Modeling and Economic Optimization of Carbon Capture in Malaysia' Power Plants

by

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CERTIFICATION OF APPROVAL

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Chemical Engineering Programme
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Approved by,

(Khor Cheng Seong)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MOHD HAIQAL BIN HASHIM)

ABSTRACT

This paper presents an optimization cost model that was developed to calculate the cost of installing CO_2 Capture technology in Malaysia main power plants. This so-called CO_2 Capture technology is expected help to reduce the CO_2 emission from main power plants until they meet a specified CO_2 emission target without compromising the national electrical supply to the customers. There is also consideration to use new technology power plants such as Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC) and to use non-fossil energy like hydroelectric, wind and nuclear in order to reduce the CO_2 emissions by 50% from current CO_2 emission level. There is still ongoing research about using CO_2 capture technology in fossil-fuel power plant around the globe but, Malaysia has a great potential to accept this new technology install in main power plant based on government determination in national budget to fight global warming.

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Firstly, I would like to thank to God because by His willing, I have completed my Final Year Project (FYP).

I would personally give my big appreciation to my supervisor, Mr. Khor Cheng Seong for his countless effort and guidance that motivated me to work on this project. There are no equivalent words that can describe his determination and contribution to me.

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

Reducing the emission of greenhouse gases are the most challenging environmental issue facing the advance industrial countries. Increasing concentration of greenhouse gases including carbon dioxide, methane, nitrous oxide and sulfur oxide has increased the average earth surface temperature over time. As a result of the global temperature rises, a lot of unpredictable phenomena happen such as precipitation patterns, storm severity, and abnormal rise in sea levels.

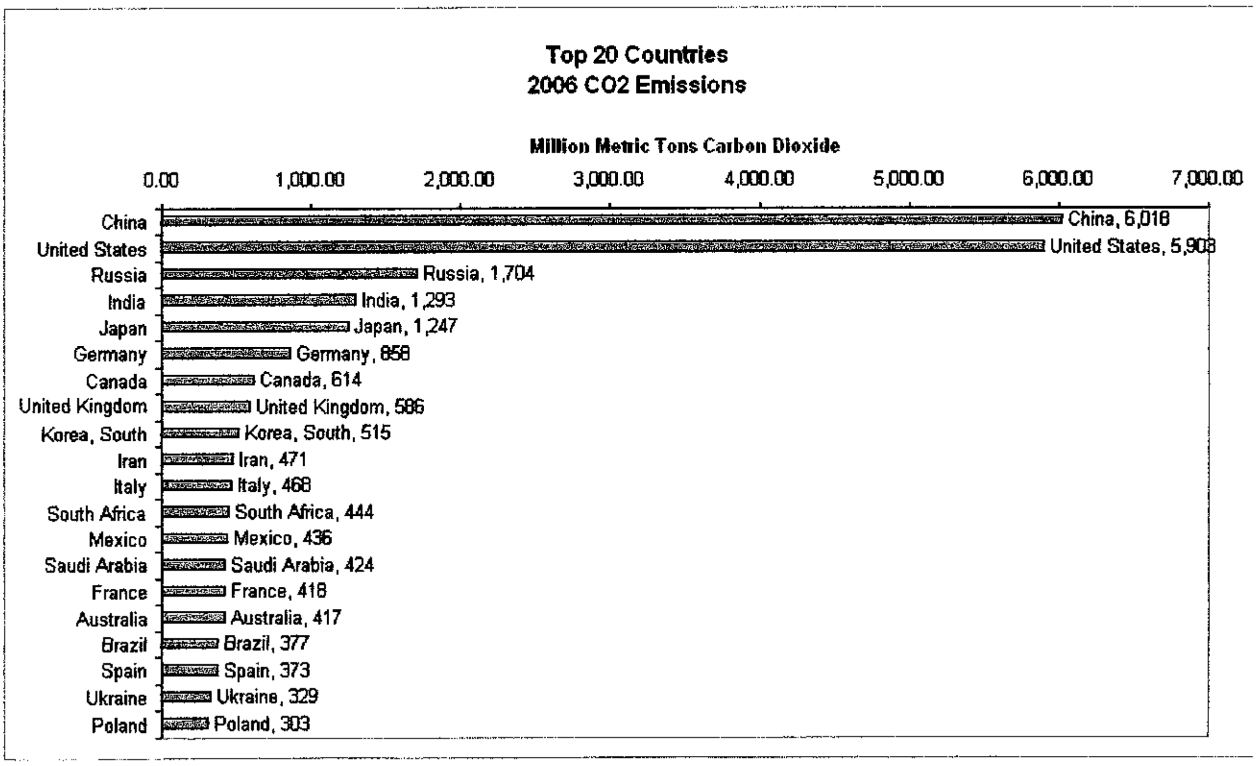

Figure 1: Carbon Dioxide Emissions Top 20 Main Contributors (Each Country's Share of CO_2 Emissions, 2010)

The Kyoto Protocol is initiated on 11 December 1997 in Kyoto, Japan and become fully law enforcement on 16 February. In November 2009, 187 states have signed and enforced the protocol. Under this Protocol, 37 industrialized countries pledge themselves to a reduction of four greenhouse gases (carbon dioxide, methane, nitrous oxide, sulfur hexafluoride and two others (hydrofluorocarbons and perfluorocarbons) produced by them. The enforcement of Kyoto Protocol does not reduce the greenhouse gases emission rate significantly because the main contributors of greenhouse gases emission, China and United States do not give full commitment to the protocol. China is not one of country that signs the protocol and while United States had signed the protocol but US government does not enforce the protocol.

If we narrow down to South East Asian countries, we will found out that Malaysia is the highest CO_2 contributor. This result is due to rapid transformation of Malaysia economy from an agricultural economy to an industrialized one over the last three decades which also put Malaysia on 26th largest greenhouse emitter in the world. Rapid growing of heavy industries causes the increase of electrical demand from power plants. Electricity is mainly generated by Tenaga National Berhad (TNB) and Independent Power Producers (IPP). Total electricity generated in Peninsular Malaysia is 17,623MW with TNB share at 48.1% IPP, including IPP in Sabah, Sarawak, Sabah Electricity Sdn. Bhd. (SESB) and Syarikat SESCO Berhad (SESO), owning 46.9% and private generation (Energy Commission Annual Report, 2006)

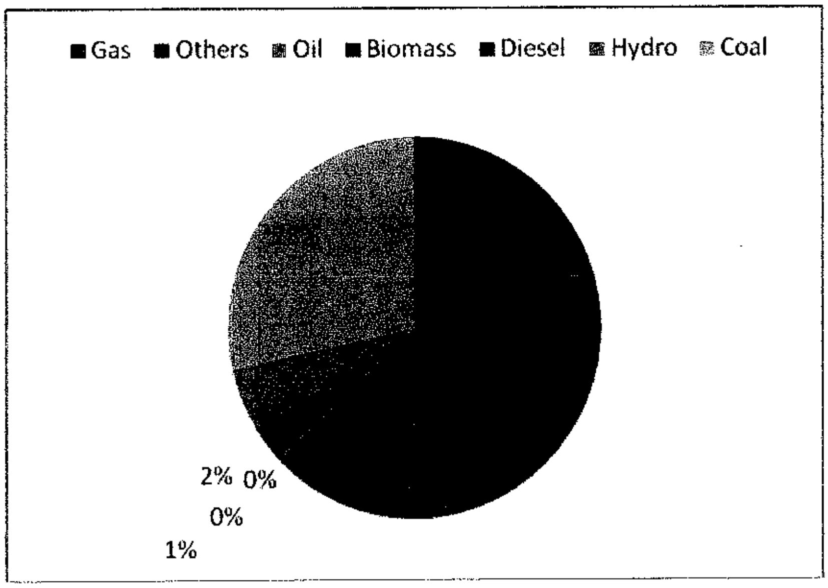

Figure 2: Malaysia's current installed generation capacity in percentage (Ministry of Energy, Water and Communication, 2006)

Rapid growth in power generation capacity and increasing in global CO_2 emission in Malaysia, there is need for the government to plan the electricity generation capacity expansion to meet the electricity demand as well as to achieve an overall reduction in CO_2. Therefore, this paper is aims to develop an optimization cost modeling to minimize the cost of electricity generation and simultaneously fulfill the forecasted electricity demand a specified CO_2 emission reduction targets using a mix of fossil fuel as well as renewable energy. Conventional electricity generation using fuels such as pulverized coal, natural gas and hydroelectricity, new power generation technologies such as Pulverized Coal (PC), Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC), nuclear and wind were considered in the model

1.2 Problem Statement

Electricity generation is one of the main sources of carbon dioxide emission, particularly coal-fired based power plants. This problem can be solved with capture and sequestration. Retrofitting the existing combustion-fired plants with carbon capture could be promising because we can continue burn fossil fuel without increasing CO_2 emissions. CCS can reduce CO_2 emissions by 85 to 95% compared to the same processes without CCS but it is a relatively costly emission reduction strategy because CCS required a large amount of energy for regeneration. There are two main options for coal-fired power plants with CO_2 capture: flue gas scrubbing with amine solvent and oxyfuel combustion (A. Elkamel et al., 2009). Amine scrubbing is generally considered to be proven option but it the most expensive method due to energy input required for solvent regeneration. Common chemical solvents are amine such as monoethanolamine (MEA), diethanolamine (DEA), ammonia, and potassium carbonate. MEA is the common practise for flue gas applications because the existing coal power plants have low CO_2 concentration 13-15% wet basis in the flue gas and amine-based solvents have been viewed as the potential solution to this problem (Singh D et al., 2003). For the IGCC (Integrated Gasification Combine Cycle), Selexol is a better CO_2 capture solvent due to the high pressure synthesis gas. Chemical absorption imposes an energy penalty of about 15% to 30% for natural gas and 30 to 60% for coal plants (Herzog H et al., 1997). The CO_2 capture system is energy hunger because the energy requirement is about 22% of gross plant capacity, mostly for sorbent regeneration (54%) and CO_2 product compression (36%). Sorbent circulation and fan power account for the remaining share (10%) of the total energy consumption of a CO_2 capture unit (Rubin ES et al., 2004). For the most part, this project is focus on combustion-based power plants (natural gas and coal), which are a major source of CO_2 emissions. The objective of this project is to formulate and solve an optimization model with the following attributes objective function of minimizing of total cost, continuous decision variables, discrete

1.3 The Scope of Study

For the most part, this project is focus on combustion-based power plants (natural gas and coal), which are a major source of CO_2 emissions.

1.4 Objectives

The objective of this project is to:

To formulate and solve an optimization model with the following attributes:

1) Objective function of minimizing of total cost
2) Continuous decision variables:
3) Discrete decision variables:
4) Constraints:
    i. Energy balance/demand satisfaction
    ii. Energy balance on capture process

CHAPTER 2: LITERATURE REVIEW

2.1 General Model Formulations

Several energy models for power generation technologies, such as Pulverized Coal (PC), Integrated Gasification Combined Cycle (IGCC) and Natural Gas Combined Cycle (NGCC) in the field of carbon capture and sequestration. For example, Rubin et al, for instance developed the Integrated Environmental Control Model (IECM) to provide an analytical tool to compare various environmental control options for fossil fuel power plants. The model was developed in a modular fashion that allowed new technologies to be easily incorporated into an overall framework. IECM can configure and evaluate a particular environmental control system design which current environmental control options include a variety of conventional and advanced systems for controlling SO_2, NO_x, and CO2, particulates and mercury emissions for both new and retrofit applications. Number of studies is performed on how to make use of new power station technology. A. Elkamel et al. (2009) considered replacing existing coal plants with new plants such as NGCC, IGCC and PC and studied the impact of the incremental cost of CO_2 reduction on the cost of electricity (COE) by implementing different technology options. Singh D et al. (2003) for example develop model for regional energy supply systems. The model calculates the energy demand and then suggests fuel switching, retrofitting and installing CO_2 capture technology to meet the required CO_2 emission targets at minimum cost. Rubin ES et al. (2004) develop a mixed 0-1 Multiple Objective Linear Programming (MOLP) model and applied it to the Greek electricity generation sector for identifying the number and output of each type of boiler unit needed to meet expected electricity demand. The objectives of MOLP are to minimize the annual cost of electricity and minimize the total amount of SO_2 emissions and this model did put CO_2 mitigation into account A. Elkamel et al. (2009) develop a linear programming model to evaluate the effectiveness of possible CO_2 mitigation options for the electricity sector in Taiwan. The strategies that they use included fuel alternatives, reduced peak load, energy conservation, improving power generation efficiency, and CO_2 capture. The combination of reduced peak production and increasing power plant efficiency with CO_2 conservation was an effective strategy to meet significant CO_2 emission reductions.

2.2 Model Superstructure

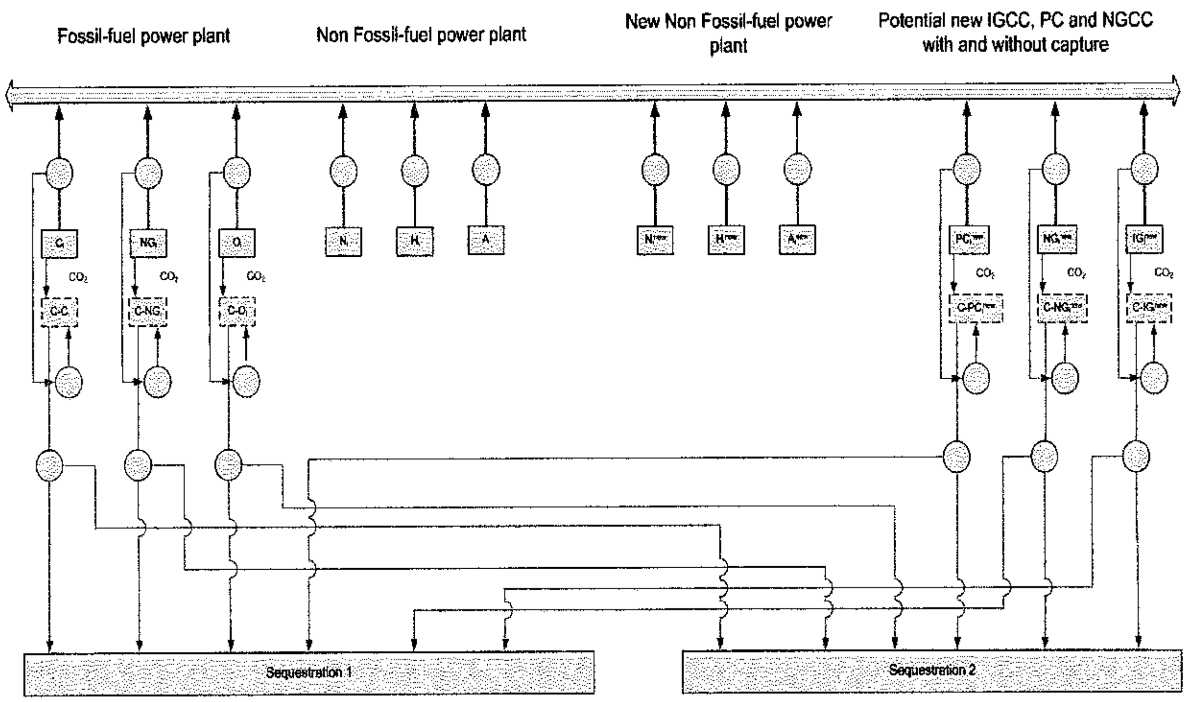

Figure 3: Superstructure representing a power generation fleet (A. Elkamel et al., 2009)

A. Elkamel, H. Hashim, P. L. Douglas and E. Croiset introduce superstructure power generation fleet in AICHE JOURNAL. This superstructure representing all possible alternative fuel mix which can be very complex indeed. Figure 3 illustrate energy supply C_i, NG_i, D_i, O_i, and H_i represents existing coal, natural gas, diesel, oil, and hydroelectric power plants respectively. New technology power plants are represented by PC_i^{new}, IG_i^{new}, NG_i^{new}, SO_i^{new}, B_i^{new} and N_i^{new} for pulverized coal, Integrated Gasification Combined Cycle (IGCC), Natural Gas Combined Cycle (NGCC),solar, biomass and nuclear respectively. Three methods to mitigate CO_2 which are fuel balancing, fuel switching and use of alternative energy as well as advanced technologies. This strategy involves increasing electricity generation by non-fossil fuel plants. Therefore, fossil fuel plants will generate less electricity and hence, less CO_2 emission. Fuel switching involves changing from carbon-intensive fuels (coal) to less carbon-intensive fuel (natural gas). Existing generation stations must be retrofitted in order to use alternative fuel. Energy produced by alternative fuel (solar, wind) emits zero CO_2 and this will reduce CO_2 emission. The third methods of CO_2 mitigation strategy is to increase the usage of renewable energy such as solar, wind and hydroelectric.

Table 1: Actual electricity generation for existing power plant (Economic Planning Unit, 2005)

Power Plant		Generation MWh per year	Operating and Maintenance cost (RM per MWh)	
Type	Location		Coal	Natural gas
Coal	Pelabuhan Klang	639,918	69-104	138-208
	Janamanjung	1,254,870		
	Tanjung Bin	1,254,870		
	Pasir Gudang	646,926		
	Prai	1,073,100		
	Jimah	745,000		
Natural Gas	Glugor	1,734,480	5.63	
	Pelabuhan Klang	1,734,480		
	Connaught Bridge	6,559,488		
	Serdang	3,740,520		
	Pasir Gudang	3,066,876		
	Paka	8,979,876		
Hydroelectric	Kenyir	1,486,199	1.67	
	Temenggor	823,900		
	Bersia	231,000		
	Kenering	427,000		
	Chenderoh	154,700		
	Jor	280,700		
	Pergau	457,800		
	Who	429,800		
	Piah & Odak	315,000		

Table 2: Capital Cost and Operating and Maintenance Cost for New Power Plant (Urmee T et al., 2009)

Sources	Capital cost (RM/MW	Variable O&M cost (RM/MWh)	Fixed O&M cost (RM/MW)	Fuel cost (RM/tone)
Pulverized coal (PC)	5078400	9.184	76.032	272
Integrated Gasification combine cycle	6787200	3.968	76.032	15.264
Natural gas combine cycle	1974400	8.64	76.032	15.264
Nuclear	7725440	17.696	76.032	403.2

Data from Table 1 and Table 2 is used for the model formulation. Some of the data is assumed because there is not much research being conducted by local to study the cost for new technology power station such as Pulverized coal (PC), Integrated Gasification combine cycle (IGCC), Natural gas combine cycle (NGCC) and new nonfossil-fuel energy such as nuclear.

An extensive research to attain important data must be conducted in the future to improve this cost modeling so that researcher can do deeper analysis to study the cost of installing CO_2 capture in Malaysia power plant.

CHAPTER 3 METHODOLOGY AND MODEL FORMULATION

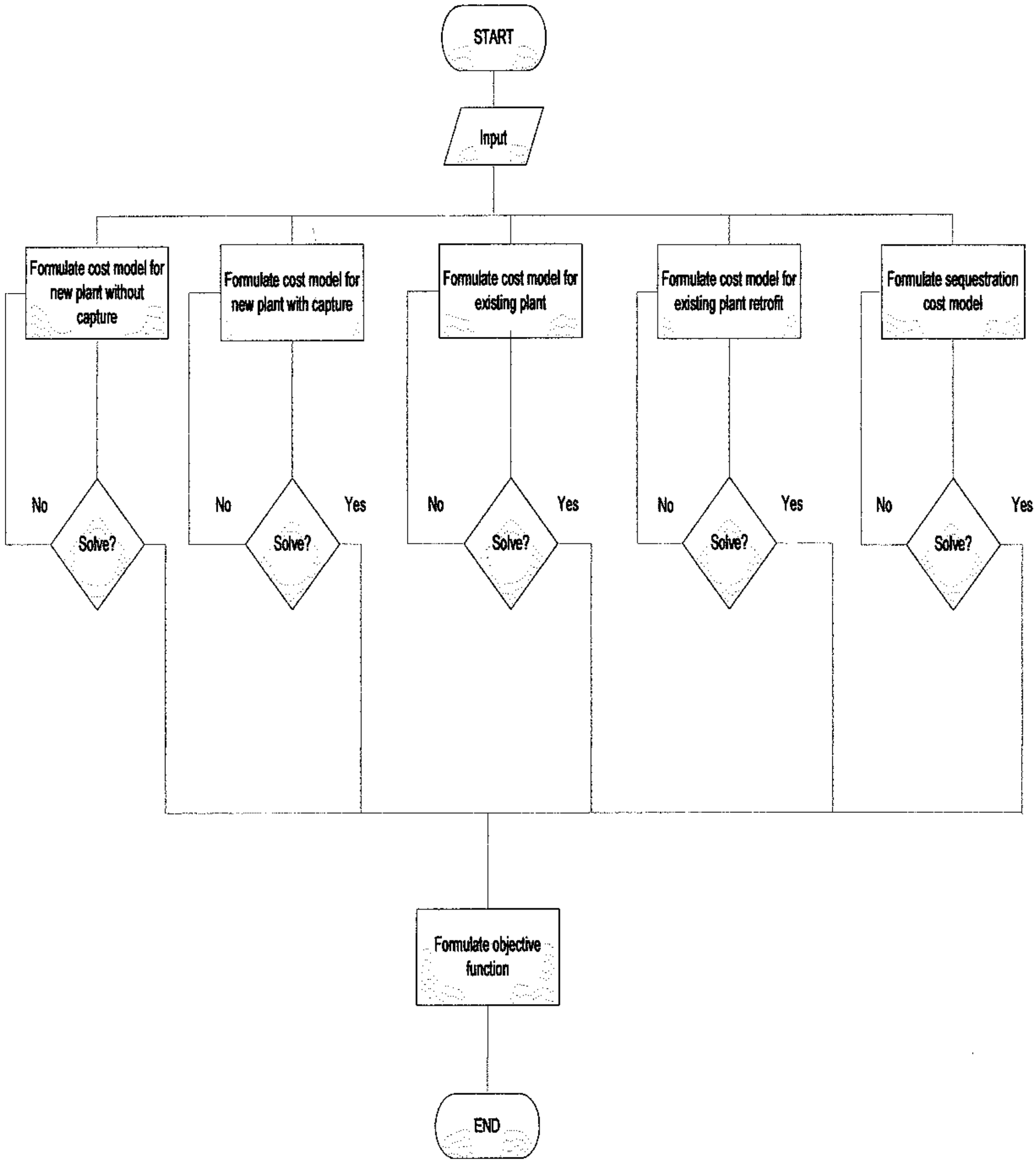

Figure 4: Methodology Flowchart

3.1 Model Formulation

The objective of this model is to choose the best plant load distribution which consists of existing and new power plant, mix of fuels, and CO_2 capture process to meet electricity demand and still achieve CO_2 mitigation target. Two main continuous variables are defined: E_{ij} represent electricity generated/load distribution from the *i*th fossil fuel boiler using fuel *j (j=1 for coal and j=2 for natural gas)*. E_i represents electricity generated/load distribution from *i*th existing non-fossil power plant and new technology power plant.

Four sets of binary variables:

1) Fuel switching coal to natural gas is represented by X_{ij}

$$X_{ij} = \begin{Bmatrix} 1 \text{ if ith plant is selected} \\ 0 \text{ otherwise} \end{Bmatrix}$$

2) The existence/non-existence of *i*th potential new boiler with and without capture is represented by y_i

$$y_{ij} = \begin{Bmatrix} 1 \text{ if ith plant is selected} \\ 0 \text{ otherwise} \end{Bmatrix}$$

3) Z_{ik} selection of *k*th capture process on *i*th existing coal-fired boiler

$$Z_{ij} = \begin{Bmatrix} 1 \text{ if ith capture process is put online} \\ 0 \text{ otherwise} \end{Bmatrix}$$

3.2 Objective Function

The objective of this model is to utilize a power generation fleet and to combine carbon capture (CCS) on existing power plant and construct new power plants with or without capture to achieve targeted CO_2 mitigation. The objective function represents the total system cost that includes operating costs of electricity, retrofit costs for switching from coal to natural gas, retrofit costs for carbon capture retrofit on existing power plants and operational costs for new power plant.

The objective function can be written as:

$$\text{Total Cost} = \underbrace{\sum_{i\in F}\sum_{j} C_{ij}E_{ij} + \sum_{i\in NF} C_i^{NF}E_i}_{\text{operational cost for existing plants}} + \underbrace{\sum_{i\in F^c}\sum_{j} R_{ij}X_{ij}}_{\text{retrofit cost}}$$

$$+ \underbrace{\sum_{i\in P^{new}} S_i^{new}E_i^{max}y_i + \sum_{i\in P^{new}} C_i^{new}E_i^{new}}_{\text{capital and operational cost for new additional stations}}$$

$$+ \underbrace{\sum_{i\in F^c}\sum_{k} S_{ik}^{c}z_{ik} + \sum_{i\in F^c}\sum_{k} C_k^{c}E_{ik}}_{\text{capital and operational cost of carbon capture retrofit}}$$

Where C_{ij} is the electricity generation cost per MWh if *j*th fuel is used in *i*th fossil-fuel boiler, C_i (C_i^{new}) is the electricity generation cost per MWh for *i*th nonfossil-fuel power plant; C^c_k is operational cost for *k*th CO_2 capture process (RM/MWh), E_i (E_i^{new}) is the electricity generated (MWh/year) from *i*th nonfossil-fuel boiler, E_{ij} is the electricity generated (MWh/year) from *i*th fossil-fuel boiler using *j*th fuel, E_{ijk} is electricity required for *k*th CO_2 capture process (MWh/year in *i*th coal-fired boiler which running with *j*th fuel, R_{ij} is retrofitting cost for switching *i*th coal-fired boiler to *j*th fuel natural gas. S_c^{jk} is annualized capital cost for *k*th capture process in RM/year; ε_{ik} is the fraction of CO_2 capture. F is the set of fossil-fuel boilers including coal F^c and natural gas F^{ng}. NF is the set of nonfossil-fuel power stations, nuclear, hydroelectric and wind. P^{new} is the set of new technology power plant that include pulverized coal, P^{PC} (P^{PCcap}), integrated gas combined cycle, P^{IGCC} ($P^{IGCCcap}$) and natural gas combined cycle, P^{NGCC} ($P^{NGCCcap}$) with and without capture.

3.3 Cost of CO_2 Avoidance

$$\text{cost of } CO_2 \text{ avoided (\$/ton)} = \frac{(\$/\text{kWh})_{ccs} - (\$/\text{kWh})_{ref}}{\underbrace{(tCO_2/\text{kWh})_{ref}}_{\text{emission}} - (tCO_2/\text{kWh})_{CCS}}$$

The avoidance of CO2 is a measure for the contribution to climate protection and thus reduces the greenhouse effect. CO2 is emitted during the generation of electrical power as a result of burning fossil fuels (e.g. coal). Electricity which is generated using renewable energy (sun, wind, water, biomass, geothermal energy) does not produce (additional) CO_2 [11]

3.4 Constraints

Energy Balance/Demand Satisfaction

Total electricity injected to the grid come from nonfossil power plant, new technology power plant and fossil-fuel power plant

$$\left[\sum_{i\in NF} E_i^{NF} + \sum_{i\in P^{new}} E_i^{new} + \sum_{i\in F}\sum_{j} E_{ij}\right] - \sum_{i}\sum_{k} E_{ik} = Demand$$

Additional energy is required for CO_2 capture processes and this energy can be supplied by existing nonfossil power generation, new technology power plant and fossil-fuel power plant.

$$E_{ik} = \left[\sum_{l\in P^{new}}\sum_{k} E_{lk} + \sum_{i}\sum_{j} E_{ijk} + G_k\right]$$

The total electricity generated for the whole fleet must be equal to the total demand.

$$\left[\sum_{i\in NF} E_i^{NF} + \sum_{i\in P^{new}} E_i^{new} + \sum_{i\in F}\sum_{j} E_{ij}\right] - \sum_{i}\sum_{k} E_{ik} = Demand$$

Energy Balance on Capture Process

The energy required E_{ik} can be supplied from the grid, G_k from existing nonfossil power plant and new power plants:

$E_i \leq My_i$ $\qquad \forall i \in P^{new}$ $\qquad$ which can be simplified to

$$E_{ik} = \sum_i \sum_j E_{ijk}$$

Capacity Constraint on Capture Process

$$E_{ik} \leq Z_{ik} E_k^{\max} \qquad \forall i \in F^c, \forall k$$

The parameter $E_k^{\max}$ represents the maximum energy required for capture technology. This constraint make sure energy required is zero when no capture process is involve in the model

Fuel Selection and Plant Shut-Down. For a fossil fuel boiler, the process is either operating or shutdown. This constraint is represented by X_{ij} that represents the fuel selection or plant shutdown:

$$\sum_j X_{ij} \leq 1 \qquad \forall i \in F$$

Plant Capacity Constraints

Existing fossil fuel boilers

$$E_{ij} \leq MX_{ij} \qquad \forall i \in F, \forall j$$

New power plants

$$E_i^{new} \leq E_i^{\max} y_i \qquad \forall i \in P^{new}$$

Upper Bound on Operational Changes

Existing fossil fuel boilers:

$$E_{ij} \leq (1 + r_i) E_i^{current} \qquad \forall i \in F, \forall j$$

Nonfossil power plants:

$$E_i^{NF} \leq (1 + r_i) E_i^{current} \qquad \forall i \in NF$$

New power plants

α_i=$CO_{2i}E_i$ $\forall i \in P^{new}$ $\forall i \in$.

Lower Bound on Operational Constraints

Existing fossil fuel boilers:

f_{ij}>$l_{ij}X_{ij}$ $\forall i \in F, \forall j$

Nonfossil power plants:

f_i>l_i $\forall i \in NF$

New power plants

f_i>$l_i y_i$ $\forall i \in NF$

Emission Constraint/ CO_2 balance. CO_2 emissions from existing coal-fired boilers and new boilers, α_i (million tone/yr) are defined as:

Existing fossil fuel boilers

α_i=$\sum_j CO_{2ij}E_{ij}$ $\forall i \in F$

New power plants

α_i=$CO_{2i}E_i$ $\forall i \in P^{new}$

The new detail objective function base on the constraints can be written as:

$$
\begin{aligned}
\text{total cost} = & \underbrace{\sum_{i\in I_{\mathrm{F}}}\sum_{j\in J} C_{i,j}E_{i,j} + \sum_{i\in I_{\mathrm{NF}}}\sum_{j\in J} C_i^{\mathrm{NF}}E_i^{\mathrm{NF}}}_{\text{1. operating cost for existing power plants without capture}} + \underbrace{\sum_{i\in I_{\mathrm{F,ng}}} R_{i,j}\left(\frac{L_i^{\max}}{\mathrm{AOP}}\right)X_{i,j}}_{\text{retrofit cost for fuel switching}} \\
& + \underbrace{\sum_{i\in I_{\mathrm{F,new}}} C_i^{\mathrm{new}}\left(\frac{P_i^{\max}}{\mathrm{AOP}}\right)\cdot y_i}_{\text{capital cost for new power plants without capture}} + \underbrace{\sum_{i\in I_{\mathrm{F,new,cap}}} C_i^{\mathrm{new,cap}}\left(\frac{P_i^{\max,\mathrm{cap}}}{\mathrm{AOP}}\right)\cdot y_i}_{\text{capital cost for new power plants with capture}} \\
& + \underbrace{\sum_{i\in I_{\mathrm{F,new}}} \mathrm{OP}_i^{\mathrm{new}}E_i^{\mathrm{new}}.yi}_{\text{operating cost for new power plants without capture}} + \underbrace{\sum_{i\in I_{\mathrm{F,new,cap}}} \mathrm{OP}_i^{\mathrm{new,cap}}E_i^{\mathrm{new,cap}}}_{\text{operating cost for new power plants with capture}} \\
& + \underbrace{\sum_{i}\sum_{j}\sum_{k} C_i^{\mathrm{CCS}}\mathrm{CO2}_{i,j}\gamma_{i,j,k}}_{\text{capital cost for retrofit of existing power plants with capture}} + \underbrace{\sum_{i}\sum_{j}\sum_{k} C_i^{\mathrm{CCS}}\cdot\varepsilon(i,k)\cdot\mathrm{CO2}_{i,j}\gamma_{i,j,k}}_{\text{operating cost for retrofit of existing power plants witht capture}} \\
& + \underbrace{\sum_{i\in I_{\mathrm{F,new,cap}}}\sum_{i\in I_{\mathrm{F}}} \frac{\mathrm{OP}_i^{\mathrm{new,cap}} - \mathrm{OP}_i^{\mathrm{new}}}{\mathrm{CO2}_i^{\mathrm{ref}} - \mathrm{CO2}_i^{\mathrm{CCS}}}}_{\mathrm{CO_2}\text{ avoidance cost}}
\end{aligned}
$$

Sets and Indices

I	set of all power plants i
I_{F}	set of fossil-fuel-fired power plants i
J	set of types of fuels j
$I_{\mathrm{F,ng}}$	set of fossil-fuel-fired power plants i using natural gas as fuel
$I_{\mathrm{F,new}}$	set of new fossil-fuel-fired power plants i
S	set of potential sequestration locations s

Parameters

L_i^{max} net electricity generation from a fossil-fuel-fired power plant *i* (MWh/yr)

AOP annual operating time of fossil-fuel-fired power plant *i* (h/yr) (8760 h/yr)

sen parameter for performing sensitivity analysis on capital cost

P_i^{max} net electricity generation from a new power plant *i* (MWh/yr)

$CO2_i$ CO2 emission from a fossil-fuel-fired power plant *i* (ton/yr)

$\varepsilon(i,k)$ fraction of CO2 captured

Continuous Decision Variable

$E_{i,j}$ amount of electricity generated from a fossil-fuel-fired power plant *i* with its boiler(s) operating using fuel *j* (MWh/yr)

E_i amount of electricity generated from a non-fossil-fuel-fired power plant *i* (MWh/yr)

E_i^{new} adjusted electricity generation from a new power plant *i* (MWh/yr)

P_{coal} price of coal ($/GJ)

hr_i heat rate of a fossil-fuel-fired power plant *i* (GJ/MWh)

$\gamma_{i,j,k}$ linearization variable related to CO2 capture at an existing fossil-fuel-fired power plant

$\phi_{i,s}$ linearization variable for a fossil-fuel-fired power plant *i* in sequestration location *s*

Integer 0–1 Binary Decision Variables

$X_{i,j}$ 1 if a power plant *i* is operated using a selected fuel *j*; 0 otherwise

y_i 1 if a new power plant *i* exists *j*; 0 otherwise

CHAPTER 4: RESULT AND DISCUSSION

4.1 Effect of renewable energy, fuel balancing and fuel switching generation mix on cost of electricity

First of all, the main objective of this model is to meet the power grid electricity demand and renewable energy play vital role in achieving power grid electricity demand. Figure 5 and 6 shows that, as we increase the renewable energy generation share in power generation fleet, the cost of generating electricity is increased. This result is expected since renewable energy based electricity generation is not cost-effective as compared to fossil fuel-based power plant. The cost of electricity is RM 0.3072/kWh for 5% renewable energy generation mix, which is double the base-case cost of electricity. The model output shows based on the sources of renewable energy currently available in Peninsular Malaysia. This is expected to increase the cost of electricity to RM 0.3616/kWh

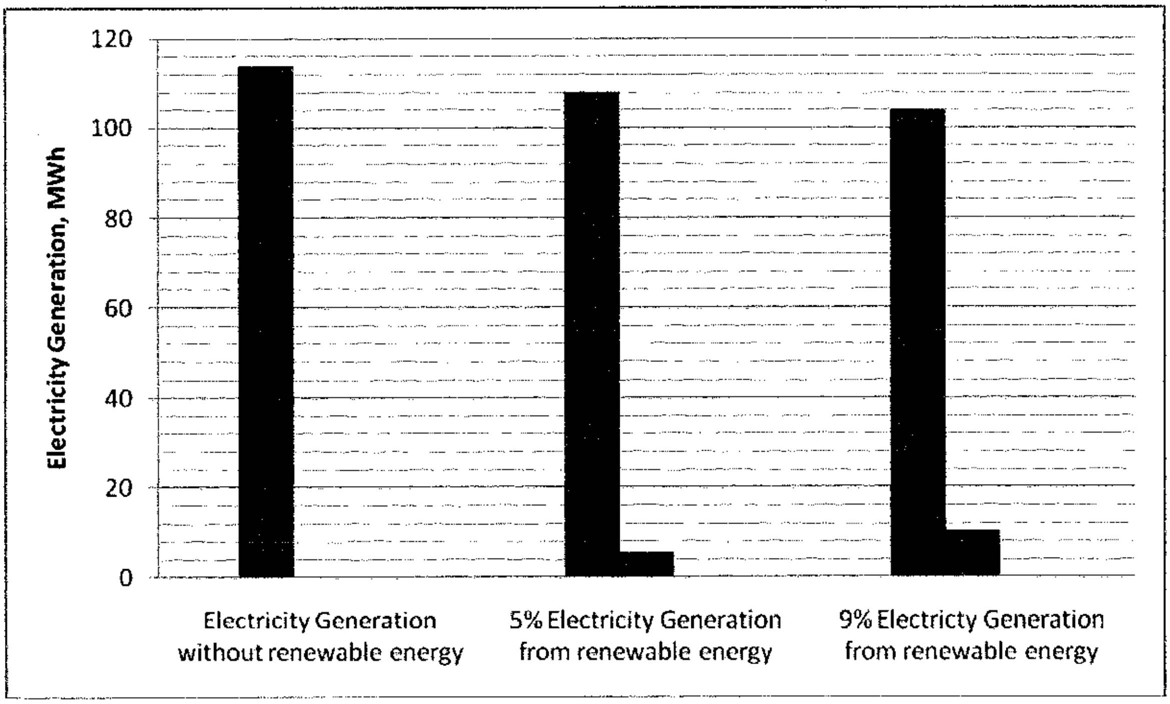

Figure 5: Electricity generation without renewable energy and with renewable energy

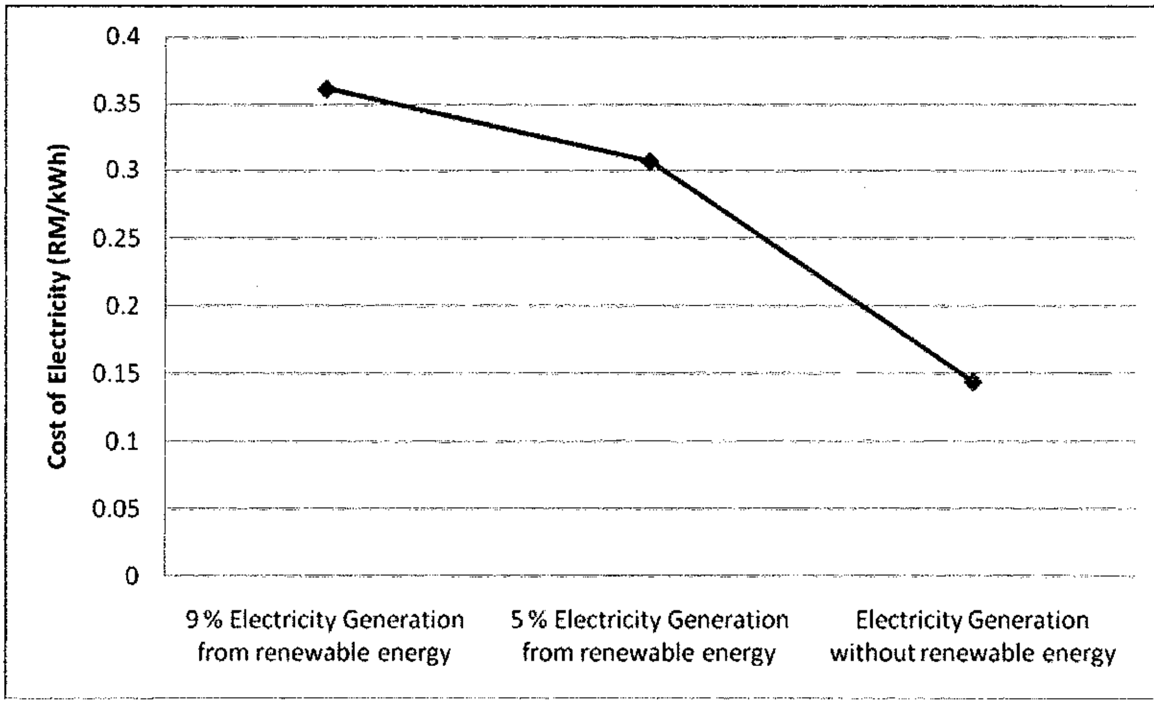

Figure 6: Cost of Electricity without renewable energy and with renewable energy

4.2 CO_2 emission reduction

Another thing that needs to discuss from this model is the impact of electricity generation for various CO_2 emission reduction while satisfying electricity demand at low cost. Three mitigation strategies including fuel balancing, fuel switching and installation new technology power plant were selected to achieve 0% and 30% and 50% CO_2 emission reduction target. However, if we want to further reduce CO_2 emission, we must mix renewable energy generation in power grid. The existing natural gas plant and hydroelectric plants were fully operational for the base case 0% reduction, 30% and 50%.

Fuel balancing and fuel switching to less carbon-intensive fuel such as natural gas and implementation of renewable energy were chosen to achieve 50% CO_2 reduction target. For example, boiler PK2 and PK6 in Pelabuhan Klang power station, boiler JM3 in Janamanjung, boiler TB1 in Tanjung Bin and boiler PG1 in Pasir Gudang will be switched to natural gas, two NGCC power plants and one nuclear plant were chosen to generate 284,570 MWh electricity per year, 3,331,000 MWh electricity per year and 850,000 MWh electricity per year respectively.

The total cost of electricity generation for CO_2 reduction target of 0% and 30% is RM 950 million. For 50% CO_2 reduction is RM 1.12 billion and this value is 18.2% higher than the total cost for 0% and 30% CO_2 reduction. From the results of the case studies, it can be concluded that IGCC, NGCC and nuclear power station are among the new technologies that need to be considered to satisfy more CO_2 emission reduction target. For specified CO_2 emission targets, hydroelectric and natural gas power station was recommended due to the emission free technology and low operating cost.

4.3 Effect of CO_2 Reduction towards Cost of Electricity and Electricity Generation for Consumer

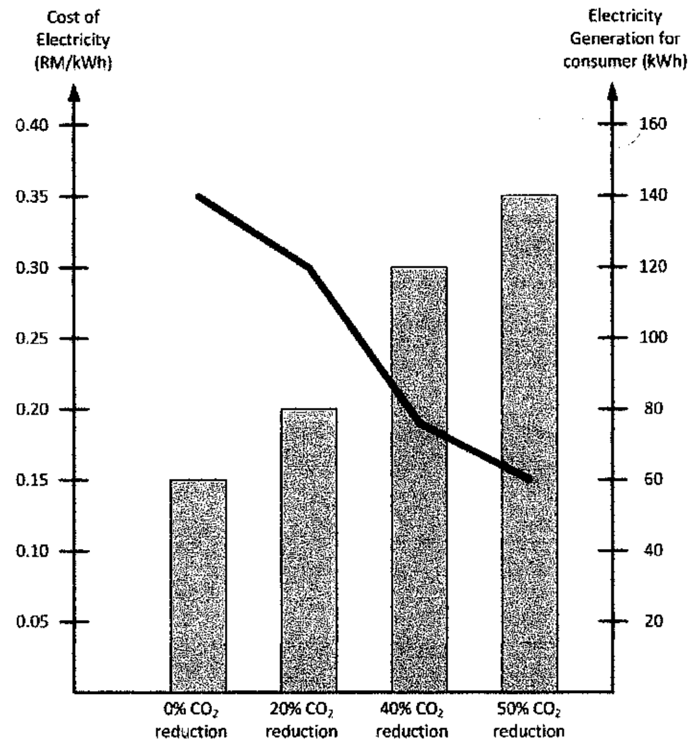

Figure 7: Effect of CO2 Reduction to cost and energy generation

Reduction of CO_2 emission causes the cost of electricity per kWh to increase and electricity generation for consumer decrease. At 0% CO_2 reduction, the cost of electricity per kWh is the lowest because all fossil-fuel power plants use coal. At 20% CO_2 reduction, fuel switching is introduced in objective function where some of fossil-fuel power plants are switch from coal to natural gas. Electricity generation for consumers per kWh is decreased because coal burn better compared to natural gas and all power plants are at same load.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From this modeling, I can conclude that it is feasible and essential to install CO_2 capture technology in Malaysia main power plants base on several justifications. One of the justifications is Malaysia is 26th largest greenhouse gases emitter in the world. This reputation is not very good for Malaysia's foreign direct investment because foreign investors do not want to contribute to the cause of increasing emission of CO_2 in Malaysia. In addition, we have to burn more fossil fuel and emit more CO_2 from our main power plant to feed the heavy industries that foreign investors brought in when they want to set up their factory and production in Malaysia. This problem can cause the rapid transformation of Malaysia economy to an industrialized over the last three decades came to stop.

Other justification is installing the CO_2 capture technology does not compromise the electricity generated by power grid for local usage because the existence of energy balance/demand satisfaction constraint inside the model. This constraint makes sure that when energy is used from power grid for CO_2 capture technology, the power grid is equal or more than customer demand satisfaction.

The CO_2 mitigation strategy using method fuel balancing and fuel switching to less carbon-intensive fuel is proved by this model that it can reduce the CO_2 emission by 50%. For instance, boiler PK2 and PK6 in Pelabuhan Klang power station, boiler JM3 in Janamanjung power station, boiler TB1 in Tanjung Bin power station and boiler PG1 in Pasir Gudang power station will be switched to natural gas, two NGCC power plants and one nuclear plant were chosen to generate 284,570 MWh electricity per year, 3,331,000 MWh electricity per year and 850,000 MWh electricity per year each respectively. The cost of electricity generation for 0% and 30% CO_2 reduction is RM 948,212,425.6. The total cost of electricity generation for 50% CO_2 reduction is RM 1,121,242,458. This is 18.2% higher than the total cost for 0% and 30% CO_2 reduction. New technologies such as IGCC, NGCC and nuclear power station need to be considered to satisfy further CO_2 emission reduction target.

5.2 Recommendation

Since the CO_2 technology is still on-going research and is not common practice even to power station around the globe, there are a few recommendation must be made in order to install this technology in Malaysia power plants.

One of recommendation is to consider emission trading, a market-based approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants.

Other recommendation is forestation which includes prevention of deforestation, afforestation (converting land back to forest), and reforestation (planting to create a new forest). This method can further reduce the emission of CO_2. Bioenergy farming is another sustainable approach for a fossil fuel replacement. If trees or plants can be used as a fuel that displaces fossil fuel use, then a net reduction in CO_2 emissions occurs.

Other method is cofiring biomass with coal and other fossil fuels. This option, which utilizes biofuel in a higher efficiency fossil fuel power plant, has been studied for many years.

Another interesting method is to use artificial photosynthesis. There has been on-going basic research to develop photochemical processes that mimic biological photosynthesis-converting solar energy into fixed chemical energy, using chlorophyll as a catalyst.

REFERENCES

A. Elkamel, H. Hashim, P. Douglas and E. Croiset. (2009). Optimization of Energy Usage for Fleet-Wide Power Generating System under Carbon Mitigation Options. AIChE Journal, Volume 55, Issue 12, Pages: 3168–3190.

B. Wicke, V. Dornburg, M. Junginger and A. Faaij. (2008). Different palm oil production systems for energy purposes and their green house gas implications. Biomass and Bioenergy, Volume 32, Issue 12, Pages: 1322-1337.

D. Singh, E. Croiset, P. Douglas and M. Douglas. (2003). Techno-Economic Study of CO_2 Capture, Energy Conversion and Management, Volume 44, Issue 19, Pages: 3073-3091.

E. Rubin, A. Rao and C. Chen. (2004). Comparative Assessments of Fossil Fuel Power Plants with CO_2 capture and storage, Energy Policy, Volume 35, Issue 9, Pages: 4444-4454.

H. Herzog, E. Adams, M. Akai and G. Alendal. (2002). Update of the International Experiment on CO_2 Sequestration, Environment Science Technology, Volume 36, Issue 21, Pages: 399-405.

N. Robert. (2003). Experience with Market-Based Environment Policy Instruments. Discussion Paper, Volume 1, Issue 9, Pages: 355-435.

T. Urmee, D. Harries, A. Schapfer. (2009). Issues Related to Rural Electrification Using Renewable Energy in Developing Countries of Asia and Pacific. Renewable Energy; Volume 34, Issue 2, Pages: 354-357.

Z. Muis, H. Hashim, Z. Manan, F. Taha and P. Douglas. (2010). Optimal Planning of Renewable Energy-Integrated Electricity Generation Schemes with CO_2 Reduction Target. Renewable Energy, Volume 35, Issue 11, Pages: 2562-2570.

APPENDIX

```
$TITLE CO2 FOR POWER PLANTS
$EOLCOM #
$ontext
*The objective of this model is to determine the best mix of power plants,
*fuels,annual capacity factor, CO2 capture and sequestration to meet the
*electricity demand while satisfying the CO2 reduction target at minimum
*cost.
$offtext
*
*.. list all sets
*
 Set
I fossil-fuel power plants
/
*Coal power plant
PK1*PK6          Pelabuhan Klang
JM1*JM3          Janamanjung
TB1*TB3          Tanjung Bin
PG1*PG2          Pasir Gudang
PR1*PR3          Prai
JIMAH1*JIMAH2       Jimah
*Natural gas power plant
Glugor
Pelabuhan Klang
Connaught_Bridge
Serdang
Pasir_Gudang
Paka
*Hydroelectric
Kenyir
Temenggor
Bersia
Kenering
Chenderoh
Jor
Pergau
Woh
Piah_Odak
NUCLEAR1
WIND1
*NEW POWER PLANTS WITHOUT CCS
PC11,PC12,PC13,PC14
PC21,PC22,PC23,PC24
IGCC11,IGCC12,IGCC13,IGCC14
IGCC21,IGCC22,IGCC23,IGCC24
IGCC31,IGCC32,IGCC33,IGCC34
NGCC11,NGCC12,NGCC13,NGCC14
NGCC21,NGCC22,NGCC23,NGCC24
NGCC31,NGCC32,NGCC33,NGCC34
*NEW POWER PLANTS WITH CCS
*PC1 PC1 w capture
PCcap11,PCcap12,PCcap13,PCcap14
*PC2 PC2 w capture
PCcap21,PCcap22,PCcap23,PCcap24
*PC3 PC3 w capture
PCcap31,PCcap32,PCcap33,PCcap34
*IC1 IGCC1 w capture
IGcap11,IGcap12,IGcap13,IGCAP14
*IC2 IGCC2 w capture
IGcap21,IGcap22,IGcap23,IGCAP24
*NC1 NGCC1 w capture
NGcap11,NGcap12,NGcap13,NGcap14
*NC2 NGCC2 w capture
NGcap21,NGcap22,NGcap23,NGcap24
/
   PP1(I) PC1         /PC11,PC12,PC13,PC14/
   PP2(I) PC2         /PC21,PC22,PC23,PC24/
   PI1(I) IGCC1        /IGCC11,IGCC12,IGCC13,IGCC14/
```

```
    PI2(I) IGCC2         /IGCC21,IGCC22,IGCC23,IGCC24/
    PI3(I) IGCC3         /IGCC31,IGCC32,IGCC33,IGCC34/
    PN1(I) NGCC1         /NGCC11,NGCC12,NGCC13,NGCC14/
    PN2(I) NGCC2         /NGCC21,NGCC22,NGCC23,NGCC24/
    PN3(I) NGCC3         /NGCC31,NGCC32,NGCC33,NGCC34/
    PC1(I) PC1 w capture  /PCcap11,PCcap12,PCcap13,PCcap14/
    PC2(I) PC2 w capture  /PCcap21,PCcap22,PCcap23,PCcap24/
    PC3(I) PC3 w capture  /PCcap31,PCcap32,PCcap33,PCcap34/
    IC1(I) IGCC1 w capture /IGcap11,IGcap12,IGcap13,IGCAP14/
    IC2(I) IGCC2 w capture /IGcap21,IGcap22,IGcap23,IGCAP24/
    NC1(I) NGCC1 w capture /NGcap11,NGcap12,NGcap13,NGcap14/
    NC2(I) NGCC2 w capture /NGcap21,NGcap22,NGcap23,NGcap24/
FOSSIL(I)   fossil-fuel power stations
/
PK1*PK6
JM1*JM3
TB1*TB3
PG1*PG2
PR1*PR3
JIMAH1*JIMAH2
Glugor
Pelabuhan Klang
Connaught_Bridge
Serdang
Pasir_Gudang
Paka
/

NONFOSSIL(I)   non-fossil-fuel power stations
/
Kenyir
Temenggor
Bersia
Kenering
Chenderoh
Jor
Pergau
Woh
Piah_Odak
NUCLEAR1
WIND1
/
PK(I)     Pelabuhan Klang /PK1*PK6/
JM(I)     Janamanjung    /JM1*JM3/
TB(I)     Tanjung Bin    /TB1*TB3/
PG(I)     Pasir Gudang   /PG1*PG2/
PR(I)     Prai           /PR1*PR3/
JIMAH(I)  Jimah          /JIMAH1*JIMAH2/
N(I)  nuclear      /NUCLEAR1/
H(I)  hydroelectric   /Kenyir
                Temenggor
                Bersia
                Kenering
                Chenderoh
                Jor
                Pergau
                Woh
                Piah_Odak/
W(I)  wind         /WIND1/
*new power plants
Pnew(I)    fossil-fuel power stations without capture
/
*PC1 wo capture
PC11,PC12,PC13,PC14
*PC2 wo capture
PC21,PC22,PC23,PC24
*IGCC1 wo capture
IGCC11,IGCC12,IGCC13,IGCC14
*IGCC1 wo capture
IGCC21,IGCC22,IGCC23,IGCC24
*NGCC1 wo capture
NGCC11,NGCC12,NGCC13,NGCC14
*NGCC2 wo capture
```

```
NGCC21,NGCC22,NGCC23,NGCC24
*NGCC3 wo capture
NGCC31,NGCC32,NGCC33,NGCC34
/
Pnew_cap(I)   fossil-fuel power stations with capture
/
*PC1 PC1 w capture
PCcap11,PCcap12,PCcap13,PCcap14
*PC2 PC2 w capture
PCcap21,PCcap22,PCcap23,PCcap24
*PC3 PC3 w capture
PCcap31,PCcap32,PCcap33,PCcap34
*IC1 IGCC1 w capture
IGcap11,IGcap12,IGcap13,IGCAP14
*IC2 IGCC2 w capture
IGcap21,IGcap22,IGcap23,IGCAP24
*NC1 NGCC1 w capture
NGcap11,NGcap12,NGcap13,NGcap14
*NC2 NGCC2 w capture
NGcap21,NGcap22,NGcap23,NGcap24
/
j  fuels         /coal,ng/
   k  capture process /MEA/
   s  sequestration location /Erie, Huron/
PP1_PC1(PP1,PC1)
/
PC11.PCcap11
PC12.PCcap12
PC13.PCcap13
PC14.PCcap14
/
PP2_PC2(PP2,PC2)
/
PC21.PCcap21
PC22.PCcap22
PC23.PCcap23
PC24.PCcap24
/
PI1_IC1(PI1,IC1)
/
IGCC11.IGcap11
IGCC12.IGcap12
IGCC13.IGcap13
IGCC14.IGCAP14
/
PI2_IC2(PI2,IC2)
/
IGCC21.IGcap21
IGCC22.IGcap22
IGCC23.IGcap23
IGCC24.IGCAP24
/
PN1_NC1(PN1,NC1)
/
NGCC11.NGcap11
NGCC12.NGcap12
NGCC13.NGcap13
NGCC14.NGcap14
/
PN2_NC2(PN2,NC2)
/
NGCC21.NGcap21
NGCC22.NGcap22
NGCC23.NGcap23
NGCC24.NGcap24
/
;
*
*.. list all scalars
*
 Scalar MaxE    Electricity generated at peak time (MWe) /13764/;
 Scalar Optime  Annual operating time (hr per year) /8760/;
 Scalar CO2     CO2 emission in tonne per year /36720000/;
```

```
 Scalar CO2red  Percent of CO2 reduction /0.6/;
PARAMETER Cnf(I)
/
Kenyir     1.67    # variable operating & maintenance (O&M) cost for hydroelectric (RM per MWh)
Temenggor  1.67
Bersia     1.67
Kenering   1.67
Chenderoh  1.67
Jor        1.67
Pergau     1.67
Woh        1.67
Piah_Odak  1.67
NUCLEAR1   21.33   # variable operating & maintenance (O&M) cost for nuclear ($ per MWh)
WIND1      2.67    # Operating cost for wind ($ per MWh)
*new               # Operating cost for wind ($ per MWh)
/
 Scalar R       allowable electricity increment /0.01/;
 Scalar Lower   ACF lower bound /0.1/;
 Scalar ACF     Annual capacity factor for new stations /0.75/;
 Scalar AF      Ammortized factor /0.15/;
 Scalar Rcost   Retrofit cost factor due to fuel switching($M20 per 1000 MW)/20000/;
 Scalar perCCS  percent CO2 capture /0.9/;
* Scalar ccsPC  cost of CO2 capture for existing PC ($ per ton CO2 capture) /34/
* Scalar ccsNG  cost of CO2 capture for existing NG ($ per ton CO2 capture) /41/
* Scalar Ereq   Elec required for CO2 capture (MWh per tonne CO2 capture)/0.317/;
PARAMETER HR(I)
/
*PP1 9.12  #heat rate for PP1 (GJ per MWh)
PC11*PC14  9.12
*PC11,PC12,PC13,PC14
*heat rate for PP2 (GJ per MWh)
PC21*PC24  9.16
*hrPI1  heat rate for PI1 (GJ per MWh)
IGCC11*IGCC14   7.37
*hrPI2  heat rate for PI2 (GJ per MWh)
IGCC21*IGCC24   7.9
*hrPI3  heat rate for PI3 (GJ per MWh)
IGCC31*IGCC34   8.78
*hrPN1  heat rate for P1 (GJ per MWh)
NGCC11*NGCC14   7.1
*hrPN2  heat rate for PN2 (GJ per MWh)
NGCC21*NGCC24   6.74
*hrPN3  heat rate for PN3 (GJ per MWh)
NGCC31*NGCC34   6.37
/
 Scalar hrPC1   heat rate for PC1 (GJ per MWh) /12.19/;
 Scalar hrPC2   heat rate for PC2 (GJ per MWh) /12.17/;
 Scalar hrPC3   heat rate for PC3 (GJ per MWh) /12.1/;
 Scalar hrIC1   heat rate for IC1 (GJ per MWh) /10.46/;
 Scalar hrIC2   heat rate for IC2 (GJ per MWh) /9.97/;
 Scalar hrNC1   heat rate for NC1 (GJ per MWh) /7.48/;
 Scalar hrNC2   heat rate for NC2 (GJ per MWh) /7.8/;
 Scalar Pcoal   price of coal ($ per GJ) /1.2/; #fuel cost ($/ton) ?? need to convert to RM per GJ
 Scalar NGcost  price of ng ($ per GJ) /4.0/;
 Scalar sen     sensitivity analysis for capital cost /1.0/;
 Scalar MaxCap  maximum energy requirement for capture (MWh per yr)/1000000000/;
 Scalar M       big number used in CO2 emission constraints /1E13/;
 Scalar Ms      big number used in linearization for CCS retrofit /1E13/;
 Scalar Mp      big number used in linearization for new plant w cap /1E13/;
 Scalar Egrowth Electricity growth rate /0.100/;
*
*.. list all parameters
*
 Parameters
*
*.. Maximum electricity generation (MWh per yr) for existing power stations
*
 PKmax(PK)      Pelabuhan Klang net electricity generation(MWh per year)
 /PK1       639918
  PK2       639918
  PK3       639918
  PK4       639918
  PK5       639918
```

```
  PK6         639918/
JMmax(JM)       Jamanjung net electricity generation(MWh per year)
 /JM1         1254870
  JM2         1254870
  JM3         1254870/
TBmax(TB)       Tanjung Bin net electricity generation(MWh per year)
 /TB1         1254870
  TB2         1254870
  TB3         1254870/
PGmax(PG)       Pasir Gudang net electricity generation(MWh per year)
 /PG1         646926
  PG2         646926/
PRmax(PR)       Prai net electricity generation(MWh per year)
 /PR1         1073100
  PR2         1073100
  PR3         1073100/
JIMAHmax(JIMAH)  Jimah Bay net electricity generation(MWh per year)
 /JIMAH1       745000
  JIMAH2       745000/
*
*.. Installed capacity (MW) for new candidate power plants without capture
*
PARAMETER Pmax(I)
/
*PP1max(PP1)   PC1 new stations net power generation (MWh per year)
  PC11        4012080
  PC12        4012080
  PC13        4012080
  PC14        4012080
*PP2max(PP2)   PC2 new stations net power generation (MWh per year)
  PC21        4590240
  PC22        4590240
  PC23        4590240
  PC24        4590240
*PI1max(PI1)   IGCC1 new stations net power generation (MWh per year)
  IGCC11       2190000
  IGCC12       2190000
  IGCC13       2190000
  IGCC14       2190000
*PI2max(PI2)   IGCC2 new stations net power generation (MWh per year)
  IGCC21       3066000
  IGCC22       3066000
  IGCC23       3066000
  IGCC24       3066000
*PI3max(PI3)   IGCC3 new stations net power generation (MWh per year)
  IGCC31       5107080
  IGCC32       5107080
  IGCC33       5107080
  IGCC34       5107080
*PN1max(PN1)   NGCC1 new stations net power generation (MWh per year)
  NGCC11       2856636
  NGCC12       2856636
  NGCC13       2856636
  NGCC14       2856636
*PN2max(PN2)   NGCC2 new stations net power generation (MWh per year)
  NGCC21       3460200
  NGCC22       3460200
  NGCC23       3460200
  NGCC24       3460200
*PN3max(PN3)   NGCC3 new stations net power generation (MWh per year)
  NGCC31       4441320
  NGCC32       4441320
  NGCC33       4441320
  NGCC34       4441320
/
parameters
PP1max(PP1)   PC1 new stations net power generation (MWh per year)
/ PC11        4012080
  PC12        4012080
  PC13        4012080
  PC14        4012080
/
PP2max(PP2)   PC2 new stations net power generation (MWh per year)
```

```
/ PC21      4590240
  PC22      4590240
  PC23      4590240
  PC24      4590240/
PI1max(PI1)  IGCC1 new stations net power generation (MWh per year)
/ IGCC11     2190000
  IGCC12     2190000
  IGCC13     2190000
  IGCC14     2190000/
PI2max(PI2)  IGCC2 new stations net power generation (MWh per year)
/ IGCC21     3066000
  IGCC22     3066000
  IGCC23     3066000
  IGCC24     3066000 /
PI3max(PI3)  IGCC3 new stations net power generation (MWh per year)
/ IGCC31     5107080
  IGCC32     5107080
  IGCC33     5107080
  IGCC34     5107080 /
PN1max(PN1)   NGCC1 new stations net power generation (MWh per year)
/ NGCC11     2856636
  NGCC12     2856636
  NGCC13     2856636
  NGCC14     2856636 /
PN2max(PN2)   NGCC2 new stations net power generation (MWh per year)
/ NGCC21     3460200
  NGCC22     3460200
  NGCC23     3460200
  NGCC24     3460200 /
PN3max(PN3)   NGCC3 new stations net power generation (MWh per year)
/ NGCC31     4441320
  NGCC32     4441320
  NGCC33     4441320
  NGCC34     4441320
/
*
*..Net power generation (MW) for new candidate power plants with capture
*
parameter Pmax_cap(I)
/
*PC1max(PC1)   PC1 with capture new stations net power generation (MWh per year)
  PCcap11     2987160
  PCcap12     2987160
  PCcap13     2987160
  PCcap14     2987160
*PC2max(PC2)   PC2 with capture new stations net power generation (MWh per year)
  PCcap21     4012080
  PCcap22     4012080
  PCcap23     4012080
  PCcap24     4012080
*PC3max(PC3)   PC3 with capture new stations net power generation (MWh per year)
  PCcap31     4309920
  PCcap32     4309920
  PCcap33     4309920
  PCcap34     4309920
*IC1max(IC1)   IGCC1 with capture new stations net power generation (MWh per year)
  IGcap11     4283640
  IGcap12     4283640
  IGcap13     4283640
  IGcap14     4283640
*IC2max(IC2)   IGCC2 with capture new stations net power generation (MWh per year)
  IGcap21     4493880
  IGcap22     4493880
  IGcap23     4493880
  IGcap24     4493880
*NC1max(NC1)   NGCC1 with capture new stations net power generation (MWh per year)
  NGcap11     3784320
  NGcap12     3784320
  NGcap13     3784320
  NGcap14     3784320
*NC2max(NC2)   NGCC2 with capture new stations net power generation (MWh per year)
  NGcap21     6570000
  NGcap22     6570000
```

```
 NGcap23     6570000
 NGcap24     6570000
/
Parameters
PC1max(PC1)   PC1 with capture new stations net power generation (MWh per year)
/ PCcap11     2987160
  PCcap12     2987160
  PCcap13     2987160
  PCcap14     2987160/
PC2max(PC2)   PC2 with capture new stations net power generation (MWh per year)
/ PCcap21     4012080
  PCcap22     4012080
  PCcap23     4012080
  PCcap24     4012080/
PC3max(PC3)   PC3 with capture new stations net power generation (MWh per year)
/ PCcap31     4309920
  PCcap32     4309920
  PCcap33     4309920
  PCcap34     4309920/
IC1max(IC1)   IGCC1 with capture new stations net power generation (MWh per year)
/ IGcap11     4283640
  IGcap12     4283640
  IGcap13     4283640
  IGcap14     4283640/
IC2max(IC2)   IGCC2 with capture new stations net power generation (MWh per year)
/ IGcap21     4493880
  IGcap22     4493880
  IGcap23     4493880
  IGcap24     4493880/
NC1max(NC1)   NGCC1 with capture new stations net power generation (MWh per year)
/ NGcap11     3784320
  NGcap12     3784320
  NGcap13     3784320
  NGcap14     3784320/
NC2max(NC2)   NGCC2 with capture new stations net power generation (MWh per year)
/ NGcap21     6570000
  NGcap22     6570000
  NGcap23     6570000
  NGcap24     6570000/
*
*.. Actual electricity generation (MWh per yr) for existing power plants
*
ElecPK(PK)     Pelabuhan Klang actual electricity generation in MWh per year
/PK1         639918
 PK2         639918
 PK3         639918
 PK4         639918
 PK5         639918
 PK6         639918/
ElecJM(JM)     Jamanjung actual electricity generation in MWh per year
/JM1         1254870
 JM2         1254870
 JM3         1254870/
ElecTB(TB)     Tanjung Bin actual electricity generation in MWh per year
/TB1         1254870
 TB2         1254870
 TB3         1254870/
ElecPG(PG)     Pasir Gudang actual electricity generation in MWh per year
/PG1         646926
 PG2         306875/
ElecPR(PR)     Prai actual electricity generation in MWh per year
/PR1         1073100
 PR2         1073100
 PR3         1073100/
ElecJIMAH(JIMAH)   Jimah actual electricity generation in MWh per year
/JIMAH1       745000
 JIMAH2       745000/
ElecN(N)       Nuclear actual electricity generation in MWh per year
/NUCLEAR1       14300000/
ElecH(H)       Hydroelectric actual electricity generation in MWh per year
/Kenyir       1486100
 Temenggor     823900
 Bersia       231000
```

```
 Kenering     427000
 Chenderoh    154700
 Jor        280700
 Pergau       457800
 Woh          429800
 Piah_Odak    315000/
ElecW(W)      Wind actual electricity generation in MWh per year
 /WIND1      713000/;
*
*..Operational cost ($ per MWh) for existing fossil stations
*
PARAMETER aa(I)
/
PCcap11    0.9
PCcap12    0.9
PCcap13    0.9
PCcap14    0.9
PCcap21    0.9
PCcap22    0.9
PCcap23    0.9
PCcap24    0.9
PCcap31    0.9
PCcap32    0.9
PCcap33    0.9
PCcap34    0.9
IGcap11    0.8
IGcap12    0.8
IGcap13    0.8
IGCAP14     0.8
IGcap21    0.6
IGcap22    0.6
IGcap23    0.6
IGCAP24     0.6
NGcap11     0.9
NGcap12     0.9
NGcap13     0.9
NGcap14     0.9
NGcap21     0.9
NGcap22     0.9
NGcap23     0.9
NGcap24     0.9
/
;
PARAMETER bb(I)
/
PCcap11    0.1
PCcap12    0.1
PCcap13    0.1
PCcap14    0.1
PCcap21    0.1
PCcap22    0.1
PCcap23    0.1
PCcap24    0.1
PCcap31    0.1
PCcap32    0.1
PCcap33    0.1
PCcap34    0.1
IGcap11    0.2
IGcap12    0.2
IGcap13    0.2
IGCAP14     0.2
IGcap21    0.4
IGcap22    0.4
IGcap23    0.4
IGCAP24     0.4
NGcap11     0.1
NGcap12     0.1
NGcap13     0.1
NGcap14     0.1
NGcap21     0.1
NGcap22     0.1
NGcap23     0.1
NGcap24     0.1
```

```
/
;
TABLE C(I,J)
*OprPK(PK,j) Pelabuhan Klang operational cost (RM per MWh)
        coal    ng
  PK1     69     138
  PK2     69     138
  PK3     69     138
  PK4     69     138
  PK5     69     138
  PK6     69     138
*OprJM(JM,j) Jamanjung operational cost (RM per MWh)
  JM1     69     138
  JM2     69     138
  JM3     69     138
*OprTB(TB,j) Tanjung Bin operational cost (RM per MWh)
  TB1     69     138
  TB2     69     138
  TB3     69     138
*OprPG(PG,j) Pasir Gudang operational cost (RM per MWh)
  PG1     69     138
  PG2     69     138
*OprPR(PR,j) Prai operational cost (RM per MWh)
  PR1     69     138
  PR2     69     138
  PR3     69     138
*OprJ(JIMAH,j)  Jimah operational cost (RM per MWh)
  JIMAH1   69     138
  JIMAH2   69     138
;
*=====================================================================
*CO2 emissions (tonne per MWh) from existing fossil-fuel-based power stations
*=====================================================================
Table CO2emission(I,j) CO2 emissions from existing fossil-fuel-based power stations (tonne per MWh)
*CO2PK(PK,j) CO2 emission from Pelabuhan Klang (tonne per MWh)
        coal    ng
  PK1     0.063   0.023
  PK2     0.063   0.023
  PK3     0.063   0.023
  PK4     0.063   0.023
  PK5     0.063   0.023
  PK6     0.063   0.023
*CO2JM(JM,j) CO2 emission from Jamanjung (tonne per MWh)
  JM1     0.316   0.169
  JM2     0.316   0.169
  JM3     0.316   0.169
*CO2TB(TB,j) CO2 emission from Tanjung Bin (tonne per MWh)
  TB1     0.461   0.291
  TB2     0.461   0.291
  TB3     0.461   0.291
*CO2PG(PG,j) CO2 emission from Pasir Gudang (tonne per MWh)
  PG1     1.50    0.317
  PG2     1.50    0.317
*CO2LN(PR,j) CO2 emission from Prai (tonne per MWh)
  PR1     0.651   0.651
  PR2     0.651   0.651
  PR3     0.651   0.651
*CO2JIMAH(JIMAH,j) CO2 emission from Jimah (tonne per MWh)
  JIMAH1   1.023   0.6138
  JIMAH2   1.023   0.6138;
TABLE CO2PK(PK,j) CO2 emission from Pasir Gudang (tonne per MWh)
        coal    ng
  PK1     0.063   0.023
  PK2     0.063   0.023
  PK3     0.063   0.023
  PK4     0.063   0.023
  PK5     0.063   0.023
  PK6     0.063   0.023
;
TABLE CO2JM(JM,j) emission from Jamanjung (tonne per MWh)
        coal    ng
  JM1     0.316   0.169
  JM2     0.316   0.169
```

```
 JM3     0.316    0.169
;
TABLE CO2TB(TB,j) CO2 emission from Tanjung Bin (tonne per MWh)
         coal     ng
  TB1     0.461    0.291
  TB2     0.461    0.291
  TB3     0.461    0.291
;
TABLE CO2PG(PG,j) CO2 emission from Pasir Gudang (tonne per MWh)
         coal     ng
  PG1     1.50     0.317
  PG2     1.50     0.317
;
TABLE CO2PR(PR,j) CO2 emission from Prai (tonne per MWh)
         coal     ng
  PR1     0.651    0.651
  PR2     0.651    0.651
  PR3     0.651    0.651
;
TABLE CO2JIMAH(JIMAH,j) CO2 emission from Jimah (tonne per MWh)
         coal     ng
  JIMAH1    1.023    0.6138
  JIMAH2    1.023    0.6138
;
*
*.. Capital cost ($ per MW) for new plants without capture
*
 parameter Cnew(I)
/
*PP1cost(PP1) capital cost for new PC ($ per MW)
  PC11    5049600
  PC12    5049600
  PC13    5049600
  PC14    5049600
*PP2cost(PP2) capital cost for new PC ($ per MW)
  PC21    5049600
  PC22    5049600
  PC23    5049600
  PC24    5049600
*PI1cost(PI1) capital cost for new IGCC ($ per MW)
  IGCC11   6787200
  IGCC12   6787200
  IGCC13   6787200
  IGCC14   6787200
*PI2cost(PI2) capital cost for new IGCC ($ per MW)
  IGCC21   6787200
  IGCC22   6787200
  IGCC23   6787200
  IGCC24   6787200
*PI3cost(PI3) capital cost for new IGCC ($ per MW)
  IGCC31   6787200
  IGCC32   6787200
  IGCC33   6787200
  IGCC34   6787200
*PN1cost(PN1) capital cost for new NGCC ($ per MW)
  NGCC11   1974400
  NGCC12   1974400
  NGCC13   1974400
  NGCC14   1974400
*PN2cost(PN2) capital cost for new NGCC ($ per MW)
  NGCC21   1974400
  NGCC22   1974400
  NGCC23   1974400
  NGCC24   1974400
*PN3cost(PN3) capital cost for new NGCC ($ per MW)
  NGCC31   1974400
  NGCC32   1974400
  NGCC33   1974400
  NGCC34   1974400
/
*===================================================================
*.. capital cost ($ per MW) for new plants with capture (REFERENCE: Rubin et al. (2007), p. 4446, Table 1: total capital requirement with capture)
```

```
*================================================================
parameter Cnew_cap(I)
/
*PC1cost(PC1) capital cost for new PC with capture ($ per MW)
  PCcap11  6707200
  PCcap12  6707200
  PCcap13  6707200
  PCcap14  6707200
*PC2cost(PC2) capital cost for new PC with capture ($ per MW)
  PCcap21  6707200
  PCcap22  6707200
  PCcap23  6707200
  PCcap24  6707200
*PC3cost(PC3) capital cost for new PC with capture ($ per MW)
  PCcap31  6707200
  PCcap32  6707200
  PCcap33  6707200
  PCcap34  6707200
*IC1cost(IC1) capital cost for new IGCC with capture ($ per MW)
  IGcap11  5840000
  IGcap12  5840000
  IGcap13  5840000
  IGcap14  5840000
*IC2cost(IC2) capital cost for new IGCC with capture ($ per MW)
  IGcap21  5840000
  IGcap22  5840000
  IGcap23  5840000
  IGCap24  5840000
*NC1cost(NC1) capital cost for new NGCC with capture ($ per MW)
  NGcap11  3193600
  NGcap12  3193600
  NGcap13  3193600
  NGcap14  3193600

*NC2cost(NC2) capital cost for new NGCC with capture ($ per MW)
  NGcap21  3193600
  NGcap22  3193600
  NGcap23  3193600
  NGcap24  3193600
/
*
*.. operational cost ($ per MWh) for new power plants without capture
*
parameter OPEXnew(I)
/
*PP1Op(PP1) O&M cost for new PC ($ per MWh)
  PC11    9.184
  PC12    9.184
  PC13    9.184
  PC14    9.184
*PP2Op(PP2) O&M cost for new PC ($ per MWh)
  PC21    9.184
  PC22    9.184
  PC23    9.184
  PC24    9.184
*PI1Op(PI1) O&M cost for new IGCC ($ per MWh)
  IGCC11   3.968
  IGCC12   3.968
  IGCC13   3.968
  IGCC14   3.968
*PI2Op(PI2) O&M cost for new IGCC ($ per MWh)
  IGCC21   3.968
  IGCC22   3.968
  IGCC23   3.968
  IGCC24   3.968
*PI3Op(PI3) O&M cost for new IGCC ($ per MWh)
  IGCC31   3.968
  IGCC32   3.968
  IGCC33   3.968
  IGCC34   3.968
*PN1Op(PN1) O&M cost for new NGCC ($ per MWh)
  NGCC11   8.64
  NGCC12   8.64
```

```
  NGCC13   8.64
  NGCC14   8.64
*PN2Op(PN2) O&M cost for new NGCC ($ per MWh)
  NGCC21   8.64
  NGCC22   8.64
  NGCC23   8.64
  NGCC24   8.64
*PN3Op(PN3) O&M cost for new NGCC ($ per MWh)
  NGCC31   8.64
  NGCC32   8.64
  NGCC33   8.64
  NGCC34   8.64
/
*
*.. operational cost ($ per MWh) for new power plants with capture
*
parameter PP1Op(PP1) O&M cost for new PC ($ per MWh)
 /PC11    2.53
  PC12    2.53
  PC13    2.53
  PC14    2.53/
 parameter PP2Op(PP2) O&M cost for new PC ($ per MWh)
 /PC21    2.47
  PC22    2.47
  PC23    2.47
  PC24    2.47/
 parameter PI1Op(PI1) O&M cost for new IGCC ($ per MWh)
 /IGCC11   8.61
  IGCC12   8.61
  IGCC13   8.61
  IGCC14   8.61/
 parameter PI2Op(PI2) O&M cost for new IGCC ($ per MWh)
 /IGCC21   6.91
  IGCC22   6.91
  IGCC23   6.91
  IGCC24   6.91/
parameter PN1Op(PN1) O&M cost for new NGCC ($ per MWh)
 /NGCC11   8.1
  NGCC12   8.1
  NGCC13   8.1
  NGCC14   8.1/
 parameter PN2Op(PN2) O&M cost for new NGCC ($ per MWh)
 /NGCC21   9.37
  NGCC22   9.37
  NGCC23   9.37
  NGCC24   9.37/
parameter PC1Op(PC1) O&M cost for new PC with capture ($ per MWh)
 /PCcap11   18.03
  PCcap12   18.03
  PCcap13   18.03
  PCcap14   18.03/;
 parameter PC2Op(PC2) O&M cost for new PC with capture ($ per MWh)
 /PCcap21   18.06
  PCcap22   18.06
  PCcap23   18.06
  PCcap24   18.06/;
parameter PC3Op(PC3) O&M cost for new PC with capture ($ per MWh)
 /PCcap31   18.16
  PCcap32   18.16
  PCcap33   18.16
  PCcap34   18.16/;
 parameter IC1Op(IC1) O&M cost for new IGCC with capture ($ per MWh)
 /IGcap11   7.59
  IGcap12   7.59
  IGcap13   7.59
  IGcap14   7.59/;
 parameter IC2Op(IC2) O&M cost for new IGCC with capture ($ per MWh)
 /IGcap21   7.11
  IGcap22   7.11
  IGcap23   7.11
  IGcap24   7.11/;
parameter NC1Op(NC1) O&M cost for new NGCC with capture ($ per MWh)
 /NGcap11   9.68
```

```
 NGcap12  9.68
 NGcap13  9.68
 NGcap14  9.68/;
parameter NC2Op(NC2) O&M cost for new NGCC with capture ($ per MWh)
/NGcap21  5.3
 NGcap22  5.3
 NGcap23  5.3
 NGcap24  5.3/;
*==========================================================================
*CO2 emissions (tonne per MWh) from new  power plants without capture
*==========================================================================
parameter CO2PP1(PP1) CO2 emissions from new PC without capture (ton per MWh))
/PC11    0.762
 PC12    0.762
 PC13    0.762
 PC14    0.762/;
parameter CO2PP2(PP2) CO2 emissions from new PC (tonne per MWh)
/PC21    0.762
 PC22    0.762
 PC23    0.762
 PC24    0.762/;
parameter CO2PI1(PI1) CO2 emissions from new IGCC (tonne per MWh)
/IGCC11    0.773
 IGCC12    0.773
 IGCC13    0.773
 IGCC14    0.773/
parameter CO2PI2(PI2) CO2 emissions from new IGCC (tonne per MWh)
/IGCC21    0.773
 IGCC22    0.773
 IGCC23    0.773
 IGCC24    0.773/;
parameter CO2PI3(PI3) CO2 emissions from new IGCC (tonne per MWh)
/IGCC31    0.773
 IGCC32    0.773
 IGCC33    0.773
 IGCC34    0.773/;
parameter CO2PN1(PN1) CO2 emissions from new NGCC (tonne per MWh)
/NGCC11    0.367
 NGCC12    0.367
 NGCC13    0.367
 NGCC14    0.367/;
parameter CO2PN2(PN2) CO2 emissions from new NGCC (tonne per MWh)
/NGCC21    0.367
 NGCC22    0.367
 NGCC23    0.367
 NGCC24    0.367/;
parameter CO2PN3(PN3) CO2 emissions from new NGCC (tonne per MWh)
/NGCC31    0.367
 NGCC32    0.367
 NGCC33    0.367
 NGCC34    0.367/;
*==========================================================================
*..CO2 emissions (tonne per MWh) from new  power plants with capture
*==========================================================================
parameter CO2new_cap(I) CO2 emissions from new PC with capture(tonne per MWh)
/
* parameter CO2PC1(PC) CO2 emissions from new PC with capture (tonne per MWh)
  PCcap11  0.112
  PCcap12  0.112
  PCcap13  0.112
  PCcap14  0.112
* parameter CO2PC2(I) CO2 emissions from new PC with capture(tonne per MWh)
  PCcap21  0.112
  PCcap22  0.112
  PCcap23  0.112
  PCcap24  0.112
*  parameter CO2PC3(I) CO2 emissions from new PC with capture(tonne per MWh)
  PCcap31  0.112
  PCcap32  0.112
  PCcap33  0.112
  PCcap34  0.112
*parameter CO2IC1(I) CO2 emissions from new IGCC with capture (tonne per MWh)
  IGcap11 0.108
```

```
  IGcap12  0.108
  IGcap13  0.108
  IGcap14  0.108
*parameter CO2IC2(I) CO2 emissions from new IGCC with capture (tonne per MWh)
  IGcap21  0.108
  IGcap22  0.108
  IGcap23  0.108
  IGcap24  0.108
*parameter CO2NC1(I) CO2 emissions from new NGCC with capture(tonne per MWh)
  NGcap11  0.052
  NGcap12  0.052
  NGcap13  0.052
  NGcap14  0.052
* parameter CO2NC2(I) CO2 emissions from new NGCC with capture(tonne per MWh)
  NGcap21  0.052
  NGcap22  0.052
  NGcap23  0.052
  NGcap24  0.052
/
parameter CO2PC1(I) CO2 emissions from new PC with capture (tonne per MWh)
 /PCcap11  0.112
  PCcap12  0.112
  PCcap13  0.112
  PCcap14  0.112/
parameter CO2PC2(I) CO2 emissions from new PC with capture(tonne per MWh)
 /PCcap21  0.112
  PCcap22  0.112
  PCcap23  0.112
  PCcap24  0.112/
parameter CO2PC3(I) CO2 emissions from new PC with capture(tonne per MWh)
 /PCcap31  0.112
  PCcap32  0.112
  PCcap33  0.112
  PCcap34  0.112/
parameter CO2IC1(I) CO2 emissions from new IGCC with capture (tonne per MWh)
 /IGcap11  0.108
  IGcap12  0.108
  IGcap13  0.108
  IGcap14  0.108/
parameter CO2IC2(I) CO2 emissions from new IGCC with capture (tonne per MWh)
 /IGcap21  0.108
  IGcap22  0.108
  IGcap23  0.108
  IGcap24  0.108/
parameter CO2NC1(I) CO2 emissions from new NGCC with capture(tonne per MWh)
 /NGcap11  0.052
  NGcap12  0.052
  NGcap13  0.052
  NGcap14  0.052/
parameter CO2NC2(I) CO2 emissions from new NGCC with capture(tonne per MWh)
 /NGcap21  0.052
  NGcap22  0.052
  NGcap23  0.052
  NGcap24  0.052/
*===============================================================================
* CCS retrofit cost (RM per per tonne CO2 captured) due to capture process on existing fossil fuel stations
*===============================================================================
 parameter  CCScost_existing(I)  CO2 capture cost for existing power plants ($ per tonne CO2 captured)
/
*ccsPK(PK) capture cost from Pelabuhan Klang (RM per ton CO2 captured)
  PK1    144.43
  PK2    144.43
  PK3    144.43
  PK4    144.43
  PK5    144.43
  PK6    144.43
/
parameter  ccsJM(JM) capture cost for Jamanjung (RM per ton CO2 captured)
 /JM1    144.43
  JM2    144.43
  JM3    144.43/;
 parameter  ccsTB(TB) capture cost for Tanjung Bin (RM per ton CO2 captured)
 /TB1    144.43
```

```
 TB2   144.43
 TB3   144.43/;
parameter  ccsPG(PG) capture cost for Pasir Gudang (RM per ton CO2 captured)
 /PG1    144.43
 PG2   144.43/;
* Table  ccsLN(LN,s) capture cost for Lennox ($ per tonne CO2 capture)
*        erie   huron
*  LN1   300    300
*  LN2   300    300
*  LN3   300    300
*  LN4   300    300 ;
parameter  ccsPR(PR) capture cost from Thunder Bay (RM per tonne CO2 captured)
 /PR1   144.43
 PR2   144.43
 PR3   144.43/;
*Change the data base on Malaysia case
*=====================================================================
* Electricity required for CO2 capture: consider using the formula "(inverse of cost of electricity (COE) (MWh/RM)) (note: COE is in
RM/MWh) * (cost of CO2 avoided (RM/ton CO2))"
*=====================================================================
Table  EreqPK(PK,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
       coal   ng
 PK1    0.317  0.356
 PK2    0.317  0.356
 PK3    0.317  0.356
 PK4    0.317  0.356
 PK5    0.317  0.356
 PK6    0.317  0.356
;
Table  EreqJM(JM,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
       coal   ng
 JM1    0.317   0.356
 JM2    0.317   0.356
 JM3    0.317   0.356
;
Table  EreqTB(TB,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
       coal   ng
 TB1    0.317   0.356
 TB2    0.317   0.356
 TB3    0.317   0.356
;
Table  EreqPG(PG,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
      coal    ng
 PG1   0.317   0.356
 PG2   0.317   0.356
;
Table  EreqPR(PR,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
      coal    ng
 PR1   0.356   0.356
 PR2   0.356   0.356
 PR3   0.356   0.356
;
Table  EreqJIMAH(JIMAH,j)  Elec required for CO2 capture (MWh per tonne CO2 capture)
      coal    ng
JIMAH1   0.317   0.356
JIMAH2   0.317   0.356
;
*=====================
*COST OF SEQUESTRATION
*=====================
PARAMETER     SEQUESTRATION(I,S) sequestration cost for a power plant at a storage location (RM per ton CO2 stored) (reference:
IPCC (2005) p. 33 - see spreadsheet)
;
SEQUESTRATION(I,S) = 14.24
;
$ONTEXT
*seqPK(PK,s) sequestration cost for Pelabuhan Klang ($ per tonne CO2 storage)
        Erie  Huron
  PK1    40.64  51.25
  PK2    40.64  51.25
  PK3    43.08  53.69
  PK4    43.08  53.69
  PK5    43.08  53.69
```

```
 PK6   43.08  53.69
*seqJM(JM,s) sequestration cost for Nanticoke ($ per tonne CO2 storage)
 JM1   37.43  53.07
 JM2   37.43  53.07
 JM3   40.49  56.13
;
Table seqTB(TB,s) sequestration cost for Atikokan ($ per tonne CO2 storage)
       Erie  Huron
 TB1   196.10 163.26
 TB2   196.10 163.26
 TB3   196.10 163.26
;
Table seqPG(PG,s) sequestration cost for Lakeview ($ per tonne CO2 storage)
      Erie  Huron
 PG1  127.77  136.51
 PG2  127.77  136.51
;
* Table seqLN(LN,s) sequestration cost for Lennox ($ per tonne CO2 storage)
*       Erie  Huron
* LN1   10.5  11.0
* LN2   10.5  11.0
* LN3   10.5  11.0
* LN4   10.5  11.0;
Table seqPR(PR,s) sequestration cost for Thunder Bay ($ per tonne CO2 storage)
        Erie  Huron
 PR1      221.26 144.02
 PR2      221.26 144.02
;

Table seqPC1(I,s) sequestration cost for new PC with capture ($ per tonne CO2 storage)
        Erie  Huron
 PCcap11   15   33
 PCcap12   15   33
 PCcap13   15   33
 Pccap14   15   33;
Table seqPC2(I,s) sequestration cost for new PC with capture ($ per tonne CO2 storage)
        Erie  Huron
 PCcap21   12   25
 PCcap22   12   25
 PCcap23   12   25
 Pccap24   12   25 ;
Table seqPC3(I,s) sequestration cost for new PC with capture ($ per tonne CO2 storage)
        Erie  Huron
 PCcap31   11   22
 PCcap32   11   22
 PCcap33   11   22
 Pccap34   11   22 ;
Table seqIC1(I,s) sequestration cost for new IGCC with capture ($ per tonne CO2 storage)
        Erie  Huron
 IGcap11   12   26
 IGcap12   12   26
 IGcap13   12   26
 IGcap14   12   26 ;
Table seqIC2(I,s) sequestration cost for new IGCC with capture ($ per tonne CO2 storage)
        Erie  Huron
 IGcap21   12   26
 IGcap22   12   26
 IGcap23   12   26
 IGcap24   12   26 ;
Table seqNC1(I,s) sequestration cost for new NGCC with capture ($ per tonne CO2 storage)
        Erie  Huron
 NGcap11   28   64
 NGcap12   28   64
 NGcap13   28   64
 NGcap14   28   64 ;
Table seqNC2(I,s) sequestration cost for new NGCC with capture ($ per tonne CO2 storage)
        Erie  Huron
 NGcap21   20   44
 NGcap22   20   44
 NGcap23   20   44
 NGcap24   20   44
;
$OFFTEXT
```

```
*
 parameter
NomE   Nominal electricity generated in MW
*TEST
;
 NomE    =
( sum(PK,ElecPK(PK)) + sum(JM,ElecJM(JM)) + sum(TB,ElecTB(TB))
+ sum(PG,ElecPG(PG))+ sum(PR,ElecPR(PR))+sum(JIMAH,ElecJIMAH(JIMAH))+
        sum(N,ElecN(N))+sum(H,ElecH(H))+
        sum(W,ElecW(W)))/(Optime);
*TEST = SUM ( (PC1,PP1) $ ( ORD(PC1) EQ ORD(PP1) ), ( PC1Op(PC1) - PP1Op(PP1) ) / ( CO2PP1(PP1) - CO2PC1(PC1) ) )
;
*
Display NomE
*TEST
;
*
*.. list all variables
*
Positive Variables
E(I,J)
Enf(I)
Enew(I)
 Epk(PK)    adjusted elec generation for Pelabuhan Klang power stations (MWh per year)
 Ejm(JM)    adjusted elec generation for Jamanjung power stations (MWh per year)
 Etb(TB)    adjusted elec generation for Tanjung Bin power stations (MWh per year)
 Epg(PG)    adjusted elec generation for Pasir Gudang power stations (MWh per year)
 Epr(PR)    adjusted elec generation for Prai power stations (MWh per year)
 Ejimah(JIMAH) adjusted elec generation for Jimah power stations (MWh per year)
 En(N)      adjusted elec generation for nuclear power plants (MWh per year)
 Eh(H)      adjusted elec generation for hydro power plants (MWh per year)
 Ew(W)      adjusted elec generation for wind power plants (MWh per year)
 Epp1(I)    adjusted elec generation for PC (MWh per year)
 Epp2(I)    adjusted elec generation for PC (MWh per year)
 Epi1(I)    adjusted elec generation for IGCC (MWh per year)
 Epi2(I)    adjusted elec generation for IGCC (MWh per year)
 Epi3(I)    adjusted elec generation for IGCC (MWh per year)
 Epn1(I)    adjusted elec generation for NGCC (MWh per year)
 Epn2(I)    adjusted elec generation for NGCC (MWh per year)
 Epn3(I)    adjusted elec generation for NGCC (MWh per year)
 Epc1(I)    adjusted elec generation for PC with capture (MWh per year)
 Epc2(I)    adjusted elec generation for PC with capture (MWh per year)
 Epc3(I)    adjusted elec generation for PC with capture (MWh per year)
 Eic1(I)    adjusted elec generation for IGCC with capture (MWh per year)
 Eic2(I)    adjusted elec generation for IGCC with capture (MWh per year)
 Enc1(I)    adjusted elec generation for NGCC with capture (MWh per year)
 Enc2(I)    adjusted elec generation for NGCC with capture (MWh per year)
 Epkj(PK,j)     Pelabuhan Klang adjusted elec gen used j fuels
 Ejmj(JM,j)     Jamanjung adjusted elec gen used j fuels
 Etbj(TB,j)     Tanjung Bin adjusted elec gen used j fuels
 Epgj(PG,j)     Pasir Gudang adjusted elec gen used j fuels
 Eprj(PR,j)     Prai adjusted elec gen used j fuels
 Ejimahj(JIMAH,j) Jimah adjusted elec gen used j fuels
 EkPK(PK)
 EkJM(JM)
 EkTB(TB)
 EkPG(PG)
* EkPR(PR)
 EkJIMAH(JIMAH)
 EkPKj(PK,j,k)       Electricity required for capture process in Pelabuhan Klang(MWh per year)
 EkJMj(JM,j,k)       Electricity required for capture process in Jamanjung(MWh per year)
 EkTBj(TB,j,k)       Electricity required for capture process in Tanjung Bin(MWh per year)
 EkPGj(PG,j,k)       Electricity required for capture process in Pasir Gudang(MWh per year)
* EkPRj(PR,j,k)      Electricity required for capture process in Prai(MWh per year)
 EkJIMAHj(JIMAH,j,k)  Electricity required for capture process in Jimah(MWh per year)
GAMA(I,J,K)
 gamaPK(PK,j,k)
 gamaJM(JM,j,k)
 gamaTB(TB,j,k)
 gamaPG(PG,j,k)
* gamaPR(PR,j,k)
 gamaJIMAH(JIMAH,j,k)
phi(I,S)
```

```
phiPK(PK,s)
phiJM(JM,s)
phiTB(TB,s)
phiPG(PG,s)
* phiPR(PR,s)
phiJIMAH(JIMAH,s)
beta(I,S)
betaPC1(I,s)
betaPC2(I,s)
betaPC3(I,s)
betaIC1(I,s)
betaIC2(I,s)
betaNC1(I,s)
betaNC2(I,s)
* betaL(L,j)
* betaNN(NN,j)
* betaA(A,j)
* betaLV(LV,j)
* betaLN(LN,j)
* betaTB(TB,j)
;
* grid      Electricty from the grid for CO2 capture;
Variables cost,CO2F1,CO2F2,CO2F3,CO2F4,CO2F5,CO2F6,CO2P,
MWred, TEST;
*dummy;
*RF1,RF2,RF3,RF4,RF5,RF6;
Binary variable
Y(I)
Xpk(PK,j)      Pelabuhan Klang fuel selection
Xjm(JM,j)      Jamanjung fuel selection
Xtb(TB,j)      Tanjung Bin fuel selection
Xpg(PG,j)      Pasir fuel selection
Xpr(PR,j)      Prai fuel selection
Xjimah(JIMAH,j) Jimah Bay fuel selection
yPP1(PP1) decision either to build a new PC
yPP2(PP2) decision either to build a new PC
yPI1(PI1) decision either to build a new IGCC
yPI2(PI2)
yPI3(PI3)
yPN1(PN1) decision either to build a new NGCC
yPN2(PN2)
yPN3(PN3)
yPC1(PC1) decision either to build a new PC with capture
yPC2(PC2)
yPC3(PC3)
yIC1(IC1) decision either to build a new IGCC with capture
yIC2(IC2)
yNC1(NC1) decision either to build a new NGCC with capture
yNC2(NC2)
zpk(PK,j,k)
zjm(JM,j,k)
ztb(TB,j,k)
zpg(PG,j,k)
* zpr(PR,j,k)
zjimah(JIMAH,j,k)
wpk(PK,s)
wjm(JM,s)
wtb(TB,s)
wpg(PG,s)
* wpr(PR,s)
wjimah(JIMAH,s)
wpc1(PC1,s)
wpc2(PC2,s)
wpc3(PC3,s)
wic1(IC1,s)
wic2(IC2,s)
wnc1(NC1,s)
wnc2(NC2,s)
;
*
*.. list all the equations
*
Equations
```

totcost   total annual cost ($ per year)
*TESTEQ
totCO2   total CO2 emission (tonne per year)
totCO2F1
totCO2F2
totCO2F3
totCO2F4
totCO2F5
totCO2F6
totCO2P
* emis
totMW   total electricity generation (MWh per year)
totMWred
swiPK(PK)
swiJM(JM)
swiTB(TB)
swiPG(PG)
swiPR(PR)
swiJIMAH(JIMAH)
gas1
gas2
gas3
*gas4
pkE(PK)
jmE(JM)
tbE(TB)
pgE(PG)
prE(PR)
jimahE(JIMAH)
eppk(PK,j)
epjm(JM,j)
eptb(TB,j)
eppg(PG,j)
eppr(PR,j)
epjimah(JIMAH,j)
newPK(PK,j)
newJM(JM,j)
newTB(TB,j)
newPG(PG,j)
newPR(PR,j)
newJIMAH(JIMAH,j)
newN(N)
newH(H)
newW(W)
newPP1(PP1)
newPP2(PP2)
newPI1(PI1)
newPI2(PI2)
newPI3(PI3)
newPN1(PN1)
newPN2(PN2)
newPN3(PN3)
newPC1(PC1)
newPC2(PC2)
newPC3(PC3)
newIC1(IC1)
newIC2(IC2)
newNC1(NC1)
newNC2(NC2)
UpPP1(PP1)
UpPP2(PP2)
UpPI1(PI1)
UpPI2(PI2)
UpPI3(PI3)
UpPN1(PN1)
UpPN2(PN2)
UpPN3(PN3)
UpPC1(PC1)
UpPC2(PC2)
UpPC3(PC3)
UpIC1(IC1)
UpIC2(IC2)
UpNC1(NC1)

UpNC2(NC2)
lowPK(PK,j)
lowJM(JM,j)
lowTB(TB,j)
lowPG(PG,j)
lowPR(PR,j)
lowJIMAH(JIMAH,j)
t1(PK,k)
t2(JM,k)
t3(TB,k)
t4(PG,k)
* t5(PR,k)
t6(JIMAH,k)
totEkPK(PK,j,k)
totEkJM(JM,j,k)
totEkTB(TB,j,k)
totEkPG(PG,j,k)
* totEkPR(PR,j,k)
totEkJIMAH(JIMAH,j,k)
c1(PK,j,k)
c2(JM,j,k)
c3(TB,j,k)
c4(PG,j,k)
* c5(PR,j,k)
c6(JIMAH,j,k)
select1, select2
select4
select5
select6
select7
select8
select9
select10
select11
select12
select13
select14
select16
select17
f1(PK)
f2(JM)
f3(TB)
f4(PG)
* f5(PR)
f6(JIMAH)
* cap1
* cap2
* cap3
* cap4
** cap5
* cap6
* s1(L,j,k)
* s2(NN,j,k)
* s3(A,j,k)
* s4(LV,j,k)
* s5(LN,j,k)
* s6(TB,j,k)
w1(PK,j)
w2(JM,j)
w3(TB,j)
w4(PG,j)
* w5(PR,j)
w6(JIMAH,j)
z1(PK,k)
z2(JM,k)
z3(TB,k)
z4(PG,k)
* z5(PR,k)
z6(JIMAH,k)
sPK(PK)
sJM(JM)
sTB(TB)
sPG(PG)

```
* sPR(PR)
sJIMAH(JIMAH)
stPK1
stPK2
stPK3
stPK4
stPK5
*stPK6
stJM1
stJM2
*stJM3
stTB1
stTB2
*stTB3
stPG1
*stPG2
*stJIMAH1
*stJIMAH2
scapPK(PK)
scapJM(JM)
scapTB(TB)
scapPG(PG)
* scapPR(PR)
scapJIMAH(JIMAH)
scapPC1(PC1)
scapPC2(PC2)
scapPC3(PC3)
scapIC1(IC1)
scapIC2(IC2)
scapNC1(NC1)
scapNC2(NC2)
conPK1(PK,j,k)
conPK2(PK,j,k)
conPK3(PK,j,k)
conJM1(JM,j,k)
conJM2(JM,j,k)
conJM3(JM,j,k)
conTB1(TB,j,k)
conTB2(TB,j,k)
conTB3(TB,j,k)
conPG1(PG,j,k)
conPG2(PG,j,k)
conPG3(PG,j,k)
* conPR1(PR,j,k)
* conPR2(PR,j,k)
* conPR3(PR,j,k)
conJIMAH1(JIMAH,j,k)
conJIMAH2(JIMAH,j,k)
conJIMAH3(JIMAH,j,k)
conPK1s(PK,j,s)
conPK2s(PK,j,s)
conPK3s(PK,j,s)
conJM1s(JM,j,s)
conJM2s(JM,j,s)
conJM3s(JM,j,s)
conTB1s(TB,j,s)
conTB2s(TB,j,s)
conTB3s(TB,j,s)
conPG1s(PG,j,s)
conPG2s(PG,j,s)
conPG3s(PG,j,s)
* conPR1s(PR,j,s)
* conPR2s(PR,j,s)
* conPR3s(PR,j,s)
conJIMAH1s(JIMAH,j,s)
conJIMAH2s(JIMAH,j,s)
conJIMAH3s(JIMAH,j,s)
conPC11(PC1,s)
conPC12(PC1,s)
conPC13(PC1,s)
conPC21(PC2,s)
conPC22(PC2,s)
conPC23(PC2,s)
```

```
conPC31(PC3,s)
conPC32(PC3,s)
conPC33(PC3,s)
conIC11(IC1,s)
conIC12(IC1,s)
conIC13(IC1,s)
conIC21(IC2,s)
conIC22(IC2,s)
conIC23(IC2,s)
conNC11(NC1,s)
conNC12(NC1,s)
conNC13(NC1,s)
conNC21(NC2,s)
conNC22(NC2,s)
conNC23(NC2,s)
;
totcost.. cost =e=
* operating cost for existing fossil-fuel power plants
(
SUM ( (I,J) $ FOSSIL(I), C(I,J) * E(I,J) )
*SUM ( (I,J) $ FOSSIL(I), C(I,J) * E(I,J) )
* 1. operating cost for existing non-fossil-fuel power plants
+ SUM ( I $ NONFOSSIL(I), Cnf(I) * Enf(I) )
$ontext
        (sum((L,j),Elj(L,j)*OprL(L,j))+
        sum((NN,j),Ennj(NN,j)*OprNN(NN,j))+
        sum((A,j),Eaj(A,j)*OprA(A,j))+
        sum((LV,j),Elvj(LV,j)*OprLV(LV,j))+
        sum((LN,j),Elnj(LN,j)*OprLN(LN,j))+
        sum((TB,j),Etbj(TB,j)*OprTB(TB,j))+
        sum(N,En(N)*NucOpr)+sum(H,Eh(H)*HydOpr)+
        sum(W,Ew(W)*WindOpr)+
$offtext
* 2. retrofit cost due to fuel switching
+       sum(PK,(Rcost*(PKmax(PK)/optime)*AF)*Xpk(PK,'ng'))+
        sum(JM,(Rcost*(JMmax(JM)/optime)*AF)*Xjm(JM,'ng'))+
        sum(TB,(Rcost*(TBmax(TB)/optime)*AF)*Xtb(TB,'ng'))+
        sum(PG,(Rcost*(PGmax(PG)/optime)*AF)*Xpg(PG,'ng'))+
        sum(PR,(Rcost*(PRmax(PR)/optime)*AF)*Xpr(PR,'ng'))+
        sum(JIMAH,(Rcost*(JIMAHmax(JIMAH)/optime)*AF)*Xjimah(JIMAH,'ng'))
* 3. capital cost for new plants without capture
+ SUM ( I $ Pnew(I), Cnew(I)*SEN*(Pmax(I)/optime)*AF*Y(I) )
$ontext
        sum(PP1,PP1cost(PP1)*sen*(PP1max(PP1)/optime)*AF*yPP1(PP1))+
        sum(PP2,PP2cost(PP2)*sen*(PP2max(PP2)/optime)*AF*yPP2(PP2))+
        sum(PI1,PI1cost(PI1)*sen*(PI1max(PI1)/optime)*AF*yPI1(PI1))+
        sum(PI2,PI2cost(PI2)*sen*(PI2max(PI2)/optime)*AF*yPI2(PI2))+
        sum(PI3,PI3cost(PI3)*sen*(PI3max(PI3)/optime)*AF*yPI3(PI3))+
        sum(PN1,PN1cost(PN1)*sen*(PN1max(PN1)/optime)*AF*yPN1(PN1))+
        sum(PN2,PN2cost(PN2)*sen*(PN2max(PN2)/optime)*AF*yPN2(PN2))+
        sum(PN3,PN3cost(PN3)*sen*(PN3max(PN3)/optime)*AF*yPN3(PN3))+
$offtext
* 4. capital cost for new plants with capture
+ SUM ( I $ Pnew_cap(I), Cnew_cap(I)*SEN*(Pmax_cap(I)/optime)*AF*Y(I) )
$ontext
        sum(PC1,PC1cost(PC1)*sen*(PC1max(PC1)/optime)*AF*yPC1(PC1))+
        sum(PC2,PC2cost(PC2)*sen*(PC2max(PC2)/optime)*AF*yPC2(PC2))+
        sum(PC3,PC3cost(PC3)*sen*(PC3max(PC3)/optime)*AF*yPC3(PC3))+
        sum(IC1,IC1cost(IC1)*sen*(IC1max(IC1)/optime)*AF*yIC1(IC1))+
        sum(IC2,IC2cost(IC2)*sen*(IC2max(IC2)/optime)*AF*yIC2(IC2))+
        sum(NC1,NC1cost(NC1)*sen*(NC1max(NC1)/optime)*AF*yNC1(NC1))+
        sum(NC2,NC2cost(NC2)*sen*(NC2max(NC2)/optime)*AF*yNC2(NC2))+
$offtext
* 5. operating cost for new plants (VOM + fuel cost)
+ SUM (I $ ( Pnew(I) AND Pnew_cap(I) ), ( OPEXnew(I) + Pcoal*hr(I) ) * Enew(I) )
$ontext
        sum(PP1,(PP1Op(PP1)+(Pcoal*hrPP1))*Epp1(PP1))+
        sum(PP2,(PP2Op(PP2)+(Pcoal*hrPP2))*Epp2(PP2))+
        sum(PI1,(PI1Op(PI1)+(Pcoal*hrPI1))*Epi1(PI1))+
        sum(PI2,(PI2Op(PI2)+(Pcoal*hrPI2))*Epi2(PI2))+
        sum(PI3,(PI3Op(PI3)+(Pcoal*hrPI3))*Epi3(PI3))+
        sum(PN1,(PN1Op(PN1)+(NGcost*hrPN1))*Epn1(PN1))+
        sum(PN2,(PN2Op(PN2)+(NGcost*hrPN2))*Epn2(PN2))+
```

```
            sum(PN3,(PN3Op(PN3)+(NGcost*hrPN3))*Epn3(PN3))+
            sum(PC1,(PC1Op(PC1)+(Pcoal*hrPC1))*Epc1(PC1))+
            sum(PC2,(PC2Op(PC2)+(Pcoal*hrPC2))*Epc2(PC2))+
            sum(PC3,(PC3Op(PC3)+(Pcoal*hrPC3))*Epc3(PC3))+
            sum(IC1,(IC1Op(IC1)+(Pcoal*hrIC1))*Eic1(IC1))+
            sum(IC2,(IC2Op(IC2)+(Pcoal*hrIC2))*Eic2(IC2))+
            sum(NC1,(NC1Op(NC1)+(NGcost*hrNC1))*Enc1(NC1))+
            sum(NC2,(NC2Op(NC2)+(NGcost*hrNC2))*Enc2(NC2))+
$offtext
* 6. capital and operating cost for capture process on existing fossil stations
+ SUM ( (I,J,K) $ FOSSIL(I) , CCScost_existing(I)*perCCS*CO2emission(I,J)*GAMA(I,J,K) )
* 7. sequestration cost for CCS retrofit on existing coal-fired power plants
+ SUM ( (I,J,S), SEQUESTRATION(I,S)*CO2emission(I,J)*perCCS*phi(I,S) )
*8. sequestration cost for new plant with capture
+ SUM ( (I,S) $ Pnew_cap(I), (aa(I)/bb(I))*CO2new_cap(I)*beta(I,S)*SEQUESTRATION(I,S) )
$ontext
            sum((PC1,s),(0.9/0.1)*CO2PC1(PC1)*betaPC1(PC1,s)*seqPC1(PC1,s))+
            sum((PC2,s),(0.9/0.1)*CO2PC2(PC2)*betaPC2(PC2,s)*seqPC2(PC2,s))+
            sum((PC3,s),(0.9/0.1)*CO2PC3(PC3)*betaPC3(PC3,s)*seqPC3(PC3,s))+
            sum((IC1,s),(0.8/0.2)*CO2IC1(IC1)*betaIC1(IC1,s)*seqIC1(IC1,s))+
            sum((IC2,s),(0.6/0.4)*CO2IC2(IC2)*betaIC2(IC2,s)*seqIC2(IC2,s))+
            sum((NC1,s),(0.9/0.1)*CO2NC1(NC1)*betaNC1(NC1,s)*seqNC1(NC1,s))+
            sum((NC2,s),(0.9/0.1)*CO2NC2(NC2)*betaNC2(NC2,s)*seqNC2(NC2,s))
TABLE(I,
      aa   bb
PC1    0.9  0.1
PC2    0.9  0.1
$offtext
)/1E10
* cost of CO2 avoidance
*==============================
* cost of electricity (i.e., operating cost) ($/kWh) for CCS
*TESTEQ..   TEST =E= SUM ( (PC1,PP1) $ ( ORD(PC1) EQ ORD(PP1) ), ( PC1Op(PC1) - PP1Op(PP1) ) / ( CO2PP1(PP1) -
CO2PC1(PC1) ) );
*+ SUM ( (I,I)$
* for PC1 plants:
+ SUM ( (PP1,PC1) $ PP1_PC1(PP1,PC1), ( PC1Op(PC1) - PP1Op(PP1) ) / ( CO2PP1(PP1) - CO2PC1(PC1) ) )
* for PC2 plants:
+ SUM ( (PC2,PP2) $ PP2_PC2(PP2,PC2), ( PC2Op(PC2) - PP2Op(PP2) ) / ( CO2PP2(PP2) - CO2PC2(PC2) ) )
* does not consider PC3 set because there is no PP3 set
* for IGCC1 plants:
+ SUM ( (PI1,IC1) $ PI1_IC1(PI1,IC1), ( IC1Op(IC1) - PI1Op(PI1) ) / ( CO2PI1(PI1)  - CO2IC1(IC1) ) )
* for IGCC2 plants:
+ SUM ( (PI2,IC2) $ PI2_IC2(PI2,IC2), ( IC2Op(IC2) - PI2Op(PI2) ) / ( CO2PI2(PI2)  - CO2IC2(IC2) ) )
* does not consider PI3 set because there is no IC3 set
*for NGCC1 plants:
+ SUM ( (PN1,NC1) $ PN1_NC1(PN1,NC1), ( NC1Op(NC1) - PN1Op(PN1) ) / ( CO2PN1(PN1)  - CO2NC1(NC1) ) )
*for NGCC2 plants:
+ SUM ( (PN2,NC2) $ PN2_NC2(PN2,NC2), ( NC2Op(NC2) - PN2Op(PN2) ) / ( CO2PN2(PN2)  - CO2NC2(NC2) ) )
* does not consider PN3 set because there is no nC3 set
;
$ontext
ORD('PC11') = 1
ORD('PC12') = 2
for set PC1:
ORD('PCcap11') = 1
ORD('PCcap12') = 2
$offtext
* ( O&M cost for new PC with capture ($ per MWh) ) - (O&M cost for new PC without capture ($ per MWh)) /CO2 emissions from new
PC without capture (tonne per MWh) (ref plant)
* Pelabuhan Klang CO2 emissions
totCO2F1.. CO2F1 =e= sum((PK,j),CO2PK(PK,j)*EPKj(PK,j))-
           (sum((PK,j,k),CO2PK(PK,j)*perCCS*gamaPK(PK,j,k)));
* Janamanjung CO2 emissions
totCO2F2.. CO2F2 =e= sum((JM,j),CO2JM(JM,j)*EJMj(JM,j))-
           (sum((JM,j,k),CO2JM(JM,j)*perCCS*gamaJM(JM,j,k)));
* Tanjung Bin CO2 emissions
totCO2F3.. CO2F3 =e= sum((TB,j),CO2TB(TB,j)*ETBj(TB,j))-
           (sum((TB,j,k),CO2TB(TB,j)*perCCS*gamaTB(TB,j,k)));
* Pasir Gudang CO2 emissions
totCO2F4.. CO2F4 =e= sum((PG,j),CO2PG(PG,j)*EPGj(PG,j))-
           (sum((PG,j,k),CO2PG(PG,j)*perCCS*gamaPG(PG,j,k)));
* Prai CO2 emissions
```

```
totCO2F5.. CO2F5 =e= sum((PR,j),CO2PR(PR,j)*EPRj(PR,j));
*              (sum((LN,j,k),CO2LN(LN,j)*perCCS*gamaLN(LN,j,k)));
* Jimah CO2 emissions
totCO2F6.. CO2F6 =e= sum((JIMAH,j),CO2JIMAH(JIMAH,j)*EJIMAHj(JIMAH,j))-
             (sum((JIMAH,j,k),CO2JIMAH(JIMAH,j)*perCCS*gamaJIMAH(JIMAH,j,k)));
* New plants CO2 emissions
totCO2P.. CO2P =e= sum(PP1,CO2PP1(PP1)*Epp1(PP1))+ sum(PP2,CO2PP2(PP2)*Epp2(PP2))+
          sum(PI1,CO2PI1(PI1)*Epi1(PI1))+ sum(PI2,CO2PI2(PI2)*Epi2(PI2))+
          sum(PI3,CO2PI3(PI3)*Epi3(PI3))+
          sum(PN1,CO2PN1(PN1)*Epn1(PN1))+ sum(PN2,CO2PN2(PN2)*Epn2(PN2))+
          sum(PN3,CO2PN3(PN3)*Epn3(PN3))+
          sum(PC1,CO2PC1(PC1)*Epc1(PC1))+ sum(PC2,CO2PC2(PC2)*Epc2(PC2))+
          sum(PC3,CO2PC3(PC3)*Epc3(PC3))+
          sum(IC1,CO2IC1(IC1)*Eic1(IC1))+ sum(IC2,CO2IC2(IC2)*Eic2(IC2))+
          sum(NC1,CO2NC1(NC1)*Enc1(NC1))+ sum(NC2,CO2NC2(NC2)*Enc2(NC2));
* Total CO2 emissions (tonne per yr)
totCO2.. CO2F1+CO2F2+CO2F3+CO2F4+CO2F5+CO2F6+CO2P =l= (1-CO2red)*CO2;
*emis.. emisCO2 =e= (CO2F1+CO2F2+CO2F3+CO2F4+CO2F5+CO2F6+CO2P)/10000000;
* try
t1(PK,k)..      EkPK(PK) =e= sum(j,EkPKj(PK,j,k));
t2(JM,k)..      EkJM(JM) =e= sum(j,EKJMj(JM,j,k));
t3(TB,k)..      EkTB(TB) =e= sum(j,EKTBj(TB,j,k));
t4(PG,k)..      EkPG(PG) =e= sum(j,EkPGj(PG,j,k));
*t5(PR,k)..      EkPR(PR) =e= sum(j,EkPRj(PR,j,k));
t6(JIMAH,k)..     EkJIMAH(JIMAH) =e= sum(j,EkJIMAHj(JIMAH,j,k));
* energy required for capture on fossil stations (MWh per yr)
totEkPK(PK,j,k).. EkPKj(PK,j,k) =e= CO2PK(PK,j)*EreqPK(PK,j)*perCCS*gamaPK(PK,j,k);
totEkJM(JM,j,k).. EkJMj(JM,j,k) =e= CO2JM(JM,j)*EreqJM(JM,j)*perCCS*gamaJM(JM,j,k);
totEkTB(TB,j,k).. EkTBj(TB,j,k) =e= CO2TB(TB,j)*EreqTB(TB,j)*perCCS*gamaTB(TB,j,k);
totEkPG(PG,j,k).. EkPGj(PG,j,k) =e= CO2PG(PG,j)*EreqPG(PG,j)*perCCS*gamaPG(PG,j,k);
*totEkPR(PR,j,k).. EkPRj(PR,j,k) =e= CO2PR(PR,j)*EreqPR(PR,j)*perCCS*gamaPR(PR,j,k);
totEkJIMAH(JIMAH,j,k).. EkJIMAHj(JIMAH,j,k) =e=
CO2JIMAH(JIMAH,j)*EreqJIMAH(JIMAH,j)*perCCS*gamaJIMAH(JIMAH,j,k);
* total energy required for capture process on all fossil stations
totMWred..   MWred =e= sum((PK,j,k),EkPKj(PK,j,k))+ sum((JM,j,k),EkJMj(JM,j,k))+ sum((TB,j,k),EkTBj(TB,j,k))+
              sum((PG,j,k),EkPGj(PG,j,k))
*+sum((PR,j,k),EkPRj(PR,j,k))
              +sum((JIMAH,j,k),EkJIMAHj(JIMAH,j,k));
* total net electricity generated
totMW.. ((sum((PK,j),EPKj(PK,j))+sum((JM,j),EJMj(JM,j))+
       sum((TB,j),ETBj(TB,j))+sum((PG,j),EPGj(PG,j))+
       sum((PR,j),EPRj(PR,j))+sum((JIMAH,j),EJIMAHj(JIMAH,j))+
       sum(N,En(N))+sum(H,Eh(H))+sum(W,Ew(W))+
       sum(PP1,Epp1(PP1))+sum(PP2,Epp2(PP2))+
       sum(PI1,Epi1(PI1))+sum(PI2,Epi2(PI2))+sum(PI3,Epi3(PI3))+
       sum(PN1,Epn1(PN1))+sum(PN2,Epn2(PN2))+sum(PN3,Epn3(PN3))+
       sum(PC1,Epc1(PC1))+sum(PC2,Epc2(PC2))+sum(PC3,Epc3(PC3))+
       sum(IC1,Eic1(IC1))+sum(IC2,Eic2(IC2))+
       sum(NC1,Enc1(NC1))+sum(NC2,Enc2(NC2)))
       -(MWred))/Optime =g= (1.0+Egrowth)*NomE;
* Fuel selection and plant shut down
swiPK(PK)..       sum(j,Xpk(PK,j)) =l= 1;
swiJM(JM)..       sum(j,Xjm(JM,j)) =l= 1;
swiTB(TB)..       sum(j,Xtb(TB,j)) =l= 1;
swiPG(PG)..       sum(j,Xpg(PG,j)) =l= 1;
swiPR(PR)..       sum(j,Xpr(PR,j)) =l= 1;
swiJIMAH(JIMAH)..    sum(j,Xjimah(JIMAH,j)) =l= 1;
gas1..        Xpr('PR1','ng') =e= 1;
gas2..        Xpr('PR2','ng') =e= 1;
gas3..        Xpr('PR3','ng') =e= 1;
pkE(PK)..       Epk(PK) =e= sum(j,Epkj(PK,j));
jmE(JM)..       Ejm(JM) =e= sum(j,Ejmj(JM,j));
tbE(TB)..       Etb(TB) =e= sum(j,Etbj(TB,j));
pgE(PG)..       Epg(PG) =e= sum(j,Epgj(PG,j));
prE(PR)..       Epr(PR) =e= sum(j,Eprj(PR,j));
jimahE(JIMAH)..   Ejimah(JIMAH) =e= sum(j,Ejimahj(JIMAH,j));
* switching constraints
eppk(PK,j)..      Epkj(PK,j) =l= PKmax(PK)*Xpk(PK,j);
epjm(JM,j)..      Ejmj(JM,j) =l= JMmax(JM)*Xjm(JM,j);
eptb(TB,j)..      Etbj(TB,j) =l= TBmax(TB)*Xtb(TB,j);
eppg(PG,j)..      Epgj(PG,j) =l= PGmax(PG)*Xpg(PG,j);
eppr(PR,j)..      Eprj(PR,j) =l= PRmax(PR)*Xpr(PR,j);
epjimah(JIMAH,j)..   Ejimahj(JIMAH,j) =l= JIMAHmax(JIMAH)*Xjimah(JIMAH,j);
```

```
* Upper bound on operational changes for existing plants
newPK(PK,j)..        Epkj(PK,j) =l= (1+R)*ElecPK(PK);
newJM(JM,j)..        Ejmj(JM,j) =l= (1+R)*ElecJM(JM);
newTB(TB,j)..        Etbj(TB,j) =l= (1+R)*ElecTB(TB);
newPG(PG,j)..        Epgj(PG,j) =l= (1+R)*ElecPG(PG);
newPR(PR,j)..        Eprj(PR,j) =l= (1+R)*ElecPR(PR);
newJIMAH(JIMAH,j)..    Ejimahj(JIMAH,j) =l= (1+R)*ElecJIMAH(JIMAH);
* Non fossil plants capacity constraints
newN(N)..     En(N) =l= (1+R)*ElecN(N);
newH(H)..     Eh(H) =l= (1+R)*ElecH(H);
newW(W)..      Ew(W) =l= (1+R)*ElecW(W);
* New plants capacity constraints
newPP1(PP1)..  Epp1(PP1) =l= PP1max(PP1)*yPP1(PP1);
newPP2(PP2)..  Epp2(PP2) =l= PP2max(PP2)*yPP2(PP2);
newPI1(PI1)..  Epi1(PI1) =l= PI1max(PI1)*yPI1(PI1);
newPI2(PI2)..  Epi2(PI2) =l= PI2max(PI2)*yPI2(PI2);
newPI3(PI3)..  Epi3(PI3) =l= PI3max(PI3)*yPI3(PI3);
newPN1(PN1)..  Epn1(PN1) =l= PN1max(PN1)*yPN1(PN1);
newPN2(PN2)..  Epn2(PN2) =l= PN2max(PN2)*yPN2(PN2);
newPN3(PN3)..  Epn3(PN3) =l= PN3max(PN3)*yPN3(PN3);
newPC1(PC1)..  Epc1(PC1) =l= PC1max(PC1)*yPC1(PC1);
newPC2(PC2)..  Epc2(PC2) =l= PC2max(PC2)*yPC2(PC2);
newPC3(PC3)..  Epc3(PC3) =l= PC3max(PC3)*yPC3(PC3);
newIC1(IC1)..  Eic1(IC1) =l= IC1max(IC1)*yIC1(IC1);
newIC2(IC2)..  Eic2(IC2) =l= IC2max(IC2)*yIC2(IC2);
newNC1(NC1)..   Enc1(NC1) =l= NC1max(NC1)*yNC1(NC1);
newNC2(NC2)..  Enc2(NC2) =l= NC2max(NC2)*yNC2(NC2);
* Upper bound for new plants
UpPP1(PP1)..  Epp1(PP1) =l= ACF*PP1max(PP1);
UpPP2(PP2)..  Epp2(PP2) =l= ACF*PP2max(PP2);
UpPI1(PI1)..  Epi1(PI1) =l= ACF*PI1max(PI1);
UpPI2(PI2)..  Epi2(PI2) =l= ACF*PI2max(PI2);
UpPI3(PI3)..  Epi3(PI3) =l= ACF*PI3max(PI3);
UpPN1(PN1)..  Epn1(PN1) =l= ACF*PN1max(PN1);
UpPN2(PN2)..  Epn2(PN2) =l= ACF*PN2max(PN2);
UpPN3(PN3)..  Epn3(PN3) =l= ACF*PN3max(PN3);
UpPC1(PC1)..  Epc1(PC1) =l= ACF*PC1max(PC1);
UpPC2(PC2)..  Epc2(PC2) =l= ACF*PC2max(PC2);
UpPC3(PC3)..  Epc3(PC3) =l= ACF*PC3max(PC3);
UpIC1(IC1)..  Eic1(IC1) =l= ACF*IC1max(IC1);
UpIC2(IC2)..  Eic2(IC2) =l= ACF*IC2max(IC2);
UpNC1(NC1)..  Enc1(NC1) =l= ACF*NC1max(NC1);
UpNC2(NC2)..  Enc2(NC2) =l= ACF*NC2max(NC2);
* lower bound
lowPK(PK,j)..       Epkj(PK,j) =g= (Lower*PKmax(PK))*Xpk(PK,j);
lowJM(JM,j)..       Ejmj(JM,j) =g= (Lower*JMmax(JM))*Xjm(JM,j);
lowTB(TB,j)..       Etbj(TB,j) =g= (Lower*TBmax(TB))*Xtb(TB,j);
lowPG(PG,j)..       Epgj(PG,j) =g= (Lower*PGmax(PG))*Xpg(PG,j);
lowPR(PR,j)..       Eprj(PR,j) =g= (Lower*PRmax(PR))*Xpr(PR,j);
lowJIMAH(JIMAH,j)..   Ejimahj(JIMAH,j) =g= (Lower*JIMAHmax(JIMAH))*Xjimah(JIMAH,j);
* CO2 capture energy constraints
c1(PK,j,k)..      EkPKj(PK,j,k) =l= (MaxCap*zpk(PK,j,k));
c2(JM,j,k)..      EkJMj(JM,j,k) =l= (MaxCap*zjm(JM,j,k));
c3(TB,j,k)..      EkTBj(TB,j,k) =l= (MaxCap*ztb(TB,j,k));
c4(PG,j,k)..      EkPGj(PG,j,k) =l= (MaxCap*zpg(PG,j,k));
*c5(PR,j,k)..      EkPRj(PR,j,k) =l= (MaxCap*zpr(PR,j,k));
c6(JIMAH,j,k)..     EkJIMAHj(JIMAH,j,k) =l= (MaxCap*zjimah(JIMAH,j,k));
* Selection of additional new plants
select1..     sum(PP1,yPP1(PP1)) =l= 3;
select2..     sum(PP2,yPP2(PP2)) =l= 3;
select4..     sum(PI1,yPI1(PI1)) =l= 3;
select5..     sum(PI2,yPI2(PI2)) =l= 3;
select6..     sum(PI3,yPI3(PI3)) =l= 3;
select7..     sum(PN1,yPN1(PN1)) =l= 3;
select8..     sum(PN2,yPN2(PN2)) =l= 3;
select9..     sum(PN3,yPN3(PN3)) =l= 3;
select10..      sum(PC1,yPC1(PC1)) =l= 3;
select11..      sum(PC2,yPC2(PC2)) =l= 3;
select12..      sum(PC3,yPC3(PC3)) =l= 3;
select13..      sum(IC1,yIC1(IC1)) =l= 3;
select14..      sum(IC2,yIC2(IC2)) =l= 3;
select16..      sum(NC1,yNC1(NC1)) =l= 3;
select17..      sum(NC2,yNC2(NC2)) =l= 3;
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* Selection of CO2 capture process
f1(PK)..       sum((j,k),zpk(PK,j,k)) =l= 1;
f2(JM)..       sum((j,k),zjm(JM,j,k)) =l= 1;
f3(TB)..       sum((j,k),ztb(TB,j,k)) =l= 1;
f4(PG)..       sum((j,k),zpg(PG,j,k)) =l= 1;
*f5(PR)..      sum((j,k),zpr(PR,j,k)) =l= 1;
f6(JIMAH)..    sum((j,k),zjimah(JIMAH,j,k)) =l= 1;
* Incorporation of capture process on existing coal-fired boilers
*cap1..        sum((L,j,k),zl(L,j,k)) =l= 4;
*cap2..        sum((NN,j,k),znn(NN,j,k)) =l= 8;
*cap3..        sum((A,j,k),za(A,j,k)) =l= 1;
*cap4..        sum((LV,j,k),zlv(LV,j,k)) =l= 8;
**cap5..       sum((LN,j,k),zln(LN,j,k)) =l= 4;
*cap6..        sum((TB,j,k),ztb(TB,j,k)) =l= 2;
* If the fossil plants shut down no capture process will put online
*w1(j)..   sum((L,k),zl(L,j,k)) =l= sum(L,Xl(L,j));
*w2(j)..   sum((NN,k),znn(NN,j,k)) =l= sum(NN,Xnn(NN,j));
*w3(j)..   sum((A,k),za(A,j,k)) =l= sum(A,Xa(A,j));
*w4(j)..   sum((LV,k),zlv(LV,j,k)) =l= sum(LV,Xlv(LV,j));
*w5(j)..   sum((LN,k),zln(LN,j,k)) =l= sum(LN,Xln(LN,j));
*w6(j)..   sum((TB,k),ztb(TB,j,k)) =l= sum(TB,Xtb(TB,j));
w1(PK,j)..   sum(k,zpk(PK,j,k)) =l= Xpk(PK,j);
w2(JM,j)..   sum(k,zjm(JM,j,k)) =l= Xjm(JM,j);
w3(TB,j)..   sum(k,ztb(TB,j,k)) =l= Xtb(TB,j);
w4(PG,j)..   sum(k,zpg(PG,j,k)) =l= Xpg(PG,j);
*w5(PR,j)..  sum(k,zpr(PR,j,k)) =l= Xpr(PR,j);
w6(JIMAH,j)..   sum(k,zjimah(JIMAH,j,k)) =l= Xjimah(JIMAH,j);
* If there is fuel switching no capture
*s1(L,j,k)..     Xl(L,j)+zl(L,j,k) =l= 1;
*s2(NN,j,k)..    Xnn(NN,j)+znn(NN,j,k) =l= 1;
*s3(A,j,k)..     Xa(A,j)+za(A,j,k) =l= 1;
*s4(LV,j,k)..    Xlv(LV,j)+zlv(LV,j,k) =l= 1;
*s5(LN,j,k)..    Xln(LN,j)+zln(LN,j,k) =l= 1;
*s6(TB,j,k)..    Xtb(TB,j)+ztb(TB,j,k) =l= 1;
* no capture process on natural gas power plants
z1(PK,k)..     zpk(PK,'ng',k) =e= 0;
z2(JM,k)..     zjm(JM,'ng',k) =e= 0;
z3(TB,k)..     ztb(TB,'ng',k) =e= 0;
z4(PG,k)..     zpg(PG,'ng',k) =e= 0;
*z5(PR,k)..    zpr(PR,'ng',k) =e= 0;
z6(JIMAH,k)..  zjimah(JIMAH,'ng',k) =e= 0;
* for one identical boilers: only one sequestration location will be selected
sPK(PK)..      sum(s,wpk(PK,s)) =l= 1;
sJM(JM)..      sum(s,wjm(JM,s)) =l= 1;
sTB(TB)..      sum(s,wtb(TB,s)) =l= 1;
sPG(PG)..      sum(s,wpg(PG,s)) =l= 1;
*sPR(PR)..     sum(s,wpr(PR,s)) =l= 1;
sJIMAH(JIMAH)..   sum(s,wjimah(JIMAH,s)) =l= 1;
* for one coal-fired stations: only one sequestration site will be selected
stPK1..   wPK('PK1','erie')+wPK('PK2','huron') =l= 1;
stPK2..   wPK('PK1','erie')+wPK('PK3','huron') =l= 1;
stPK3..   wPK('PK1','erie')+wPK('PK4','huron') =l= 1;
stPK4..   wPK('PK1','erie')+wPK('PK5','huron') =l= 1;
stPK5..   wPK('PK1','erie')+wPK('PK6','huron') =l= 1;
*stPK6..  wPK('PK1','erie')+wPK('PK7','huron') =l= 1;
stJM1..   wjm('JM1','erie')+wjm('JM2','huron') =l= 1;
stJM2..   wjm('JM1','erie')+wjm('JM3','huron') =l= 1;
*stJM3..  wjm('JM1','erie')+wjm('JM4','huron') =l= 1;
stTB1..   wtb('TB1','erie')+wtb('TB2','huron') =l= 1;
stTB2..   wtb('TB1','erie')+wtb('TB3','huron') =l= 1;
*stTB3..  wtb('TB1','erie')+wtb('TB4','huron') =l= 1;
stPG1..   wpg('PG1','erie')+wpg('PG2','huron') =l= 1;
*stPG2..  wpg('PG1','erie')+wpg('PG3','huron') =l= 1;
* Retrofit CCS: if carbon capture retrofit is put online - CO2 need to be stored
scapPK(PK)..       sum((j,k),zpk(PK,j,k)) =e= sum(s,wpk(PK,s));
scapJM(JM)..       sum((j,k),zjm(JM,j,k)) =e= sum(s,wjm(JM,s));
scapTB(TB)..       sum((j,k),ztb(TB,j,k)) =e= sum(s,wtb(TB,s));
scapPG(PG)..       sum((j,k),zpg(PG,j,k)) =e= sum(s,wpg(PG,s));
*scapPR(PR)..      sum((j,k),zpr(PR,j,k)) =e= sum(s,wpr(PR,s));
scapJIMAH(JIMAH)..   sum((j,k),zjimah(JIMAH,j,k)) =e= sum(s,wjimah(JIMAH,s));
* New plant with capture to put online - find location for CO2 storage
scapPC1(PC1)..   ypc1(PC1) =e= sum(s,wpc1(PC1,s));
scapPC2(PC2)..   ypc2(PC2) =e= sum(s,wpc2(PC2,s));
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scapPC3(PC3)..   ypc3(PC3) =e= sum(s,wpc3(PC3,s));
scapIC1(IC1)..   yic1(IC1) =e= sum(s,wic1(IC1,s));
scapIC2(IC2)..   yic2(IC2) =e= sum(s,wic2(IC2,s));
scapNC1(NC1)..   ync1(NC1) =e= sum(s,wnc1(NC1,s));
scapNC2(NC2)..   ync2(NC2) =e= sum(s,wnc2(NC2,s));
*eqdummy..        dummy =g= 0;
** LINEARIZATION ****PROF.SAMIR****
conPK1(PK,j,k).. gamaPK(PK,j,k) =l= EPKj(PK,j);
conPK2(PK,j,k).. gamaPK(PK,j,k) =g= EPKj(PK,j)-M*(1-zPK(PK,j,k));
conPK3(PK,j,k).. gamaPK(PK,j,k) =l= M*zPK(PK,j,k);
conJM1(JM,j,k).. gamaJM(JM,j,k) =l= EJMj(JM,j);
conJM2(JM,j,k).. gamaJM(JM,j,k) =g= EJMj(JM,j)-M*(1-zJM(JM,j,k));
conJM3(JM,j,k).. gamaJM(JM,j,k) =l= M*zJM(JM,j,k);
conTB1(TB,j,k).. gamaTB(TB,j,k) =l= ETBj(TB,j);
conTB2(TB,j,k).. gamaTB(TB,j,k) =g= ETBj(TB,j)-M*(1-zTB(TB,j,k));
conTB3(TB,j,k).. gamaTB(TB,j,k) =l= M*zTB(TB,j,k);
conPG1(PG,j,k).. gamaPG(PG,j,k) =l= EPGj(PG,j);
conPG2(PG,j,k).. gamaPG(PG,j,k) =g= EPGj(PG,j)-M*(1-zPG(PG,j,k));
conPG3(PG,j,k).. gamaPG(PG,j,k) =l= M*zPG(PG,j,k);
*conLN1(LN,j,k).. gamaLN(LN,j,k) =l= Elnj(LN,j);
*conLN2(LN,j,k).. gamaLN(LN,j,k) =g= Elnj(LN,j)-M*(1-zln(LN,j,k));
*conLN3(LN,j,k).. gamaLN(LN,j,k) =l= M*zln(LN,j,k);
conJIMAH1(JIMAH,j,k).. gamaJIMAH(JIMAH,j,k) =l= EJIMAHj(JIMAH,j);
conJIMAH2(JIMAH,j,k).. gamaJIMAH(JIMAH,j,k) =g= EJIMAHj(JIMAH,j)-M*(1-zJIMAH(JIMAH,j,k));
conJIMAH3(JIMAH,j,k).. gamaJIMAH(JIMAH,j,k) =l= M*zJIMAH(JIMAH,j,k);
** LINEARIZATION ****sequestration for CCS retrofit****
conPK1s(PK,j,s).. phiPK(PK,s) =l= EPKj(PK,j);
conPK2s(PK,j,s).. phiPK(PK,s) =g= EPKj(PK,j)-Ms*(1-wPK(PK,s));
conPK3s(PK,j,s).. phiPK(PK,s) =l= Ms*wPK(PK,s);
*
conJM1s(JM,j,s).. phiJM(JM,s) =l= EJMj(JM,j);
conJM2s(JM,j,s).. phiJM(JM,s) =g= EJMj(JM,j)-Ms*(1-wJM(JM,s));
conJM3s(JM,j,s).. phiJM(JM,s) =l= Ms*wJM(JM,s);
*
conTB1s(TB,j,s).. phiTB(TB,s) =l= ETBj(TB,j);
conTB2s(TB,j,s).. phiTB(TB,s) =g= ETBj(TB,j)-Ms*(1-wTB(TB,s));
conTB3s(TB,j,s).. phiTB(TB,s) =l= Ms*wTB(TB,s);
*
conPG1s(PG,j,s).. phiPG(PG,s) =l= EPGj(PG,j);
conPG2s(PG,j,s).. phiPG(PG,s) =g= EPGj(PG,j)-Ms*(1-wPG(PG,s));
conPG3s(PG,j,s).. phiPG(PG,s) =l= Ms*wPG(PG,s);
*
*conLN1s(LN,j,s).. phiLN(LN,s) =l= Elnj(LN,j);
*conLN2s(LN,j,s).. phiLN(LN,s) =g= Elnj(LN,j)-Ms*(1-wln(LN,s));
*conLN3s(LN,j,s).. phiLN(LN,s) =l= Ms*wln(LN,s);
*
conJIMAH1s(JIMAH,j,s).. phiJIMAH(JIMAH,s) =l= EJIMAHj(JIMAH,j);
conJIMAH2s(JIMAH,j,s).. phiJIMAH(JIMAH,s) =g= EJIMAHj(JIMAH,j)-Ms*(1-wJIMAH(JIMAH,s));
conJIMAH3s(JIMAH,j,s).. phiJIMAH(JIMAH,s) =l= Ms*wJIMAH(JIMAH,s);
** LINEARIZATION ****sequestration for new plant with capture****
conPC11(PC1,s).. betaPC1(PC1,s) =l= Epc1(PC1);
conPC12(PC1,s).. betaPC1(PC1,s) =g= Epc1(PC1)-Mp*(1-wpc1(PC1,s));
conPC13(PC1,s).. betaPC1(PC1,s) =l= Mp*wpc1(PC1,s);
conPC21(PC2,s).. betaPC2(PC2,s) =l= Epc2(PC2);
conPC22(PC2,s).. betaPC2(PC2,s) =g= Epc2(PC2)-Mp*(1-wpc2(PC2,s));
conPC23(PC2,s).. betaPC2(PC2,s) =l= Mp*wpc2(PC2,s);
conPC31(PC3,s).. betaPC3(PC3,s) =l= Epc3(PC3);
conPC32(PC3,s).. betaPC3(PC3,s) =g= Epc3(PC3)-Mp*(1-wpc3(PC3,s));
conPC33(PC3,s).. betaPC3(PC3,s) =l= Mp*wpc3(PC3,s);
conIC11(IC1,s).. betaIC1(IC1,s) =l= Eic1(IC1);
conIC12(IC1,s).. betaIC1(IC1,s) =g= Eic1(IC1)-Mp*(1-wic1(IC1,s));
conIC13(IC1,s).. betaIC1(IC1,s) =l= Mp*wic1(IC1,s);
conIC21(IC2,s).. betaIC2(IC2,s) =l= Eic2(IC2);
conIC22(IC2,s).. betaIC2(IC2,s) =g= Eic2(IC2)-Mp*(1-wic2(IC2,s));
conIC23(IC2,s).. betaIC2(IC2,s) =l= Mp*wic2(IC2,s);
conNC11(NC1,s).. betaNC1(NC1,s) =l= Enc1(NC1);
conNC12(NC1,s).. betaNC1(NC1,s) =g= Enc1(NC1)-Mp*(1-wnc1(NC1,s));
conNC13(NC1,s).. betaNC1(NC1,s) =l= Mp*wnc1(NC1,s);
conNC21(NC2,s).. betaNC2(NC2,s) =l= Enc2(NC2);
conNC22(NC2,s).. betaNC2(NC2,s) =g= Enc2(NC2)-Mp*(1-wnc2(NC2,s));
conNC23(NC2,s).. betaNC2(NC2,s) =l= Mp*wnc2(NC2,s);
*
* Initial guess
```

```
*
cost.l = 1
*
*.. define model name
*
Model kyoto /all /;
File opt/dicopt.opt 'maxcycles 1000'/;
kyoto.optfile = 1;
*
*.. more commands
*
option LIMROW = 100000;
option LIMCOL = 100000;
option optcr = 0.0;
option optca = 0.0;
*option minlp = dicopt;
*option nlp = conopt;
option mip = cplex;
*option maxcycles = 10000000;
```