SYSTEM DYNAMICS MODELLING FOR ENERGY EFFICIENCY ANALYSIS

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ABSTRACT

A System Dynamics model specially built to analyze residential energy policies is presented. The model allows to simulate substitution of household equipments for more efficient ones using a two stage economic decision process. In the first stage the user selects the most economic alternative and in the second stage the user compares the financial condition to acquire the chosen energy alternative considering his buying capacity during the period of analysis (delays are considered). The model allows to examine several aspects such as: alternatives on technology diffusion, energy consumption growth and effects of pricing policies on diverse energetic demands. The model was applied to the Medellín Metropolitan Area, Colombia. Results are included.

1. INTRODUCTION

Energy planning needs decision support systems based on detailed modelling of different interrelationships between diverse economic sectors, energy subsectors, energy demand and energy alternative sources, so decisions can be made trying to understand a large number of possible consequences.

Few developments have been reported on energy planning applications using system dynamics methods such as Naill (1977), Naill (1992), Naill et al (1992) and Sterman (1984), but almost none focusing the residential subsector considering regional particularities.

Because of its complexities sometimes it is best to model the national energy sector by subsectors (i.e. industry, residential and transportation). Also because of regional differences such as climate, infrastructure, energy sources availability and cultural background, it could be better to develop subsectorial regional models. A national single global energy model can then be developed by coupling several subsectorial regional models. With this respect some work has been done by Dyner et al (1990), Dyner et al (1993) and Smith (1991).

The model at large has to take into account macroeconomic financial restrictions and has to consider energy supply and demand for each subsector as may be seen in Figure 1.

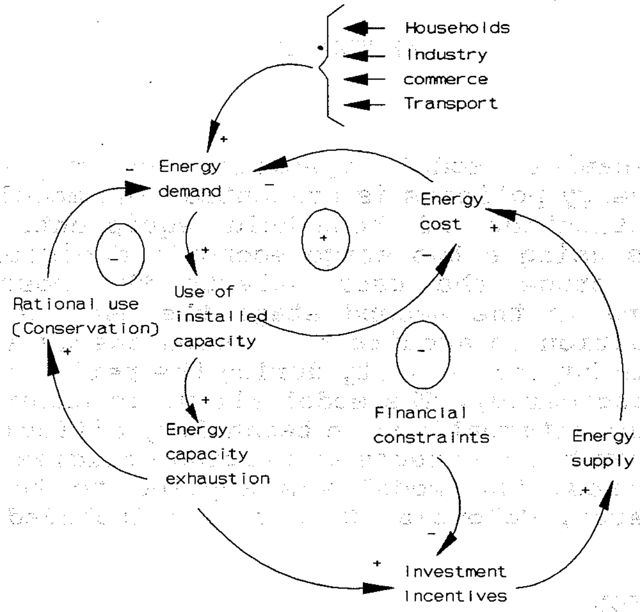

FIGURE 1. Energy Dynamics

As illustrated, to more households, industry, transport and commerce, there is more energy demand, making on one hand more use of installed capacity which causes less energy cost and less energy demand. On the other hand, the use of installed capacity causes energy exhaustion which induces investment incentives and rational use practices. Now, subject to financial constraints there is an increment in energy supply, increasing energy cost (this, because of the least cost planning criteria) but decreasing energy demand.

The first loop is positive (+), indicating exponential energy demand growth of available installed capacity. The other loops are negative (-), forcing energy demand to reach a local maximum value - Energy capacity decay stimulate investment and its rational use causing an increment in energy cost which reduces its demand.

2. ENERGY ALTERNATIVES FOR THE RESIDENTIAL SECTOR

The residential energy sector includes all resources and activities developed to satisfy households energy requirements. In Latin America the residential sector accounts for about 23% of the total electric energy consumption and in Colombia for about 45%. This is a complex sector where energy requirements varies according to factors such as: Regional characteristics, urban or rural location, energy substitution availability and income levels. This is also a dynamic sector with time variations according to factors such as: rural to urban population migrations, new energy sources availability and, technological developments.

The average energy efficiency consumption in the Latin American residential sector could improve by more than 10% during the next ten years, while in Colombia alone this should be higher than 15%. It looks then that there are two main efforts that are worthwhile in this sector: to improve energy consumption efficiency and to offer several energy alternatives (electricity, gas and coal) to all users.

Because of the comparative energy importance, an effort to diminish electricity consumption in this sector would mean that new investments in electric generation plants can be postponed for some time. The Latin American energy sector accounts for about 20% of the global external debt and it may be observed as one of the causes of the regional impoverishment. Efforts have to be made oriented to electricity substitution by more efficient and/or less expensive alternatives and conservation programs.

A great deal of consumers will not have the buying capacity or incentives to change their traditional electric equipments for other energy alternative, or even to accept any kind of conservation program. Most of the people in the region can be classified in the low income socioeconomic groups with a reduced buying capacity. On the other hand the electricity or fuel prices they pay (tariffs) are much lower than the real economic costs due to governmental policies. In this case the only possibilities for energy substitution is offering new equipments with prices artificially lower than their real commercial prices, so that they become attractive to an important proportion of residential users.

There is a need to develop programs to offer alternative energy sources, including conservation programs, for the residential sector. Tools to analysis the proposed energy programs will allow to determine the impact of government policies on energy consumption patterns, and to define if such programs may be successful or not.

3. RESIDENTIAL ENERGY DYNAMICS MODEL

The causal diagram in Figure 2 represents in general terms the residential energy dynamics. The reader may appreciate that to more average population income there is more electricity consumption (the elasticity depends on the income level), but to a higher electricity tariff there is less consumption (it takes sometime to react to tariff increments and the elasticity depends on the tariff level). As the electricity generation capacity is exhausted there will be a more rational energy use, but as there are more energy alternatives there is less electricity consumption.

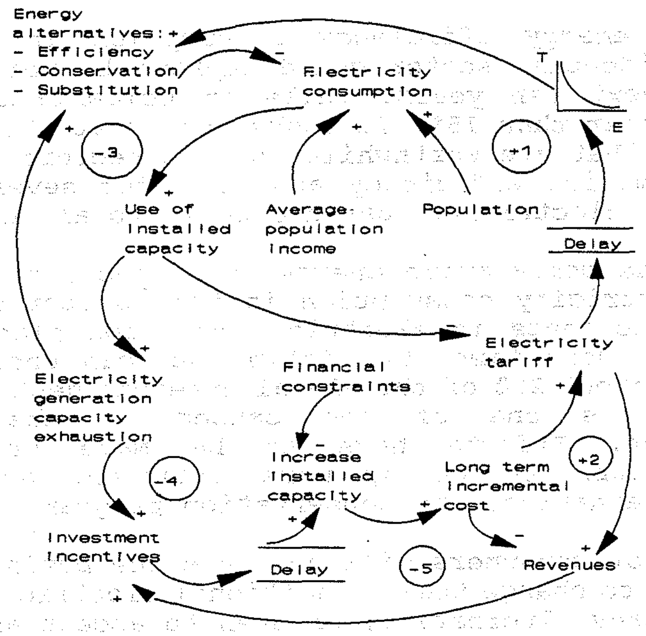

FIGURE 2. Residential Energy Dynamics.

The other causal-effect relations are similar to the ones exhibit in Figure 1 except for the variable revenue which encourages investment incentives.

A System Dynamics model was developed to analyze energy alternatives penetration in the urban residential subsector. The model assumes that all decisions are made under the least cost principle. An individual user will choose always the least cost option considering all available energy alternatives. He will take into account all related economic variables such as: expected fuel prices, investments, expected maintenance costs, and, if it is the case, selling prices of old equipments.

In Colombia individual users are classified in six socioeconomic groups according to the household location in the city, which is directly related to the income level of its inhabitants. In this way a geographical buying capacity map can be made for every city in the country. Fuel prices and energy consumption patterns varies for each socioeconomic group. Differences in fuel prices are due to governmental tariff underpricing policies, in which the lower socioeconomic groups (1 to 4) have tariffs lower than the real economic costs and higher socioeconomic groups (5 and 6) have a tariff higher than the real economic costs.

Least cost decisions are then evaluated for each user, for each end-use equipment alternative and for each socioeconomic group. To apply the least cost decision criteria the annual equivalent cost procedure is used. The option with the lower annual equivalent cost will be selected as the best one. If the selected option is to replace the traditional electric equipment, a decision process is represented in the model in which financial conditions to acquire a new equipment are compared with the user buying capacity.

The use of the annual equivalent cost as the economic decision criteria allows to compare options with different lasting life. In general the annual equivalent cost of any option energy option, for each end use equipment and each socioeconomic group, is given as a function of the tariff ($/consumption), the energy consumption, the net investment and the maintenance cost.

Three energy options are available (Figure 3) to each user and each end-use equipment in the urban energy residential sector:

- Continues with the same energy consumption practices.
- Changes to an alternative energy consumption equipment.
- New energy management saving practices (conservation).

The decision process is slightly different if a traditional electric equipment is to be replaced or if there is a need to buy a new equipment because the old one is not longer usable. In the first case users explore the possibility to replace a traditional electric equipment using the least cost criteria and considering its selling price. In the second case the equipment is no longer usable because of obsolescence and a new equipment have to be bought. Every year a percentage of equipments become obsolete and new equipments have to be bought.

With the annual equivalent cost criteria an energy option is selected for each end use equipment and each socioeconomic group. If the selected option is to replace the traditional electric equipment a decision process is modeled in which the users buying capacity is compared to the resulting monthly installments to acquire the new equipment. A normal distribution function is first fitted to the monthly income of each socioeconomic group using the average value as the mean. In this decision process the monthly installment to acquire the new equipment is used as input into the fitted cumulative normal distribution function of the buying capacity (a non-constant percentage of the monthly income) in order to establish the probability of buying the equipment. The amount of users in that socioeconomic group acquiring the new equipment will be the total number of users in the group multiplied by that probability.

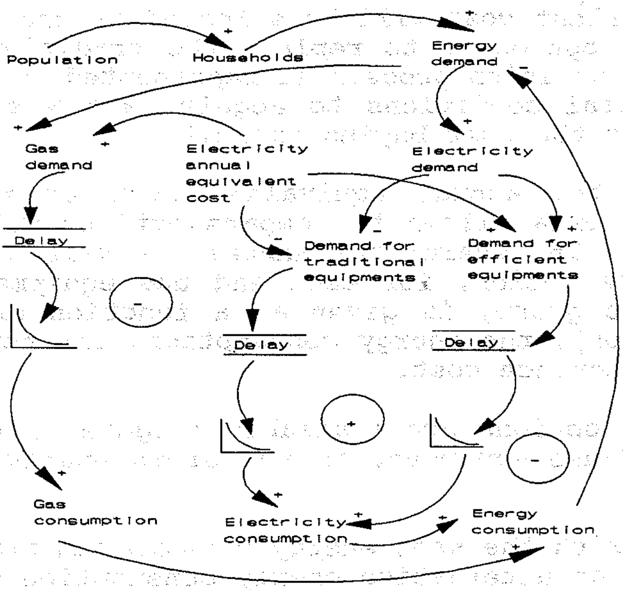

FIGURE 3. Energy Alternatives Dynamics.

If several end-use equipments are selected by the annual equivalent cost criteria for replacements, the new equipments are ordered accordingly to its cost/efficiency relationship (cost per energy units saved). Equipments with lower cost/efficiency relationships are selected first for replacement. The procedure continues in this way until no users in the socioeconomic group will acquire a new equipment.

Once the number of users in each socioeconomic group decide to switch to a new equipment the model assumes that there is a delay in the buying process to take into account several aspects such as:

- Information diffusion. Not all people get to know at the same time that there is a more economic favorable energy option.
- Cultural aspects. People accustom to use electricity will take some time to switch to gas fueled equipments.

The above computations allow to calculate for a given year, for each socioeconomic group and each end use equipment, the amount of users that continues using traditional electric equipments and the amount of users that switch to electricity efficient equipment and/or gas fueled equipments. On these bases it may be possible to calculate electricity and gas demands, electricity consumption savings, changes in the load curve, and other variables.

Finally the model takes into account the socioeconomic mobility between groups. Each year, besides population growth within each socioeconomic group, there are flows of individuals between groups. These flows are complex social matters that represent new employment opportunities, education and training. These flows depend on long term government macroeconomic policies.

4. CASE OF STUDY

The developed model was used to describe the propagation dynamics of energy efficient and gas fueled equipments in the Medellín Metropolitan Area, Colombia, with a population of 2'500.000 inhabitants. Because there is not yet a program to promote the use of more efficient electricity consumption equipments in the Medellín Metropolitan Area, two different scenarios were analyzed: introduction of only gas fueled equipments and introduction of gas and electricity efficient equipments.

In the first case, results show that if the government does not use a cross subsidized tariff between socioeconomic groups (higher socioeconomic groups have a tariff greater than lower socioeconomic groups, with an average tariff corresponding to the real economic cost) it will only be used by high socioeconomic groups, due to underpricing electricity policies which are geared to large subsidies to the low income groups. If a tariff distribution similar to the one used in other colombian cities is applied (preserving its real average cost), combined with a electricity tariff that reflects real economic costs, gas will be used by all socioeconomic groups. Figure 4 shows simulation results of electricity consumption with and without gas substitution. Figure 5 shows the projected gas consumption by stoves in each socioeconomic group. Both figures illustrate a rapid increment in demand for gas due to financial conditions and costs.

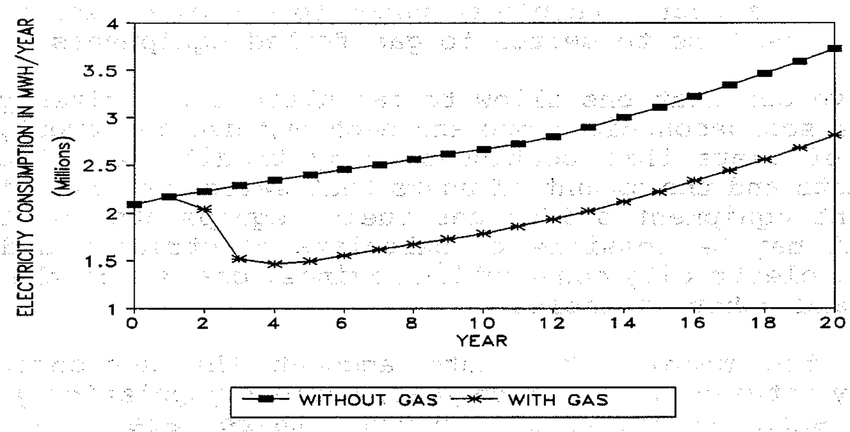

FIGURE 4. Electricity consumption projections with and without electricity substitution by gas.

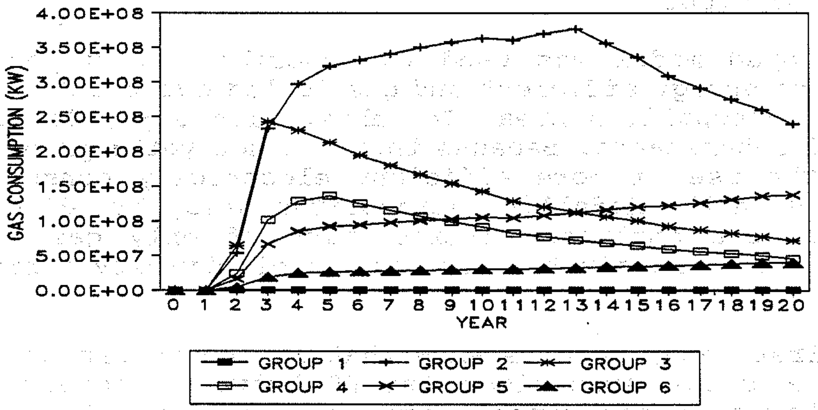

FIGURE 5. Projection of Gas consumption by stoves in each socioeconomic group.

In the second case, results shows that the availability of efficient electricity equipments with a 15% improvement in energy consumption (efficiency) and 40% more expensive than traditional electric equipments will result in lower gas consumption levels. Figure 6 shows a rapid increase in gas consumption and then a continuous decay because of the introduction of a electricity efficient program. The rapid increase in gas consumption is because the gas program starts earlier than the supply of competitive electricity equipments.

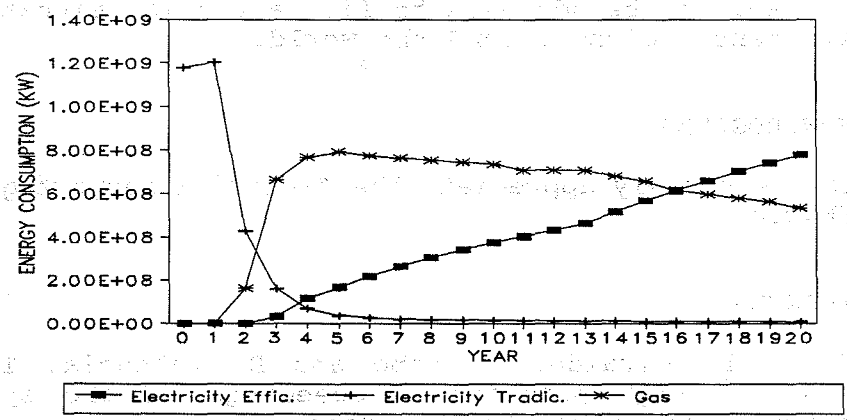

FIGURE 6. Projections of energy consumption by stoves.

5. ELEMENTS FOR ENERGY POLICIES AND CONCLUSIONS

From previous discussions, the following conclusions and elements for energy policies may be drawn:

- The gas program for the Medellín Metropolitan Area will be successful if the energy underpricing policies are considered globally by the local government. If an adequate tariff distribution is applied among the different socioeconomic groups, the gas program will prove to be successful from energy efficiency and financial perspectives.

- The future of the gas program depends on other energy efficient alternatives. The supply of electricity equipments significantly more efficient than the ones now available will mean lower gas consumption and will make the efficient electricity use the main energy alternative for the Medellín Metropolitan Area.

- Combined gas supply and efficient electricity equipments availability may represent total energy savings of about 37% by 1997.

- Other variables not discussed or not included in the model such as service continuity, operational risks, outfits supply and advertisement, have to be considered.

- System Dynamics proves to be appropriate to support integrated planning and management problems related to energy efficiency issues. The model developed is fairly general and may be adequate to fit particular situations of different regions around the world.

6. ACKNOWLEDGEMENTS

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