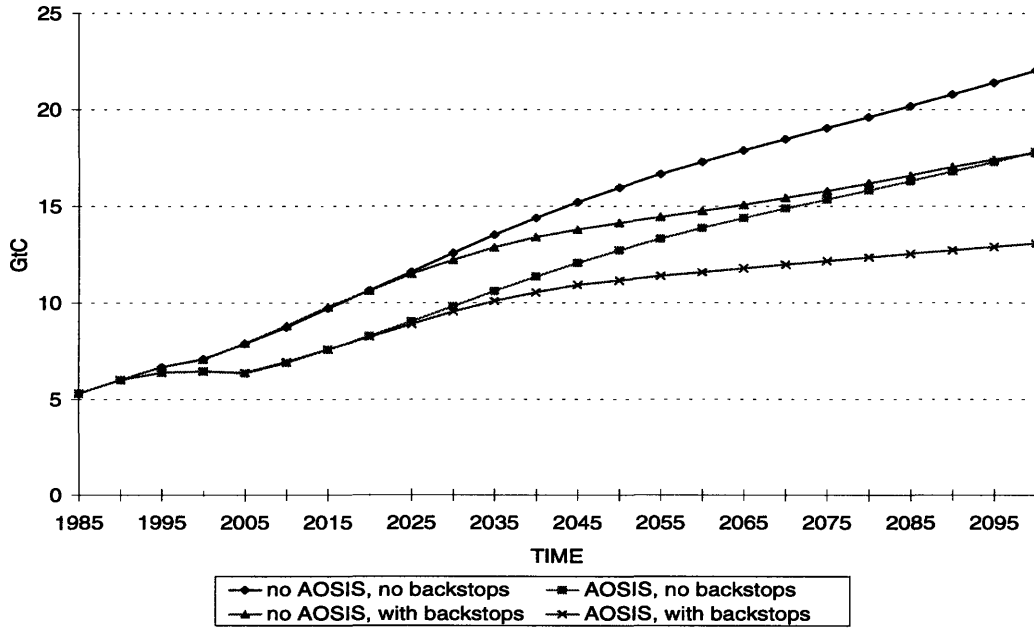
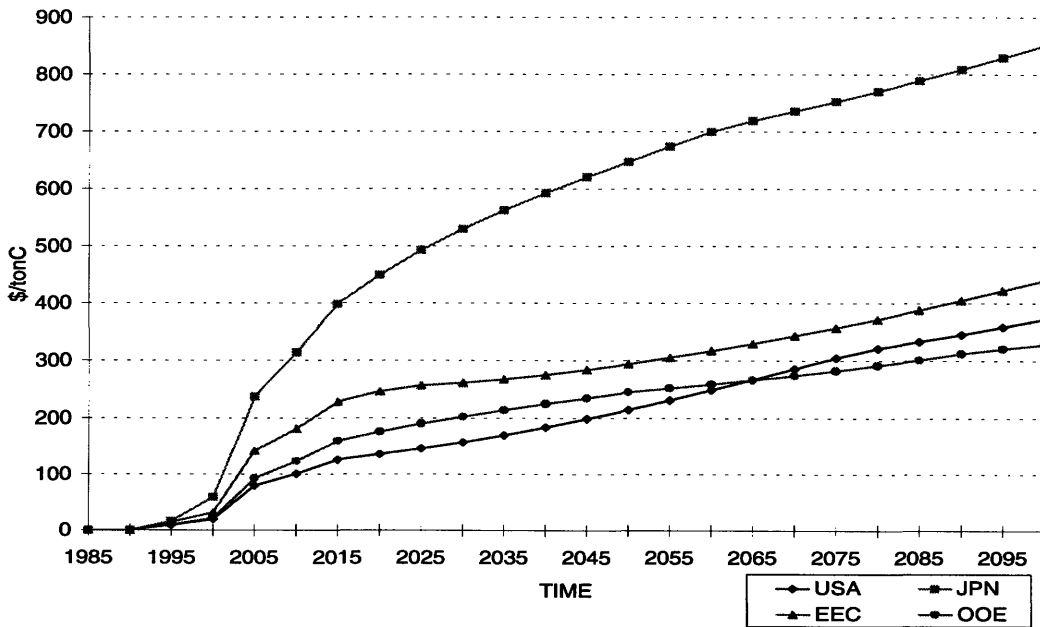


Figure 7-2: Carbon Quota Price, under AOSIS, with No Backstops and No Trading in Emissions Permits



emissions from electricity generation, and save their quota for other carbon-intensive industries. In other words, the marginal *value* contributed from capturing and disposing one ton of carbon would equal the value of one ton of carbon quota. Consequently, it is economical for an OECD region to engage in a CO_2 capture and disposal technology only if the cost of capturing and disposing one ton of carbon is *equal to or less than* the region's price per ton of carbon quota shown in Figure 7-2.

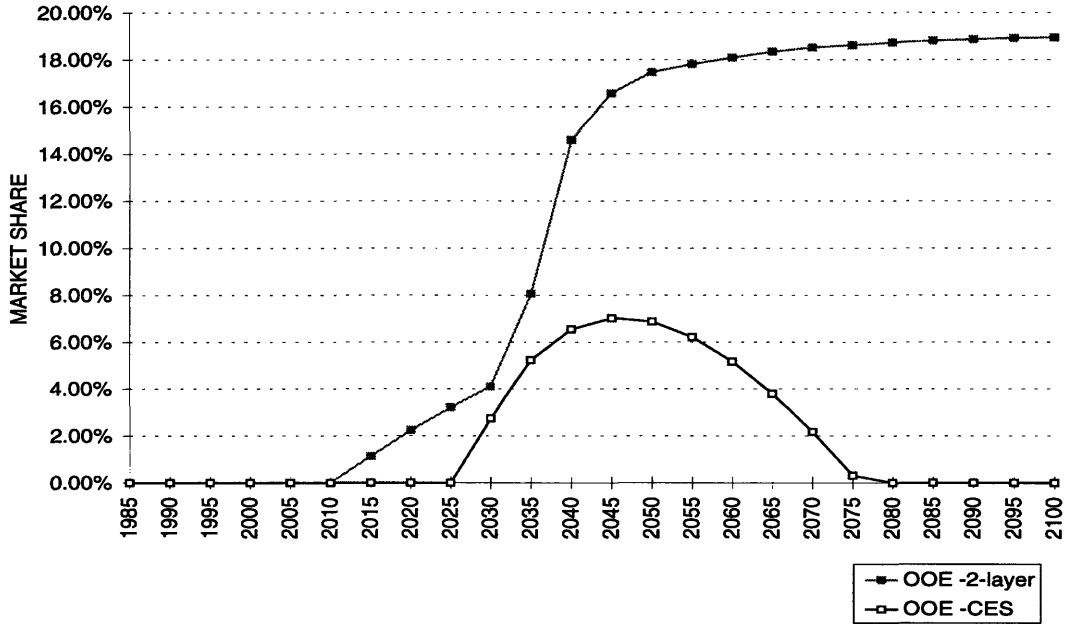
7.2 Comparison of Alternative Implementations

A major difference, in the representation of the CO_2 capture and disposal technology, of the two-layer structure (Section 5.3.2) from the CES structure (Section 5.3.3) is the linearity of its top and bottom layers, with no substitution among inputs. The CES structure, on the other hand, is elastic among the inputs, such that more expensive inputs can be *partially substituted* by cheaper inputs, thereby lowering the total costs of CO_2 capture and disposal. Consequently, the CO_2 capture and disposal technologies are expected to come in *more readily* in the CES case than in the two-layer case.

It turns out that, however, that the reverse is true for our model. A set of capture and disposal cost inputs in \$/ton of CO_2 (*CAPCOST* and *DISCOST*) for the two-layer structure, and a set of corresponding premiums (**a** and **b** in Figure 5-3) for the CES structure are used. At this presumably equivalent cost levels, the capture and disposal technology is used more readily in the two-layer case than in the CES case. For instance, Figure 7-3 shows OOE's market shares of capture and disposal technology in the two-layer case (solid square) at *CAPCOST*=30 and *DISCOST*=20, and in the CES case (empty square) with **a** = 20% and **b** = 25%. The capture and disposal technology comes in more readily in the two-layer case than in the CES case. Similar phenomena are observed for USA, JAPAN and the European Community.

Setting the two-layer structure and the CES structure at *what we assume* the same capture and disposal cost level does not necessarily imply price equivalency, because the two structures are essentially different, in terms of input substitution

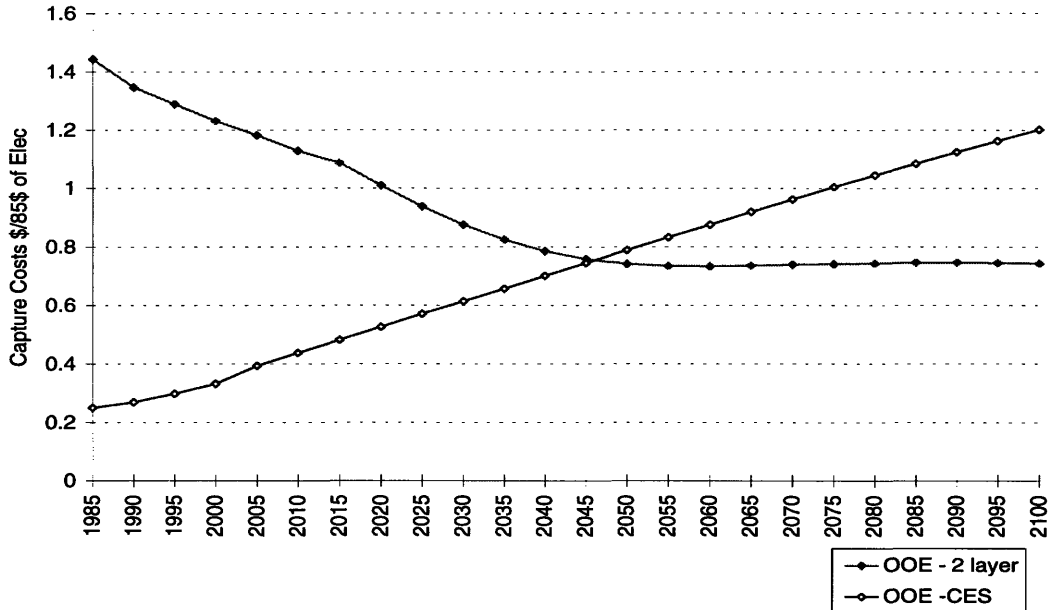
Figure 7-3: Market Shares of Capture and Disposal Technology in OOE for the Two-Layer Case ($CAPCOST=30$ $DISCOST=20$) and the CES case ($a=20\%$ $b=25\%$)



and factor proportions. Figure 7-4 shows OOE’s capture costs in \$/kWh for the two-layer case (solid diamond) and the CES case (empty diamond). The rising capture costs projected by the CES case explains why it does not come in as readily as the two-layer case in Figure 7-3. Analyzing the two-layer structure in Figure 5-2, only the lower capture layer, but not the upper disposal layer, takes in fixed factor FF . Compared to the CES structure in Figure 5-3, however, FF is consumed in the *combined* capture and disposal processes. Since FF represents depletable reserves whose prices keep increasing as the reserves are used up, the higher dependence on FF in the CES case than in the two-layer case leads to higher capture costs in the CES case.

The above observation can be error-prone because of the inaccuracies when translating the cost data from $CAPCOST$ and $DISCOST$ for the two-layer case to a and b for the CES case.

Figure 7-4: Capture Costs in OOE for Two-Layer Case ($CAPCOST=30$ $DISCOST=20$) and CES Case ($a=20\%$ $b=25\%$)



7.3 Boundary Cost Effectiveness

The following analysis is based on simulations from the two-layer case.

7.3.1 Varying $CAPCOST$ and $DISCOST$

Figure 7-5 shows the market shares of capture and disposal technology in OOE, with $CAPCOST$ fixed at \$60/ton of CO_2 captured and $DISCOST$ varying from \$30/ton to \$90/ton of CO_2 disposed; Figure 7-6 shows the market shares of capture and disposal technology in OOE, with $DISCOST$ fixed at \$60/ton of CO_2 disposed and $CAPCOST$ varying from \$60/ton to \$90/ton of CO_2 captured. As observed from both figures, the higher the total costs of capture and disposal, the later the technology enters the market. Because the higher the total costs of capture and disposal technology, the more expensive it is compared to conventional electricity. The less competitive capture and disposal technology is, the less readily it enters the market.

Figure 7-5: Market Shares of Capture and Disposal Technology in OOE, with $CAPCOST = \$60/\text{ton}$ of CO_2 and Different $DISCOST$ (Two-Layer Case)

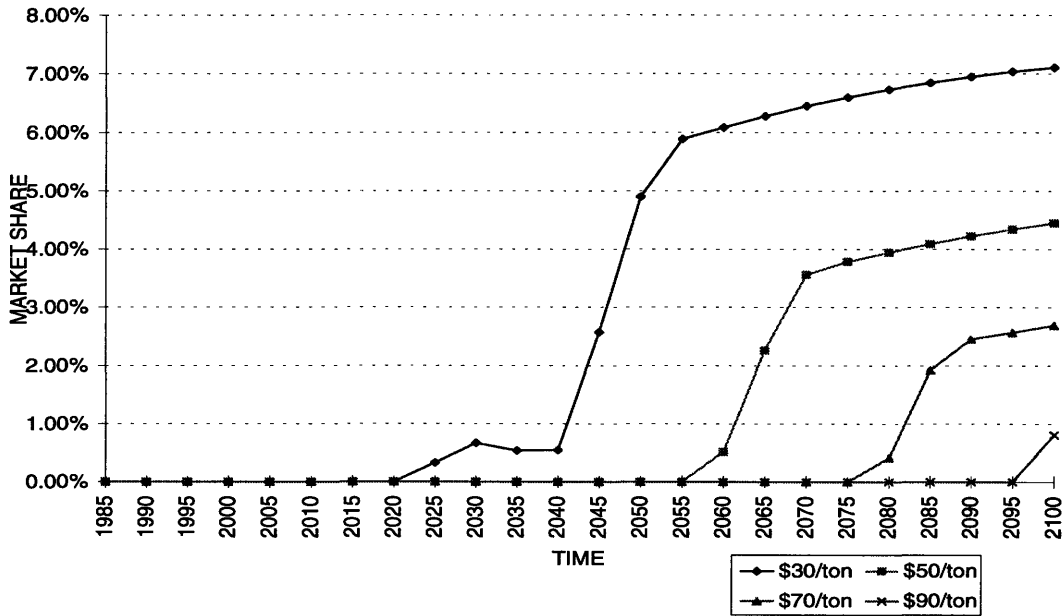
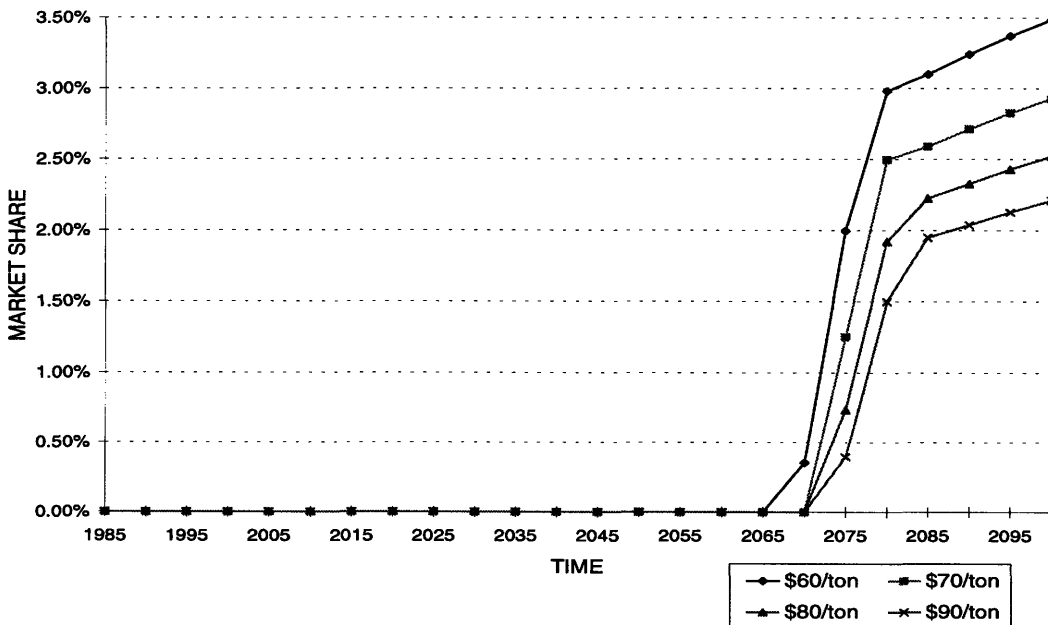


Figure 7-6: Market Shares of Capture and Disposal Technology in OOE, with $DISCOST = \$60/\text{ton}$ of CO_2 and Different $CAPCOST$ (Two-Layer Case)

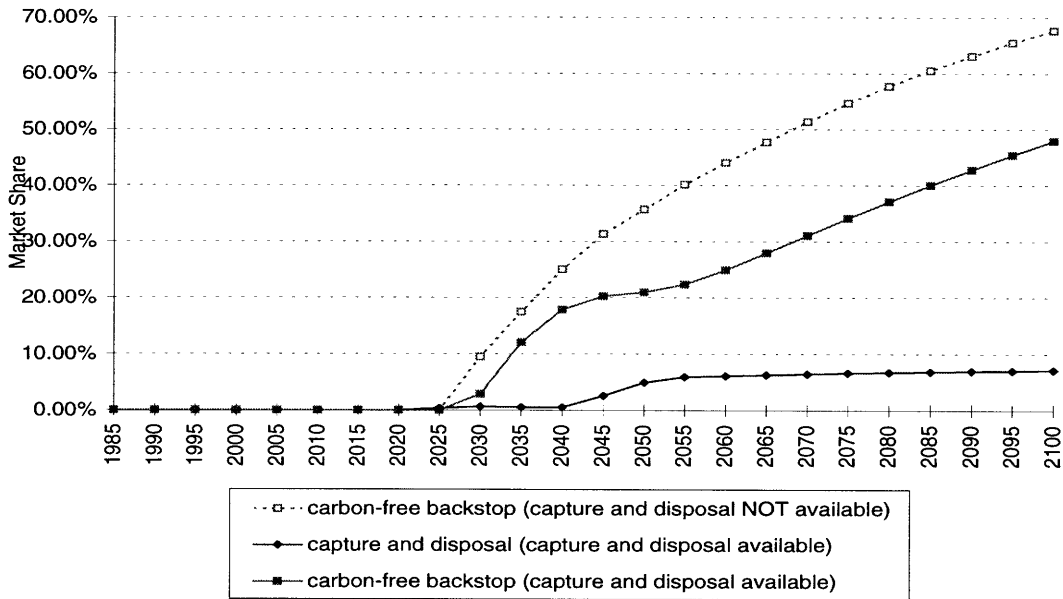


7.3.2 Backstop Availability Assumptions

The carbon-free backstop provides a perfect substitute for electricity, and releases no carbon. Consequently, the CO_2 capture and disposal technology, when made available, will compete with the carbon-free backstop for market share, because both technologies are relatively *clean* electricity sources.

Figure 7-7 shows that when capture and disposal technology is not available, carbon-free backstop (empty square) can take up almost 70% of the OOE electricity market in 2100. However, the presence of capture and disposal technology (at $CAPCOST=60$ and $DISCOST=30$) steals some market share from the carbon-free backstop (solid square).

Figure 7-7: Market Shares of Capture and Disposal Technology and Carbon-Free Backstop in OOE (Two-Layer Case)

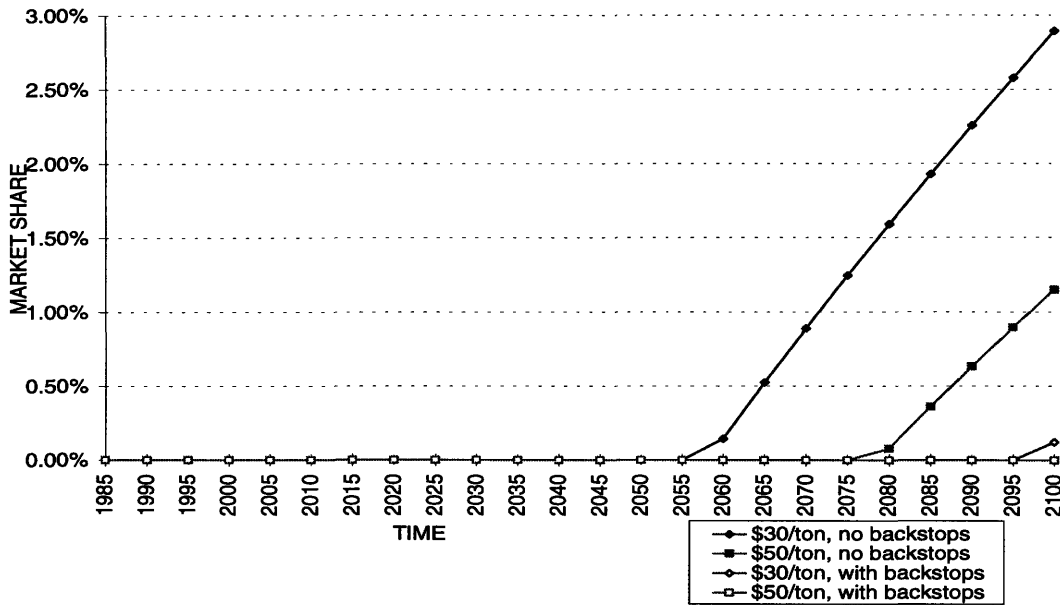


On the other hand, the availability of the electric backstop alternative may not only delay the entry, but may also lower the market share of CO_2 capture and disposal technology.

Figures 7-8 and 7-9 shows the market shares of CO_2 capture and disposal under different backstop availability assumptions for USA and OOE respectively. The filled markers are the cases without backstops, and the empty markers are the cases with

backstops.

Figure 7-8: Market Shares of Capture and Disposal Technology in USA, with $CAPCOST = \$60/\text{ton}$ of CO_2 and Different $DISCOST$, with and without Backstops (Two-Layer Case)



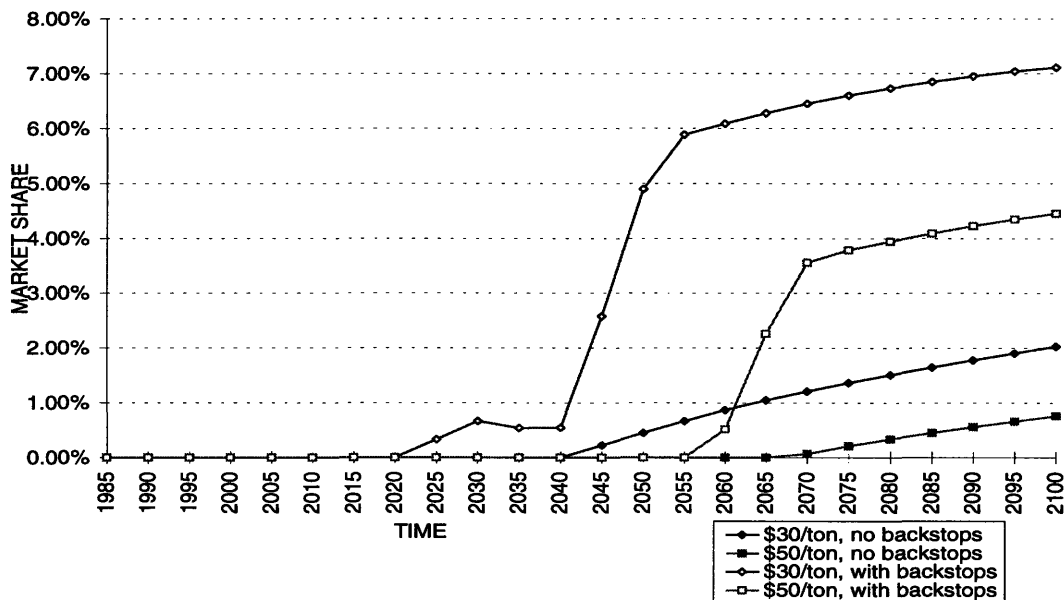
As shown in Figure 7-8, at $CAPCOST = \$60/\text{ton}$ of CO_2 and $DISCOST = \$30/\text{ton}$ of CO_2 , CO_2 capture and disposal technology enters in USA in 2060 in the absence of backstop technologies. The introduction of backstop technologies delays the entry from 2060 to 2100.

In Figure 7-9 for OOE, however, CO_2 capture and disposal enters earlier and is used more under the with backstop assumption, than under the without backstop assumption. Because OOE, being a heavy user of the carbon backstop, needs to utilize the capture and disposal technology for cleaner electricity so as not to exceed its emission quota under *AOSIS*.

7.3.3 *AOSIS* Stringency

The more stringent the *AOSIS* constraint is, the less CO_2 the OECD regions can emit, and the more restricted they have to use a cleaner fuel. Figure 7-10 shows the different market shares of capture and disposal technology in OOE, as a result of

Figure 7-9: Market Shares of Capture and Disposal Technology in OOE, with $CAPCOST = \$60/\text{ton}$ of CO_2 and Different $DISCOST$, with and without Backstops (Two-Layer Case)



strengthening the *AOSIS* constraint from *20% reduction by 2010* to *40% reduction by 2020*. Such stringency not only pushes the technology’s entry year from 2060 *earlier* to 2020, but also forces OOE to use *more* of the technology.

7.4 Conclusion

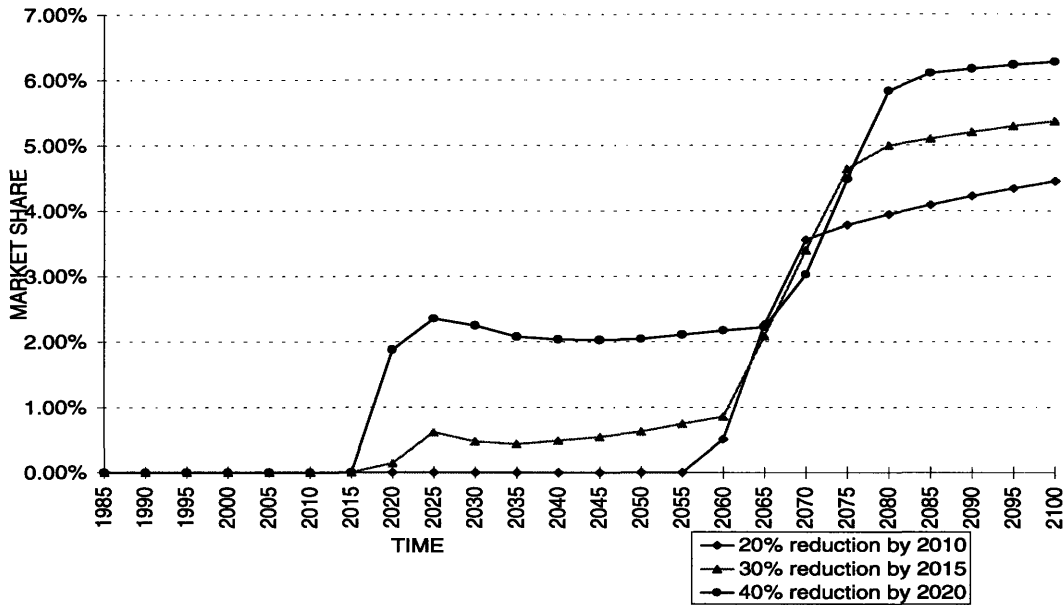
Alternative Implementations

Comparing the three alternative implementations of the CO_2 capture and disposal technology in Section 5.3, we choose the two-layer structure over the Leontief and the CES structures.

The Leontief structure is appropriate for the the backstop technologies (Figure 4-2) because the generation of the future backstops is still highly uncertain. But the Leontief structure would over-simplify the CO_2 reduction technology that in fact consists of *separate* capture and disposal processes.

The CES structure models the electricity generation with CO_2 capture and dis-

Figure 7-10: Market Shares of Capture and Disposal Technology in OOE, with Different *AOSIS* Stringency (Two-Layer Case)



posal to be identical to conventional electricity generation, but at a higher premium cost. Parameters *a* and *b* represent the *aggregate* percentage increases in inputs, that are due to a *combined* capture and disposal process. Since most of the available cost estimates for CO_2 capture and disposal technology are in \$/ton of CO_2 , there are possible transformation errors when translating the cost estimates into *a* and *b*.

The two-layer structure allows a logical, easily comprehensible representation by explicitly modelling the separate capture and disposal processes. Parameters *CAPCOST* and *DISCOST* allow researchers to investigate the impact of different combinations of capture and disposal costs on the market. One shortcoming of the two-layer structure, however, is that the electricity generation process it represents differs from that of conventional electricity. The most obvious difference is that there is no substitution among inputs in the two-layer structure.

Because CO_2 capture and disposal technology is a not highly commercialized yet, there are high uncertainties embedded with the cost data for the various capture and disposal technologies. In any reasonable implementation, the costs of conventional electricity generation should *never* exceed the costs of electricity generation with CO_2

capture and disposal.

Cost Effectiveness of CO_2 Capture and Disposal

There are several factors that affect the entry of CO_2 capture and disposal technology into the market.

Since the EPPA model solves for general equilibria, when under CO_2 emission constraints, every region attempts to maximize its utility while meeting the constraints. Therefore, the CO_2 capture and disposal technology would be employed only if the benefits of reducing CO_2 emissions, as measured by the carbon quota price, are greater than the costs of capture and disposal.

On one hand, the higher the carbon quota is valued, the more easily capture and disposal technology will enter the market. Carbon quota is priced higher, when the CO_2 emission constraints are more stringent, or when carbon-free backstop is not available. On the other hand, the lower the total costs of capture and disposal technology, the less expensive it is compared to the carbon quota price, and therefore the more readily it enters the market.

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