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The Mexican energy sector: integrated dynamic analysis of the natural gas/refining system

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Abstract

Environmental regulations in Mexico could dramatically increase demand for natural gas in the following years. This increase could lead to gas price shocks and a counter-intuitive increase in carbon emissions. The effect would be accentuated if Mexico lacks the funds required to carry on with investments in gas development and processing capacity. With the use of a dynamic computer model, this study addresses responses of the Mexican oil and gas industries to perturbations such as: changes in regulatory and environmental policies; changes in institutional arrangements such as those arising from market liberalization; and lack of availability of investment funds. The study also assesses how regulatory policies can be designed to minimize the economic inefficiencies arising from the business cycle disruptions that some perturbations may cause. In addition, this study investigates how investment responses will shape the Mexican energy sector in the future, particularly with respect to both the relative importance of different fuels for power generation and heating purposes and the nature of competition in the Mexican natural gas market. Furthermore, this study explores the direct consequences of these responses on the level of carbon emissions. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Natural gas; Refining; Dynamic modelling

1. Recent perturbations to Mexican energy sector

With the use of a dynamic computer model, this paper presents likely responses of the Mexican oil and gas industries to perturbations such as: changes in regulatory and environmental policies; changes in the natural gas regulatory framework (leading to the liberalization of the gas sector); and budgetary restrictions on the state oil and gas company, *Petróleos Mexicanos* (PEMEX). This article presents a series of scenarios illustrating the supply structure evolution of the competing fuels natural gas and fuel oil, as well as the relationship between fuel prices and substitution. Furthermore, the study assesses the impact that the choice of fuels will have on the environment, particularly with respect to carbon emissions.

1.1. Changes in regulatory and environmental policies

New federal environmental regulations were established in November 1994 and came into effect in January 1998, raising environmental standards for SO_x and NO_x emissions in Mexico's most important metropolitan and industrial areas. By doing so, these regulations essentially forbid the national power monopoly, the Federal Commission of Electricity (CFE), to burn high sulphur fuel oil for power generation in environmentally critical areas. These new environmental regulations have put significant pressure on CFE, as compliance would require two-thirds of the country's thermoelectric plants to be converted from fuel oil to natural gas by 2005 (Barnes de Castro et al., 1996). The industrial sector, which has traditionally used fuel oil for heating purposes, could also be forced to shift to gas. In

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addition, future electricity demand is expected to grow dramatically in the next years and it is anticipated that most of this growth will be met by combined cycle units powered by natural gas (SE, 1997).[1] As natural gas penetration in the residential sector is likely to happen at a fast rate through the replacement of liquid propane, gas demand could more than double in the period from 1998–2006 (SE, 1998). This potential increase in gas demand would put pressure on PEMEX to develop additional production and processing capacity to meet demand as well as coking capacity to convert the fuel oil displaced by natural gas. Coking capacity reduces the conversion of crude to fuel oil while increasing the conversion of other lighter products like gasoline and diesel which are in high demand in Mexico. However, coke accumulation could become a problem of its own. As Mexican fuel oil is very rich in sulphur, it is hard to place it in international markets at a good price. Failure to develop adequate coking capacity could force PEMEX to sell excess fuel oil at a very reduced price, subsequently incurring substantial economic losses.

1.2. Liberalization of the gas sector

In May 1995, the Mexican Congress approved amendments to the Regulatory Law of Constitutional Article 27 on Petroleum. This legal reform authorizes both domestic and foreign private investors to construct, operate and own natural gas transmission, distribution and storage systems (IEA, 1996). In practice, this change allows third parties to import gas from the United States and Canada into Mexico. These reforms have been followed by the total elimination of gas import taxes in 1999 (OGJ, 1999a). It is expected that this step will accelerate the introduction of competition, lowering natural gas prices. However, this may not necessarily occur as PEMEX, the incumbent, could use its market power to deter competition from entering the market. In addition, an explosive growth in natural gas demand resulting from new environmental regulations could put upward pressure on the price of natural gas. A significant increase in gas prices could favour high sulphur fuel oil over gas in non-regulated environmental areas, or everywhere if environmental regulations are not enforced.

1.3. Budgetary restrictions

In the last ten years Mexico has experienced a pervasive lack of funds for investment in its energy sector. Furthermore, the lack of investment funds is aggravated during periods of low oil prices. As in many oil-exporting countries, oil revenues constitute a major part of government income in Mexico's financial structure (approximately 30%). Oil revenues are used for infrastructure projects and to provide services such as education, healthcare and defence. Such dependence on oil makes Mexico very susceptible to oil price shocks. There is historical evidence that when the Fiscal Treasury is faced with a drop in oil price, PEMEX absorbs a great portion of the impact. An oil price shock poses an immediate problem to state-run firms like PEMEX, as already insufficient capital spending is likely to be slashed significantly. This was the case in 1999 when an oil price drop forced PEMEX to implement three rounds of investment cuts. In the event of a prolonged collapse in the price of oil, investment cuts would very likely follow and cause PEMEX to postpone long-term projects. Such postponement could adversely affect the oil and gas industry. For example, the development of an appropriate supply of national natural gas could be hindered due to lack of investment in production and processing capacity. In addition, failure to restructure the refining system could occur, particularly with lack of investment in coking capacity. If either of these were to happen, Mexico could suffer severe environmental and economic consequences such as increased emissions, fuel oil accumulation, lack of gasoline and diesel supply, and gas price shocks.

2. Background

In the past, models have been developed to give a better understanding of the links between the refining, gas and power sectors in Mexico. The Fuel Policy Group was formed some years ago with the intention of giving energy a more co-ordinated approach. Presided by the Ministry of Energy (in which CFE, PEMEX and the Ministry of Economics participate), this group meets periodically to discuss issues that are of importance to the energy sector. One of the obvious outputs of this group was the revision of the environmental regulations recently enforced, particularly those referring to SO_x and NO_x emissions (Poder Ejecutivo Federal, 1995). In addition, the group has addressed problems such as determining, in a simultaneous way, the type of investments that would be optimal for all of the sectors involved and for the country as a whole. A sophisticated linear programming model, the Supply and Demand Model for Energy and Fuels (MOSDEC), was developed to justify a great part of the chosen energy planning programs. However, this model is an optimization (not a simulation) model; it is a linear (not a non-linear) model; and it is a static (not a dynamic) model. As will be discussed, the differences in concept and uses

[1] It is expected that electricity sales will be on the order of 208.3 TWh by 2006 with an average annual growth rate of 5.2% between 2001–2006. At current gas prices, the economics and efficiency parameters favour the use of combined cycle units powered by natural gas over any other alternative option.

between MOSDEC and the model proposed in this study are very important.

Optimization models are very detailed and extremely important in comparing and evaluating policies on an explicit basis. However, as stated by Munasinghe and Meier (1993), they tend to "convey the impression that an 'optimal energy policy' can in fact be identified …There is no such thing." It is our belief that a simulation approach that constructs different possible scenarios will be essential in improving the understanding of such complex problems. In addition, such an approach will help in considering the best ways of dealing with the potential problems brought by these unfolding futures. However, this does not mean that optimization will be completely ignored. Once the most relevant policy parameters in the model have been identified (i.e., those that the firm or government has control over), then the 'optimal parameters' that maximize a given objective function can be determined. This paper presents a combination of simulation and optimization techniques.

A non-linear methodology is required in order to grasp the behaviour of such a complex system and to understand the links involving the oil and gas sectors. Such a model will have to point out the most important reinforcing and balancing feedback loops governing the system. It will also need to determine both the reasons for falling into vicious cycles and how to stop such events from occurring.

In addition, we believe that it is impossible to achieve a thorough understanding of the dynamic behaviour of such a system without dealing with demand, price and substitution between fuels in an endogenous way. Given the rapid structural change in Mexico's economy and energy sector, we further believe that a dynamic simulation rather than a static approach is required to obtain a proper understanding of the system. To date, the policy-designing tools in Mexico have fallen short of capturing the dynamic interactions between public policies and the different energy subsectors. The use of a static approach implies a serious limitation when assuming that the policy effects will take place in an environment that is constant over time. Any attempt to design a policy that incorporates at least some of these issues of dynamic complexity requires a rigorous analysis of the structure of the system.

Another important difference between both models is the details involved. MOSDEC involves thousands of linear equations and was created through the concerted effort of PEMEX, CFE and private consulting companies, involving resources and time that are far beyond the aspirations of this work. Furthermore, it is a complex model out of reach of understanding for most of the policy makers (i.e., it is basically a black box operated by technical experts). Although extremely helpful in obtaining accurate quantitative values, such a model lacks a didactical nature, yet its purpose is to improve decision-making in industry and policy. The richness of such a model is in the exactitude of its output, not in its development or use. The added value of the model we developed comes from giving strategic insight into the behavioural characteristics of the system, not from numeric precision.

Dynamic models have been used extensively in the past to address energy policy issues. Models dealing with the dynamics of the electricity sector are numerous, particularly in the UK (Bunn and Larsen, 1992a, ,b; Larsen and Bunn, 1999; Bunn, 1994; Bunn et al., 1993, 1997), but also in the US (Ford, 1997; Lyneis, 1997) and Colombia (Dyner, 1995; Dyner and Bunn, 1997). These models were created to analyse particular issues resulting from structural changes in the electricity industry and regulatory framework. With the exception of Ford (which is aimed at developing conservation policies), the models are aimed at understanding particular aspects of policies seeking to achieve total or partial liberalization. In short, they attempt to identify the effects of particular policies on the dynamics of the system.

Several models have also been constructed to deal with the dynamics of the oil and gas sectors. Of particular relevance to this study are Ruth and Cleveland (1993), which deal with oil scarcity and resource extraction, as well as Sternman and Richardson (1985), Chowdhury and Sahu (1992), and Davidsen et al. (1990), which deal with the dynamics of oil and gas exploration. Also of importance is Mashayekhi (1998), as his model addresses the dynamics of public finance and oil revenue expenditure. However, none of these models accounts for the relationship of the oil and gas sectors with other energy subsectors, and none of them incorporates a liberalized system accounting for competition. Other authors (Morecroft and Marsh, 1997) have focused their work on the dynamics of international oil producers. However, the objective of that study is to understand the dynamics of the global oil market and its players, not the internal dynamics across energy subsectors. A dynamic computer model has also been created to address issues in the refining sector (Lane, 1997). However, that model addresses a different problem, as it is constrained exclusively to a particular Shell refinery and does not take into account linkages with other energy subsectors.

In addition, dynamics models have been created to account for environmental problems. A relevant example of this type of model is Leautaud and Perez-Barnes (1997), as it deals with the problem of ozone formation in Mexico City and its relationship with the transport sector. However, the environmental problems differ from those addressed in the present work.

Like every dynamics model developed to address policy issues, these models are similar in the objectives they pursue. However, every model (like every system) is different in nature. The Mexican electricity market is completely different from liberalized markets in England and Wales (Bunn et al., 1993; Banks, 1996), Australia (Brennan and Melanie, 1998), or the US (O'Neill, 1992), including the one recently developed in California (Borenstein et al., 1995). Although partially liberalized, the Mexican gas market is likewise different from more mature gas markets like the British (Stern, 1997) or American (O'Neill, 1992; Tussing and Hatcher, 1994; DeVany and Walls, 1994a, b).

Maybe even more important than the differences between energy subsectors across countries are the differences in the inter-relationships of these subsectors (e.g. power sector) with others energy subsectors (e.g. refining or natural gas) across countries. In Mexico, the relative importance of fuels (mostly fuel oil) for power generation is different from other countries like the UK or the US. Also, the inter-dependence of the power sector and the refinery sector in Mexico is unique, probably only shared with a few nations across the world. As such, the novelty of this study comes not just from using a system dynamics approach for the energy sector, but rather from identifying a particular problem where a dynamic approach is used in order to better understand its essence.

3. The dynamic model

Specifically, the proposed model attempts to capture the following dynamic processes:

- PEMEX's associated gas production schedule resulting from oil production and constrained by processing capacity in place.[2]
- PEMEX's non-associated gas production decision based on profit-maximizing principles and subject to an expected competitor entrance rate, production costs, gas reserve levels and the rate of interest.
- PEMEX's investment decisions in gas production and processing capacity.
- PEMEX's actions to deter entry of competition to the Mexican gas market.
- Entrance rate of new gas competitors to the Mexican gas market subject to changes in gas prices, competitor cost functions, demand growth, and PEMEX's entrance-deterring actions.
- Gas demand calculated endogenously and affected by gas and fuel oil prices and cross elasticity of demand.
- Gas price determined endogenously and subject to market clearing.
- PEMEX's investment in refining capacity (i.e., coking) to reduce the supply of fuel oil and minimize fuel oil accumulation resulting from gas displacement.
- Fuel oil imports if fuel oil supply is reduced at a faster pace than demand.
- Fuel oil demand calculated endogenously and affected by gas and fuel oil prices and cross elasticity of demand.
- PEMEX's fuel oil price determination subject to the deviation of fuel oil inventory and fuel oil desired inventory as well as to the deviation of fuel oil sales and demand.
- Total carbon emissions subject to the total national supply of natural gas and fuel oil.

4. Model structure

The model is divided into three main modules as illustrated in Fig. 1 and described below:

- Natural Gas Industry—computes total gas supply (PEMEX associated and non-associated gas and gas imports) and gas prices.
- Refining Industry—computes total fuel oil supply (PEMEX and imports) and fuel oil prices.
- Environmental Impacts—computes total carbon emissions and total coke accumulation.

Each of these modules can be considered as a model of its own. As illustrated in Fig. 1, the gas and refining industry modules of the model are linked to each other by the prices of gas and fuel oil. The price of gas is an output of the gas module and requires the price of fuel oil as an input. Likewise, the price of fuel oil is an output of the refining module and requires the price of gas as an input. If these modules were to be operated independently of each other, the prices fed into each model would have to be determined in an exogenous way. However, by doing so, information regarding the dynamics of fuel substitution in the system would be lost. In a similar way, the environmental impacts module uses the outputs of the natural gas industry module (total gas consumption) and refining industry

[2] Natural gas in Mexico can be produced either in associated form or in non-associated form. Associated gas is produced simultaneously with oil and accounted for 81% of Mexico's total gas production in 1997. Non-associated gas is produced independently of oil and accounted for 19% of Mexico's total gas production in 1997 (SE, 1998). Mexico's associated gas production is very rich in natural gas liquids (i.e., "wet") and contains significant amounts of sulphur (i.e. "sour"). The associated sour wet gas is first submitted to a sweetening process where most of the sulphur is stripped from the gas in sulphur recuperation post-Claus plants. The gas leaving the post-Claus units is referred to as associated sweet wet gas. This associated sweet wet gas, is then sent to cryogenic units where liquids with high added value such as propanes, butanes, and natural gasolines are stripped from the gas. The gas leaving the cryogenic units is referred to as associated dry gas. To date, spare capacity still exists in the majority of sweetening and cryogenic processing facilities. However, this is likely to change as the demand for gas increases in the future and more processed gas is required.

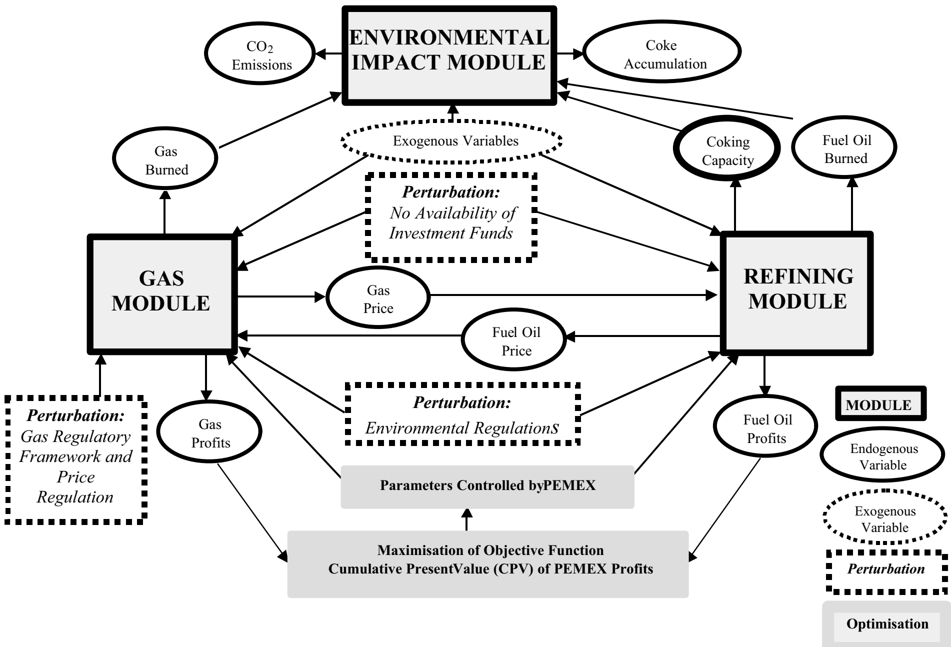

Fig. 1. Model structure.

module (total fuel oil consumption and coke production) as inputs.

As shown in Fig. 1, each of these modules is fed by a number of exogenous variables that PEMEX has little or no control over (e.g. unit cost of investments, cross elasticity of demand, fuel heat content, etc.). In addition, each of these modules is fed by a number of variables that PEMEX has control over (e.g. amount to expand output to deter competition from entering the market, price response to the deviation of inventory with respect to desired inventory, etc.). These variables are determined by maximizing the cumulative present value of PEMEX total profits. This function considers, among others, gas and fuel oil revenues; revenues resulting from additional gasoline and diesel production (resulting from coking capacity investments); investment costs of gas processing and gas production addition; investment costs of coking capacity; variable costs of gas production; costs of maintaining a fuel oil inventory (i.e., storage costs plus the opportunity cost of not selling the fuel oil held in the inventory). The time horizon chosen for the simulation is seven years (2000–2007).

4.1. Gas module

Fig. 2 depicts a more elaborate version of the Gas Module than the simplified one provided in Fig. 1. It provides a more detailed picture of the dynamics of the gas industry and it better represents the linkages and feedback among key variables. In addition, Fig. 2 depicts the methodologies followed for the calculation of some of the essential variables shown in the diagram. Although Fig. 2 is still a simplified version of the dynamic computer model, it serves to illustrate the core structure of the natural gas industry.

Gas prices are calculated endogenously in the model such that supply matches demand for every period of the simulation.

For purposes of this study, demand is considered to consist of the following two components:

- The demand of gas that depends solely on factors other than price due to the lack of substitutes in the time period of the simulation (e.g. penetration of natural gas in the domestic sector, natural gas used as a feed stock by the petrochemical sector, natural gas used to raise the pressure of the oil reservoirs, etc.).
- The demand of gas that will be affected by both gas and fuel oil price changes because of the possibility of substituting one for the other in the short term (e.g., gas for power generation, gas for heat purposes in industry and in the oil sector, etc.).

Total supply of gas is given by the sum of PEMEX production of associated and non-associated gas and by gas imports. It is assumed that PEMEX will produce the amount of associated gas derived normally with oil production and constrained only by the amount of processing capacity available. For the calculation of non-associated gas, an optimal control methodology adapted from Hannon and Ruth (1994) is used. This modelling approach is based on the theory of extraction of non-renewable resources initially developed by Hotelling (1931). Using this approach, the amount of non-associated gas production that maximizes the

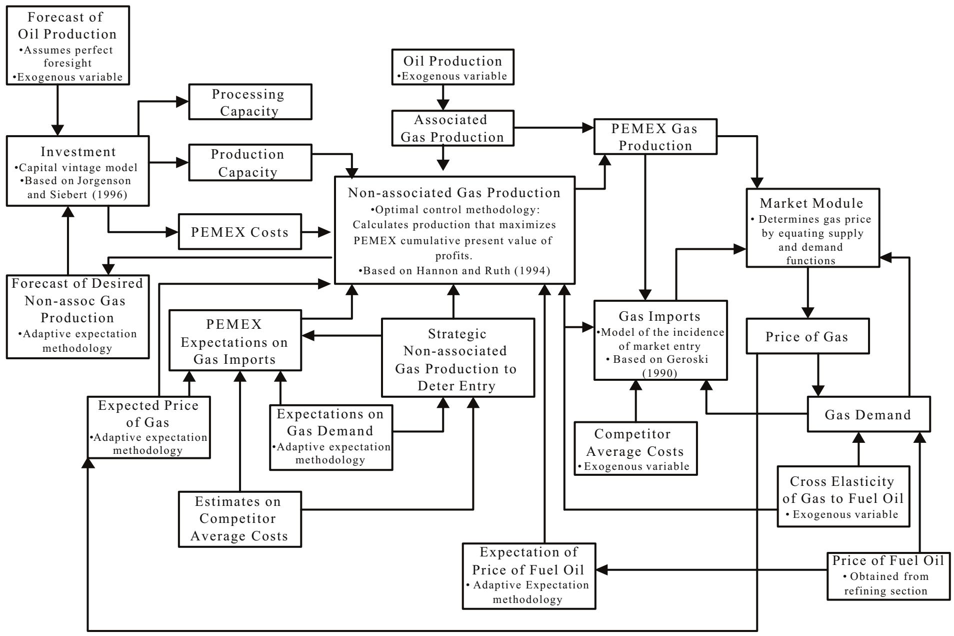

Fig. 2. Gas module structure.

cumulative present value of PEMEX profits is determined. This function is maximized subject to costs of production of non-associated gas; expectations of competition that will enter the gas market in a given year; expected price of fuel oil; cross elasticity of demand of gas to fuel oil; interest rate; and the level of non-associated gas reserves. We have introduced an innovation to Hannon and Ruth's methodology by maximizing the objective function subject to the incumbent (PEMEX) strategies to deter competition from entering the market.[3] In the absence of regulator intervention and financial constraints, PEMEX can either accommodate all of the expected entry or pursue expansion policies to deter total or partial expected entry. The model assumes rational behaviour, allowing for PEMEX to adopt the strategy that maximizes the cumulative present value of profits.

Extensive work has been conducted regarding entrance into an incumbent-dominated market, focusing particularly on strategic actions taken by the incumbents to deter entry.[4] For the calculation of gas imports we have adapted the Geroski (1991) model of entry to account for the incidence of foreign competition in the Mexican gas market. The Geroski model assumes that the number of firms observed at any point in time is the equilibrium number appropriate for that industry. As such, this model assumes that the number of new firms entering the market causes expected post entry profits to be zero. The Geroski model alsoassumes that all firms entering the market are equal in size and cost schedule. The amount of gas imports will depend on both the conditions of the market (e.g., demand growth and elasticity of demand) as well as the nature of the incumbent's response to entry (i.e., accommodation or entry deterrence) and on the competitor cost function. Gas imports are expected to increase with both market growth and an increase in demand elasticity, and to decrease with incumbent deterring strategies.

In order to have a dynamic model, it is necessary to consider that investment in capacity occurs endogenously. To determine capacity investments, this model uses a capital vintage procedure based on Jorgenson and Siebert (1996a, b). The addition of capacity is of extreme importance, as the level of capacity will directly affect total supply of energy fuels, having thus a direct impact on energy prices and shaping the way the energy industry will develop in the future. This model of investment will be used in the dynamic simulation model to compute changes in processing capacity (sweetening and cryogenic) and non-associated gas production capacity.

4.2. *Refining module*

Fig. 3 depicts a more elaborate version of the Refining Module than the simplified one provided in Fig. 1.

Within the model, fuel oil prices are a function of the deviation of the actual inventory of fuel oil held by

[3] Such strategies include investment resulting in additional production to cause an over supply of gas, thus lowering prices below the competitor's average cost.

[4] Baron, 1973; Bulow et al., 1985; Dixit, 1979, 1980; Friedman, 1981; Gaskins, 1971; Geroski, 1991; Salop, 1979; Spence, 1977; Spulber, 1981.

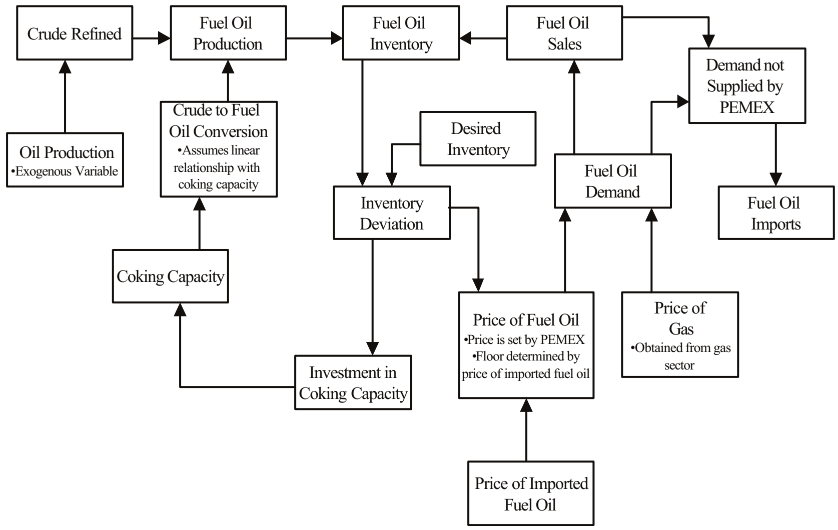

Fig. 3. Refining module structure.

PEMEX and the desired fuel oil inventory. When fuel oil production exceeds demand and fuel oil accumulation exceeds PEMEX desired level of inventory, prices of fuel oil are decreased in order to stimulate demand and decrease inventory to its desired level. Conversely, if the level of inventory is below the desired level, prices are increased to suppress demand and increase inventory to PEMEX desired levels.

Inventory is a stock determined by the inflow of fuel oil production and the outflow of fuel oil sales. Fuel oil production is the product of the amount of crude oil refined and the conversion of crude to fuel oil.

Inventory changes are not the only effects on prices. If PEMEX fuel oil sales are unable to match demand due to a decrease in fuel oil production resulting from new coking capacity in place, fuel oil will be imported. If this occurs, PEMEX will very likely increase the price of its fuel oil to take advantage of high demand levels. The limit to which PEMEX can increase fuel oil prices is given by the price of imported fuel oil (the alternative option in this particular case). Also, if the price of gas increases with respect to the price of fuel oil, PEMEX will have the incentive to increase fuel oil prices up to the critical level where a substitution towards natural gas would be encouraged. As such, the price of fuel oil given by PEMEX will depend on: the magnitude of the effect of the deviation of inventory and desired inventory; the effect of the difference between fuel oil demand and fuel oil sales; and the effect of difference between gas and fuel oil prices.

The decrease in the conversion of crude to fuel oil involves an important feedback effect on prices that is not felt immediately, but rather with a delay in time. PEMEX will invest in coking capacity when inventory exceeds desired levels. The conversion of crude to fuel oil is a negative function of coking capacity. As a result, when capacity is added, the conversion of fuel oil is decreased while the yield of other valued products such as gasoline is simultaneously increased. A decrease in the value of conversion of crude to fuel oil will lead to a reduction in the level of fuel oil production, leading to a change in fuel oil inventory. For simplicity and due to the lack of available information, a linear relationship is assumed between coking capacity and fuel oil conversion.

4.3. *Environmental impact module*

This module incorporates two types of environmental impacts:

- *Carbon emissions*—In the model, only carbon emissions are quantified since the magnitude of SO_x and NO_x emissions depends in great part on the technology used when burning the fuels. As this type of information is not readily available, this analysis has been excluded from the study. The pollution problems associated with combustion of fossil fuels in Mexico are historical. Between 1970 and 1995, carbon emissions in Mexico increased by 221%. In 1995, energy-related carbon emissions in Mexico were 95 million metric tons. This represented about 1.5% of total world emissions and made Mexico the eleventh most carbon-emitting country in the world (EIA, 1996) and the third most polluting country of the developing world (just below China and India). According to the Energy Information Administration (EIA), Mexico's carbon emissions are expected to reach 165 million metric tons by 2015, representing 1.8% of total world emissions. In 1994, carbon emissions per thousand dollars of gross domestic product were 0.44 tons for Mexico versus 0.29 tons for the US. In the model, carbon emissions are a function of total gas and fuel oil burnt, heat content of the respective fuels, and carbon content per unit of heating value of each fuel.

- *Coke accumulation*—At least in principle, coking capacity seems to be a good investment for the Mexican energy sector since it helps reduce the production of high sulphur fuel oil and increases the production of other distillates. However, coking also poses a potential problem, as coke accumulation could become an environmental issue. In the model, coke accumulation is a function of both coking capacity (assuming all available capacity is used) and the yield of coke production per coking capacity in place.

5. Application of the model to three scenarios

In the construction of different scenarios, the following possibilities have been considered:

- *Environmental regulation enforcement*—Even though new environmental regulations that restrict SO_x and NO_x emissions for fixed sources came into effect at the beginning of 1998, they have yet to be enforced. In the past, the lack of regulatory enforcement, not the lack of regulations, has been a general problem in Mexico as in other developing countries. However, important efforts have been made towards solving this problem. The Federal Attorney General for Environmental Protection (PROFEPA), an organization linked to the Secretary of the Environment, is the body in charge of verifying enforcement of environmental regulations.

  The enforcement of environmental regulations is expected to become more stringent in the next years. The model allows for the construction of scenarios considering both regulatory enforcement and lack thereof. In order to take these regulations into account, the effects they will have on gas and fuel oil demand must be understood. It is to be expected that regulatory pressure prohibiting the use of high sulphur fuel oil will force both the power sector and industrial sector to convert plants burning fuel oil to natural gas. As such, for the purposes of this model, regulatory enforcement will translate into a decrease in fuel oil demand and an increase in gas demand.
- *Price regulation*—Price regulation could prove to be of extreme importance for the development of the natural gas market in Mexico. The 1995 Natural Gas Act states that price regulation will prevail whenever competitive conditions do not exist. Regulated prices must reflect opportunity costs, but also competitive conditions in international markets, and should also allow a reasonable return on investment.

  There is extensive theoretical work regarding price regulation of a monopoly. The most efficient approach is setting price equal to marginal costs. However, setting prices at this level incurs losses for industries presenting significant economies of scale. In these cases, an approach setting prices at average cost levels is preferred. This is fine if the ultimate goal is to regulate a monopoly, but not if it is to introduce competition in the Mexican market. PEMEX production costs are lower than most American producers since most of the natural gas is found in associated form and most of the extraction costs are assigned to oil production. Variable costs are also difficult to measure given that Mexico's natural gas is very rich in liquids such as ethane, propane, butane, and natural gasoline (C^{+5}). These liquids are obtained when the Mexican natural gas is processed and it is very easy for PEMEX to distribute its natural gas production costs among these products. It will be crucial for the regulator to establish whether PEMEX reported variable costs are low enough to prevent competition from gaining share of the market.

  In this model, price regulation is considered by fixing the price of gas rather than allowing for its free determination by the market. To fix the price, a level above PEMEX average cost has been chosen to allow for competition to enter the market. Different scenarios should be built for different levels of the regulated price.
- *Lack of availability of investment funds*—The model allows for the possibility of not having the required investment funds readily available. This lack of availability will translate into a partial rather than a total completion of PEMEX investment, as calculated endogenously by the model.

Although the model allows for the construction of many different scenarios, Table 1 summarizes the three scenarios which are presented and compared to the noted base case scenario.

Scenario A (Base Case) is considered as free of the effects of the perturbations presented. It is by no means considered as the ideal scenario, but rather as the basis by which the effects of the different perturbations can be compared. It is a hypothetical scenario in which environmental regulations are not enforced by the government, the regulator does not intervene in price control, and PEMEX has the necessary funds to carry on with its desired investments.

Scenario B represents the response of the energy system to the single perturbation concerning the enforcement of environmental regulations. In this scenario, environmental regulations are expected to have the following effects: incentives are given to force the substitution from fuel oil to natural gas; a

Table 1
Summary of Scenarios

Scenario A: Base case No environmental regulation enforcement Price determined by the market Full availability of investment funds	Scenario C: Price regulation *Environmental regulation enforcement* *Regulated price* Full availability of investment funds
Scenario B: Environmental regulation *Environmental regulation enforcement* Price determined by the market Full availability of investment funds	Scenario D: Lack of investment funds No environmental regulation enforcement Price determined by the market *No availability of investment funds*

competitive gas market is expected to develop (thus requiring no intervention from the energy regulator to diminish market power from the incumbent); and PEMEX is expected to be able to make all the required investments in gas production capacity (to increase the supply of natural gas) and in refining (to minimize displaced fuel oil). However, when analysing the results of this scenario, it will be shown that the outcome could be far from ideal and gas price shocks as well as increased CO_2 emissions could in fact occur.

Scenario C considers price regulation introduced as a means of counteracting potential negative responses of the system (e.g., gas price shocks) to environmental regulatory enforcement.

Scenario D represents the case in which PEMEX does not have the funds to carry on with its investment schedule in production, processing and refining capacity. Although we have assumed a situation where PEMEX has no investment funds at all, this scenario is by no means extreme. Both currently and in the past, PEMEX has not been able to fully conduct its desired investment programs. This has occurred both because PEMEX is held to a very tight tax regime and because the government takes most of its profits. Furthermore, the investment budget is assigned on a yearly basis after several rounds of negotiations between the Ministries of Finance and Energy, PEMEX, and Congress, a system that allows only short-term planning and introduces significant levels of uncertainty. Other uncertainties are also present such as unexpected economic recessions like the one suffered in 1994[5] and prolonged periods of low world oil prices like that experienced in 1999.

6. Results and discussion

Figs. 4–11 depict predicted results from the simulation runs for the noted scenarios.

When environmental regulations are enforced (Scenario B), a subsequent demand for gas is expected since

[5] The real value of the peso fell to one-half of its value with respect to the dollar during the economic recession of 1994.

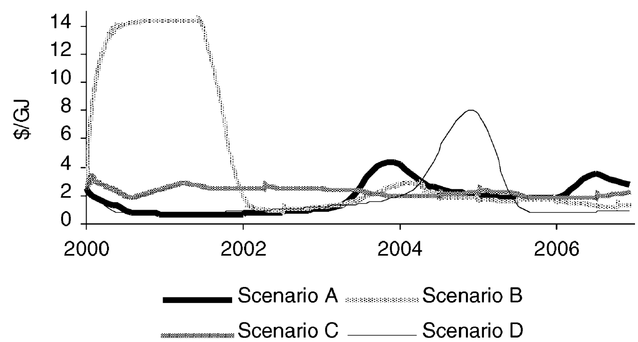

Fig. 4. Scenario comparison—Gas price.

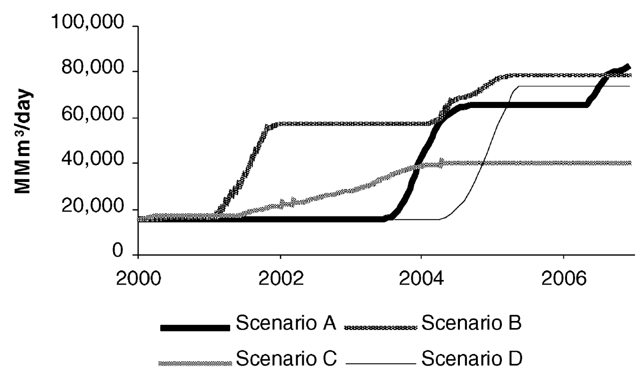

Fig. 5. Scenario comparison—Gas imports.

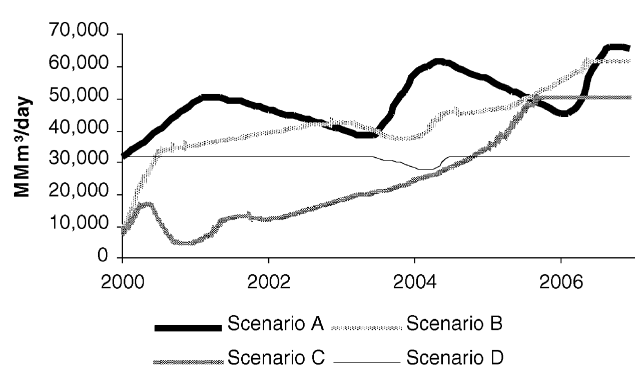

Fig. 6. Scenario comparison—Total non-associated gas production.

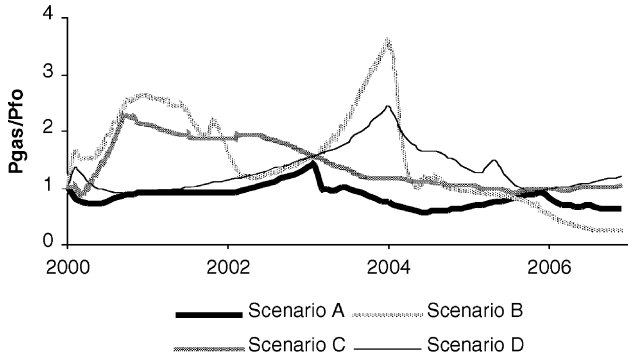

Fig. 7. Scenario comparison—Relative price of gas to fuel oil.

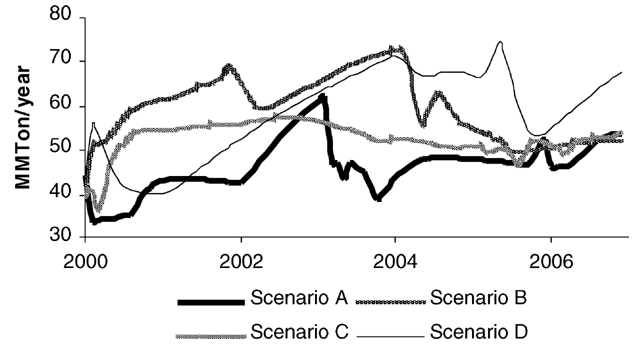

Fig. 10. Scenario comparison—Carbon emissions.

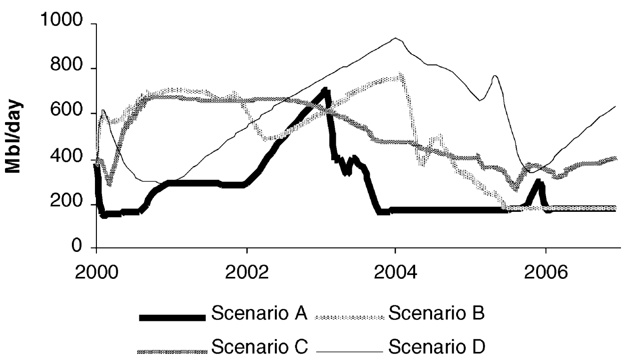

Fig. 8. Scenario comparison—Fuel oil production.

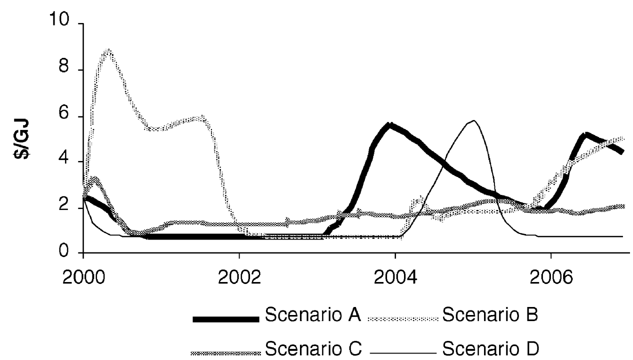

Fig. 11. Scenario comparison—Fuel oil prices.

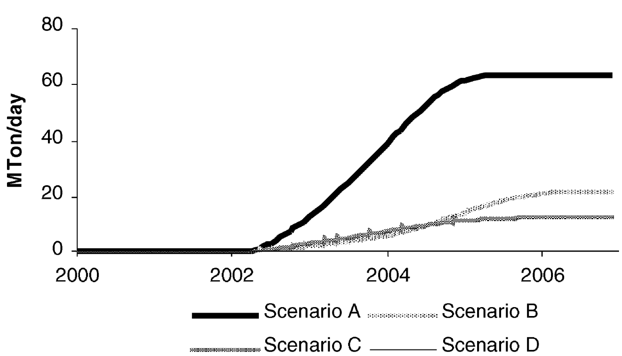

Fig. 9. Scenario comparison—Coke production.

some of the thermal electric plants powered by fuel oil will have to be converted to gas and all of the industrial plants burning fuel oil for heating purposes in environmentally critical areas will have to be converted to burn gas. With such a dramatic increase in the demand for gas, the initial periods of the simulation show a spike in gas prices (see Fig. 4). This spike is carried forward to other variables such as gas imports (Fig. 5), non-associated gas production (Fig. 6), etc. However, it is also shown that the system adapts to the perturbation fairly quickly. High gas prices serve as an incentive to international competitors to enter the Mexican market. As seen in Fig. 5, an increase in the level of gas imports is observed with respect to the base case. Comparison of Scenarios A and B in Fig. 6 illustrates a decrease in the level of non-associated gas production for the case where environmental regulations are enforced. This is consistent with Hotelling's theory regarding the extraction of non-renewable resources. With higher expected relative prices of gas to fuel oil in comparison to the base case, PEMEX has less incentive to produce non-associated gas and more incentive to leave the gas in the ground for more profitable extraction at a later date when gas prices are expected to be higher. However, there are other dynamic effects affecting the levels of non-associated gas production such as the amount of gas imports, the desire to block competition from entering the market, etc.

As also represented by Scenario B, the enforcement of environmental regulations by itself can have negative repercussions. Due to the increase in the relative price of gas to fuel oil (Fig. 7), demand for fuel oil may increase in areas that are not affected by environmental regulations (i.e., non-critical areas). This price increase may also force the power and industry sectors to switch from gas to fuel oil consumption. An increase in the demand for fuel oil (Fig. 8) leads to decreased investment in coking capacity (as shown by decreased coke production in Fig. 9), and thus to increased conversion of crude to fuel oil. This effect translates into higher volumes of fuel oil being burned than in the base case, leading to higher levels of carbon emissions (Fig. 10). Regardless of the fact that environmental regulations are addressed at reducing the level of SO_x and NO_x emissions (not carbon emissions), this counter-intuitive response of the system to environmental regulation enforcement is obviously non-desirable. One would expect that creating an incentive to move to less carbon-intensive fuels such as gas would also reduce the level of carbon emissions. In addition, reduced levels of investment in coking capacity translate into a reduction in the national supply of gasoline and diesel. Although not considered by the model, a low level of national gasoline and diesel supply could result in increased imports of gasoline and diesel into Mexico.

In an effort to control both gas and fuel oil price shocks as well as reduce the levels of carbon emissions, Scenario C considers price regulation in addition to the enforcement of environmental regulations. When the price of gas is set at 1.5 times PEMEX average cost of non-associated gas production, both gas prices (Fig. 4) and fuel oil prices (Fig. 11) are reduced significantly from the case with environmental regulations alone. This effect leads to lower levels of both domestic gas production and gas imports (Fig. 5) than in Scenario B. Furthermore, Scenario C leads to higher investment in coking capacity resulting in a lower conversion of crude to fuel oil. As shown in Fig. 10, this simultaneous effect of lower gas and fuel oil consumption leads to lower levels of carbon emissions than in Scenario B.

However, lower fuel prices together with lower levels of gas and fuel oil production leads to high losses for PEMEX. The regulator must determine whether environmental benefits and low energy prices for consumers justify a reduction in the profits made by the state oil company. It is important to remember that the government depends on PEMEX revenues to carry out most of its investments in infrastructure and social development programs, making this issue even more prone to debate. Also, it must be clarified that the choice for choosing a regulated price equal to 1.5 times PEMEX average cost was completely arbitrary and several additional scenarios must be run to compare different outcomes if price regulation is to be pursued. In addition, sensitivity analysis must be conducted on PEMEX and the competitor cost functions to evaluate their impact on supply and prices of both fuels, carbon emissions and total profits.

Scenario D accounts for the case where no investment takes place in some key energy areas (e.g., processing capacity, non-associated gas production capacity and coking capacity). Without investment, gas production by PEMEX decreases considerably with respect to the base case. As a result, total gas supply reaches a much lower level than in the base case, resulting in increased gas prices during some periods of the simulation (see Fig. 4). High gas prices relative to fuel oil (see Fig. 7) stimulate fuel oil demand (see Fig. 8). In addition, lack of investment in coking capacity leads to a higher crude to fuel oil conversion, resulting in a higher supply of fuel oil. As shown in Fig. 10, increased fuel oil consumption translates into increased levels of carbon emissions.

7. Conclusions

Environmental regulations in Mexico could dramatically increase demand for natural gas in the next years. This could lead to severe oscillations in gas prices, reaching very high peaks in some periods. Very high gas prices could cause both negative impacts on important national industries (e.g., glass, petrochemicals, cement, etc.) and discontent and even social unrest among the lowest income groups which are already under severe financial limitations. Furthermore, environmental regulations could also force an increase in demand of fuel oil in non-regulated areas, translating into lower investment in coking capacity. This could result in substantial imports of gasoline and diesel which are highly demanded in Mexico. In addition, a higher domestic consumption of fuel oil could lead to higher levels of carbon emissions with respect to a scenario without enforcement of environmental regulations. This outcome would hardly be considered a success, especially now that Mexico is trying to acquire an international image as an environmentally concerned country.

Fuel price shocks could become accentuated if Mexico lacks the funds required to carry on with investments in gas development and processing capacity. In addition, lack of availability of investment funds could by itself lead to gas price shocks in some periods of the simulation. Until more financial independence is given to the state owned company or until PEMEX finds innovative alternative approaches to involve the private sector without compromising ownership, this will continue to be the case.[6]

Price regulation could be a way not only to reduce gas and fuel oil prices, but also to reduce its variability. However, this could occur at the expense of impacting

[6] It must be said that PEMEX has already made important progress in this field. Currently, Congress allows PEMEX to contract a special debt that is owed to private service companies undertaking work on some of PEMEX large strategic projects (OGJ, 1999b). The debt is not paid by PEMEX until the work is completed. In the past year, Congress allowed an increase in the level of this special debt. State-ownership of the oil industry is a matter of pride for most Mexicans and very little flexibility is allowed in this issue, even by the Mexican Constitution.

PEMEX level of profits in a dramatic way. An improvement in consumer welfare at the expense of a reduction in PEMEX profits is not necessarily a better outcome. PEMEX is one of the most important engines of the country's economic growth and the government relies on PEMEX's heavy taxation to carry out important development programs in education, health and housing. As such, a reduction of PEMEX income could force the government to raise taxes in other areas of the economy.

In addition to emissions, other environmental impacts to be considered include the potential accumulation of coke. Although beneficial to improve the supply of gasoline and diesel, investments in coking capacity could result in huge amounts of coke produced. If no markets or ways of disposal of coke are found at the same rate than its production, coke accumulation could become a serious environmental issue. Means of taking advantage of the amounts of coke produced exist.[7] However, further investments in infrastructure would be required. The lack of funds available for both the power sector and the oil industry complicate this outcome.

An ideal scenario for the government would be one where the national gas market develops (with PEMEX developing its own gas fields), but where competition eventually takes place; where PEMEX invests in coking capacity to reduce levels of environmentally unfriendly fuel oil while obtaining higher yields of highly demanded products such as gasoline and diesel; and where PEMEX obtains profits that allow reinvestment in strategic projects and contribution to the government budget. However, this would need to occur without high fuel prices with high variability, but rather with fuel price stability.

Obviously, it is very unlikely that this ideal scenario could be achieved. Policy makers are aware that achieving a particular benefit will almost invariably involve a given trade-off. However, price regulation seems like a potential way of controlling price shocks resulting from enforcement of environmental regulations and lack of investment funds. This model could allow the regulator to explore different alternative levels of price regulation to ultimately find the most desirable potential outcome.

[7] With prior gasification, coke could be use as a pollution free fuel (H_2-syngas) that could be used to replace natural gas for power generation, helping to reduce the demand for gas and thus reducing the potential for price shocks. Gasification could be carried on in the refinery and H_2-syngas could be used not only to produce power for the internal needs in the refinery, but also to alleviate the high demand for hydrogen in some processes (hydrocracking, hydrodesulphurization, etc.). However, for gasification to occur, important investments should be conducted. Other means of coke disposal also exist and include burning it in the furnaces of the cement industry (see Barnes de Castro and Castellanos, 1996; Castellanos and del Rosal, 1996; Wender, 1996).

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