Systems simulation to assess DSM policies for energy sustainability

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Abstract: The complexities of energy systems and the policy issues that emerge are intricate and wide-ranging, yet the need to undertake demand-side management (DSM) of energy resources for sustainability is especially crucial in developing economies. In this paper it is argued that systems simulation can provide the broad and policy oriented framework required for this purpose. Applications to Colombian energy policy issues at both the national and the regional level are presented to indicate the range of issues which can be so integrated on this modelling platform.

Keywords: Colombia, demand-side management, energy models, sustainability, system dynamics.

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1 BACKGROUND

Many studies have pointed to the inevitability of sustainable energy policies being crucial to future world economic development. For example, under a relatively plausible scenario, the world will reach a population of about 10.6 billion inhabitants by the year 2050, Eden [1]. This would be approximately double the population of 1990. The same author calculates the total energy demand at about 20.5 Gtoe (gigatones of oil equivalent), by the middle of the next century, compared to 7.9 Gtoe in 1988. He claims that this may be reduced by as much as 40%. to around 12.6 Gtoe, under a special demand scenario which embodies targets for energy efficiency. As a consequence, Eden [1], Schramm [2] and others argue that major efforts with respect to conservation, the development of new fuel resources and schemes for capacity financing will be needed in the energy sector of both developed and developing counties to support even a satisfactory rate of world economic growth.

Thus, for developing countries, especially, efficient integrated energy expansion planning is crucial to fulfil economic growth objectives. Integration here principally refers to the incorporation of demand-side management (DSM) into capacity planning. However, we interpret planning in this paper not in the narrow sense of applying only to centrally administered, public sector energy systems, but, for both public and private market-based systems, as a flexible process to aid rational resource allocation when markets are known to be imperfect. In this case, price regulation seeks to incorporate externalities and subsidies, whilst anti-monopoly regulation seeks to ensure competitive pricing in the consumer interest. Yet there is recognition that regulated markets by themselves are not enough to ensure efficient energy policy in the overall national interest. For example, even in the UK, Helm [3, 4] argues in favour of co-ordination of regulation in the energy sector and states that markets are not sufficiently reliable to guarantee security of supply, have only a short-term perspective and do not account for important externalities.

Additionally, Meyers *et al.* [5], in a study of nine countries that account for some 55% of the total electricity generation in the developing world, found that past plans have provided to be very optimistic. Financial, institutional and environmental constraints have made it difficult to achieve the planned growth. The conclusion is the need for an integrated approached to planning in order to ensure the best use of limited resources, and to construct a future for sustainable economic and social development.

In a general overview, Munasinghe [6] scopes out the dimensions and key components of an integrated approach for successful policy analysis, planning and implementation in the energy sector. Because of the complexities of modern society, the decision making process must deal with a multiplicity of actors, criteria, levels, policy tools and impediments; the links between the energy sector and the rest of the economy; the interactions among subsectors, including substitutions between sources and the necessity to incorporate the regional and spatial dimensions. But, just how well IRP can co-exist with the accelerating trend to market liberalisation and retail competition in electricity is a major open question. The US Energy Policy Act of 1992 establishes that all utilities are required to employ Integrated Resource Planning (IRP) for new capacity, yet many states are moving rapidly into liberalised, competitive, markets where the future role of DSM is as yet unclear. Furthermore, how one should develop a modelling framework for these diverse issues is a crucial issue. The purpose of this paper is to demonstrate the feasibility of a simulation platform in providing this breadth of focus.

MODELS TO SUPPORT PLANNING AND POLICY MAKING

At one level of interpretation, the analysis of options for Integrated Energy Planning can be seen as the management of links between separate, conventional energy planning models (e.g. the US National Energy Modelling System - NEMS). In this context, large-scale optimisation and econometric techniques are perhaps the most widely used functional techniques to support various aspects of planning and policy making at the subsectoral level (for example electricity, oil, transportation). But when one looks at the characteristics of these conventional approaches, a number of methodological limits become apparent. They are:

Normative and directive: In this sense the solutions are prescriptive and the planning methods associated with them tend to be *normative*. The methodology makes no assessment of the social efforts needed nor the way things can be done, nor the participative, organisational or political limitations of achieving compromised solutions.

Deterministic: The optimum is the main goal and it is usually considered unique, despite the often observed situation of 'flat optima' in such large-scale models. After the sensitivity analyses and robustness tests are performed there are generally no further questions on the adequacy of the solution found. There is almost no explicit consideration on the uncertainty of the parameters and the associated risks. Expected values are used or runs with exogenous sample variants may be performed, but with the present state of the art it is not computationally realistic to include many random variables endogenously.

Linearity: For computational and specification reasons, most optimisation and econometric techniques are predominantly linear in their parametric relationships. This limits the consideration of higher-order interactions between variables, for example.

Absence of feedback: Most strategic modelling in other business contexts requires the use of feedback dynamics to aid policy making, but such capabilities are not common within the conventional energy analysis methods. Issues, such as delays or strategic initiatives, and the corresponding organisational reaction, will thus not be integrated in a systems fashion.

Mechanistic and non-behavioural: Since strategic and human behaviour are not modelled, there is very little room for social, organisational and political considerations within the framework of the classical approach. This may be particularly relevant to modelling, for example, the cultural aspects of consumer behaviour effectively in demand-side modules.

Stationarity in model induction: The econometric approaches generally used to project energy demand make strong assumptions about the system stability. So in general, the system structure and the corresponding parameters are assumed to remain invariant for long-term forecasting. However, the history of energy policy has demonstrated major structural changes and technology switches. If nuclear is not an alternative source for oil and gas by the year 2050, the energy market will comprise a large selection of new competitive sources. Historical trends will clearly not work. In general, parameters, such as elasticities, remain fixed during the simulation period, when for example it is known that the production systems will be more energy intensive or that electricity prices will have a much larger weight in the final production costs. Also, change of ownership has an important effect on energy production systems and price rates. Demand patterns will change and energy efficiency may penetrate more rapidly. Reserve margins and system reliability may vary significantly. With these very important structural differences, medium and long-term forecasts cannot be obtained just by projecting historical behaviour.

All of the above characteristics refer to features of the modelling techniques. At a different level of interpretation, we need to identify the range of policy issues to which the integrated model can provide some support. Many important issues are a matter of concern to DSM in the energy sector in both developing and developed countries. A non exhaustive list contains:

- power generation expansion
- ownership and privatisation
- market forces
- regulation
- energy efficiency
- energy substitution

- technology propagation
- power generation technologies
- end-use energy efficient technologies
- barriers for technology propagation
- energy transport
- the environment.

To provide useful policy support across some or all of these issues, the framework for the integration of modules needs to be able to give both a strategic 'view from above' and the required level of detail on a particular aspect when required. This may imply the need for a hierarchical structure to model integration with fully dynamic interaction between components to cope with feedback at different levels of the hierarchy, as in Ninios *et al.* [7].

It is clear that a single modelling approach will not unify all of these separate modelling and policy issues, yet there is a clear need for them to operate in a co-ordinated way. Thus, it may be necessary to design complementary methodologies capable to support energy analysis and planning in search for optimal and sub-optimal solutions representing the main social, political and economical realities of a national or regional community, Bunn *et al.* [8].

THE SYSTEMS MODELLING AND SIMULATION FRAMEWORK

Thus, an integrated approach should allow the co-ordinated analysis of supply-demand, national-region, technology diffusion, rational energy use, efficiency, substitution, losses, cultural aspects, policies and environmental issues. And all in a way that facilitates scenarios that embody structural changes and future uncertainties. The methodology should make it possible to relax some of the modelling constraints in econometric and optimisation models, and couple them in a systemic fashion that allows policy analysis at different levels of detail. In this section we pose as an open question whether a renewed attempt at using the general approach of System Dynamics (SD) can provide a framework to integrate these separate policy issues and modelling requirement.

The history of SD models in energy analysis and planning can be traced back to the early seventies when research conducted at MIT was primarily concerned with world dynamics, including factors such as economic and population growth, depletion of resources and pollution. Separate studies soon followed to examine the behaviour of energy sources. This research was the basis for a SD model, called COAL2, created under contract to the US government, Naill [9]. Improvements to the model have led to the latest version called FOSSIL2 which has been used as an important tool to support all US energy plans since 1977 and The National Energy Strategy 1991. During the last fifteen years Ford [10, 11, 12] has applied SD to a number of issues in the electricity sector of the US. Perhaps his most important research is related to: policy evaluation in the electricity industry, Ford [10]; investments and uncertainty, Ford [11]; and conservation policy analysis, Ford and Bull [12]. Also in the US, Geraghty and Lyneis [13] study the effect of external agents on utility performance.

Outside the US, Moxness [14] presents an interesting model on interfuel substitution in OECD-European electricity production. The paper focuses on the fossil fuels oil, gas and coal, in a way which overcomes the inappropriate interfuel substitution representation yielded by the constant elasticity demand models. In the UK, SD is being used to explore a diversity of issues related to the privatisation of the electricity industry, Bunn *et al.* [15] and Bunn *et al.* [8]. Problems related to the reserve margin, market share and plant retirements are examined in these papers. There is still scope for further research in this new area of privatisation and regulation.

Roche [16] establishes the importance of the SD approach in the electricity sector of France and points out that there is a large amount of research needed to be done in the area. Slesser [17] reports an interesting application using this methodology to support energy planning in Kenya. The model developed intends to give insights into the problem of sustainability and carrying capacity of a country based on a detailed resource accountancy, where energy is the driving force. The oil industry has had some attention by the SD community. For example Mashayekhi [18] examines the effect of the exchange rate policy in country that faces a decline in oil exports. At the other end Davidsen *et al.* [19] developed a petroleum life cycle model for the United States.

An application of SD to the electricity sector in Argentina was pursued from the beginning of the eighties, Rego [20]. In Colombia this tool is being used to study energy efficiency penetration and electricity substitution by gas in the residential and industrial sectors. Dyner *et al.* [21].

Despite the original Club of Rome criticism of the early SD work, the renewed SD methodology has proven to be appropriate and there is potential for further research in different areas of energy planning and policy making. It offers the policy focus which we identified earlier a being necessary to go beyond just the passive co-ordination of separate conventional subsector module. There is still an issue of scope to be considered, however, insofar as most of the policy-oriented models to date have tended to be rather limited in detail and range of issues. In the following sections we seek to address this point by looking at two case studies that cover national and regional policy levels. By showing that they have both succeeded in such different *contexts*, but within the same methodology, we seek to establish the feasibility of the

SD platform for broader and more general integrated energy analysis support.

OVERVIEW OF THE COLOMBIAN ENERGY SYSTEM

Before exploring some policy issues, let us first briefly describe the global energy environment in Colombia. Final energy consumption in this country had been growing at about 3.4% between 1975 and the early part of the 1990's, which had been basically driven by significant economic and population expansion dynamics. On the one hand, although GDP exhibited growth-rates above 5% per annum during the 1960's and early 1970's, these dropped to slightly less than 4%, on average, between 1975 and the early 1990's, to rise back again to over 5%, a few years later. On the other hand, population has been evolving at a steadily declining rate from 3% in the 60's to 1.7% in the early 1990's.

Specifically on the electricity supply side, Colombia has a potential of well over 93 GW of hydroelectric resources, while its total installed power generation capacity was only about 11 GW in 1996 (80% of which is hydroelectric). On the demand side, this sector has been growing at about 6% per annum since the late 1980's. On the transmission side, the interconnected service covers at the present time almost the totality of urban households and about 80% of the total population. Nonetheless, all recent government plans have aimed for extensions of the network to remote rural areas of the country. System losses amount to almost 24% of the electricity generated. In spite of abundant energy resources for power generation, during a time span of less than 12 years, the country suffered two major periods of electricity blackouts, namely in the middle of 1981 and between 1992 and 1993.

With respect to the natural gas sector, it is important to note that Colombia had over 8.3 Giga cubic feet of proven reserves in 1993. Recent discoveries associated with the search for oil deposits almost double the natural gas availability [22]. Colombia initiated in the early 1990's a large-scale gas plan for household consumption, expecting to increase the coverage from 8% in 1995 to about 50% by the year 2010. It is also expected that the gas used for electricity generation will expand from 10% in 1995 to over 35% by the year 2010, UPME [23]. This plan includes the construction of a comprehensive pipeline system, which for the most significant part should be concluded by early 1997.

Figure 1 shows the corresponding total energy consumption and electricity demand split between the different socio-economic sectors. It can be seen that the residential sector accounts for about 25% of the total energy consumption and for about 47% of the electricity used, and the industrial sector of 27% and 31% respectively, UPME [26].

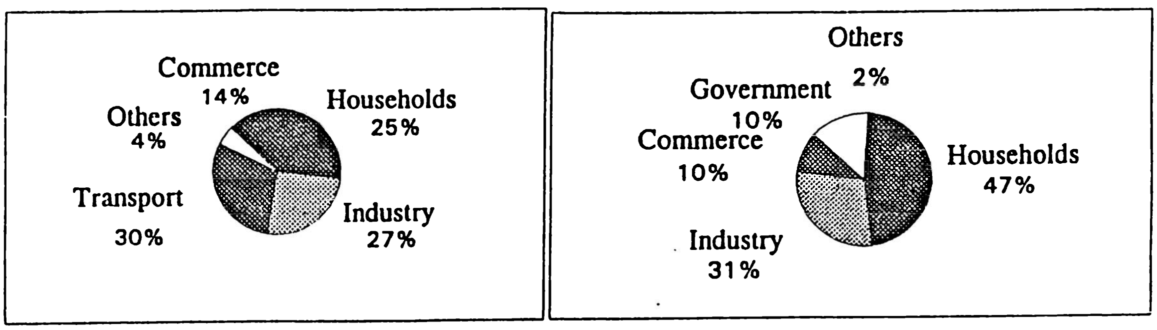

Figure 1 *(a) Energy consumption, and (b) electricity consumption by socio-economic sector.*

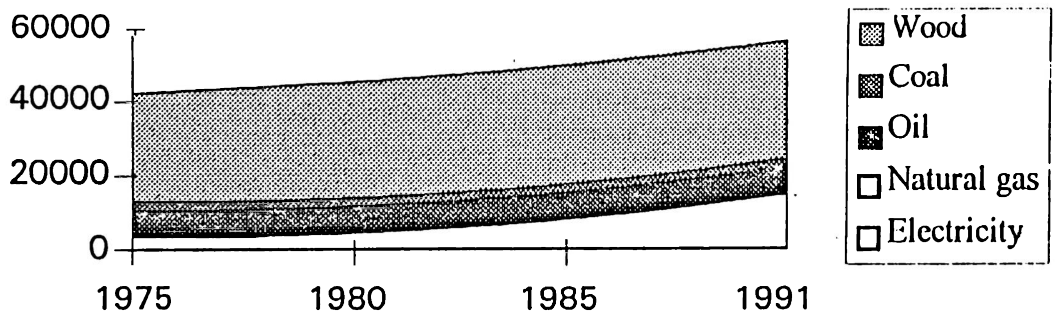

Figure 2 *Evolution of energy consumption (in teracalories) by source in the domestic sector.*

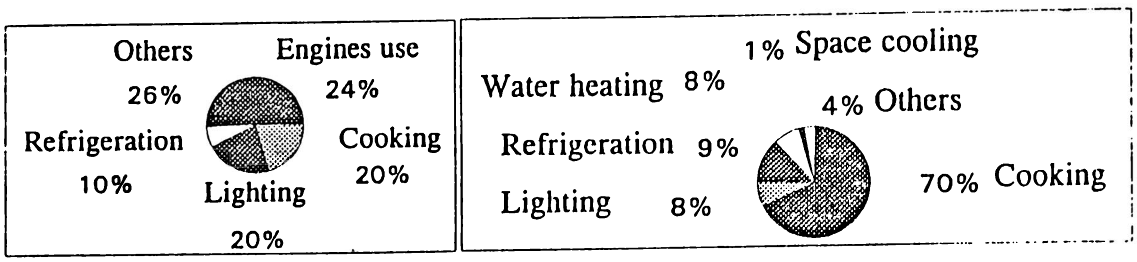

Figure 3 *(a) Electricity consumption according to end-use, (b) household energy consumption according to end-use.*

Briefly, a number of issues arise when making an overall assessment of the Colombian energy sector. On the supply-side we can establish that:

- The country possess abundant energy resources.
- The development of resources have had an uneven evolution over the years.
- The supply of sources are unbalanced within and across sectors.
- Wood continues being an important source, especially in the rural areas.
- Electricity has been very much a monopoly in the residential sector.
- The large scale gas plan is in the first stages.

In particular, some of the problematic features that have an important effect over the power generation sector are:

- Power generation depends heavily on hydroelectricity.
- Uncertainty in the hydrology behaviour plays a very important role.
- Thermoelectricity is heavily inefficient.
- Planning for new capacity has had problems (blackouts).
- Heavy non-technical losses are endemic in the system.
- The expansion of the transmission network still requires major investments.

The energy sector has been driven historically by supply-side management criteria. In actual practice this has meant that the central government has played an omniscient role in the specification of required resources. Hence, interesting characteristics in the Colombian demand-side sector include:

- Energy markets are very underdeveloped.
- The domestic sector have not had sufficient energy alternatives.
- The variety of fuels supplied to industry have also been limited.
- The electricity pool started operations in July 1995.
- Cross subsidies exist in the domestic sector for electricity, according to income.
- No rational energy use programmes have been implemented yet.

The complexities manifested in the Colombian energy sector are immense and require major intervention from different angles. Although economic growth has been an encouraging factor, energy policy has shown weaknesses to support the overall developing climate from the supply perspective, with respect to: alternatives, expansion, security and efficiency. Thus, for example, in most Colombian regions gas is still not available (in spite of abundance); electricity is the only alternative in some Departments; power generation is largely hydroelectric, with a small portion of very inefficient thermoelectricity plants; electric non-technical losses exceed 12%; and, electricity subsidies are applied extensively.

The recent Colombian Public Service and Electricity laws [24, 25] have created a completely new environment for the Colombian energy sector. The laws confer on the Ministry of Mines and Energy special functions for regulation, planning co-ordination and evaluation of all activities related to the public services of electricity and gas. They also define criteria to harness energy resources (under integral, efficient and sustainable management) and to promote efficient and rational energy end-use.

The main idea behind these laws is: (a) to promote a gradual evolution of free markets in all activities, when possible, under a regulated framework to protect end-users from market 'failures', and (b) to incorporate in planning: the major environmental issues involved, the appropriate generation capacity requirements to satisfy demand, and the essential resources to meet subsidies to the lower income socio-economic groups.

Nonetheless the transition towards a more liberalised environment turns out to be a delicate affair as low prices, low reserve margin and high subsidies, appear not as the most favourable initial conditions. Thus a number of open questions emerge with respect to:

- Evolution of prices
- Subsidies regime
- Supply reliability
- Supply alternatives
- Demand side management
- Competition in the market of large consumers
- Competition in the retailed market.

DSM AT THE NATIONAL LEVEL IN COLOMBIA

As previously discussed, the Colombian energy sector has been driven historically by supply-side management criteria, which have had a tendency for the monopsony specification of resources. Although demand-side management had been almost not-existent in the past, rational energy use programmes started to emerge during 1995, at the time when the electricity market for large consumers was created. The strategy for DSM programmes appears to be a long term one and ought to take into account the new market arrangements. These present challenges, some of which will be investigated for policy purposes further ahead.

In this paper we present a platform design to aid policy analysis, at a global level, in the Colombian case, considering a prioritisation strategy with respect to the most important problems involved. Rational energy use programmes, the large scale gas plan and the indicative power generation expansion plan are at the top of the agenda. These are very much interrelated and required immediate attention.

Figure 4 shows the general platform structure along with its most relevant components and the corresponding interrelationships between them. This design facilitates the analysis of the plans and programmes mentioned above, as will be discussed below.

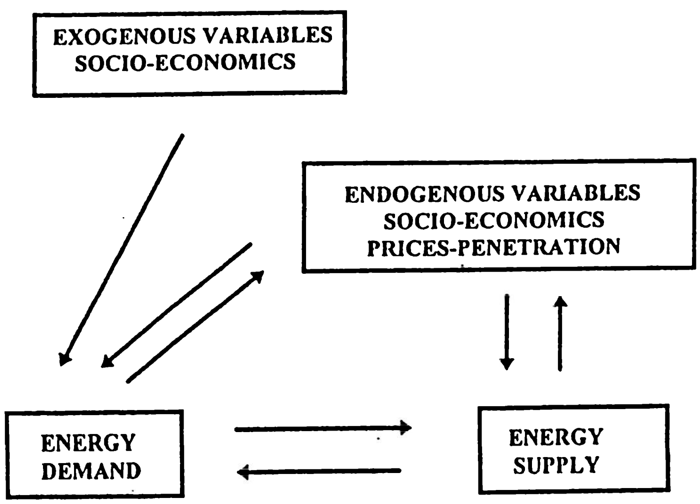

Figure 4 *General platform structure.*

Figure 5 shows some of the most relevant forces that influence the decision making mechanics for appliances acquisition by end users. This decision making process depends on the equipment annual equivalent cost and on the economic and population growth. At the same time, the annual equivalent cost is represented here as a function of appliance prices, their corresponding fuel prices to run these and their life time cycle. It is important to note that the penetration speed of a new efficient technology influences other customers (making it 'acceptable'), which has an effect on price reduction and, closing the cycle, making it more accessible to newcomers.

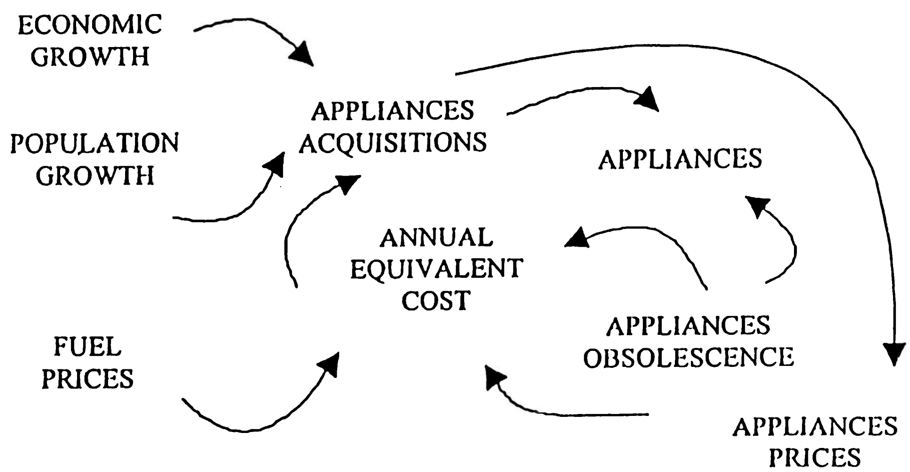

Figure 5 *Driving forces within the appliances acquisition dynamics.*

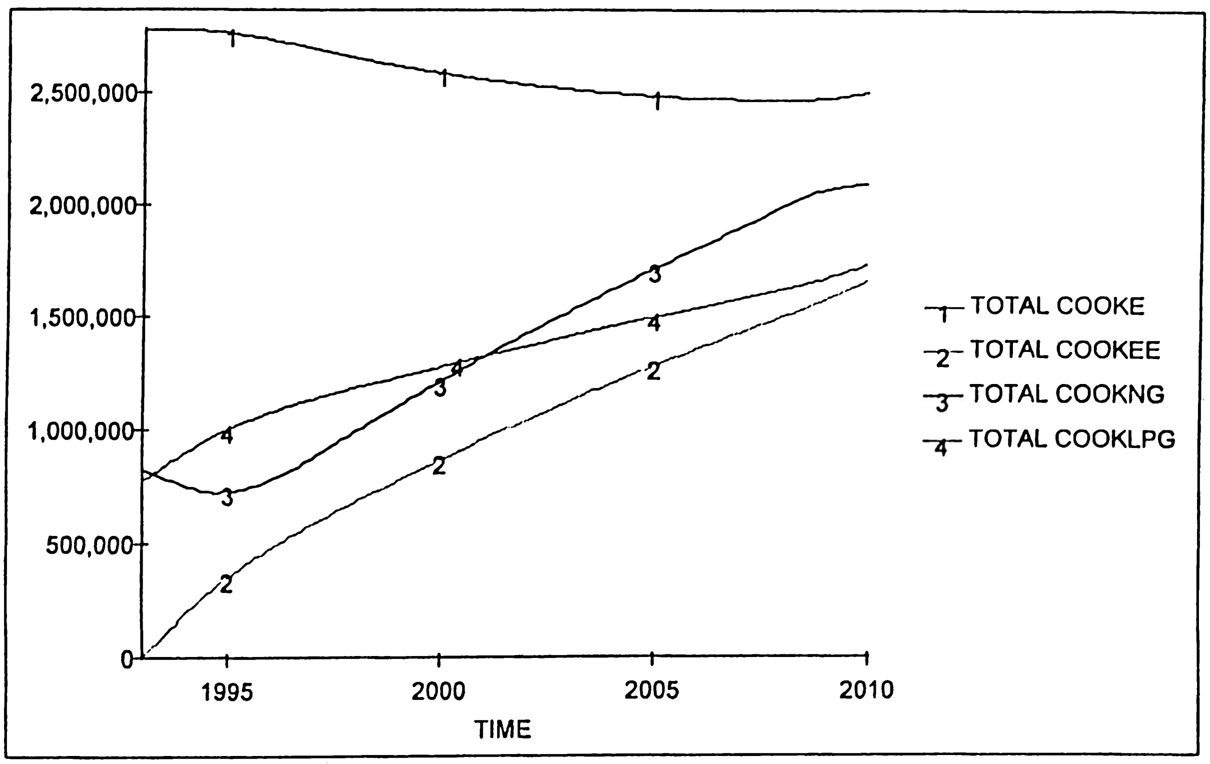

Figure 6 *Simulation of DSM programmes under a moderately pessimistic scenario. (COOKE-Electricity COOKing, COOKEE-Electricity Efficient COOKing, and so on).*

We will explore some policies, programmes and actions, on DSM as well as on the supply side. The intention is to establish synergy effects of several concurrent programmes on the overall energy system.

On the supply side, the electricity grid expansion plan is supposed to go ahead according to government expectations, but the gas plan is assumed to suffer some delays. On the demand side, DSM programmes are applied in the areas of lighting, cooking, space cooling and refrigeration.

The following specific assumptions are made in this case:

- only 40% of the gas plan is reached.
- 60% of electricity grid expansion is accomplished.
- on average one light bulb is intended to be replace per household.
- financial arrangements for paying appliance acquisition are not available.

Yet, simulations show promising results in this case:

- Electricity savings reach to about 70% of the electricity generated in 1995 (which was about 40,000 Gwh/year). This is equivalent to slightly less than the additional supply requirements to satisfy demand under about the year 2005.
- Figure 6 shows how electricity cooking declines steadily in the urban areas, while natural gas, LPG and electricity efficient have important penetration rates. As expected, demand for natural gas grew more rapidly than for any other energy source.

Let us explore further some policy issues currently under discussion. The Colombian government has decided to increase electricity prices by more than 35%, in real terms, during a short period of time starting in 1996. We assume here that this takes place in during five years. Also the government is considering providing financial support for the acquisition of energy efficiency appliances. If gas appliances and light bulbs are supplied with favourable financial incentives, results will vary considerably. In this case, as discount rates available to utilities are transferred to customers, these will attain further benefits. Figure 7 shows how a further 5% of the total electricity generated will be saved.

DSM and energy substitution policies could show an enormous impact on the profile of energy use. Figure 8 shows how electricity consumption in the residential sector will remain almost stable under these plausible energy policies, while other sectors continue growing at important rates, especially the industrial sector.

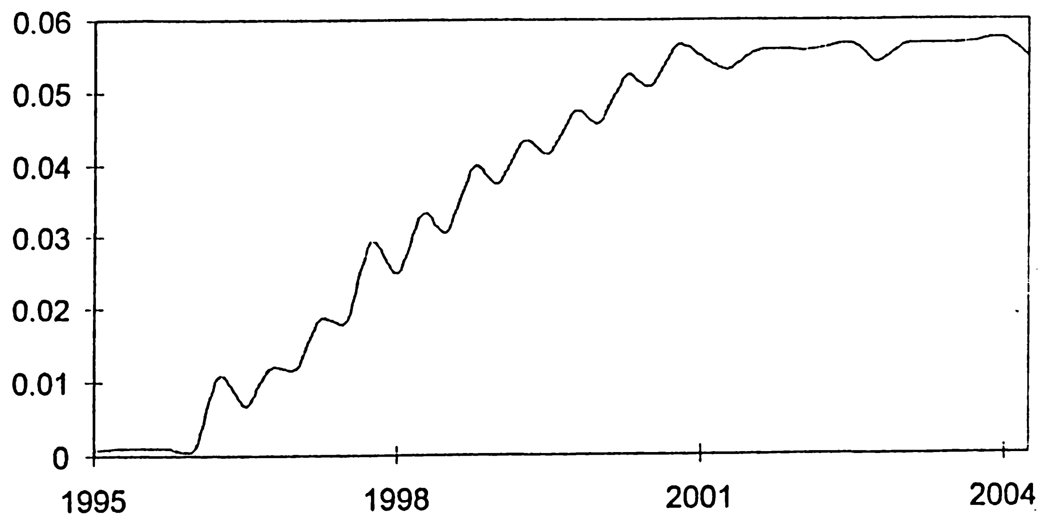

Figure 7 *Percentage electricity savings under a scenario considering financial incentives to acquire energy efficiency appliances.*

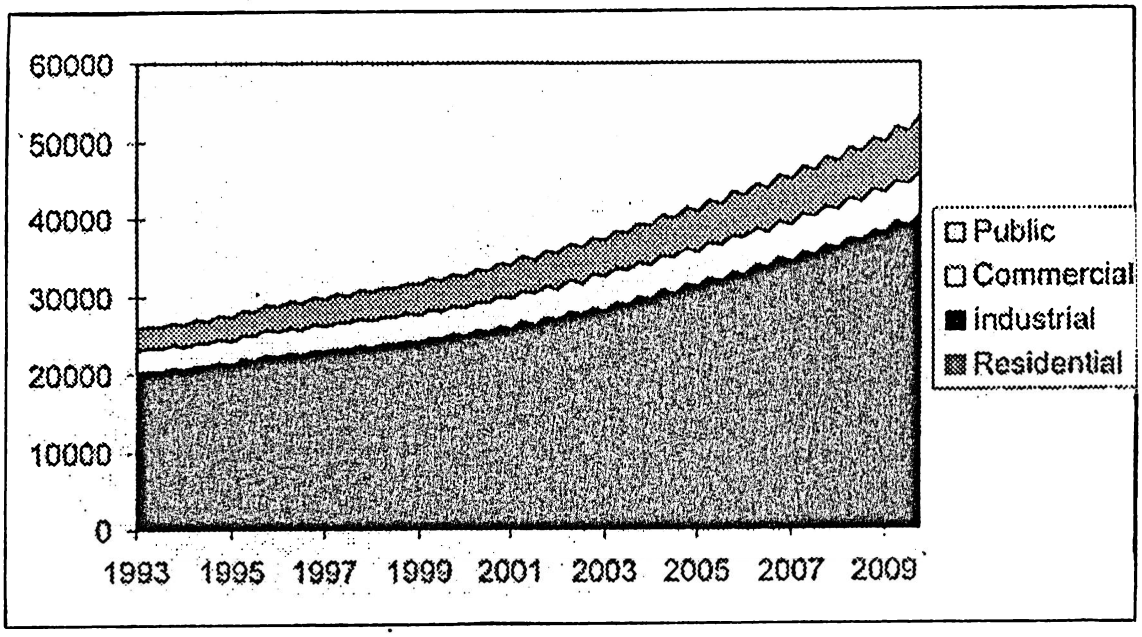

Figure 8 *Evolution of electricity demand by diverse socio-economic sector under a DSM scenario.*

We turn now to the second case study, which addresses some of these DSM issues at the regional level in Colombia.

EFFICIENT ELECTRICITY SUBSTITUTION BY GAS

Colombia's regions are very diverse, and much needs to be done in the energy sector with respect to DSM policies at this level. Also, specific efforts have to be made to substitute electricity by more efficient sources and/or less expensive alternatives, i.e. gas and new appliances.

The problem is not simple. First, because on the demand side, a large number of customers do not have the buying capacity or incentives to change their traditional electric appliances by more efficient or gas fuelled ones. And second, because on the supply side, there does not exist the gas or appliance production infrastructure. For a more detailed discussion see Dyner *et al.* [21].

The model in this case contains much more detail and reference to the particular regional circumstances. It needs to describe the general dynamics of energy efficient and gas fuelled appliance penetration in the Medellin Metropolitan Area, Colombia, with a population of 2.5M inhabitants. However, the general causal diagrams in this case do not vary at all from the ones described above. Some policy issues were also examined here, such as availability and pricing.

The main issues of energy policy which emerge include:

- The gas programme will be successful if energy pricing is considered globally.
- The gas programme depends on energy efficient alternatives.
- Combined gas supply and efficient electricity equipment availability may represent total energy savings of about 37% in the domestic electricity sector by 1997.

Overall, the key issues modelled in these case studies were quite different in scope and focus from the earlier national example to the regional case, and both included consumer behaviour, product substitution dynamics and energy conservation.

CONCLUSIONS

In two different applications of systems dynamics we have demonstrated its capability to deal with complex DSM and energy substitution issues both at the national as well as at the regional levels. The scope of these two case studies is reassuring in validating the potential of the SD approach to provide a framework of the breadth that integrated planning requires. It is evident from our discussion of the modelling needs that a platform for integrated analysis must facilitate dynamic and systematic investigation of policy, and not just perform a co-ordination function in managing the inputs and outputs of separate, conventional modules. SD has the strategic focus and breadth to do this. With respect to the modelling features identified earlier, the SD framework is

- *Non-normative and non-directive.* The basic framework is meant to be descriptive of how the system works in practice.
- *Non-deterministic.* It requires subjective interpretation of the issues and their solutions.

- *Non-linear.* Non-linearity is clearly incorporated.
- *Feedback driven.* This is a fundamental feature.
- *Behavioural* focus in consumers and investment.
- *Structural dynamic.* Changes can be modelled by the causal relationships and decision rules that are embodied in the model.

From the policy perspective, we identified plausible DSM programmes for energy sustainability in the Colombian residential sector. Specifically, the large-scale gas plan, along with gradual electricity price increments and some financial incentives for energy efficiency appliances, have important benefits. Further research will encourage the exploration of 'sensible' policies especially in the industrial and public sectors.

Open modelling questions still remain however with respect to the management of ownership arrangement in a transparent way, the hierarchical organisation of detail and the explicit treatment of uncertainty. It does however give the initial strategic 'view from above' that is necessary in the early stages of policy analysis, and, as the case studies have shown can be built up to include a wide range of issues. We suggest that Integrated Energy Planning should start from a policy oriented focus, rather than from a collection of case models. This seems to be the most important advantage of the approach.

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