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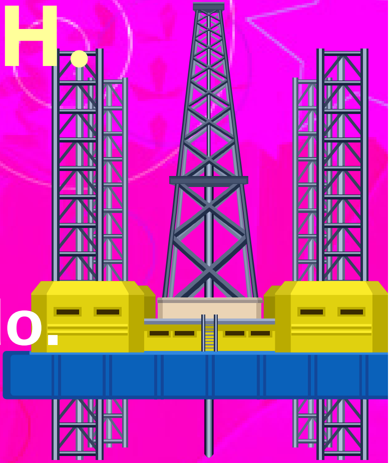
INCREASING THE ECO-EFFICIENCY AND ECONOMY OF AN ENERGY SYSTEM: A MULTIOBJECTIVE OPTIMIZATION APPROACH.



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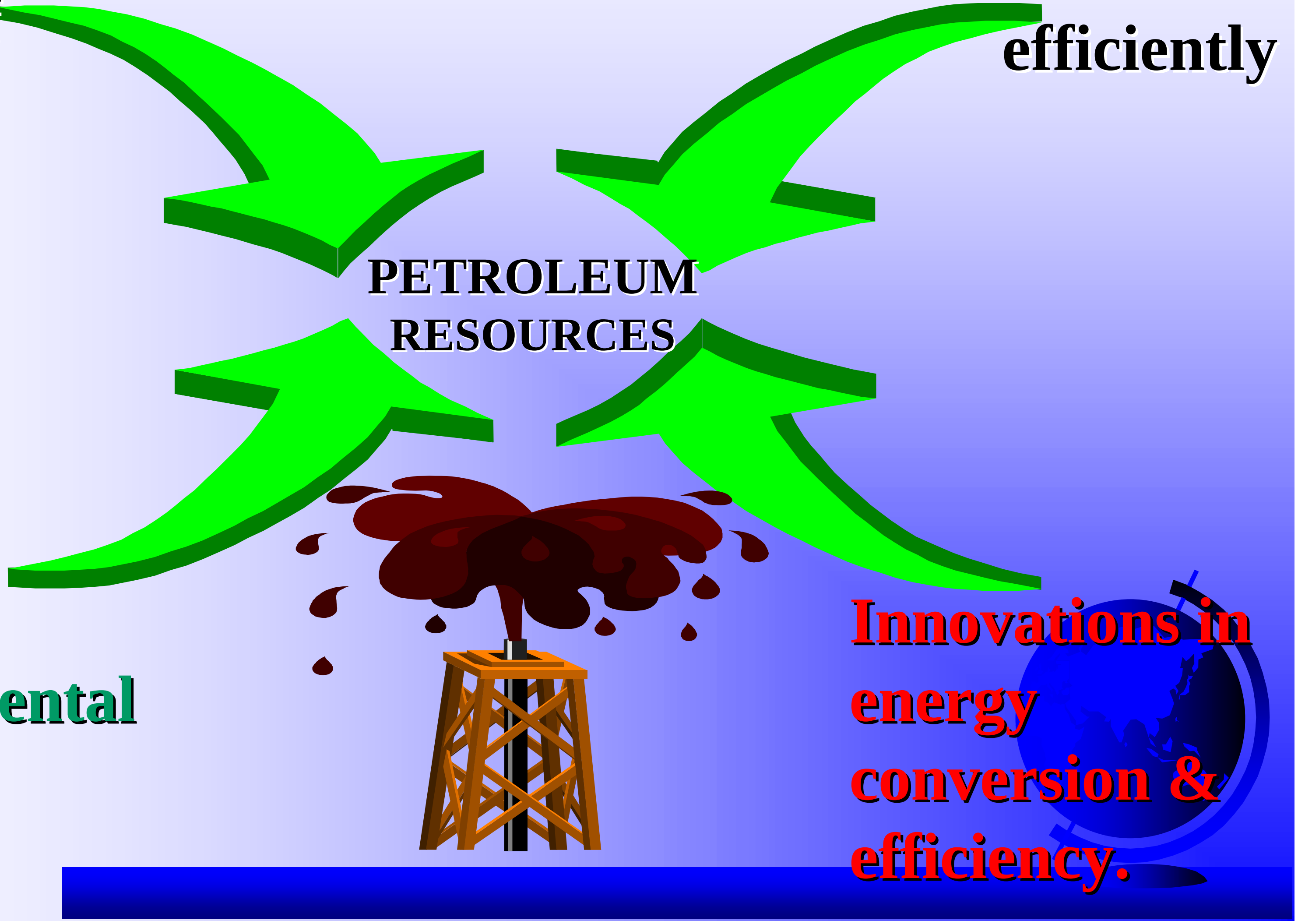
Abstract

Energy is fundamental in the sustainable developing strategy, because:

☞ The necessity to perform scenarios for both, energy demand and energy availability to sustain the economic and social development of the country.

☞ To measure the effects of environment quality.

INCREASING THE OVERALL ECO-EFFICIENCY & ECONOMY OF ENERGY SYSTEMS.



Discovery of large new reserves of HC at low costs.

Produce more efficiently

PETROLEUM RESOURCES

Avoid environmental damage.

Innovations in energy conversion & efficiency.

Abstract

- We propose a multiple objective model optimization system for planning the energy production/generation, the environment effects and the full economy, in order to evaluate the fuel policy.
- We also built an assessment methodology for evaluating and selecting new energy technologies clustered into a set of projects, in a framework of an R&D program.....

METHODOLOGICAL FRAMEWORK FOR R&D PRIORITY SETTING

ENERGY R&D STRATEGY & PRIORITIES

ANALYSIS OF THE NATIONAL ENERGY SYSTEM

ANALYSIS OF ENERGY SYSTEMS

CHARACTERIZATION OF ENERGY TECHNOLOGIES

VISION & OBJECTIVES

VISION: To promote the development of sustainable strategies, which provide energy required for supporting economic growth and improving quality of life, while minimizing health and environmental negative impacts of energy supply.

MAIN OBJECTIVE: To enhance capabilities for comparative assessment of different energy supply options and strategies in the process of planning and decision making for the energy sector.

- The second objective, is to study the economic and environmental impacts of expansion of the generating/production system until 2025, using one base and several alternative cases. The study is realized in four stages:

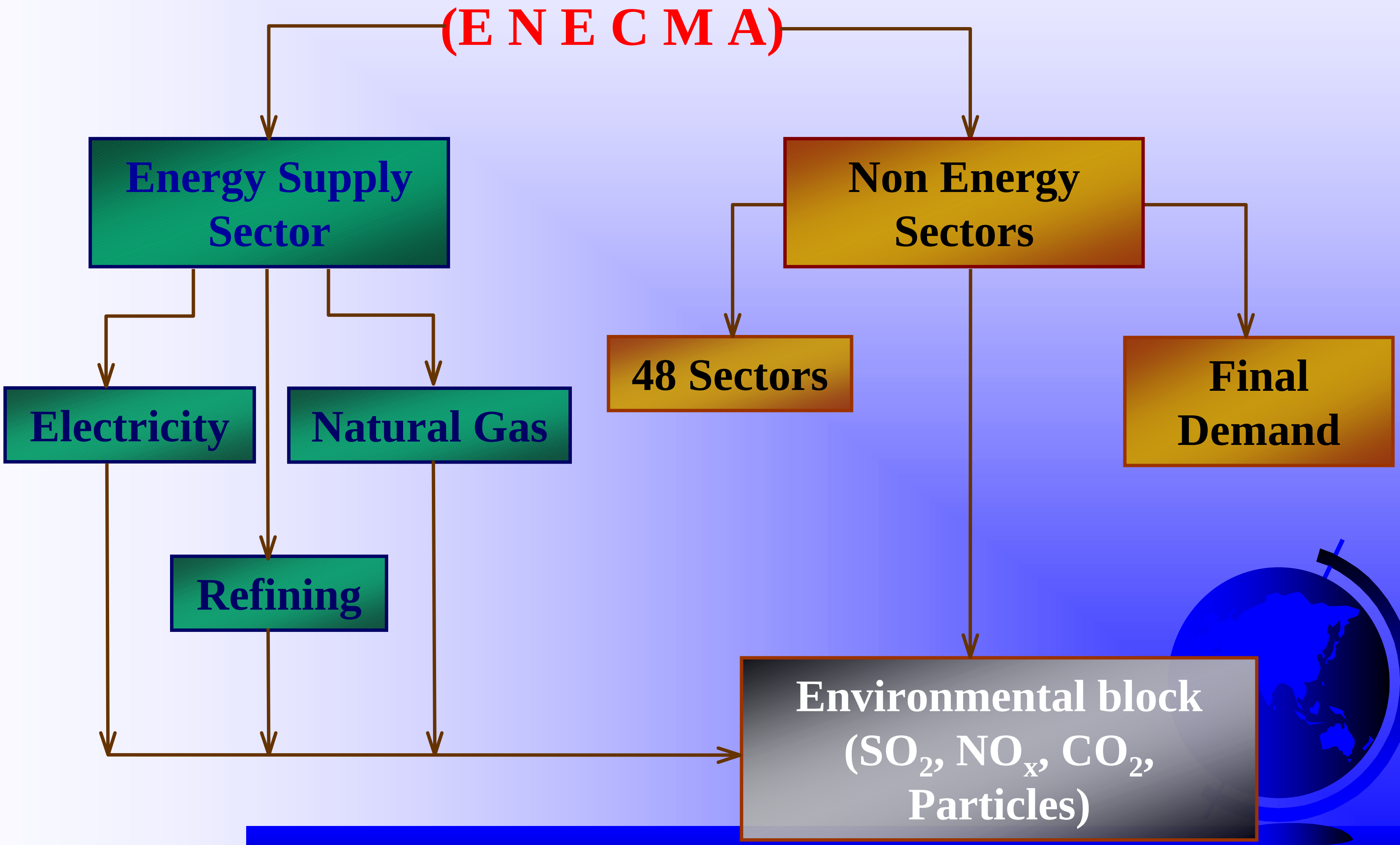
  - ✓Plant level analysis.
  - ✓Fuel chain level analysis.
  - ✓System level analysis.
  - ✓Decision making analysis.

In order to achieve these objectives, the work was divided in two parts :

- The implementation and use of the computer-based tool; this is the MULTIOBJECTIVE model that includes environmental factors in the process of planning and decision making for the **Energy sector**.

- The acquisition, implementation and use of the Energy and Power Evaluation Program (ENPEP), a model for planning and decision making for the **Energy System**, from IAEA Project MEX/0/012 .

ENERGY, ECONOMY AND ENVIRONMENTAL MODEL



(E N E C M A)

Energy Supply Sector

Non Energy Sectors

Electricity

Natural Gas

48 Sectors

Final Demand

Refining

Environmental block (SO_2, NO_x, CO_2, Particles)

THE ENECMA SYSTEM

The system has 3 sub models :

- **The energy sector: the primary energy availability is represented by crude oil and natural gas and consequently by refining products and by hydrocarbons separated from wet natural gas: C_1, C_2,…C_5^+.**
  - **For electricity it was considered specifically dry natural gas, fuel-oil, nuclear, hydro and some renewable (solar and wind).**
- **The non energy sectors. They are represented by 48 sectors of the economy including the final demand.**

THE ENECMA MODEL

(Cont.)

- The relationship between fuel production/generation and consumption is represented in the environmental block through 4 pollutants: SO_2, NO_x, CO_2, and particles. It exists coefficients relating the pollutants emissions and constraints limiting them.

INPUT-OUTPUT MODEL

$X = AX + Y$ or: $\longrightarrow$ $X = (I - A)^{-1} Y$

Where, Y vector of goods and services to satisfy the final demand;

$$Y = CP + GC + EXP + CF$$

CP=Private Consummation GC=Government Consummation; EXP=Exportations; CF=Capital Formation; X=vector of goods and services for economy's total production; A= matrix of technical coefficients.

INPUT-OUTPUT MODEL

(CONTINUATION)

$$TF = C\ X$$

TF = Vector of total use of fuels; C= fuel use coefficient matrix per unit of total output of each sector.

$$TEM = (EM)\ (TF)$$

TEM= total emissions output; EM= matrix of coefficients relating pollution emissions per unit of fuel utilized. TEM, is the constraints imposed by the Ministry of the Environment.

Multiple objectives model

Max (Min) {GDP, Labour, Taxes, Emissions}

$$\sum_{j} a_{ij} x_j + (\mathrm{PC}_i\, x_{\mathrm{PC}} + \mathrm{GC}_i\, x_{\mathrm{GC}} + \mathrm{EXP}_i\, x_{\mathrm{EXP}} + \mathrm{CF}_i\, x_{\mathrm{CF}}) - x_i = 0$$

$$\sum_{j} c_{fj}\, x_j \le \mathrm{TF}_f$$

$$\sum_{j} em_{lj} \le \mathrm{TEM}_l$$

$$i, j \in [\text{sectors, imports, taxes, labour}]$$

$$f \in [\text{fuels, gaz naturel, électricité}]$$

$$l \in [\mathrm{SO}_2, \mathrm{CO}_2, \mathrm{NO}_x, \mathrm{PSM}]$$

ELECTRICITY SUB MODEL:

MIN TC = GENC + EC

Where:

GENC = generation cost

EC = cost of emissions.

REFINERY SUB MODEL :

MIN [TC, EC, -UPM]

where :

CT = total cost

UPM = maximum utilisation of " Maya " crude oil

And in all cases,

$$EC = \sum_{i=1}^{n} E_i \sum_{j=1}^{k} \alpha_j \; EMIS(i, j)$$

Where :

E_i = energy produced in unit " i "

α_j = weight of emissions ; $\alpha_j \geq 0$

EMIS(i,j) = quantity of the emission " j " coming of unit " i "

SOME NEW PETROLEUM REFINING TECHNOLOGIES IN R&D PROJETS

- ULTRASOUND & MICROWAVES FOR FRONT-END CRUDE TREATMENT.
- ELECTRICAL/CHEMICAL PROCESSES.
- CRUDE OIL HYDROSTRIPPING.
- BIOTECHNOLOGY FOR SULPHUR REDUCTION.
- MOLECULAR DESIGN FOR CATALYST SYNTHESIS.
- MICROREACTION, HEAT & MASS TRANSFER.

SOME NEW PETROLEUM REFINING TECHNOLOGIES TAKEN INTO ACCOUNT IN THE R&D PROJECTS

- USE OF MEMBRANES IN HC SEPARATION PROCESSES.
- SENSOR TECHNOLOGY.
- INNOVATIVE WASTE TREATMENT.
- NATURAL GAS CONVERSION TO LIQUID FUELS.
- COKE MANAGEMENT.

ELECTRICITY TECHNOLOGIES

- Gas fired combined cycle units
- Gas fired turbines.
- Coal fired dual units (fuel-oil) with gas desulphurization systems.
- Nuclear Power plants.
- Dendroenergy, wind, solar
- Hydro

- **There are 14 alternative cases selected for study:**

A. Impact of higher demand growth

✓ A1: Demand growth of 6 % per year.

B. Analysis of the nuclear option

✓ B1. Nuclear unit cost of only 1,292 USD/kW.

✓ B2. Forced Nuclear introduction: one unit forced in 2012.

C. Impact of fossil fuel prices

✓ C1. Slightly higher fossil fuel prices.

✓ C2. Natural gas prices 38% higher.

✓ C3. Relative to 1998, the natural gas price increases to a factor of 4.14 higher in 2010 and declines to 1.38 higher in 2024.

D. Limitation on the introduction of new gas-fired units

✓ D1. Limitation to only 3 combined cycle units per year.

✓ D2. Limitation in the supply of natural gas starting in 2010.

E. Variation of the discount rate

✓ E1. Real discount rate of 12 % per year.

✓ E2. Real discount rate of 8% per year.

F. Changes of the System reliability

✓ F1. Loss of load probability of 1 day per year.

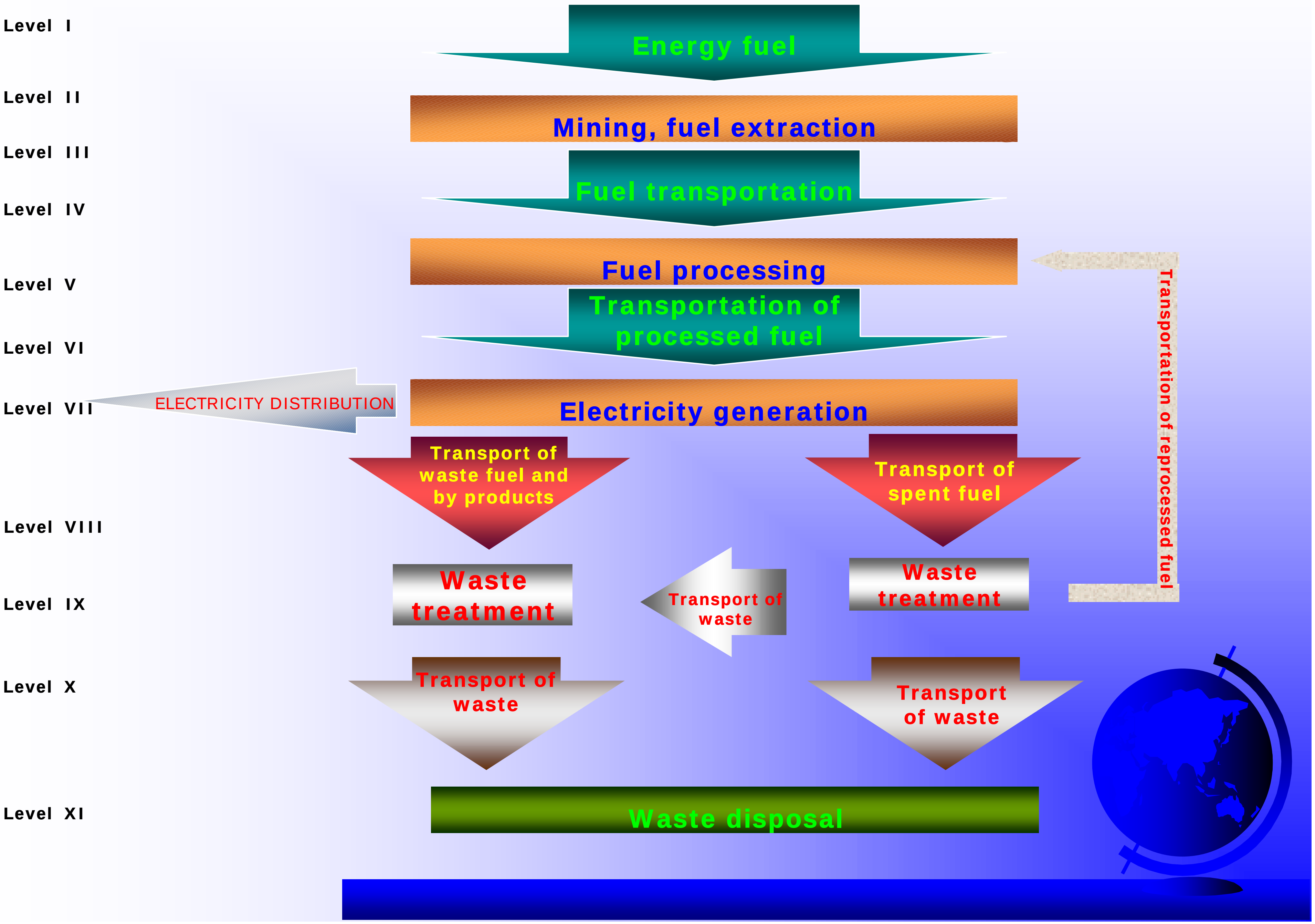
✓ F2. Loss of load probability of 5 days per year.

✓ F3. Decreased cost of energy not served.

H. Introduction of renewal technologies

✓ H2. New solar and wind candidates, which will not be evaluated for lack of data.

Graphical representation of a generalized fuel chain.



Level I
Energy fuel

Level II
Mining, fuel extraction

Level III
Fuel transportation

Level IV
Fuel processing

Level V
Transportation of processed fuel

Level VI
Electricity generation

Level VII
ELECTRICITY DISTRIBUTION

Transport of waste fuel and by products

Transport of spent fuel

Level VIII

Level IX
Waste treatment

Transport of waste

Waste treatment

Transportation of reprocessed fuel

Level X
Transport of waste

Transport of waste

Level XI
Waste disposal

SYSTEM LEVEL ANALYSIS

General assumptions for the base case:

✓Nuclear cost of 2, 485 USD/kW.

✓Price of natural gas of 2.66 USD/GJ in 1998, with an average escalation of 0.08% per year.

✓No supply limit for natural gas.

✓Real discount rate of 10% per year.

✓Cost of energy not served of 1.50 USD/kWh.

✓A maximum reserve margin of 30% and a minimum of 10%.

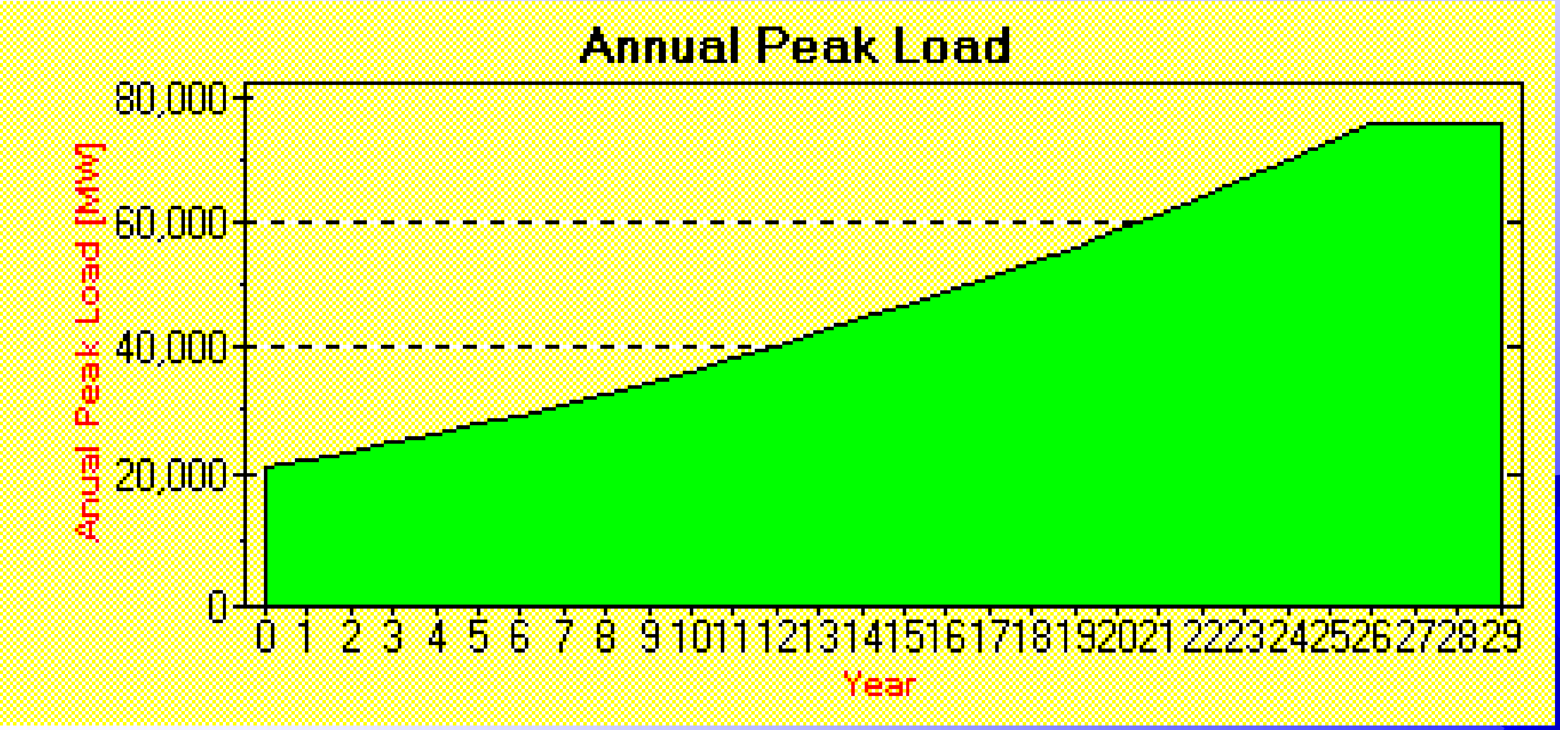
✓Wet flue gas desulphurization (FGD) on new dual coal fired units.

DEMAND

- The scenario of evolution of the demand of electricity adopted for the **system level analysis** is:

  ✓ Starting with 21,236 MW in 1998, an average growth rate of 5.4% per year to reach 37,962 MW in 2009.

  ✓ A projection until 2027 with an average growth rate of 4.5% per year, to reach 73,686 MW.

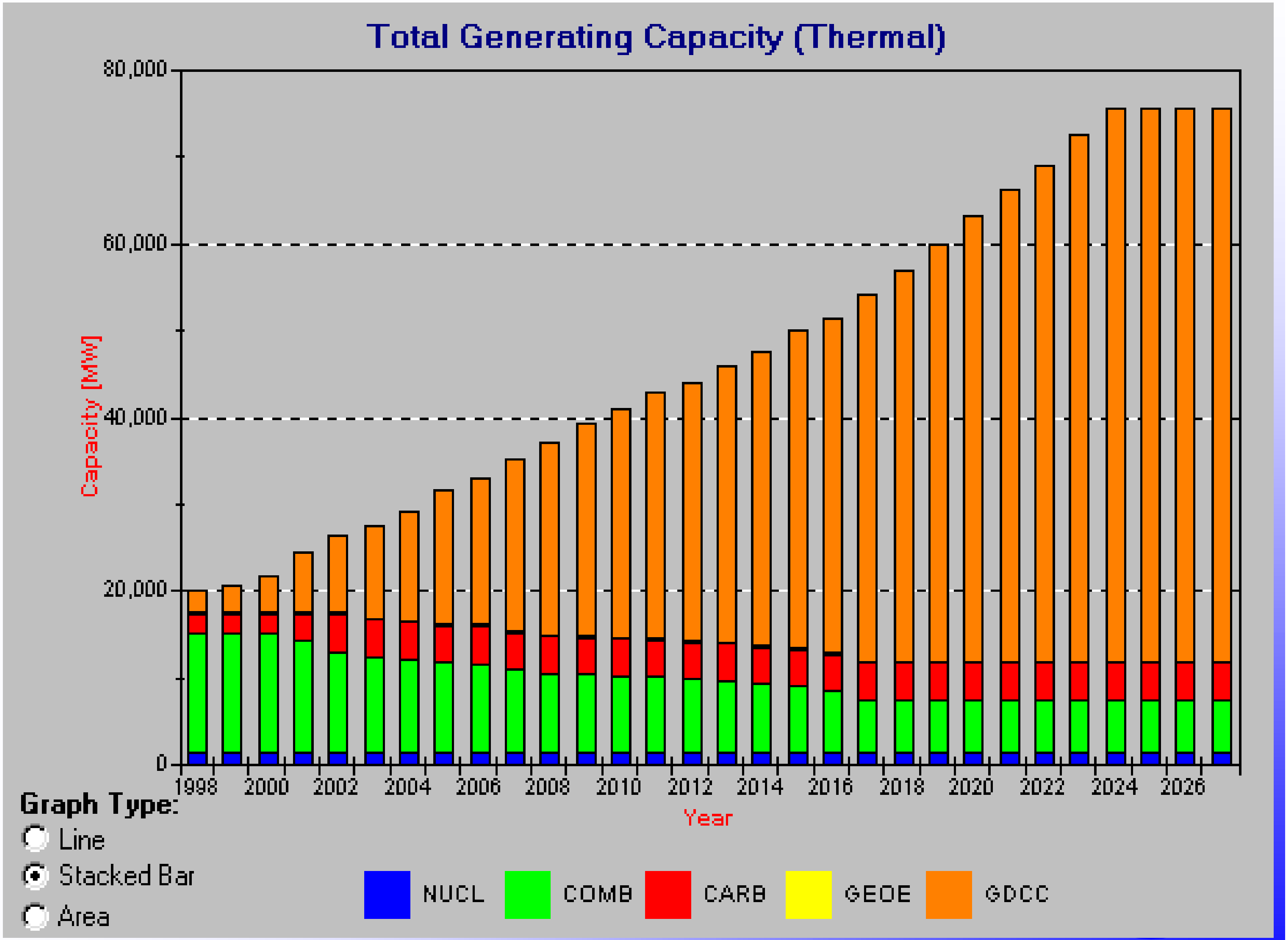


RESULTS

- The least cost expansion plan in the base case was:
  - ✓118 combined cycle plants, with 64,428 MW.
  - ✓6 gas turbines, with 1,074 MW.
  - ✓2,539 MW of 5 committed hydro projects.

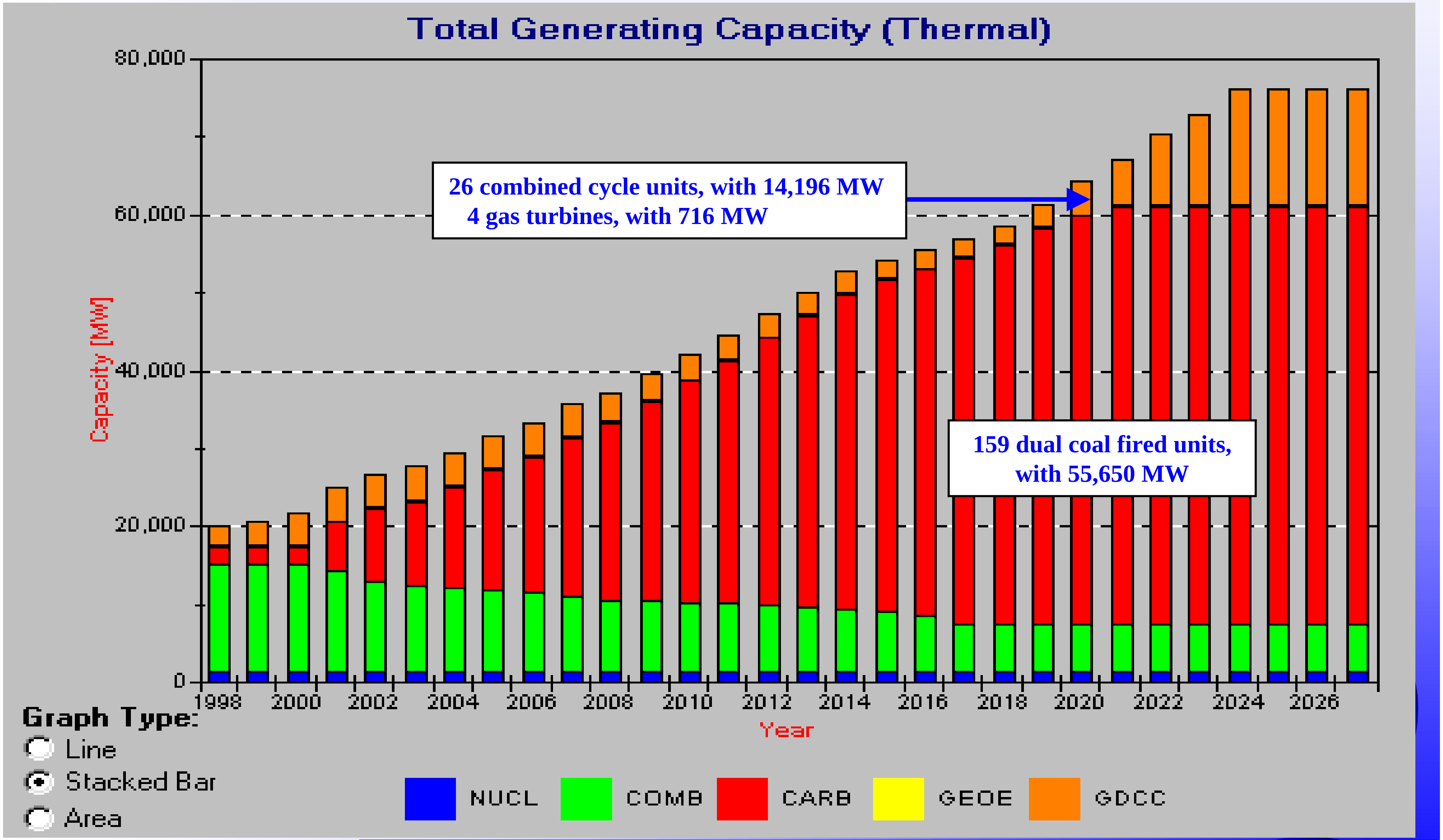
PLANT LEVEL ANALYSIS

- The principal results of the plant level analysis are:
  - ✓ For base loaded operation at 80% capacity factor, the combined cycle has the lowest annual unit cost, at 179 USD/yr-kW.
  - ✓The dual plant with 260 USD/yr-kW and the nuclear with 329 USD/yr-kW are not competitive, not even at 100% capacity factor.
  - ✓For peak load operation below 20% capacity factor, the gas turbine with 85 USD/yr-kW has the lowest annual unit cost.



Graph Type:
- ○ Line
- ● Stacked Bar
- ○ Area

- Relative to the base case, case of high gas prices (C3) has the highest impact in the expansion plan. Total discounted cost increases to 76.3 billion USD.

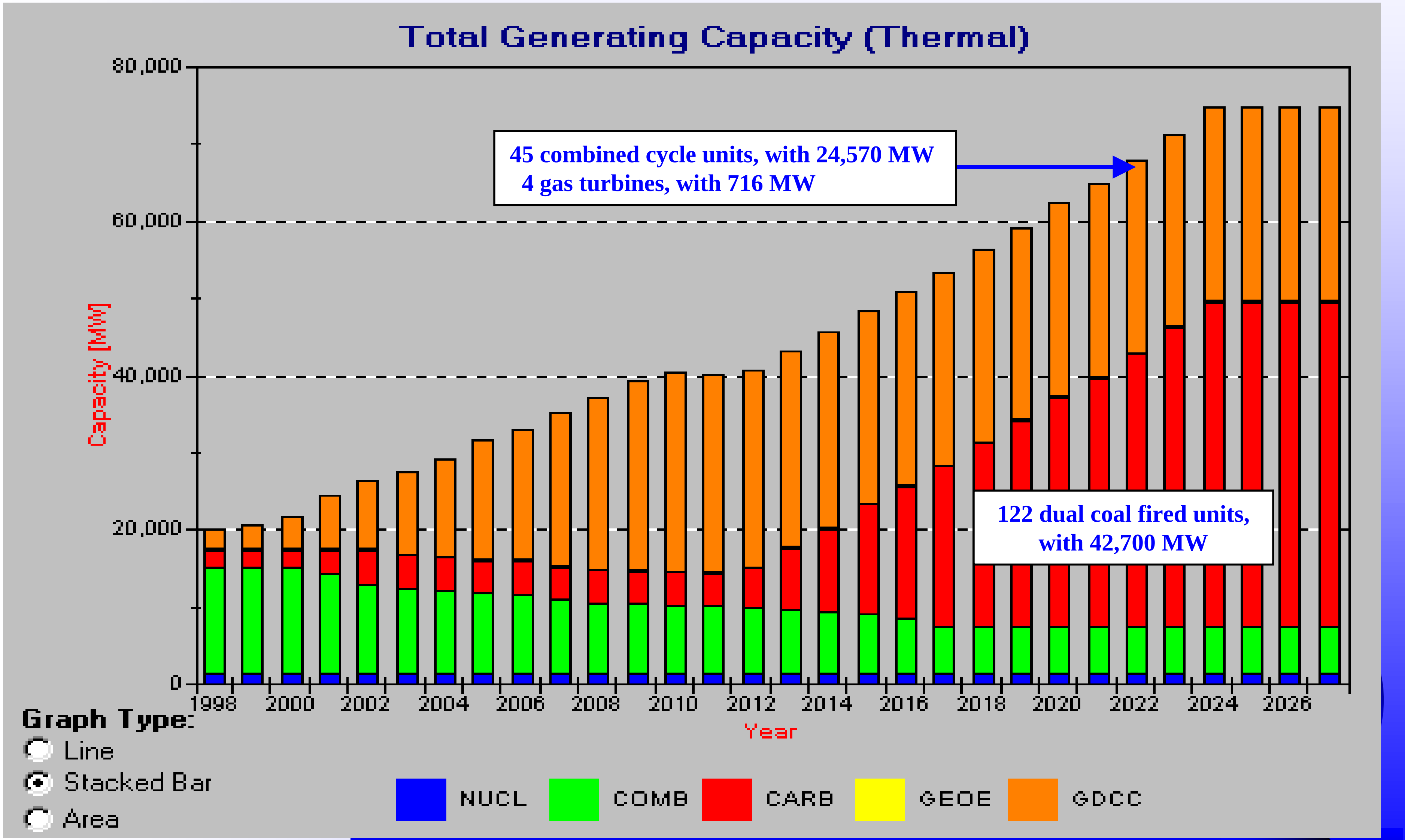


26 combined cycle units, with 14,196 MW
4 gas turbines, with 716 MW

159 dual coal fired units, with 55,650 MW

Graph Type:
○ Line
● Stacked Bar
○ Area

- Relative to the base case, case of gas supply limitation (D2) decreases 61% the capacity based on natural gas in the expansion plan. Total discounted cost increases to 55.9 billion USD.

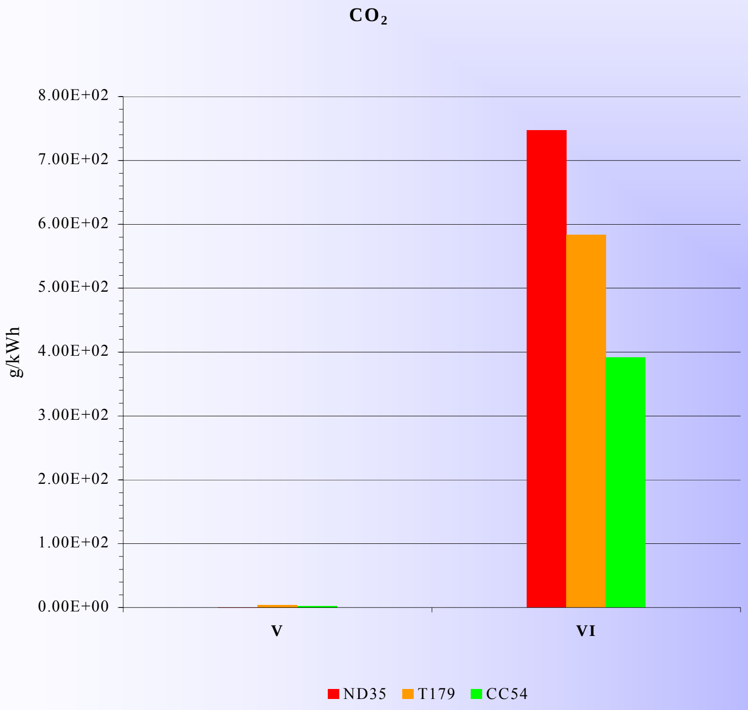


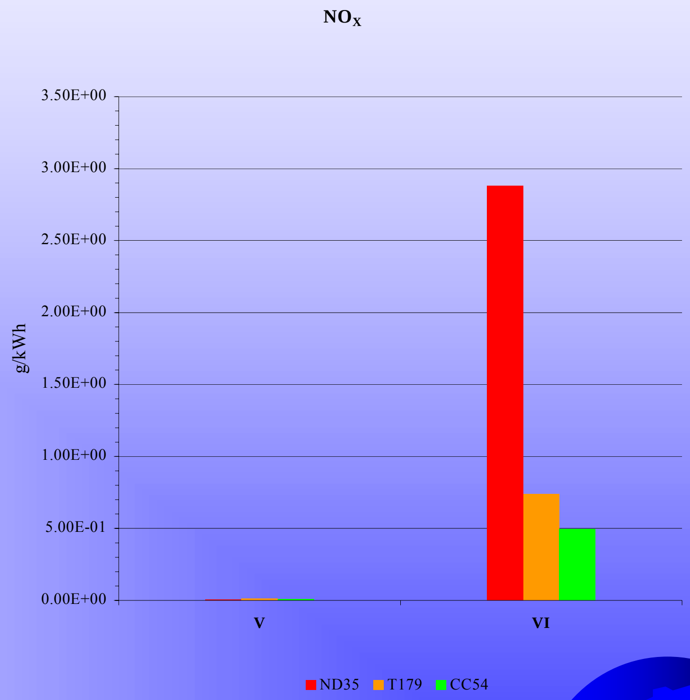
45 combined cycle units, with 24,570 MW
4 gas turbines, with 716 MW

122 dual coal fired units, with 42,700 MW

Graph Type:
- ○ Line
- ● Stacked Bar
- ○ Area

CO_2 and NO_x emissions for full energy chains





DECISION ANALYSIS

The decision analysis serves to compare the base case objective function cost and environmental emissions:

✓B2. One forced nuclear plant in 2012

✓D1. Limitation to only 3 combined cycle units per year.

✓D2. Limitation in the supply of natural gas starting in 2010.

✓F1. Loss of load probability of 1 day per year.

✓F2. Loss of load probability of 5 days per year.

- **If only cost is considered, the decreased reliability case and the base case are the best ones.**
- **If the emissions costs are included, then the case of forced nuclear and the high reliability case are the best.**

A range of costs for the emissions taken from the European ExternE study were chosen as follows:

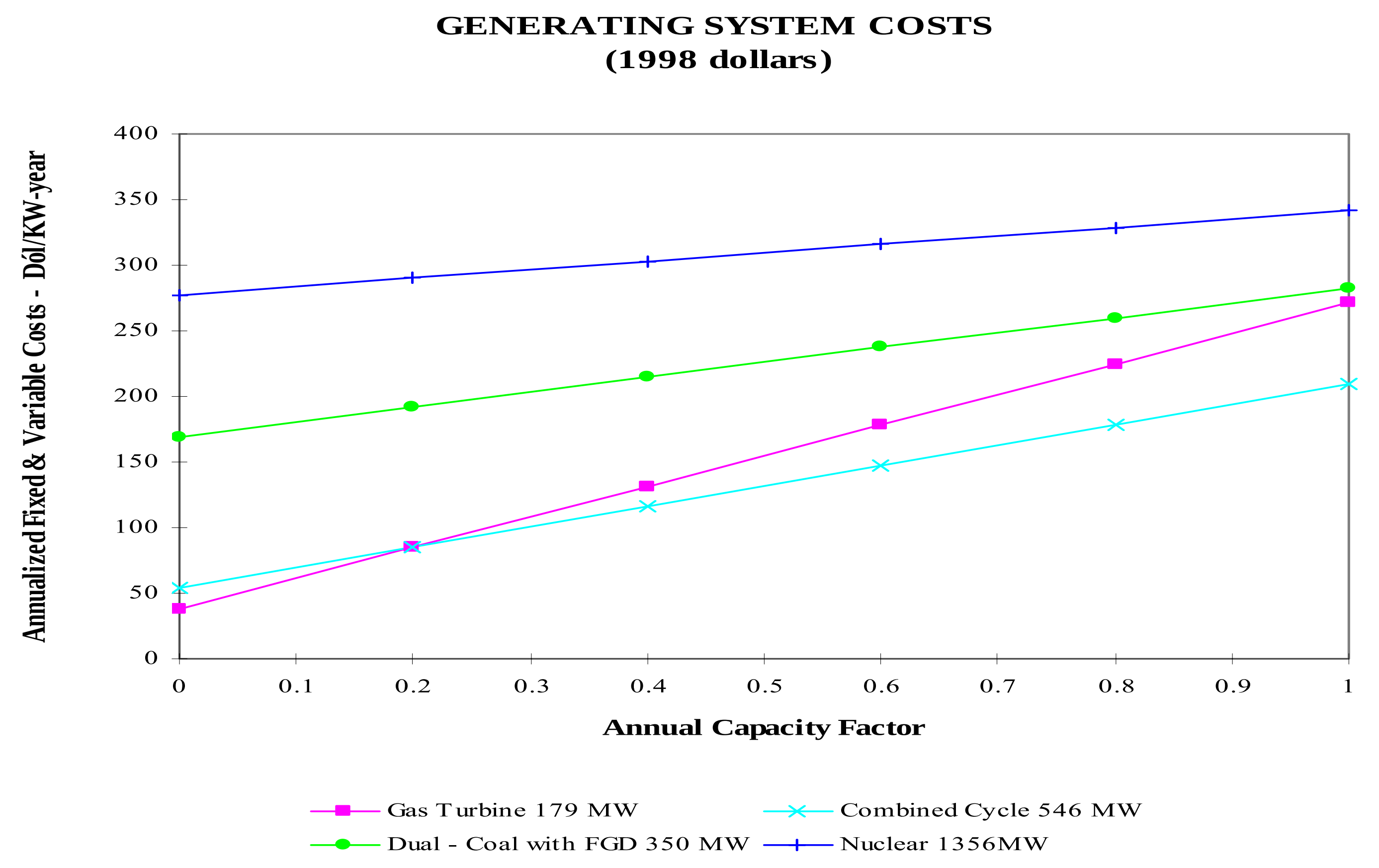
18-100 USD/ t of CO2.

1,115-3,300 USD/t of SO2.

1,265-3,850 USD/t of NOx.

1,210-5,775 USD/t of TSP.

The nuclear option always is the more expensive, later the dual-coal with FGD. On the other hand, for capacity factors less than 20% the gas turbine units are the most attractive ones. For capacity factors greater than 20%, the most attractive plants are the combined cycle.



CONCLUSIONS

The main results are:

1. The plant level analysis produced an initial selection of candidate technologies.
2. The fuel chain level analysis is completed (with some difficulties because of the type of information required).
3. The system level analysis is performed for the base case and 10 alternatives.
4. The model gives useful information about the optimal expansion plans, taking into account costs, environmental emissions and diversity of the energy capacity mix.

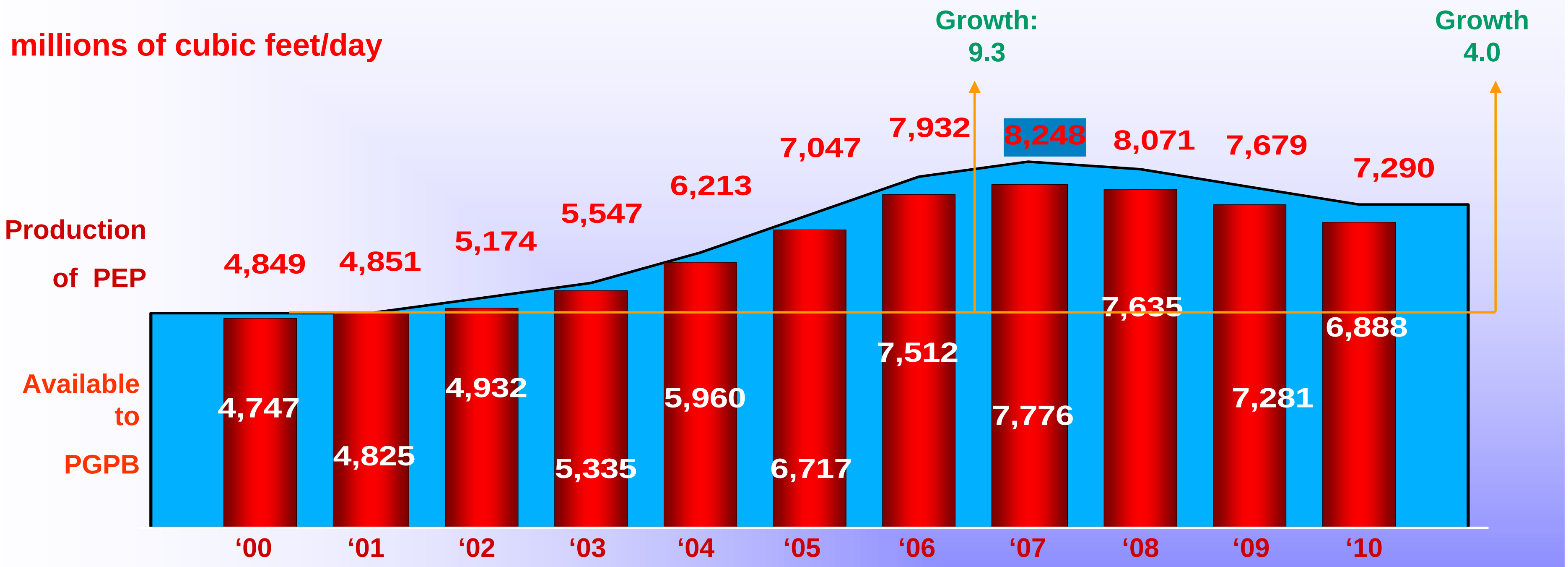
5. The possibility of increases in natural gas prices or gas supply limitations makes it desirable to consider some diversification using alternative technologies such as coal-fired units, fuel oil units, or nuclear units.
6. The potential of wind, solar and dendroenergy was not evaluated because of lack of technical and economic information. Therefore, it is recommended to include in the future such technologies in others evaluations of the model.

- The specific environmental emissions of the alternatives included are:
    - ✓Combined cycle (natural gas): 0.496 g NOx/kWh; 392 g CO_2/kWh.
    - ✓Gas turbine (natural gas): 0.730 g NOx/kWh; 583 g CO_2/kWh.
    - ✓Dual (coal): 0.880 g SO_2/kWh; 2.880 g NOx/kWh; 0.122 g PST/kWh; 747 g CO_2/kWh.
    - ✓Nuclear (enriched uranium): 35.963 kBq/kWh.

OPTIMAL PARETO SOLUTION UNTIL 2024

CASE ID	DESCRIPTION	NUC 1356	DUAL 350	C.C. 546	TG 179	HIDA	HIDB	10^6 t CO_2	10^3 t SOx	10^3 t NOx	10^3 t Part	OBJ. FUNC. (M$98)
106	BASE CASE	0	0	118	6	3	2	195.52	344.00	338.01	16.27	53,124.55
65	HIGH DEMAND Growth 6%	0	0	157	27	3	2	250.86	378.15	409.09	18.33	60232.13
63	LOW NUCLEAR COST - 48 % Investment Costs	5	0	105	9	3	2	177.03	356.58	315.16	17.02	53325.42
74	FORCED NUCLEAR Year 2012	1	0	115	9	3	2	191.96	352.82	333.92	16.80	53530.67
71	SLIGHTLY HIGHER FUEL SCENARIO	0	0	119	4	3	2	195.14	326.41	336.48	15.21	57510.68
78	HIGH SCENARIO FOR GAS 4 $/tcf	0	0	110	30	3	2	205.33	845.04	361.12	46.44	61907.21
82	MEDIUM-TERM INCR. GAS PRICE 2.88, 12 , 4 $/tcf	0	159	26	4	3	2	322.60	630.00	1192.42	58.26	76269.05
68	LIMITATION C.C. 3 units year	0	57	85	4	3	2	241.29	444.32	646.08	31.25	54266.12
70	LIMITED GAS Gas supply is limited (2010)	0	122	45	4	6	2	293.37	590.39	998.76	50.22	55870.5
58	DISCOUNT RATE 12%	0	0	118	5	3	2	195.52	344.01	338.02	16.27	44714.56
31	DISCOUNT RATE 8%	0	0	118	8	3	2	195.52	343.63	337.94	16.25	64346.51
73	INCREASED RELIABILITY 1 day/year, ENSC = 13 $/kWh	0	0	119	15	3	2	195.16	327.00	336.35	15.24	53230.12
66	DECREASED RELIABILITY 5 days/year, ENSC = 0.55 $/kWh	0	0	116	4	3	2	196.52	394.93	341.22	19.34	53089.17
77	DECREASED RESERVE MARGIN ENSC = 0.25 $/kWh	0	0	113	4	3	2	198.12	476.82	346.29	24.29	53056.69

Gas supply scenario, 2001-2010



The availability to PGPB for period 2001-2010 will increase in 2,063 Mcfd.

- **The more important projects are: Cuenca de Burgos, Sur de Burgos, Cantarell, Crudo Ligero Marino, Veracruz y Macuspana.**

Region	*Increase Mcf/d*	*Growth %*
North	993	6.2
South	949	4.8
Sea	121	0.8
Total	2,063	4.0

Processing infrastructure

gas sweetening
Mcf/d

2000	4,020
2005	4,754
2010	5,604

liquids recuperation
Mcf/d

2000	4,732[a]
2005	6,116
2010	6,926

Fractioning
Mb/d

2000	577
2005	734
2010	764

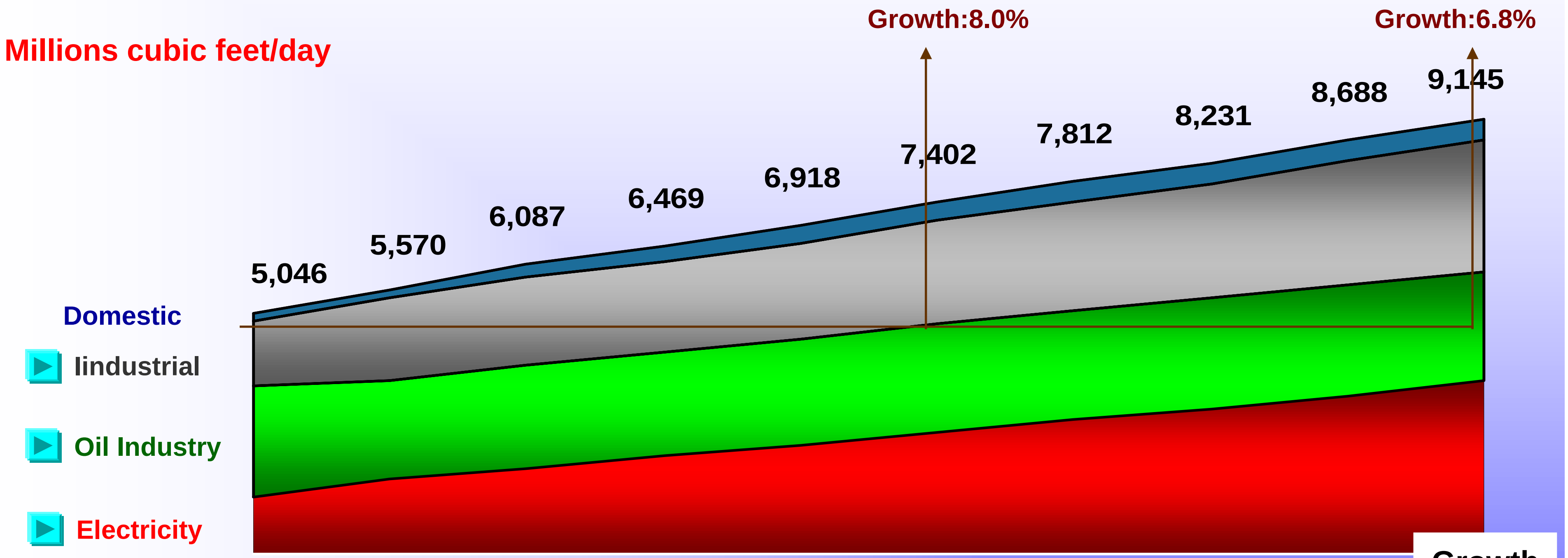
condensate sweetening
Mbbl/d

2000	144
2005	192
2010	192

Sulphur Recuperation
Ton/d

2000	3,236
2005	3,790
2010	3,920

Natural gas Demand, 2001-2010



Sector	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	Growth (%)
Electricity	1,187	1,587	1,807	2,054	2,271	2,580	2,802	3,053	3,327	3,626	13.2
Oil Industry	2,342	2,061	2,190	2,167	2,250	2,285	2,332	2,356	2,358	2,312	(0.1)
Industrial	1,382	1,727	1,825	1,920	2,023	2,137	2,260	2,391	2,558	2,749	7.9
Domestic	135	195	265	329	373	401	419	431	444	458	14.5
Total	5,046	5,570	6,087	6,469	6,918	7,402	7,812	8,231	8,688	9,145	6.8

Investment Program 2001-2010

PGPB's Growth of production

PGPB Supply	2001	2010
Natural Gas (millions of cubic feet/day	4,214	5,973
GLP (million barrels/day)	290	392
Ethane (millions barrels/day)	182	239
Natural Gasoline (millions barrels/day)	115	146

Growth %