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On the substitution of energy sources: Prospective of the natural gas market share in the Brazilian urban transportation and dwelling sectors

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Abstract

The substitution process resultant of the competition between two opponents fighting for the same resource or market is pointed out through a dynamic model derived from biomathematics. A brief description of the origin of the method based on coupled non-linear differential equations (NLDE) is presented. Numerical adherence of the proposed model to explain several substitution phenomena which have occurred in the past is examined. The proposed method is particularly suitable for prospective analysis and scenarios assessment. In this sense, two applications of the model to prospect the dynamic substitution process in the Brazilian case are done: firstly, the development of the urban gas pipeline system in substituting for the bottled LPG in the dwelling sector and, secondly, the substitution of the urban Diesel transportation fleet by compressed natural gas (CNG) buses.

Keywords: Natural gas; Energy substitution; Mathematical models

1. Introduction

The presence of natural gas (NG) in the Brazilian energy balance has grown up rapidly over the last decade. According to BEN (2004), the market share of NG in the total energy gross domestic supply was 3.1% in 1990 and has increased its percentage to 7.7% in the year 2003, equivalent to 15.5×10^6 tOE. This fact was due, basically, to the construction of Brazil–Bolivia pipeline and discovery of new resources in Campos and Santos basin, whose consequences was a higher NG supply than the final user sectors could consume.

Great efforts have been taken to increase the use of NG in finding a substitution for traditional energy sources. However, the natural barriers to a new product in an established market are well known. Even in the case in which the new product represents an appropriate and advantageous consumption alternative the acceptance decision of a new product is not straight and the obstacles to acquiring even a small market share are not trivial. As it is well known from the marketing specialists, the transition rate intensities between the "old" and "new" products are associated with behavioural, socio-economic and financial market variables: lifestyle, conservative practices, environmental cares, earnings level, tax incentives, class stratification, innovative technological level and the most important, *trust and competitive prices* of the new alternative. This fact is particularly true in the substitution process between energy-conversion techniques in which a respectable amount of investment is involved. Then the recovery time of the investment becomes the key variable, even when environmental healthiness and

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supply independence aspects are associated to the new alternative.

In order to deal with the above complex system problem, this paper presents an approach derived from biomathematics. It is well known how hard it is to deal with complex dynamic system, in which so many variables are interacting in time. In order to analyse such problems, a method similar to the models developed in the biomathematics is proposed: a set of coupled non-linear differential equations (NLDE) are established to represent two "species" fed by the same "resource". According to this reducionist approach, all the interacting variables associated with the substitution transition rate are represented by one single parameter.

Using this method and through numerical approach, the aim of this article is

- to examine the adherence of the proposed model to explain several substitution phenomena that occurred in the past;
- apply the model to examine prospectively two dynamic substitution process in the Brazilian case: firstly, the development of the urban gas pipeline system in substituting for bottled LPG in the dwelling sector and, secondly, substitution of the urban diesel transportation fleet by CNG buses.

2. Competition models based on biomathematics

One of the most powerful weapons common to all living creatures, which increase the probabilities of survival and the success of the species, is its *competitive spirit*, i.e., the craving to win any kind of dispute, going from childish game to war. Mathematical efforts to analyse the competition problems between living species have been made since the beginning of the last century; for instance, in the *predator–prey* works or models of Lotka (1925) and Volterra (1931). The basic difficulty to analyse the dynamics of interacting living systems concerns the number of *species* in competition: the mathematical problem becomes complicated, when this number is greater than *two*. There is a similar trouble in mechanics: the notorious *three-body problem*, in which it is impossible to get general solutions. The corresponding biological formulation, in which more than two species are interacting mutually, is not taken into account.

The employment of NLDE, to explain a wide class of complex dynamical phenomena, has been done not only in the physics and biology, but also in economics, medicine and sociology. Approachs for Brazilian economics, utilizing NLDE, was done by these authors in Kamimura and Guerra (2001), Kamimura et al. (2004). In the particular case of the biologic competition between two species, several approaches are known. See, for example, Clark (1990) and Boyce and DiPrima (1997). Some typical examples are given:

The Lotka–Volterra *predator–prey* system, mentioned above, in which one of the species (predator) devours the prey. The prey maintenance comes from the environment, which is considered infinite. It is obvious that this NLDE set is not suitable to describe the two species competiting in the same finite "market".

A substitution model was developed by Fisher and Pry (1994). It assumes that the market shares of the "new" product follows a "logistic" solution and is a simplification of the next case.

Two "logistic" coupled NLDE, in which two species compete for the same limited resource or market. The corresponding equations are

$$\mathrm{d}N_1/\mathrm{d}t = \varepsilon_1 N_1 - \sigma_1 N_1^2 - \alpha_{12} N_1 N_2, \tag{2.1}$$

$$\mathrm{d}N_2/\mathrm{d}t = \varepsilon_2 N_2 - \sigma_2 N_2^2 - \alpha_{21} N_1 N_2. \tag{2.2}$$

The solutions for each of the above equations, if the interaction coefficient $\boldsymbol{\alpha_{ij} = 0}$ (Verhulst equation), are also known by "logistic" or "sigmoid" curve, which behaves exponentially in the beginning due to the $\boldsymbol{\varepsilon_i N_i}$ term; after a time interval, both populations N_1 and N_2 reach "saturation" at the $N_{1,2}$ = (ε_1/σ_1 and ε_2/σ_2) values due to the "self-regulation" terms $\sigma_i N_i^2$. However, when $\boldsymbol{\alpha_{ij}}$ differ from zero, basically two solutions are observed: the two species living in equilibrium together, when $\boldsymbol{\alpha_{12}\alpha_{21} < \sigma_1\sigma_2}$, or exponential growth of one of the species with the disappearance of the other—the most frequent event. Depending on $\boldsymbol{\varepsilon_i}$, $\boldsymbol{\sigma_i}$ and $\boldsymbol{\alpha_{ij}}$ values**,** all positive coefficients, a myriad of distinct solutions are possible, but the majority of them ending in the survival of one species and the concomitant vanishing of the competitor. This is a characteristic of non-linear system: strong dependency in the initial conditions in which a little advantage of one of the opponents will carry off the other. It is easy to understand why this case is, in general, an expected and frequent solution: the tie condition between two "fighters" is not a stable state, even when the strengths of the opponents are almost equivalent. This is what happened, for example, in the famous case of the winner VHS system against the technologically better Betamax system and recently, the Windows versus IBM operational system for PC. These are, what Arthur (1990), called "positive feedbacks" phenomena in the economy. It explains also why "big" companies prefer to make "agreements" concerning its markets than the "open fight" alternative, since it, probably, would carry to the disappearance of one of them. So, the process of substitution of a given product by a "new" one is represented by this particular and frequent type of solutions of Eqs. (2.1) and (2.2), and is the focus of this actual paper.