INTEGRATED ENERGY-ENVIRONMENT-ECONOMY EVALUATION OF THE ENERGY SECTOR IN THE METROPOLITAN AREA OF THE ABURRÁ VALLEY (COLOMBIA) FOR SUSTAINABLE DEVELOPMENT

Rave, Claudia C[1]., Smith, Ricardo A[1]., Cadena, Angela I[2]., Alzate, Juan M[1]. y Vásquez, Juan. D.[1]
[1]National University of Colombia,Medellín [2], Andes University
ccraveh@unalmed.edu.co, rasmith@unalmed.edu.co

Keywords: planning, energy-environment-economy, environmental regulation, Markal

Abstract

The energy system of the Medellín Metropolitan Area (Colombia) has been modeled, under the integrated Energy-Environment-Economy modeling scheme, based on the Markal model. An energy reference system of the Metropolitan Area was set up and consolidated in a local spatial data base, that included the residential, commercial, industrial and transport sectors. The application allowed us to evaluate the system in an evolving scenario that parted from the present conditions and changes under different regulatory scenarios (economic, technological and environmental), defined according to the complex dynamic of regional development. The results obtained are very useful in terms of supporting planning processes.

INTRODUCTION

A sustainable development agenda for a country is a global strategy that must be implemented at local level, being the cities the most important actors in the energy supply and environmental control decision making.

The urban areas concentrate great amount of population and economic activities and consequently its demand for energy services is very high. This concentration also means that the population is directly exposed to the emissions by the production system and power demand. Integrated models that consider the interrelationships between Energy – Environment – Economy EAE are needed. These integrated models can be used to simulate and optimize strategies to organize urban areas as users and efficient producers of energy. The development of initiatives for an efficient energy use, the implementation of renewable energy technologies and the adjustment of the power system to reduce emission of polluting agents into the atmosphere are fundamental tasks to achieve sustainable development. A model of the EAE type is necessary to identify the regulatory trend that must be followed in order to reach the development goals.

In general, the mathematical models of EAE type, can evaluate the resulting impacts on the power supply matrix and on the emissions of polluting agents in an objective and quantifiable way, as a result of some changes in the system. The system's energy base line emits a specific amount of annual tons of each polluting agent, which can be evaluated by the knowledge of the technical and economic parameters associated to each technological device in the system, from extraction to consumption, through the transformation technologies. Thus, the environmental criterion becomes a real indicator of power efficiency and well-being.

THE MARKAL MODEL

The MARKAL model is a linear programming multi-period model, characterized by the detailed representation of the technological and energy (power) devices in each stage of extraction, transformation, distribution and consumption of the power system of a region (ETSAP, 2005; Seebregts et al, 2001).

The solution of the model aims at the satisfaction of a set of exogenously specified demands, for all time periods. The model evaluates different energy technologies combinations to fulfill the demands of the different socioeconomic subsectors and optimize a minimum cost objective function. A number of demand technological devices compete to satisfy a particular demand and a number of production technologies will compete to produce the different energy requirements.

In MARKAL, the power system is divided in 4 technological classes that help explain the energy flows from extraction to demand. The primary energy sources enter the system by means of extraction technologies like mining or oil refineries, and these could be imported or exported. The fuels can be used for electrical generation or transformed into other fuels by means of process or conversion technologies. Finally the energy is consumed in the system by a set of demand technologies.

The MARKAL minimum cost solution corresponds to the cost of all used forms of energy allocated by the model that balance the demand with the supplying of energy. Thus, it can be understood like an analytical model that calculates a partial economic equilibrium with inelastic demands.

A very important aspect is that due to the model's linear platform, the shadow prices can be obtained for all the energy forms included in the model. The model allows the user to obtain the total polluting emissions due to the energy activities for each time period and each polluting agent modeled. The emissions constraints will allow the user to obtain the shadow price of emissions reduction per time period due to the technical and economic optimal system reconfiguration for the fulfillment of emissions reduction goals. MARKAL can then be used in the evaluation of the implications of different technologies and fuel technologies to reduce Green House Gases, GHG, emissions.

The model is based on the representation of the reference energy system RES, which describes and outlines the system energy flows directions and whose representation requires a great amount of information.

THE AVMA MODEL

The specific problem is to evaluate the cost of the actual energy system for a planning horizon of 20 years, for the Residential, Commercial, Industrial and Transportation sectors of the Metropolitan Area (AVMA), and the pollutant emissions reduction costs (CO, CO_2, NOx, SO_2, MP) by energy substitution and/or technological innovation.

The solution to the previous problem is based on a model that constitutes a decision support scheme for the energy expansion and/or reorganization problem for the AVMA. In the debate related to the penetration of new technologies into the system, the consequences in real terms can be observed and confronted, for example, investment and expansion plans, impacts on the environmental system or CO2 emissions, financial consequences, risks, etc.

The developed model (Rave et al, 2005) has a high degree of detail and was designed in such a way that it connects and displays its results using the GIS software HidroSIG©. Emission maps by sources for all evaluated scenarios for each year of the planning horizon were obtained.

EAE Model for the Medellín Metropolitan Area

This application was made to identify the development pattern that must be implemented (Rave et al, 2005). This pattern is associated to a regulatory trend and the revision and design of local environmental and energy policies that will allow the sustainable energy planning of the AVMA for the next years. This project was supported financially and with basic information by Medellin´s Public Utilities Company (EPM) and by the Medellín Metropolitan Area Environmental Authority (AMDVA).

The AVMA is conformed by 10 municipalities that integrate the Medellín river valley (see Figure 1), located in the south center region of the State of Antioquia, and towards the midpoint of the valley, with lat-long coordinates of 6^{o}15'6''N and 75^{o}34'E, respectively, and an average height of 1,480 m.a.s.l. The Valley has an approximate length of 60 km and a variable width. It is surrounded by an irregular topography, with heights that oscillate between l, 300 and 2.800 m.a.s.l.

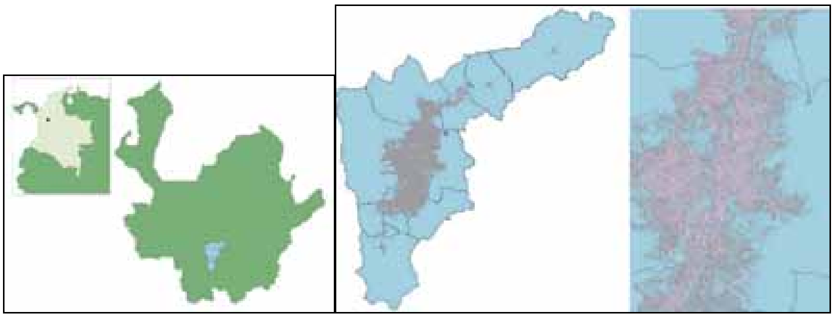


Figure 1: Left: Geographic location of the department of Antioquia in Colombia. Right: Detail of the AVMA.

The AVMA has approximately 3'200.000 inhabitants, 94% in urban areas and 6% in rural areas, and Medellín is its crowded municipality with 2'000.000 inhabitants (AMDVA, 2002). It is expected that for the year 2020 the AVMA will have 1'000.000 of new inhabitants. This scenario implies the reflection and strategic planning around diverse subjects, such as the revision and reinforcement of environmental, economic, energy and city-planning policies that will allow the sustainable projection of the Medellín river valley.

The Reference Energy System RES

The construction of the RES started from the analysis and definition of the actual scheme of demands and energy consumptions, and the consolidation of the related sub-sectors (residential, commercial, industrial and transport) for each of the modeled consumption.

Following the model's technological structure the following components were declared in the RES - AVMA:

SRC (sources): All available sources of primary energy considered were imported in the AVMA, such as Renewable such as coffee rind (BCF), coconut rind (BCO), wood pulp (BMD), Bio-Diesel (BDO) and some bio fibers (BPL) and nonrenewable like Coal (COA), Natural Gas (GNA), Liquefied Petroleum Gas (GLP), Vehicular Natural Gas (GNV), Gasoline (GSL), Diesel Fuel (DSO), Fuel Oil (DFO), Jet Fuel (JTF), Heavy Petroleum (PCC), Light Petroleum (PCL) and Electricity (ELC).

TCH (Technologies): 3 groups of technologies that represent the consumption and processing of energy in the system were considered: CON (conversion) or load dependent technologies of the load, such as energy generation and/or electrical transformation; PRC (process): or load non dependent technologies that typically transform one energy source into another one, such as the refineries; and DMD (demand devices) or demand technologies, that correspond to technologies or devices that only consume energy.

Since all primary sources of energy are imported into the AVMA the only COM and PRC technologies included in the model were the electricity transmission and distribution lines. Almost all modeled technologies correspond to demand devices or end use technologies (DMD).

MARKAL is a demand driven model and it is based on the RES of the AVMA. The model was implemented for a 20 year horizon and considers the geographical disaggregated demands for each consumption sector and its consumption characteristics. Each demand has a geographic reference that is represented in a GIS.

Demands (DM)

The energy demands included in the model were exogenous, calculated using the actual demands for energy services in the AVMA. The projections for the planning horizon were made using socioeconomic drivers.

Residential and Commercial Sectors: This demand is disaggregated by BLA (Basic Load Area) that corresponds to a geographical area of 500×500 meters in which the AVMA has been divided for balance and projection of electrical and natural gas demands. There are a total of 855 BLA's in the AVMA, which were grouped into 129 classes following the criteria of vicinity and city-planning homogeneity.

Illumination, cooking, water heating, air conditioning and refrigeration demands were considered. Electrical and gas devices were included and electricity (ELC), natural gas (GNA) and liquefied petroleum gas (GLP) were considered as the main energy sources for this sectors.

Industrial Sector: Information of 291 main industries within the AVMA were available and were classified in 11 industrial sub-sectors. The industries were grouped in 238 groups depending on whether the industries were at a distance of less than 400 meters from each other and if they belong to the same industrial sub-sector.

The modeled demands were process steam (V), direct heat (CD), motor force (M) and general uses. The considered demand technologies were boilers and furnaces, electrical motors and electric devices for the general use demand.

The energy sources included were: Coal (COA), Natural Gas (GNA), Liquefied Petroleum Gas (GLP), Diesel Oil (DSO), Fuel Oil (DFO), Heavy Petroleum (PCC), Light Petroleum (PCL) and Electricity (ELC); and industrial remnants such as coffee rind(BCF), coconut rind (BCO), wood pulp (BMD) and some bio fibers (BPL).

Transportation Sector: This sector is one of the most intensive sectors in energy consumption and around which, a great deal of effort is made in the strategic plans for metropolitan development. The entrance of the Metroplús system (a new massive transportation system complementary with the metro system) is expected in the next 2 to 3 years as part of an ambitious transportation reorganization project for the AVMA.

In the model's demands, 12 main avenues and streets were modeled, including the Metroplús project. Several transportation forms were also included in the model. The energy sources considered were Gasoline (GSL), Diesel Oil (DSO) and Natural Gas (GNV).

The demands of the transportation sector were divided in ground and aerial mobility of passengers and load. It is also possible to differentiate public and private, and individual and collective demands.

With this level of disagregation in the model, results can be obtained on the impacts that any change has on each of the BLA groupings or, only to analyze changes on one or several groupings, according to what the user wants to analyze, for example for Medellín's downtown, or any particular industrial area. It will also allow the user to review the optimal technology-fuel allocations on each grouping as a result of each individual scenario, since each BLA grouping is independent in the model.

Modeling Conditions

1. The starting year for the model was 2002 and a horizon of 20 years was used, thus modeling until 2022.

2. The energy balances for the initial years were calibrated and validated, and energy demands projections were used in correspondence with the historical energy use information and economic drivers.

3. The fossil fuel costs were calculated according to the cost projections for the country. For electricity several trend scenarios were generated according with the tariff percentage for investments in new capacity, transmission and distribution charges.

4. Emissions were calculated using the emission factors published by EPA, Environmental Protection Agency (EPA, 2005)

5. Demand Technologies, DMD: For the great majority of the modeled demands several types of technologies with different technical and economical characteristics using different energy fuels were formulated. Information on efficiencies, average annual use coefficients, and investment, installation, operation and maintenance costs were used.

6. Installed capacity of demand technological devices (DMD) for the base year. It is assumed equal to the demand and in some cases even greater. The installed capacity is a very important parameter within the modeling process since additional capacity will be installed in order to satisfy future demand requirements at the investment costs.

7. Transportation Sector: It was modeled using vehicle-km units, according to the activity of the vehicle bundle in the AVMA. Emissions were considered using emission factors related to the different available fuels and according to the fuel efficiency of each vehicle and as a function of recorded kilometers. A detailed inventory of the vehicle bundle is available.

Scenarios

Scenarios are formulated through impositions or restrictions on the numerical system (economic or environmental regulatory policies, introduction of technology or fuel substitution in the system, etc., in different time periods) so that the model adequately represents the required evaluation conditions. For the EAE- Metropolitan Area modeling 5 different scenarios were evaluated:

A scenario without technological use or emissions constraints (01). The only model constraints were associated with the demand supply. It corresponds to the technological and fuel allocation of minimum costs.

Base scenario (06): Actual fuel consumption for the years 2002 and 2003 were used for model calibration in all sectors and according to the available information.

Scenarios for the Transportation sector (13 and 14): Scenarios of natural gas penetration (GNV) and diesel oil (DSO) in the vehicle bundle and/or due to the entrance of the Metroplús system.

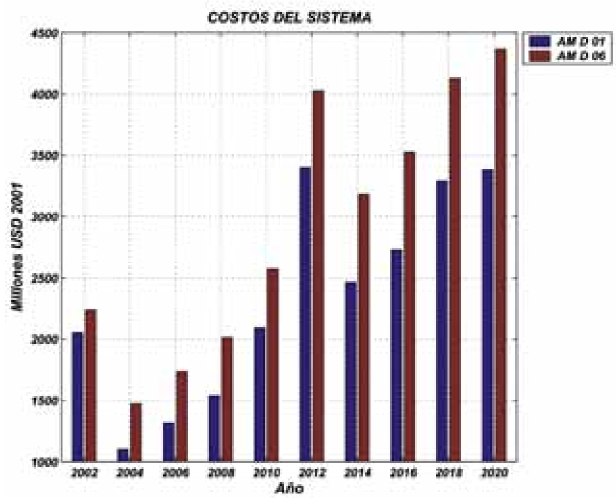
Scenarios for the Industrial sector (15 and 16): Scenarios of fuel oil (DFO) or coal (COA) substitution by natural gas (GNA) in the industry.

Emissions constraints scenarios (17 to 22): emissions constraints considered from the year 2008 onwards. These scenarios do not have technological use constraints, therefore the model will assign the optimal technology-fuel combinations of minimum cost fulfilling emissions constraints.

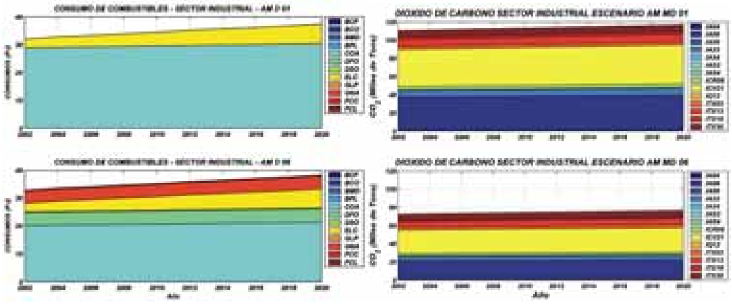
RESULTS

One of main results is the combination of selected energy-technologies, distributed in time, amounts used per period, end use energy and others that are specifically referred to each energy fuel or to each technology or combinations of both. As an environmental result, the emissions due to combinations of selected fuel-technologies, for each time period and each geographical aggregation can be obtained. The economic results include total and partial investment costs (per time period) in technology, fuels, distribution and transportation, the operational and maintenance costs for the system and for each technology, shadow costs and prices due to technological or environmental constraints (reduction costs), and many others.

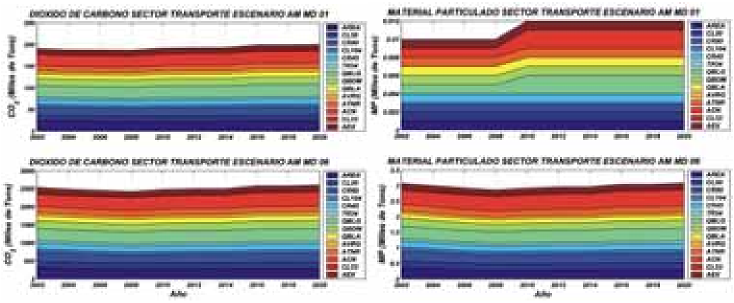
In the following figure the costs of the actual system or base scenario (06) and the optimal scenario without constraints (01) are shown. The figure shows that the cost of scenario 06 is much grater than the cost of scenario 01, indicating that there is a great potential in planning of the AVMA energy sector looking forward to reduce the costs of the system.



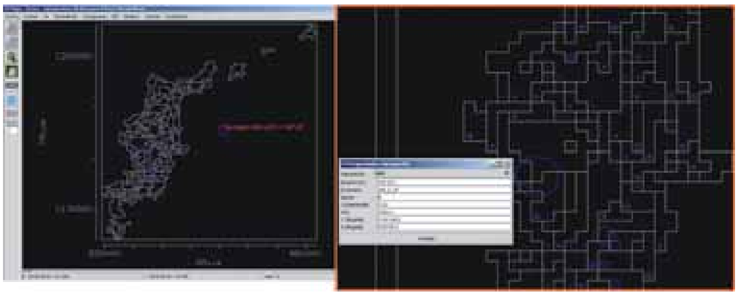
In the following figure the differences between the energy basket for the industrial sector in scenarios 01 and 06 is presented. In scenario 01 and following the logic of minimum cost, the system assigns an intensive use of COA. In scenario 06 and following the actual behavior, the system uses a more varied fuel basket. In scenario 15 the model is restricted to replace COA and DFO by GNA. In the following figure the emission results are consistent with previous statements: in scenario 01, CO2 emissions are much greater than those of scenario 06.

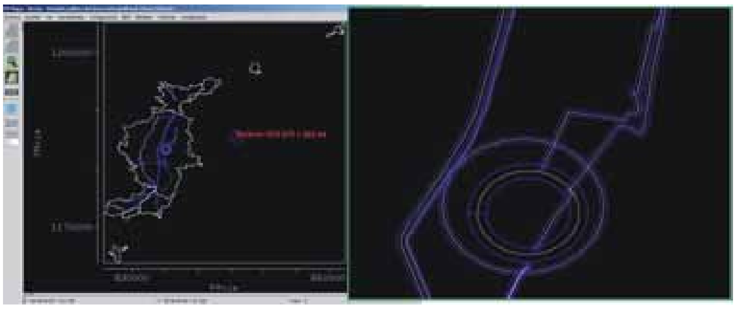


In the transportation sector, scenario 01 shows an intensive use of GNV whereas in the actual scenario 06 GSL and DSO are used, which is in agreement of the actual situation in AVMA. The emission results displayed in the following figure indicate that in scenario 06, MP and CO2 emissions are about 10 times higher than those of scenario 01, which uses a cleaner fuel.



In the following figures some of the resulting maps of the Hidrosig GIS software application are shown. CO2 maps for the residential and transport sectors are shown for year 2004.





CONCLUSSIONS

In this research an integrated evaluation Energy - Environmental - Economy, EAE, has been developed for the AVMA, using the MARKAL model. The research results and the model, constitute a decision and planning support tool with integrated EAE considerations. Important results were obtained such as a series of evaluations of the actual state and behavior of the energy and environmental system of the Metropolitan Area, evaluations of different energy substitution projects and evaluations of the implications of the implementation of different regulatory policies on the system.

Complementary results are available such as costs, technological-fuel allocation and emissions, associated to different scenarios related to different considerations for the AVMA energy system. The amount of information generated for planning processes is invaluable and their analysis and interpretation will not only allow to support effective planning processes but also to define and to project future processes.

The evaluated scenarios will allow decision makers to establish behavior thresholds for the system and to establish desired or goal scenarios to which the regulatory trends must aim. These goals will be the departure points so that the planning, regulation and services AVMAorganizations of the AVMA, draw up their own investment and operation plans, contributing in this manner with the AVMA common development strategies. The results are also a step forward in the understanding, interpretation and modeling of the complex Environmental - Economy - Energy EAE relationships.

ACKNOWLEDGEMENTS

This research was possible due to the support of Medellín Public Utility (EPM), the Medellín Metropolitan Area Environmental Authority (AMDVA) and the National University of Colombia, Medellín campus.

REFERENCES

Área Metropolitana del Valle de Aburrá. *Proyecto Metrópoli 2002 - 2020 - Plan integral de desarrollo metropolitano del Valle de Aburrá*. Medellín, Colombia, 2002.

Área Metropolitana del Valle de Aburrá (AVMA). http://www.metropol.gov.co/ Accessed on oct 2005

Energy Technology Systems Analysis Programme (ETSAP). http://www.etsap.org/index.asp Accessed on oct 2005

EPA, U.S. Environmental Protection Agency. Inventory of U.S.Greenhouse Gas Emissions and Sinks: 1990-1998, EPA 236-R-00-001, Washington, DC, Abril 2000. http://www.gcrio.org/OnLnDoc/pdf/2000_inventory.pdf. Accessed on May 2005

FEDRA, K., 2003. SUTRA. Sustainable Urban Transportation. Draft Final Report. European Commission, DG Research, Unit I.5. Environment and Sustainable Development programme. Belgium. http://www.ess.co.at/SUTRA/DELIVERABLES/PUBLIC.pdf. Accessed on May 2005

GOLDSTEIN, G., 2000. Energy/Economy/Environment Interaction using the MARKAL family of models. International Resources Group, Ltd. INFORMS 2000 - San Antonio. http://www.gams.com/presentations/present_irg.pdf. Accessed on May 2005

Rave, C., Smith, R., Cadena, A. Vásquez, J., Alzate, J., Evaluación Integrada Energía Ambiente Economía para la planificación sostenible de núcleos locales, caso de aplicación Área Metropolitana del Valle de Aburrá. Documento de Informe final, Medellín, Colombia, 2005.

SEEBREGTS, A., GOLDSTEIN, G., SMEKENS, K., 2001. Energy/Environmental modeling with the MARKAL family of models. Editado por Energy Research Centre of the Netherlands (ECN), Policy Studies unit, International Resources Group Ltd. http://www.ecn.nl/docs/library/report/2001/rx01039.pdf. Accessed on May 2005