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Optimizing the Energy Production Infrastructure Considering Uncertainty in Fossil Resource Availability

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ABSTRACT: Fossil sources scarcity and environmental contamination are the major factors that put the energy industry into focus. Considering the lack of accuracy in fossil reserves, we propose an optimization model to plan investments in the Argentinean energy structure taking into account uncertainty in the fossil source availability. Tactical decisions, such as the amount of primary and secondary sources produced, are included and the emission of greenhouse gases is penalized in the objective function to improve the environmental impact of the energy structure. Also, two different methods are used to model uncertainty. Fuzzy set theory is applied to generate scenarios that show the random behavior of resource availability parameters. In addition, a two-stage stochastic model is proposed to integrate the different decision levels involved in the problem and represent resource availability uncertainty in fossil fuels. Both approaches complement each other to obtain a comprehensive solution of the energy planning problem.

1. INTRODUCTION

Energy infrastructure is one of the most significant topics of interest in today's economy and academia. Fossil fuels have been the main source of energy to produce goods and services and meet transportation requirements and all comfort needs of human life for many years. This was not an issue while the equation availability−price−demand was fair enough for most stakeholders in the energy market and the environmental care was not a problem. In the past years, a number of factors have arisen that put the energy industry into focus. In the first place, oil demand is increasing and reserves will be not available at some point in the future. In addition, the location of known fossil reserves is concentrated in a small number of regions in the world and far from the main consumption areas. Many countries aim at energy independence by promoting new developments in renewable energy supply and production.[1−4]

Nevertheless, substituting a fossil source by other sources requires new and efficient technologies, well oriented politics, and capital investments. Multiple alternative sources have appeared but in general they are expensive and not as stable as fossil oil.

Several forecasts can be found in the literature regarding nonrenewable resources availability.[5−7] However, the future of nonrenewable sources is full of uncertainty. On the one hand, there are possible oil wells located in places very difficult to explore, in which the quantity or quality of the oil is completely unknown. On the other hand, new findings and technologies such as shale gas,[8,9] suggest that "the end" of the oil-based energy industry might be further than expected.

Finally, significant climate changes, water contamination, and greenhouse effects among others natural deteriorations make the environmental impact of human activity a point of concern in many countries. Some of these countries have committed to improve their eco-indicators in the midterm future. The Kyoto Protocol signed in 1998, is the main document that supports this international interest. One major objective is to reduce the CO_2 gas emission from fossil sources that contribute to air pollution and the greenhouse effect.

The various and multiple factors involved in this subject point out that a new balance should be found integrating the new renewable alternative with the old fossil energy sources. This is a challenge recognized in several articles.[10−12]

According to the Secretary of Energy,[13] in Argentina, more than 86% of total primary energy sources come from natural gas and crude oil. As a consequence, there are research and funding programs that promote the development of new technologies for renewable energy.

In this article we propose an optimization model to plan investments in the Argentinean energy structure considering uncertainty in the fossil source availability. Given a set of potential (renewable and nonrenewable) sources, the main objective is to determine the capacities required in each energy source in order to meet energy demand for the next 20 years assuming that the availability of oil and gas is subject to uncertainty. To take into account the environmental impact of energy decisions, the emission of greenhouse gases (GHG) is penalized in the objective function. Two different strategies are applied to model uncertainty in the fossil resources availability. In the first place, fuzzy sets are used to generate a set of possible scenarios in crude oil availability and analyze the impact of the variability of this parameter in the model solution. Then, two-stage stochastic programming is applied to model the uncertainty problem with the purpose of obtaining a more robust solution. This article is organized as follows: in section 2, a literature review is presented. Section 3 contains the models formulation, presenting the deterministic approach, the fuzzy

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set reformulation, and the two-stage stochastic model. In section 4 results are presented and discussed and finally, in section 5, conclusions are drawn.

2. LITERATURE REVIEW

As it was pointed out in the previous section, there are several articles that study the energy problem from different perspectives. The multiple objectives in conflict make it difficult to find a unique target to pursue. However, Siirola and Edgar[14] support that economic, energy, and sustainability objectives can be aligned with energy efficiency and propose operational strategies and management regulations to improve energy efficiency and consumption minimization.

Agrawal et al.[15] present hydrogen as a plausible alternative to replace fossil fuels in the long term future. They recognize that despite its abundance in nature, H_2 is not available in the free form and must be produced from another energy source. Then, their focus is placed on the key barriers to assembly an H_2 infrastructure, and the pros and cons associated with various methods of producing inexpensive H_2. The main objective is to examine hydrogen's potential as a transportation fuel and provide a framework with the major challenges to promote a successful H_2 energy system. A detailed review on energy community contributions can be found in ref 16. This article provides a comprehensive analysis of the research work in the area of energy systems for liquid transportation fuels, presenting a classification and assessment of the different approaches proposed by the literature and research groups.

Regarding the use of renewable energy sources, Zhang et al.[17] present a multiperiod model for the optimal plan in the power generation sector of China during the period 2010−2050. The horizon planning is divided into several intervals in which the power plants are installed, modified, or shutdown. The decrease of GHG emission is studied by capturing the CO_2. The authors present the results applying the model to a real data-based case study from China. Čuček et al.[18] propose a multiobjective optimization model of biomass energy supply network. They develop a novel dimensionality reduction method applied to environmental footprints, by which the number of environmental footprints is reduced to a minimum number of representative ones. The approach is illustrated using a demonstration case study of different biomass energy supply chains indicating that using this novel approach makes multiobjective optimization more practical for real life problems. Conolly et al.[19] analyze the Irish case by means of the EnergyPLAN tool that allows the analysis of several sectors such as electricity, heating, and transportation among others. They analyze different scenarios and sustainable sources and show the results obtained. They conclude that their study serves as an illustrative case but a more realistic analysis must be carried out considering environmental and economic issues. De Vries et al.[20] investigate the potential for wind, solar-PV, and biomass (WSB) to deliver energy. They evaluate the geographical, technical, and economic potential of those energy sources. For the assessment they use the soil and land-cover data provided by IMAGE 2.2 model. They also employ the model implemented by the IPCC SRES (Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios) to estimate the geographical potential of biomass for energy crops. The authors analyze four scenarios based on uncertainties in land-use land cover and some specific biomass parameters. They show that "potential production" concepts are strongly dependent on the chosen land-use scenario and should therefore be used with an indication of the underlying assumptions.

Ding and Somani[21] propose a mixed energy infrastructure integrated with renewable energy. One of the challenges they identify is that the renewable energy sources are usually located in remote areas, far from power consumption points. In addition, there are technical issues to overcome. For instance, in the case of windmills, the energy is fluctuating and may produce surplus power when it is not demanded or not enough when it is required. Then, they introduce the use of energy storage system to store energy from wind power. Assuming all parameters deterministic, they propose a mathematical model to combine fossil power and wind energy infrastructure in a long-term investment planning. Baliban et al.[22] propose an optimization-based process synthesis framework for the thermochemical conversion of biomass and natural gas to liquid fuels (BGTL). The framework includes simultaneous heat, power, and water integration minimizing cost of the BGTL refineries. Results suggest that these systems can be economically competitive with petroleum-based processes while achieving the 50% emissions reduction.

Flores et al.[23] develop a deterministic model for planning investments in renewable and conventional energy sources. The renewable energy sources considered in this work have shown to be competitive and technically mature and reliable. In this case, the objective function minimizes investments and operational costs.

The particular case of a biofuels supply chain is studied in detail by Yue et al.[24] They review the key challenges and opportunities in this subject providing the general structure and unique characteristics of biomass-to-biofuels supply chains. They also describe the multiscale modeling underlying this problem and the different levels of decisions involved. Finally, they stress the sustainable issues that should be modeled and the need to account for uncertainty in the decision process. An optimization framework for bioprocesses of lingo-cellulosic ethanol production is addressed by Morales-Rodriguez et al.[25] They develop a systematic model-based method identifying different sources of uncertainty by using sensitivity analysis and propose metrics to evaluate the performance of the system. Fleten et al.[26] evaluate investments in decentralized renewable power generation under price uncertainty. They develop a mathematical model that maximizes the Net Present Value of new projects. Investor can choose between mutually exclusive capacities and investment timing to maximize benefits. A stochastic description using geometric Brownian motions is employed to handle uncertainties for electricity prices. The model is applied to a case study of a wind turbine investment for an office building in Norway. Due to price volatility they conclude that for larger projects the optimal strategy is to wait until investment is optimal. Cai et al.[27] develop a fuzzy-random interval programming (FRIP) model to determine optimal strategies in the planning of energy management systems (EMS) under multiple uncertainties. The mathematical program allows multiple uncertainties presented as interval values, possibilistic and probabilistic distributions, and their combinations. The model is applied to a region of three cities for a planning investment for long-term time horizon. They conclude that solutions obtained can be used for generating decision alternatives and help decision makers to identify policies considering various economic and system-reliability constraints.

Uncertainty is also found in fossil fuel resources as it was addressed by Tarhan et al.[28] for offshore oil and gas field infrastructure planning. Different levels of uncertainty can be differentiated according to the type of source considered. It is assumed that these uncertainties are not immediately realized, but are gradually revealed as a function of design and operation decisions. For example, if the source is already in operation, the uncertainty is lower than if it is a potential new oil well in which case the quantity of oil and yield are hardly known. In fact, the Petroleum Resources Management System document[29] identifies three ranges of uncertainty regarding the quantity of oil that can be actually recovered in comparison to the estimated reserves.

Different approaches can be used to model uncertainty. The main approaches in the process system engineering community are stochastic programming, fuzzy programming and stochastic dynamic programming.[30] Gupta and Maranas[31] develop a two-stage stochastic programming model with demand uncertainty, which is represented using a normal distribution with a known mean and standard deviation. The model is applied to a mid-term planning of a multisite supply chain. The manufacturing decisions are modeled as "here-and-now", which are made before demand realization; while logistics decisions are postponed in a "wait-and-see" mode. The proposed bilevel-framework does not increase the model size but introduces nonlinearities in the formulation. Al-Qahtani and Elkamel[32] propose a two-stage stochastic mixed integer linear programming (MILP) model for a multisite integration problem within a network of petroleum refineries under uncertainty and using robust optimization techniques. The uncertainty is presented as coefficients of the objective function and right-hand-side parameters in the inequality constraints. The proposed method makes use of the sample average approximation (SAA) method with statistical bounding techniques. The model is applied to single and multisite refinery examples. In the conclusions, the authors point out that "the proposed approach leads to results that are more stable against variability in imported crude oil and product prices (solution robustness) as well as forecasted product demand (model robustness). Furthermore, the study shows that the refinery models bear more sensitivity to variations in prices of imported crude oil and exported final products as opposed to variations in product demand".

Regarding fuzzy set theory, Zimmermann[33] argues that fuzzy sets are tools for modeling problems involving fuzzy components or relations since the implementation enables the representation of real-world terms that are not known accurately. Therefore, there is a certain flexibility in satisfying constraints containing these parameters.

The methodology to transform a fuzzy linear programming model depends on the fuzzy relation or fuzzy parameters that have been considered. As a consequence, there are a large number of possible reformulations, some of which have been collected by Baykasŏglu et al.,[34] Diaz-Madroñero et al.[35] and Thakre et al.[36] In the latter case, the authors have considered the representation of uncertain parameters with triangular numbers. Further, Peidro et al.[37] also present an application of fuzzy logic with triangular fuzzy numbers to model a supply chain with uncertainty in the supply, demand, and production.

In the set of stochastic programming methods, probabilistic programming or chance-constrained approach focuses on the reliability of the system which is modeled as a minimum probability of satisfying constraints. On the other hand, programming with recourse (two-stage or multiple-stage stochastic programming) involves a set of decisions that must be made before the uncertainty is revealed and some others that can be decided once the uncertain parameters are known. In general the first stage decisions, called "here-and-now", are investment or long-term decisions, while operational or short-term decisions usually are treated as second stage or "wait-and-see". The integration of different techniques can bring new insights of the uncertain problem. Wang and Rong[38] integrate two methods to optimize a crude oil scheduling problem under uncertain conditions. In the first step, a chance-constrained approach is applied. In the second, fuzzy programming is used in a scenario-based approach.

In this paper, fuzzy set theory is applied to generate a set of scenarios that show the random behavior of resource availability parameters. In addition, a two-stage stochastic model is proposed to integrate the different decision levels involved in the problem and to represent resource availability uncertainty in fossil fuels. Both approaches complement each other in order to obtain a comprehensive solution of the energy planning problem.

3. PROBLEM DESCRIPTION AND MATHEMATICAL MODEL

The mathematical model proposed considers renewable and nonrenewable sources to supply energy to different types of customers and uses. The nonrenewable sources are crude oil, and natural gas, while the renewable sources taken into account are wind power, biomass, hydraulic power, and solar energy. For hydraulic power, and given the large number of rivers with significant and constant stream flows, the use of hydrokinetic turbines is considered for electricity production. Set i represents all energy sources considered in this work. Energy markets (set k) included in this article are heavy and light transportation, commercial and residential heating, industrial and residential electricity, and industrial consumption of energy. The links among energy sources, technologies, and markets are shown in Figure 1. Greenhouse gas emissions are taken into account,

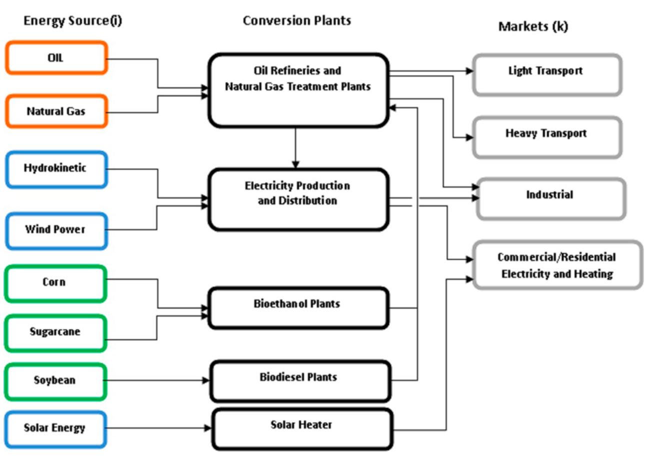

Figure 1. Energy source-technology-market links.

and they are penalized in the objective function. The use of nonrenewable resources cannot surpass the reserves during the project lifetime. Renewable sources have a limited capacity by the harvested area allowed and/or the availability of them according to political rules and geographical limitations of Argentina.

The following section describes the deterministic model. It considers investment decisions over 20 years. In this first model, we disregard the effect of uncertainty in the fossil source and apply a deterministic approach. A description of all parameters and variables used in the following formulations is presented in the Nomenclature section.

3.1. Deterministic Model. The model presented in this section, extends the previous work proposed in ref 23. However some new features have been introduced. First, the objective function not only considers investment and operational costs but also incomes from operation and takes into account the effect of taxes. It also calculates the difference between GHG emission from the initial energy matrix and the one proposed, as well as the expansion of harvested areas to produce biofuels. Both aspects are penalized in the objective function. In addition, proved and new reserves are considered for fossil fuels, which is an important feature to model different levels of uncertainty in these parameters in sections 3.2 and 3.3.

$$\max(NPV)$$

where

$$NPV = \sum_t \frac{\sum_{k \in \text{markets}_{i,k}}^{i \in \text{markets}_{i,k}} (NT \cdot \sum_{t'} CA_{i,k,t',t} - (1 - NT) \cdot (CI_{i,k,t} + CS_{i,k,t}))}{(1 + TI)^{t-1}} - \sum_{i \in NFO} AC_i \cdot AA_i + \sum_t \frac{\sum_{k \in \text{markets}_{i,k}}^{i \in \text{markets}_{i,k}} ((1 - NT) \cdot (P_{i,k,t} - CO_{i,k,t}) x_{i,k,t} \cdot hr) - Bv_t \sum_k (GGEI_{k,t} - XGEI_{k,t})}{(1 + TI)^{t-1}} \quad (1)$$

The objective function is shown in eq 1, which consists of the net present value (NPV) of the long-term energy project.

In the first term of eq 1, $NT \cdot \sum_{t'} CA_{i,k,t',t}$ represents savings in taxes due to depreciation cost, where $CA_{ik,t',t}$ is the depreciation cost corresponding to period t, of the investment made in period t' for source i, customer type k, and NT is the revenue tax rate. The annual amortization ($CA_{i,k,t',t}$) cost is calculated as percentage of the amount invested divided by the asset lifetime (in number of years).

In the next term, the annual investment cost of source i, for market k, in period t, $CI_{i,k,t}$, is considered for new installations, as well as start-up cost $CS_{i,k,t}$ which is paid only once in the lifetime of a new investment, before operation starts. This cost is multiplied by $(1 - NT)$ to discount the revenue tax rate.

The following term penalizes the increment of harvested area assigned to the production of bioethanol or biodiesel. In this term, the set NFO defines the nonfossil oil sources, the cost of each additional unit of renewable source i is given by parameter AC_i, and the additional units required of the source i is defined by variable AA_i. The parameter AC_i is the cost of adding a new area of cultivation for the production of biofuels, this cost is estimated and penalizes the use of a new area.

The annual income obtained from the source i, market k, period t is given by $P_{i,k,t} \cdot x_{i,k,t} \cdot hr$, where $P_{i,k,t}$ is the sale price, $x_{i,k,t}$ is the amount produced and sold per hour of operation, and hr is the number of hours per period. Annual operational costs of the energy system (new and old plants) are determined by $CO_{i,k,t} \cdot x_{i,k,t} \cdot hr$. This term is the product of the individual operating cost $CO_{i,k,t}$ multiplied by the amount produced $x_{i,k,t}$ and the annual operation hours hr. To calculate the net income, this term is multiplied by $1 - NT$.

Finally, in order to penalize the GHG emission, we also include the third term in the objective function. The penalty cost Bv_t is multiplied by the difference between the emission produced by the initial energy infrastructure $GGEI_{k,t}$ and the one obtained by the model decisions, $XGEI_{k,t}$. Both emissions are calculated for each market k in the period t. The parameter Bv_t is the price of the carbon credit which is taken from the corresponding commercialization market.[39] A sensitive analysis of this parameter can be found in ref 40.

Disjunction presented in eq 2 has two levels of decision; the first one decides if the investment in source i is made or not, while the second selects the capacity and investment required. When Boolean variable $w_{i,k,t-Ti,k}$ is true, a new investment is decided for source i, market k in period $t - T_{i,k}$. Note that $T_{i,k}$ represents the gap between the time the investment decision is made $(t - T_{i,k})$ and the moment the plant starts operating (t). To consider economy of scale, the second level of decisions indicates different capacity levels r, for source i, market k, and period $t - T_{i,k}$, which is handled by the Boolean variable $y_{r,i,k,t-Ti,k}$. Note that in this case only one term must be true. Variable $ICap_{i,k,t}$ represents the plant capacity which is limited by the parameter $Imax_{r,i,k}$ in each capacity level r. Similarly $CI_{i,k,t-Ti,k}$ is a variable that specifies the amount to invest, limited also by the corresponding minimum $Cm_{r,i,k}$. Finally, $CS_{i,k,t-1}$ is the start-up cost which is paid one period before operation begins.

$$\begin{bmatrix} w_{i,k,t-T_{i,k}} \\ \bigvee_{r=1\ldots R} \begin{bmatrix} y_{r,i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} \geq Cm_{r,i,k} \\ ICap_{i,k,t} \leq Imax_{r,i,k} \\ CS_{i,k,t-1} \geq CSm_{r,i,k} \end{bmatrix} \end{bmatrix} \vee \begin{bmatrix} \neg w_{i,k,t-T_{i,k}} \\ CI_{i,k,t-T_{i,k}} = 0 \\ ICap_{i,k,t} = 0 \\ CS_{i,k,t-1} = 0 \end{bmatrix}$$
$$\forall\ t > T_{i,k};\ \forall\ (i, k) \in \text{markets}_{i,k} \quad (2)$$

As it is well-known, crude oil is formed by a mixture of different type of products. Equation 3 defines the relationship between the amount of crude oil processed $x_{P,In,t}$ and the amount of different types of fuels i obtained ($\sum_{k \in \text{market}_{i,k}} x_{i,k,t}$). In this model, three types of fuels are considered: naphtha, diesel fuel, and fuel oil. The parameter fraction$_i$ determines the proportion of fuel i obtained when the crude oil is processed. The Argentinean Institute of Oil and Gas (IAPG) [41] reports the estimated values for this parameter.

$$\sum_{k \in \text{market}_{i,k}} x_{i,k,t} = \text{fraction}_i \cdot x_{P,In,t} \quad \forall\ t;\ \forall\ i \in \text{distillates} \quad (3)$$

The different customer types k such as industry, transportation, residential, and industrial heating and residential and industrial electricity, can be satisfied with diverse sources of energy i (which is set by markets$_{i,k}$). Equation 4 states that the summation of the energy flows from all possible sources i associated to customer type k must be equal to the demand of energy required in each period t (parameter $D_{k,t}$).

In the left-hand side of eq 4, $f_{i,k}$ is a parameter that relates the power source i to customer type k taking into account the performance of source i and unit conversion factor between source i and customer type k. For example, the parameter $f_{SP,CR}$ relates solar energy source with residential consume; its value is estimated as the ratio between the energy obtained from a solar collector, in function of the average radiation, the population density, and the standard calorific power of natural gas. Positive variable $x_{i,k,t}$ represents the hourly production of source i to supply customer type k in period t and parameter hr is the number of hours operating during the period.

$$\sum_{i \in \text{markets}_{i,k}} f_{i,k} \cdot x_{i,k,t} \cdot hr = D_{k,t} \quad \forall\, t;\ \forall\, k \tag{4}$$

Equation 5 states that energy production of each source k for customer type k in each period t is limited by the capacity which is a decision variable called $Cap_{i,k,t}$. Note that this capacity varies from period to period according to the investment made. All energy sources have a limited availability, but the way in which they are restricted can be very different depending on the type of source. For example, the amount produced of petroleum cannot exceed the volume of available reserves which is considered a known parameter in this deterministic model. In the case of windmills, their installation is restricted by the free area available assigned. For biomass sources, soybean crops are assumed for biodiesel and sugar cane is taken into account for bioethanol. In this case, the production is limited by the average amount of acreage, yield, and the annual harvest volume used for fuel production.

$$f_{i,k} \cdot x_{i,k,t} \le Cap_{i,k,t} \quad \forall\, t;\ \forall\, (i,\, k) \in \text{markets}_{i,k} \tag{5}$$

Equation 6 determines that the amount produced of nonrenewable resource i must be less than or equal to the available reserves for that source i in period t, represented by the variable $RD_{i,t}$. Note that set NR represents the subset of sources that are nonrenewable.

$$\sum_{k \in \text{market}_{i,k}} x_{i,k,t} \cdot hr \le RD_{i,t} \quad \forall\, t,\ \forall\, i \in NR \tag{6}$$

Capacity of renewable energy sources is restricted in eq 7 and eq 8. In the case of sources i belonging to nonfossil oil set (NFO), such as soy, corn, and sugar, eq 7 applies. For the remainder of renewable sources, such as wind power, hydraulic, and solar energies, eq 8 is used. In both cases, there is an initial limitation given by parameter CD_i that determines the available resources for each source i. For instance, in the case of wind energy, the possible area is determined by regions having airstreams blowing 80% of the time at operation ranges of wind turbines.

For the first set of sources, the initial limitation CD_i can be increased if needed by variable AA_i. Parameter CD_i is determined considering a percentage of the total crop harvested area (acres) multiplied by the average yield of crops (tons/acre) and the estimated amount of oil obtained from crops (liters/ton). These factors were taken according to the values suggested by Argentina's National Institute of Agriculture (INTA).[42] Note that if $AA_i > 0$, it means that the area assigned to produce oil is expanded.

$$\sum_{k \in \text{markets}_{i,k}} \frac{Cap_{i,k,t}}{f_{i,k}} \le CD_i + AA_i \quad \forall\, t;\ \forall\, i \in NFO \tag{7}$$

$$\sum_{k \in \text{markets}_{i,k}} \frac{Cap_{i,k,t}}{f_{i,k}} \le CD_i \quad \forall\, t;\ \forall\, i \notin (NFO \cup NR) \tag{8}$$

Equation 9 indicates that the reserves ($RD_{i,t=1}$) at the beginning of the time horizon are given by the initial availability of resources (CD_i) plus the new possible reserves ($NewR_i$). These two parameters are considered precisely known in this model, whereas eq 10 evaluates the reserves available at period t, by considering the reserves in the previous period ($RD_{i,t-1}$) minus the reserves consumed by the energy produced with source i in the period $t-1$ ($\sum_{k \in \text{market}_{i,k}} x_{i,k,t-1} \cdot hr$).

$$RD_{i,t=1} \le CD_i + NewR_i \quad \forall\, i \in NR \tag{9}$$

$$RD_{i,t} = RD_{i,t-1} - \sum_{k \in \text{market}_{i,k}} x_{i,k,t-1} \cdot hr \qquad \forall\, t > 1;\ \forall\, i \in NR \tag{10}$$

Constraints 11 and 12 define the capacity of each source i for customer type k in each period t. Capacity level is determined taking into account that there is a period from the moment the investment is decided until it starts producing, due to building and start-up time. This period is expressed by the parameter $T_{i,k}$, that depends on the energy source i and customer type k. Equation 11 indicates that the installed capacity of source i for use k at time t ($Cap_{i,k,t}$) is equal to the initial capacity ($Cap0_{i,k}$) for every period t lower than or equal to $T_{i,k}$; while eq 12 states that the capacity for source i and customer type k ($Cap_{i,k,t}$) for all periods t greater than $T_{i,k}$, is equal to the capacity in the previous period ($Cap_{i,k,t-1}$) plus the increased capacity that was decided at time $t - T_{i,k}$ (see disjunction in eq 2).

$$Cap_{i,k,t} = Cap0_{i,k} \quad \forall\, t \le T_{i,k};\ \forall\, (i,\, k) \in \text{markets}_{i,k} \tag{11}$$

$$Cap_{i,k,t} = Cap_{i,k,t-1} + ICap_{i,k,t} \qquad \forall\, t > T_{i,k};\ \forall\, (i,\, k) \in \text{markets}_{i,k} \tag{12}$$

Due to legislation and operating conditions, there might be limits in the amount of biofuel that can be used. In the particular case of Argentina, most motors in vehicle fleet require fossil fuels to function properly. For that reason, biofuels are blended with fossil fuels in certain proportion. This proportion is defined by parameters $BioNF$ and $BioD$ for bioethanol and biodiesel, respectively, as shown in eqs 13 and 14.

$$x_{BE,TN,t} + x_{EC,TN,t} \le BioNF \cdot x_{Nf,TN,t} \quad \forall\, t \tag{13}$$

$$x_{BD,TD,t} \le BioD \cdot x_{GO,TD,t} \quad \forall\, t \tag{14}$$

The straight-line method is applied to calculate the depreciation cost of investments. We assume that certain percentage α_{dep} of the invested amount can be depreciated. In the case of Argentina, 85% is considered. In the absence of new investment the amortization cost ($CA_{i,k,t,t'}$) is zero as indicated in eq 15. When new plants are installed, the depreciation is considered ($CI_{i,k,t}$) until the plants complete their period of life, which is represented by the parameter $TVU_{i,k}$, as it is shown in eq 16. It is worth mentioning that although amortization cost is only considered during the depreciation period ($TVU_{i,k}$), it is assumed that plants will operate until the project is finished.

$$CA_{i,k,t,t'} = 0 \quad \forall\, (t,\, t') < T_{i,k} \quad \forall\, (i,\, k) \in \text{markets}_{i,k} \tag{15}$$

$$CA_{i,k,t,t'} = \frac{\alpha_{dep} \cdot CI_{i,k,t-T_{i,k}}}{TVU_{i,k}} \quad \forall\, t \geq T_{i,k} \quad t \leq t' \leq TVU_{i,k} \quad \forall\, (i,\, k) \in \text{markets}_{i,k} \tag{16}$$

To estimate GHG emission, factors tabulated in Guidelines for National Greenhouse Gas Inventories [43] are considered. In eq 17 total emissions of customer type k in period t are calculated as the sum of all emissions from sources i, where $fGEI_{i,k}$ is the generation factor and $x_{i,k,t} \cdot hr$ is the annual output from the source i to customer type k in period t.

Equation 18 determines the expected emissions if the given energy structure is used to satisfy the desired demand level ($D_{k,t} - UD_{k,t}$); that is, no investments or changes are assumed. The output from each source i to each customer type k is estimated by parameter $PD_{i,k}$. Variable $XGEI_{k,t}$ defined in eq 17 and $GGEI_{k,t}$ in 18 are included in the objective function given in eq 1 to penalize GHG emissions.

$$XGEI_{k,t} = \sum_{i \in \text{market}_{i,k}} fGEI_{i,k} \cdot x_{i,k,t} \cdot hr \quad \forall\, t,\, \forall\, k \tag{17}$$

$$GGEI_{k,t} = \Big(\sum_{i \in \text{market}_{i,k}} fGEI_{i,k} \cdot PD_{i,k}\Big) D_{k,t} \quad \forall\, t,\, \forall\, k \tag{18}$$

3.2. Fuzzy Sets Reformulation. As it was mentioned in the previous section, the first model presented does not consider uncertainty in the parameters but provides a solid base to incorporate it by different approaches. In eq 9 the calculation of reserves for each source i, $RD_{i,t}$, is determined from proven reserves CD_i and new reserves $NewR_i$ that can be discovered. Although the values of these parameters have been initially estimated based on historical data, there is a margin of error which varies depending on the source considered. The lack of accuracy, can be solved by using triangular fuzzy numbers, i.e., $\widetilde{CD_i} = (\widetilde{CD_i^1}, \widetilde{CD_i^2}, \widetilde{CD_i^3})$ and $\widetilde{NewR_i} = (\widetilde{NewR_i^1}, \widetilde{NewR_i^2}, \widetilde{NewR_i^3})$, where for each source i, the central value is the most probable value (which is used in the deterministic model), while the ends identified the most pessimistic value (lower margin) and most optimiztic value (upper margin), obtained by allowing some flexibility in the approaches. Thus, eq 9 is rewritten as eq 19:

$$RD_{i,t=1} \leq \widetilde{CD_i} + \widetilde{NewR_i} \quad \forall\, i \in NR \tag{19}$$

Given two triangular fuzzy numbers $\tilde{d}_1$ and $\tilde{d}_2$, the sum of them is defined as

$$\tilde{d}_1 + \tilde{d}_2 = (d_1^1, d_1^2, d_1^3) + (d_2^1, d_2^2, d_2^3) = (d_1^1 + d_2^1,\, d_1^2 + d_2^2,\, d_1^3 + d_2^3) \tag{20}$$

then

$$\widetilde{CD_i} + \widetilde{NewR_i} = (CD_i^1 + NewR_i^1,\, CD_i^2 + NewR_i^2,\, CD_i^3 + NewR_i^3), \quad \forall\, i \in NR \tag{21}$$

Therefore, the model obtained by replacing eq 9 by 19 is a fuzzy MILP model (FMILP). To solve this type of problem, the transformation method proposed by Mula et al.[44] is adapted as follows. First, we consider a general problem FMILP:

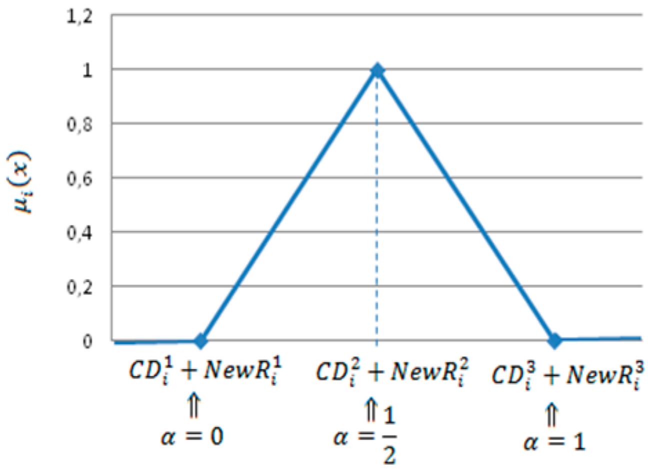

Figure 2. Membership function.

$$\max z = \sum_{j=1}^{n} c_j x_j \tag{22}$$

$$sa \sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i \quad \forall\, i = 1, \cdots, m_1 \tag{23}$$

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i \quad \forall\, i = m_1 + 1, \cdots, m \tag{24}$$

$$x_j \geq 0 \quad \forall\, j = 1, \cdots, n \tag{25}$$

where $\tilde{b}_i$ represents fuzzy numbers of symmetric triangular shape $\tilde{b}_i = (b_i^1, b_i^2, b_i^3)$ with the membership function defined by eq 26 for each $i = 1, \cdots, n$

$$\mu_i(x) = \begin{cases} \frac{1}{b_i^2 - b_i^1}(x - b_i^2) + 1, \text{ if } b_i^1 \leq x \leq b_i^2 \\ \frac{1}{b_i^2 - b_i^3}(x - b_i^2) + 1, \text{ if } b_i^2 \leq x \leq b_i^3 \\ 0, \text{ if } x \leq b_i^1 \text{ or } x \geq b_i^3 \end{cases} \tag{26}$$

The solution of this problem can be found by solving the following problem MILP considering the upper margin:

$$\max z = \sum_{j=1}^{n} c_j x_j \tag{27}$$

$$sa \sum_{j=1}^{n} a_{ij} x_j \leq \alpha b_i^3 + (1 - \alpha) b_i^1, \quad \forall\, i = 1, \cdots, m_1 \tag{28}$$

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad \forall\, i = m_1 + 1, \cdots, m \tag{29}$$

$$x_j \geq 0, \quad \forall\, j = 1, \cdots, n \tag{30}$$

where $0 \leq \alpha \leq 1$ is the cutoff established parametrically.

Therefore, replacing eq 19 by eq 31

$$RD_{i,t=1} \leq \alpha(CD_i^3 + NewR_i^3) + (1 - \alpha)(CD_i^1 + NewR_i^1), \quad \forall\, i \in NR \tag{31}$$

we transform the FMILP model into a MILP model consisting of eq 1−8, 10−18, and 31 in which each value assumed for α allows the evaluation of a possible scenario.

Figure 2 shows the triangular membership function proposed. For each α, a different value of the membership function is obtained, that is, the degree of belonging to the set $\widetilde{CD_i} + \widetilde{NewR_i}$.

3.3. Two-Stage Stochastic Reformulation. As it was mentioned in the previous section, the deterministic approach ignores the fact that some parameters may be not known precisely. Therefore, it is necessary to account for the underlying uncertainty in those parameters to improve the decision process. Fuzzy sets can help to analyze the model performance by generating different scenarios as it was shown previously. In this section, we propose a two-stage stochastic reformulation to address the uncertainty in the availability of fossil resources. This means that parameters CD_i and $NewR_i$ are random and a probability distribution is assumed to generate the different scenarios. In this new model, investment decisions are considered as first stage variables since they have to be selected before further information is revealed, while operational variables such as production rate $x_{i,k,t}$ can adapt to this information and are decided for each scenario s. Therefore, some of the nomenclature used in the model MILP is modified in this section (see Nomenclature section).

Since investment and capacity decisions are made before the resource availability is unfolded, eqs 2, 7, 8, 11, 12, 15, and 16 remain as presented in the MILP model. However, eqs 1, 3−6, 9, 10, 13, 14, 17, and 18 need the following reformulation, given by Eqs. 32−42, respectively:

$$\max(NPV)$$

where

$$NPV = \sum_t \frac{\sum_{\substack{i \in \text{markets}_{i,k} \\ k \in \text{markets}_{i,k}}} (NT \cdot \sum_{t'} CA_{i,k,t',t} - (1 - NT) \cdot (CI_{i,k,t} + CS_{i,k,t}))}{(1 + TI)^{t-1}} - \sum_{i \in NFO} AC_i \cdot AA_i + \sum_s prob_s \left(\sum_t \frac{\sum_{\substack{i \in \text{markets}_{i,k} \\ k \in \text{markets}_{i,k}}} ((1 - NT) \cdot (P_{i,k,t} - CO_{i,k,t}) x_{i,k,t,s} \cdot hr) - Bv_t \sum_k (GGEI_{k,t,s} - XGEI_{k,t,s})}{(1 + TI)^{t-1}} \right) \tag{32}$$

$$\sum_{k \in \text{market}_{i,k}} x_{i,k,t,s} = \text{fraction}_i \cdot x_{P,In,t,s} \quad \forall\ s;\ \forall\ t;\ \forall\ i \in \text{distillates} \tag{33}$$

$$\sum_{i \in \text{markets}_{i,k}} f_{i,k} \cdot x_{i,k,t,s} \cdot hr = D_{k,t} - UD_{k,t,s} \quad \forall\ s;\ \forall\ t;\ \forall\ k \tag{34}$$

$$f_{i,k} \cdot x_{i,k,t,s} \le Cap_{i,k,t} \quad \forall\ s;\ \forall\ t;\ \forall\ (i, k) \in \text{markets}_{i,k} \tag{35}$$

$$\sum_{k \in \text{market}_{i,k}} x_{i,k,t,s} \cdot hr \le RD_{i,t,s} \quad \forall\ s;\ \forall\ t, \forall\ i \in NR \tag{36}$$

$$RD_{i,t=1,s} \le CD_{i,s} + NewR_{i,s} \quad \forall\ s;\ \forall\ i \in NR \tag{37}$$

$$RD_{i,t,s} = RD_{i,t-1,s} - \sum_{k \in \text{market}_{i,k}} x_{i,k,t-1,s} \cdot hr \quad \forall\ s;\ \forall\ t > 1;\ \forall\ i \in NR \tag{38}$$

$$x_{BE,TN,t,s} + x_{EC,TN,t,s} \le BioNF \cdot x_{Nf,TN,t,s} \quad \forall\ s, \forall\ t \tag{39}$$

$$x_{BD,TD,t,s} \le BioD \cdot x_{GO,TD,t,s} \quad \forall\ s;\ \forall\ t \tag{40}$$

$$XGEI_{k,t,s} = \sum_{i \in \text{market}_{i,k}} fGEI_{i,k} \cdot x_{i,k,t,s} \cdot hr \quad \forall\ s;\ \forall\ t, \forall\ k \tag{41}$$

$$GGEI_{k,t,s} = \left(\sum_{i \in \text{market}_{i,k}} fGEI_{i,k} \cdot PD_{i,k} \right)(D_{k,t} - UD_{k,t,s}) \quad \forall\ s;\ \forall\ t, \forall\ k \tag{42}$$

Note that eq 1 is now replaced by 32 where first stage variables are investments $CI_{i,k,t}$, start-up costs $CS_{i,k,t}$, amortization costs $CA_{i,k,t',t}$, and the expansion of harvested area to produce biofuels AA_i. For these costs, no changes are required in the objective function. This means that decisions taken at the first stage of the process do not depend on future realizations of the random parameters or on future decisions. On the other hand, the second stage variables give rise to probable costs and incomes in each scenario s. Then, the total expected costs and incomes from the second stage are calculated considering the probability of occurrence of each scenario s, given by parameter $prob_s$.

Equations 3, 5, 6, 9, 10, 13, 14, 17 are simply modified by 33, and 35−41, adding the set s to variables $x_{i,k,t,s}$ and $RD_{i,t,s}$, expanding the number of variables and constraints as well.

One of the characteristics of the two-stage approach is that the second stage can correct some decisions by the recourse action. In other words, in the second stage we see a realization of the stochastic elements of the problem but are allowed to make further decisions to avoid the constraints of the problem becoming infeasible. In eq 34 and eq 42, a new variable is introduced, $UD_{k,t,s}$, which means the demand not satisfied of customer type k in period t and scenario s. In this problem, the recourse is given by the possibility of not satisfying completely the demand of energy if the limitation in resources availability is not enough for some scenarios s.

It is important to mention that eq 36 connects the first stage decisions with the second stage decisions. In this case, the production in each scenario s for each source i to provide customer type k in period t ($f_{i,k} \cdot x_{i,k,t,s}$), cannot exceed the capacity $Cap_{i,k,t}$ defined in the first stage.

Finally, the stochastic model (SMILP) is given by eqs 2, 7, 8, 11, 12, 15, 16, and 32−42.

4. RESULTS

Both models have been solved with GAMS version 23.5.1 using solver Cplex 12.2.0.0, in a PC with 2.67 GHz Intel core i5 processor

Table 1. Model Statistics.

	fuzzy	two stages
single equations	7 558	1 643 920
continuous variables	11 958	725 244
discrete variables	2 536	2 536
nonzero elements	24 966	3 407 559
CPU time (sec)	0.5[a] (0.722[b])	1 200

[a]Average time. [b]Maximum time.

having 2 GB of RAM and a 64 bits Windows 7 Professional. Table 1 shows some statistics of the models execution.

For the fuzzy model all 20 scenarios generated were solved in sequence in one run. For the 20 instances of the fuzzy formulation an absolute and relative gap of zero was obtained, while for the two stage model the gap was close to zero (relative gap = 0.000004).

4.1. Fuzzy Model Results. The fuzzy model was solved proposing 20 different scenarios changing the value of α (see eq 31). For lower values of this parameter less oil and gas reserves are available, on the contrary for higher values, more fossil reserves are considered, and a value of $\alpha = 0.5$ is assigned to the most probable amount of reserves according to historical data.

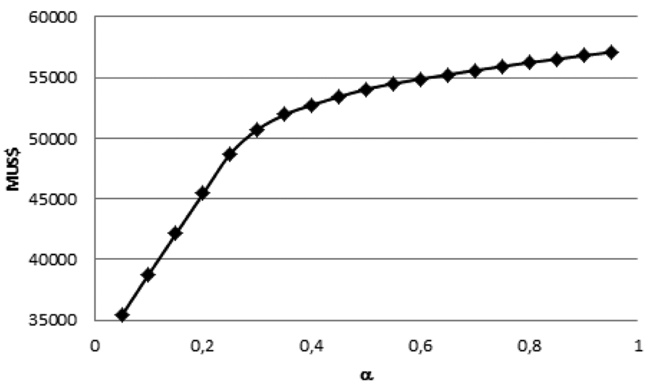

Figure 3. Net present value vs α value.

Table 3. Hydropower and Fuel Oil Investment

hydropower electricity				fuel oil electricity			
α	year	MUS$[a]	TOE	α	year	MUS$	TOE
0.05	2013	18.14	1.37	0.05	2013	59.44	97.64
0.10	2013	18.14	1.37	0.10	2013	59.44	97.64
0.15	2013	18.14	1.37	0.15	2013	59.44	97.64
0.20	2013	18.14	1.37	0.20	2013	59.44	97.64
0.25	2013	18.14	1.37	0.25	2013	59.44	97.64
0.30	2013	18.14	1.37	0.30	2013	59.44	97.64
0.35	2013	18.14	1.37	0.35	2013	59.44	97.64
0.40	2013	18.14	1.37	0.40	2013	59.44	97.64
0.45	2013	18.14	1.37	0.45	2013	59.44	97.64
0.50	2013	18.14	1.37	0.50	2013	59.44	97.64
0.55	2013	18.14	1.37	0.55	2013	59.44	97.64
0.60	2013	18.14	1.37	0.60	2013	59.44	97.64
0.65	2014	18.14	1.37	0.65	2013	59.44	97.64
0.70	2014	18.14	1.37	0.70	2013	59.44	97.64
0.75	2015	18.14	1.37	0.75	2013	59.44	97.64
0.80	2016	18.14	1.37	0.80	2013	59.44	97.64
0.85	2020	18.14	1.37	0.85	2013	59.44	97.64
0.90	2017	18.14	1.37	0.90	2013	59.44	97.64
0.95	2020	18.14	1.37	0.95	2013	59.44	97.64

[a]Millions of U.S. dollars.

Figure 3 presents the NPV obtained for each scenario. From this figure it can be observed that the revenue increases when more fossil fuels reserves are available. The NPV has a higher increase with low values of α (lower level of fossil reserves) and for $\alpha > 0.4$, the improvement has a lower slope because of the GHG emission penalty in the objective function that discourages the use of these reserves.

The investments made in energy sources are presented from Table 2 to Table 7. These tables contain the amount of money needed, the year when investments are made, and their capacity

Table 2. Wind Power Investment Decisions

wind power electricity									
α	year	MUS$[a]	TOE	year	MUS$	TOE	year	MUS$	TOE
0.05	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.10	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.15	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.20	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.25	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.30	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.35	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.40	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.45	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	398.59
0.50	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.55	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.60	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.65	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.70	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.75	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.80	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.85	2013	1868.24	417.92	2014	1868.24	417.92	2019	1868.24	417.92
0.90	2014	1868.24	417.92	2015	1868.24	417.92	2019	1868.24	417.92
0.95	2014	1868.24	417.92	2015	1868.24	417.92	2019	1868.24	417.92

[a]Millions of U.S. dollars.

Table 4. Solar Energy Investments

solar power, residential			
α	year	MUS$[a]	TOE
0.05	2013	414.13	662.43
0.10	2013	414.13	662.43
0.15	2013	414.13	662.43
0.20	2013	414.13	662.43
0.25	2013	414.13	662.43
0.30	2013	414.13	662.43
0.35	2013	414.13	662.43
0.40	2013	414.13	662.43
0.45	2013	414.13	662.43
0.50	2013	414.13	662.43
0.55	2013	414.13	662.43
0.60	2013	414.13	662.43
0.65	2013	414.13	662.43
0.70	2013	414.13	662.43
0.75	2013	414.13	662.43
0.80	2013	414.13	662.43
0.85	2013	414.13	662.43
0.90	2013	414.13	662.43
0.95	2013	414.13	662.43

[a]Millions of U.S. dollars.

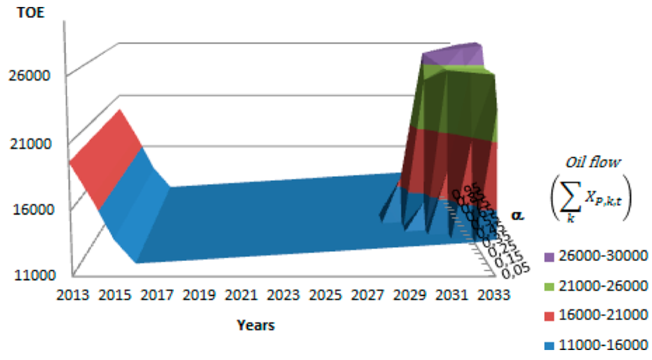

Figure 4. Oil energy flow.

Table 6. Investment in Bioethanol Plants from Sugar Cane

bioethanol (sugar cane); transport						
α	year	MUS$[a]	TOE	year	MUS$	TOE
0.05	2013	384.68	110.12			
0.10	2013	384.68	110.12	2031	230.81	55.06
0.15	2013	384.68	78.20	2030	384.68	96.96
0.20	2013	384.68	78.20	2029	384.68	96.96
0.25	2013	384.68	89.79	2029	384.68	85.37
0.30	2019	384.68	110.12	2028	384.68	65.04
0.35	2025	434.69	175.16			
0.40	2028	484.69	175.16			
0.45	2030	484.69	175.16			
0.50	2031	461.61	165.18			

[a]Millions of U.S. dollars.

expressed in tons of oil equivalent (TOE). Results are presented parametrically according to the value of α.

Table 2 shows the investment decisions in wind power. Even when the investment cost is high, this source is needed in order to cover the electricity market demands and to satisfy the GHG emissions, since this is not a contaminant source. When fossil fuels resources are higher (scenarios with $\alpha > 0.9$), from Table 1 it can be seen that the investments are delayed one year at the beginning of the period (2014−2015 instead of 2013−2014) while in the rest of the scenarios are the same.

To satisfy the electricity market demands, investments are made in hydrokinetic turbines and fuel-oil plants (Table 3). The first source is a renewable one and noncontaminant in terms of GHG emissions, so investments are decided from the beginning of the period for the upper bound capacity which is very low. Investment in fuel-oil plants is mainly justified because it is not expensive, it has a short start time, and there is availability of this combustible. But also, although it is a

Table 5. Investment in Biodiesel Plants

biodiesel (soy); transport									
α	year	MUS$[a]	TOE	year	MUS$	TOE	year	MUS$	TOE
0.05	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	32.368
0.10	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	32.368
0.15	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	11.67
0.20	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	7.492
0.25	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	32.368
0.30	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	3.314
0.35	2013	144.344	135.945	2014	144.344	135.945	2027		
0.40	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	3.314
0.45	2013	144.344	135.945	2014	144.344	135.081	2027	68.735	12.534
0.50	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	15.848
0.55	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.60	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.65	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.70	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.75	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.80	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.85	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.90	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026
0.95	2013	144.344	135.945	2014	144.344	135.945	2027	68.735	20.026

[a]Millions of U.S. dollars.

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Table 7. Investments in Bioethanol Plants from Corn

	bioethanol (corn), transport								
α	year	MUS$[a]	TOE	year	MUS$	TOE	year	MUS$	TOE
0.05	2013	327.71	231.25	2014	327.71	231.25	2015	312.11	112.23
0.10	2013	327.71	231.25	2014	327.71	231.25	2015	156.05	10.74
0.15	2013	327.71	231.25	2014	312.11	145.56			
0.20	2013	327.71	231.25	2014	156.05	49.71			
0.25	2013	327.71	187.55						
0.30	2018	327.71	179.99						
0.35	2024	327.71	179.99						
0.40	2028	327.71	179.99						
0.45	2029	327.71	179.99						
0.50	2031	327.71	179.99						

[a]Millions of U.S. dollars.

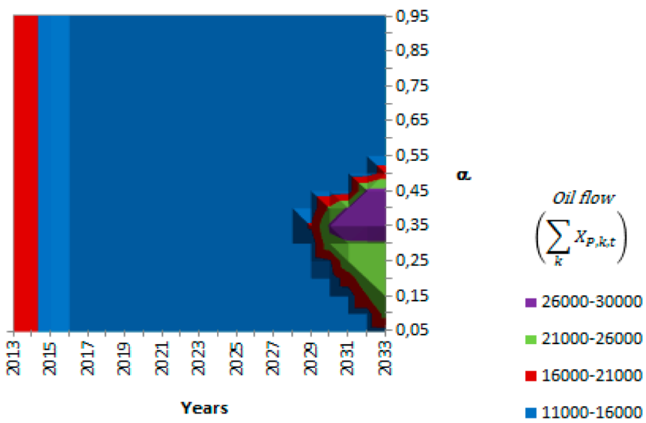

Figure 5. Oil energy flow; level curve of Figure 4.

Figure 7. Natural gas energy flow; level curve of Figure 6.

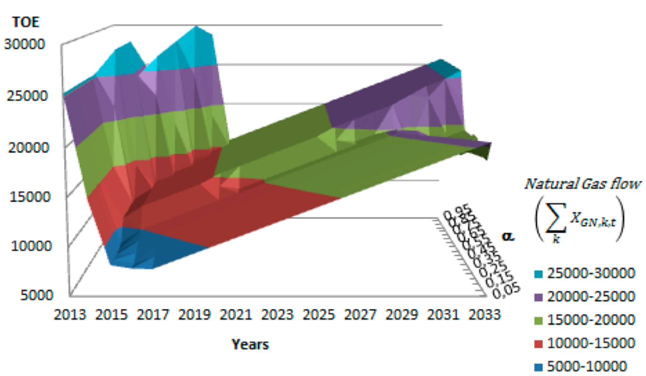

Figure 6. Natural gas energy flow.

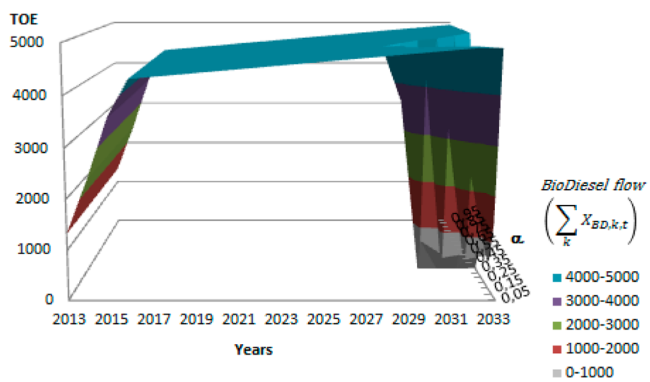

Figure 8. Biodiesel energy flow.

contaminant source, the maximum production capacity is not high and then the amount of GHG emitted is low.

Investment in solar collectors for residential and commercial heating is shown in Table 4. It can be observed that new assets are made from the beginning of the period in the whole range of α values and they cover the upper bound capacity. The explanation of this behavior is the same as for hydrokinetic turbines; it is a cheap noncontaminant source.

Investments in biodiesel and bioethanol are presented from Table 5 to Table 7. These biofuels are used for the transport market; biodiesel for heavy and bioethanol for light transportation. These fuels compete with oil derivatives and natural gas. Natural gas is the cheapest source, less contaminant than oil derivatives, and it is used for several markets: light transportation (gas is employed in cars and light trucks), electricity production, and residential and commercial heating. Biofuels are more expensive than fossil fuels but less contaminants. For these markets there are several trade-offs and the results obtained in terms of investments suggest this behavior.

According to Table 5, at the beginning of the period investments in biodiesel are made in order to cover the decrease in the use of oil derivatives to reduce penalizations for GHG emissions. Also, the installation of new biodiesel plants is needed to satisfy the demands of fuel for heavy transport. All investments are the same independently of the uncertainty in oil and gas reserves. In 2027 different investments are decided to face demands, emissions, and the economic objectives depending on the scenario (fossil reserves availability). At the end of the time horizon, as it can be observed in Figure 4 and Figure 8 below, the energy flow of oil increases as

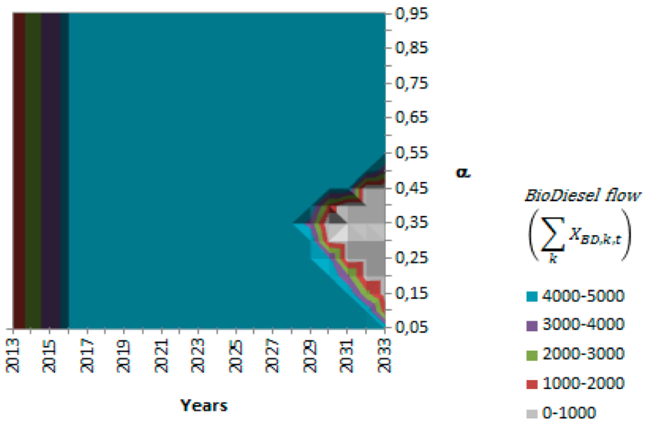

Figure 9. Biodiesel energy flow; level curve of Figure 8.

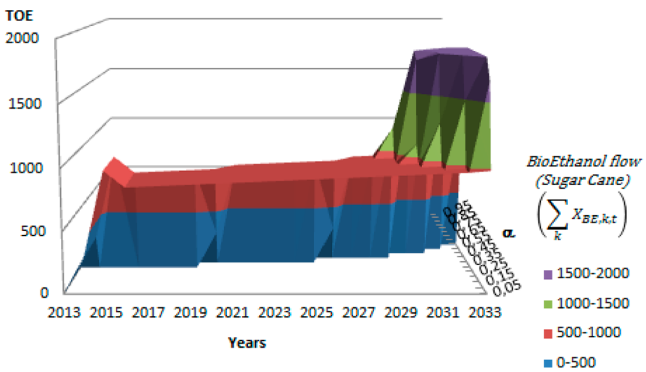

Figure 10. Bioethanol energy flow (from sugar cane).

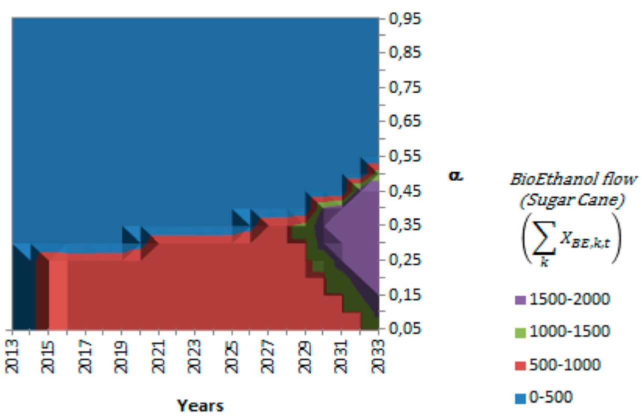

Figure 11. Bioethanol energy flow (from sugar cane); level curve of Figure 10.

the biodiesel decreases. This is due to the competition between both for the transportation market. Oil derivatives have a better economy (greater income) at the end of the period than the beginning.

Table 6 and Table 7 present investments in bioethanol from sugar cane and corn, respectively. This biofuel is more expensive than fossil fuels alternatives for light transportation. From these tables, it can be observed that investments are made for scenarios where fossil reserves are lower ($\alpha < 0.5$). Similar to the biodiesel behavior, investments are mainly decided at the beginning of the time horizon, where consumption of oil and natural gas diminishes. On the contrary, at the end of the period, the capacity levels are different in each period to comply with demands constraints and decrease GHG emissions.

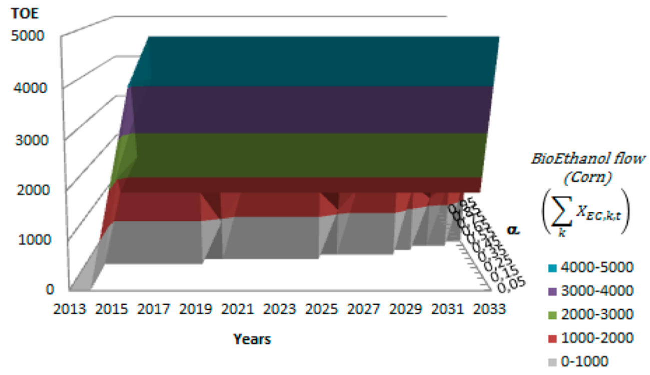

Figure 12. Bioethanol energy flow (from corn).

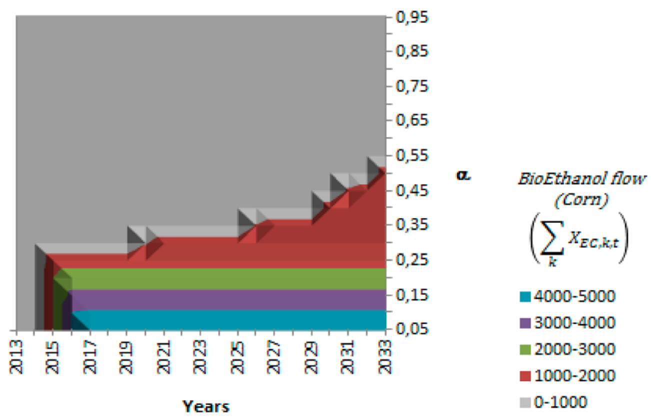

Figure 13. Bioethanol energy flow (from corn); level curve of Figure 12.

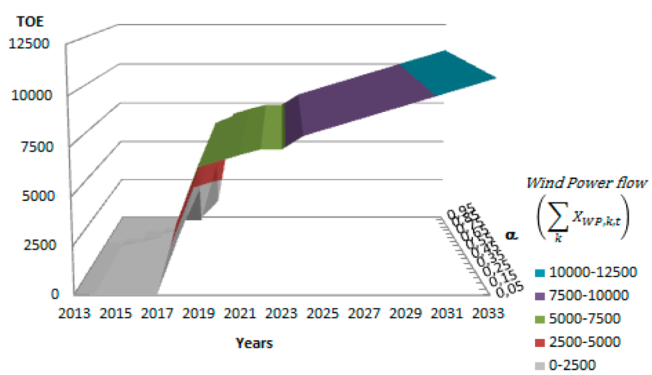

Figure 14. Wind energy flow.

In the following, Figures 4, 6, 8, 10, 12, 14, 16 and 18 are tridimensional graphs that show for each source, the energy flow in TOE (y axis) vs the time period (x axis) and the α parameter (z axis, in deep). The amount of energy flow per period is expressed by using different colors depending on the energy sources. Figures 5, 7, 9, 11, 13, 15, 17, and 19 are level curves projected over x–z axis of the previous three-dimensional ones. Different colors are used to indicate different levels in the amount of energy used. The idea behind this representation is to show the energy flow provided by each source in the horizon time and scenarios considered in this study. Tridimensional curves show better the flow variation during the time, while the level curves improve the visualization for different scenarios.

The analysis of Figure 4 must be done in conjunction with Figure 6. At the beginning of the time horizon, oil and natural

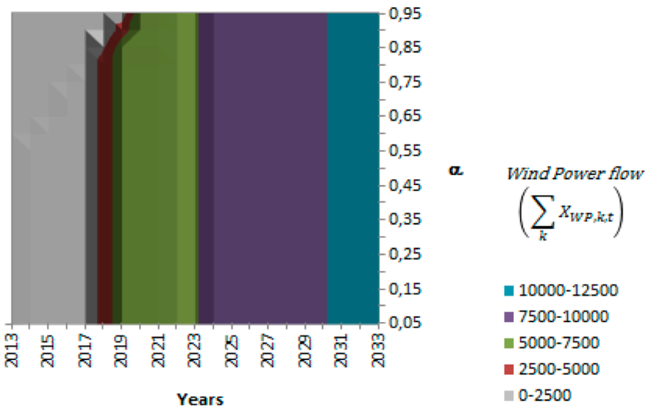

Figure 15. Wind energy flow; level curve from Figure 14.

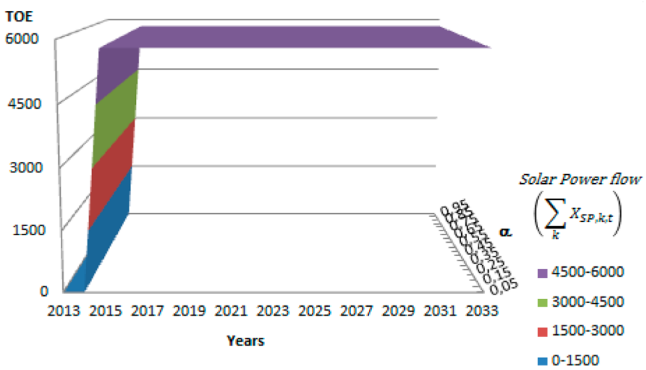

Figure 16. Solar energy flow.

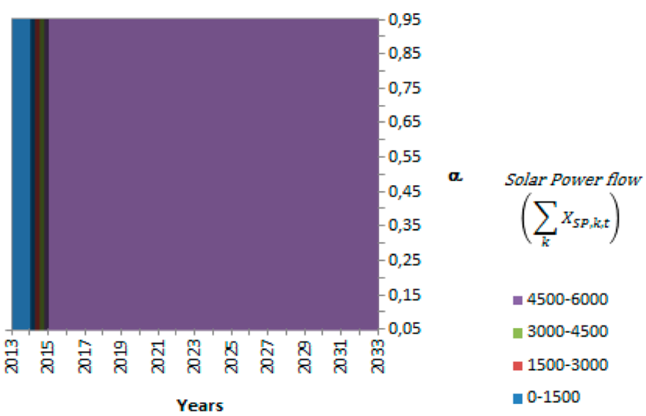

Figure 17. Solar energy flow; level curve from Figure 16.

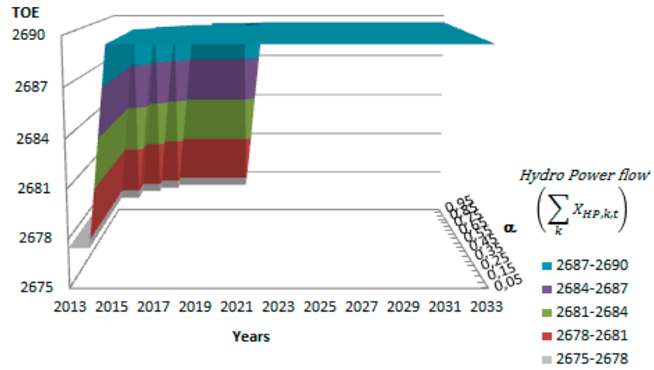

Figure 18. Hydropower energy flow.

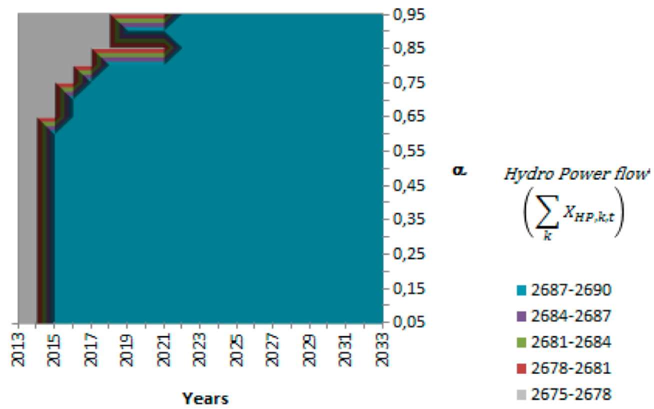

Figure 19. Hydropower energy flow; level curve from Figure 18.

gas flows diminish promoting the use of renewable and noncontaminant sources such as wind power, solar and hydrokinetic turbines. After year 2016 both flows increase having natural gas a steeper slope. Looking at Figure 5, at the end of the horizon time, it can be seen that oil energy flow increases from low values of α parameter until $\alpha = 0.5$ showing a parabolic curve. This means that for higher values of α, where the availability of oil reserves increases, the flow goes down; the explanation for this situation is that natural gas is used instead because it is cheaper and produces less GHG.

Figure 8 and Figure 9 introduce the energy flow for biodiesel. As it was expressed before, it competes directly with oil for heavy transport. In this sense, while the oil flow diminishes the biodiesel grows and vice versa. This behavior can be concluded looking at Figure 4 and Figure 5.

Figure 10−Figure 13 show the energy flow for bioethanol from sugar cane and corn as feedstock. This biofuel compete with oil and natural gas for light transportation market. From the beginning of the time horizon, investments are proposed to increase its use. This is done specially when there is a low availability of fossil fuels resources ($\alpha < 0.5$), while for scenarios with higher values, the flow is reduced. A comparison of both raw materials shows that corn has a higher flow because it has a larger capacity upper bound.

Wind power flow is represented in Figure 14 and Figure 15 for the electricity market. It can mainly replace natural gas and oil. The investments decided at the beginning of the time horizon allow starting the production in year 2017, which keeps increasing until the end of the planning horizon. The behavior is the same for all scenarios. The use of this source is justified by the absence of GHG emissions.

Solar energy flows are presented in Figure 16 and Figure 17, while Figure 18 and Figure 19 present the energy flow of hydrokinetic turbines. As it was explained at the beginning of this section, since those sources are cheap and noncontaminant, they start the production from the beginning of the time horizon and remain in the maximum capacity production for all periods. The performance is the same for all scenarios.

4.2. Two Stage Model Results. This model presents a robust solution where a unique optimal investments result (Table 8) is valid for all the scenarios proposed. The expected *NPV* value (objective function) for this case is of 54075.088 MUS$. To keep valid the first stage decisions (investments) for all scenarios, the model formulation allows unsatisfied energy demands in the second stage. In this way the model optimizes the trade-offs between profits and unfulfilled demands.

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Table 8. Energy Investment Decisions.

		2013		2014		2017		2018		2021		2024	
		MUS$[a]	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE	MUS$	TOE
fuel oil	electricity	59.44	97.64										
biodiesel	transport	144.34	135.94	144.34	130.7								
bioethanol (sugar cane)	transport							461.61	165.18			230.81	9.98
bioethanol (corn)	transport					327.71	179.99						
wind power	electricity	1868.24	417.92	1868.24	417.92			889.64	99.51	1868.2	300.54		
solar power	residential	414.13	662.43										
hydropower	electricity	18.14	1.37										

[a]Millions of U.S. dollars.

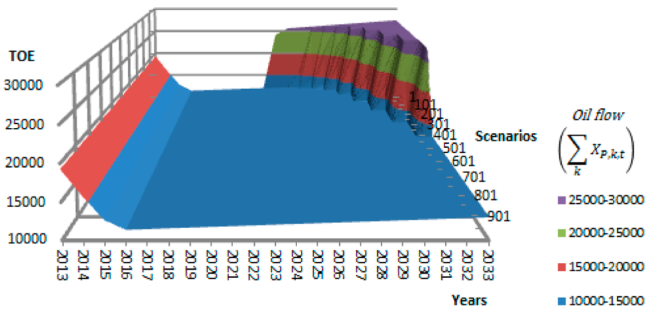

Figure 20. Temporal evolution of oil flows for each scenario.

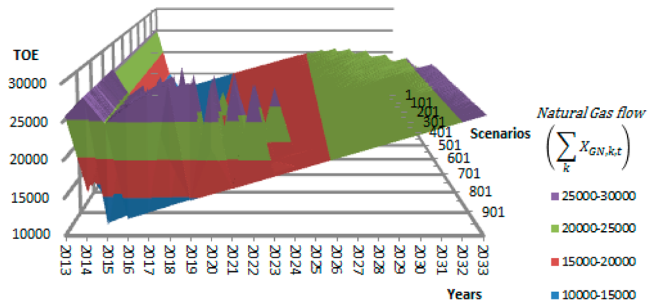

Figure 22. Temporal evolution of natural gas flows for each scenario.

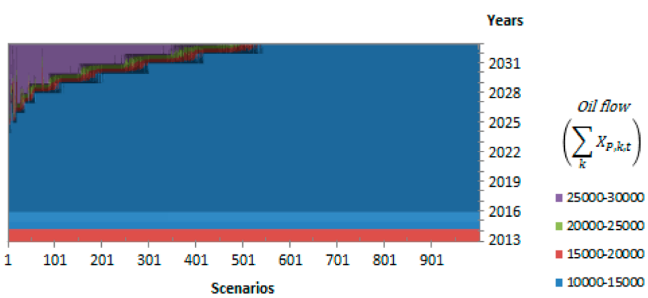

Figure 21. Oil flow per scenario and period; level curve of Figure 20.

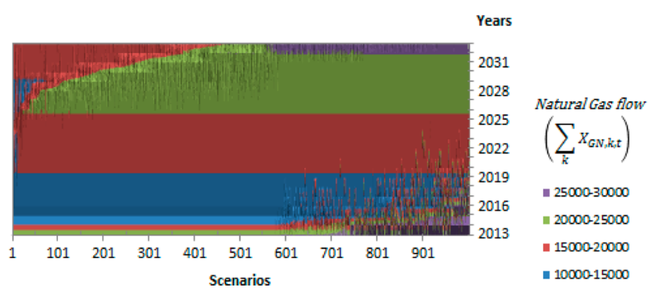

Figure 23. Natural gas flow per scenario and period; level curve of Figure 22.

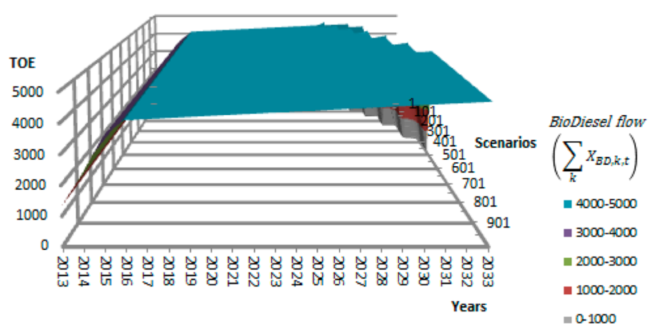

Figure 24. Temporal evolution of biodiesel flow for each scenario.

Table 8 presents the investments made for each source and market, the year of that decision, the amount and capacity (expressed in TOE).

Given a normal distribution of oil and natural gas reserves where the mean value corresponds to the current reserves, we have defined randomly one thousand scenarios with that distribution. Scenario 1 corresponds to the situation where available reserves are low and scenario 1000 to the opposite.

As it was presented in the previous model, Figures 20, 22, 24, 26, 28, 30, 32, 34 are tridimensional graphs that show the energy flow in TOE for each source (y axis) vs the time period (x axis) and the scenario (z axis, in deep), where scenario 1 is in the back and scenario 1000 in the front. The amount of energy flow per period is expressed by using different colors depending on the energy sources. Figures 21, 23, 25, 27, 29, 31, 33 and 35 are level curves projected over x-z axis of the previous three-dimensional ones, where different colors are used to identify multiple levels of energy flows.

Again, an integrated analysis of natural gas and oil flows is required. From Figure 20 and Figure 22 it can be observed that at the beginning of the time horizon both flows diminish until year 2015 and then they have a positive slope, steeper in the case of natural gas. For the case of oil, at the end of the time horizon, the energy flow from this source increases in order to meet the demands in the scenarios with lower reserves than the medium value. However, for those scenarios where more available fossil fuels reserves exists, the energy flow of oil does not increase; this is because natural gas is used instead, for economic and environmental reasons. In general this behavior is similar to the fuzzy model, but energy flows and investments are completely different. The energy matrix is highly dependent on the availability of natural gas.

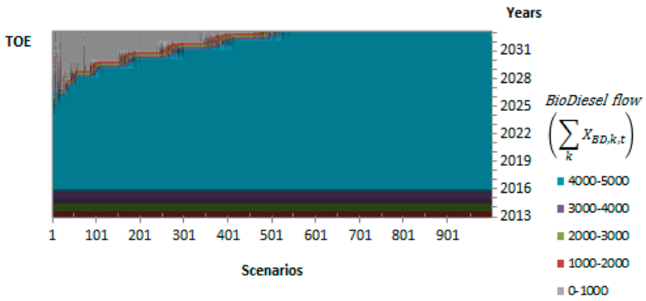

Figure 25. Biodiesel flow per scenario and period; level curve of Figure 24.

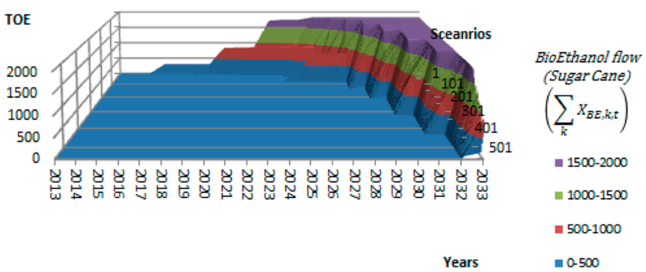

Figure 26. Temporal evolution of bioethanol flow from sugar cane for each scenario.

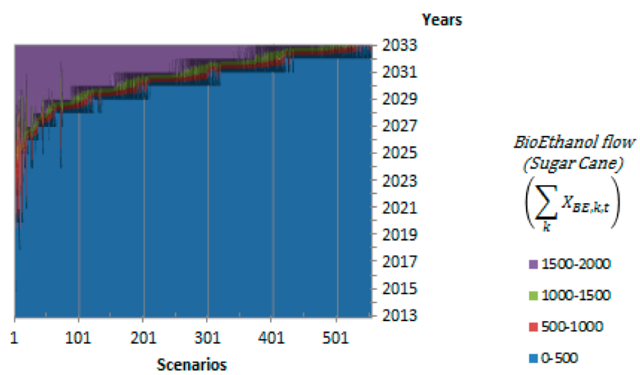

Figure 27. Bioethanol flow from sugar cane per scenario and period; level curve of Figure 26.

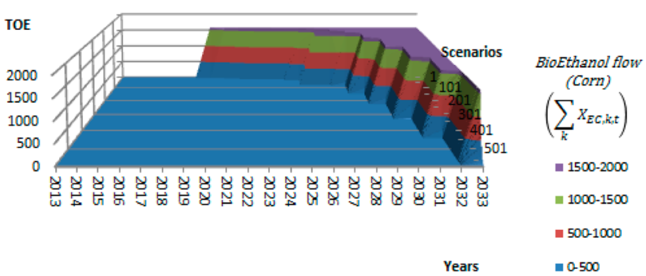

Figure 28. Temporal evolution of bioethanol flow from corn flows for each scenario.

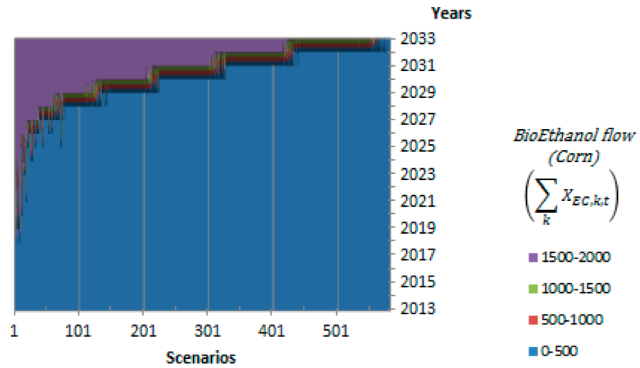

Figure 29. Bioethanol flow from corn per scenario and period; level curve of Figure 28.

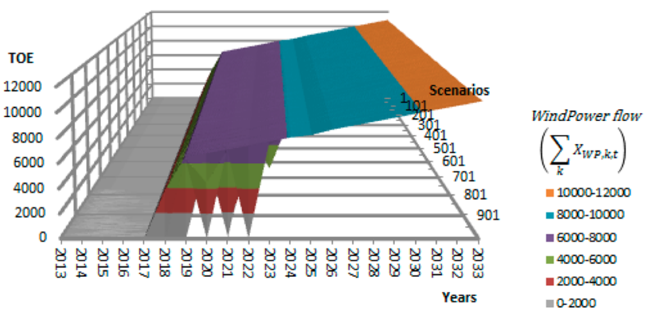

Figure 30. Temporal evolution of wind power flow for each scenario.

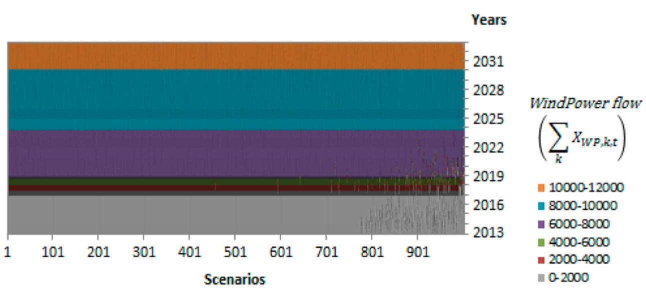

Figure 31. Wind power flow per scenario and period; level curve of Figure 30.

Figure 24 and Figure 25 correspond to the energy power of biodiesel, which in general terms is similar than in the previous model. The use of this source increases from the beginning to the end of the period, except for those scenarios where oil is employed instead (low number scenarios).

The energy flow for bioethanol from sugar cane and corn is shown from Figure 26 to Figure 29, respectively. Investments and energy production are a bit different in this model with respect to the previous (see Table 6, Table 7, and Table 8). These decisions are delayed in the time horizon, and when the availability of natural gas increases (scenarios from 556 to 1000), it replaces the biofuel decreasing its flow. The amount of energy supplied by this fuel is similar for both feedstocks.

Figure 30 and Figure 31 show the results for wind power; investment are similar than the fuzzy model at the beginning but at the end of the time horizon they are split up into two periods comparing Tables 1 and 7. There are no differences between the scenarios analyzed. The use of this source always increases from its production start-up in year 2017.

Figure 32 and Figure 33 present energy flow provided by the sun, while Figure 34 and Figure 35 show the values for hydropower. The behavior is the same as in the fuzzy model; they start the production at full capacity from the beginning of the time horizon, for all the scenarios and remain the same for all periods.

4.3. Unsatisfied Energy Demands. As it was expressed before, the two-stage model needs a recourse action to guarantee feasibility of the investment decisions in all scenarios.

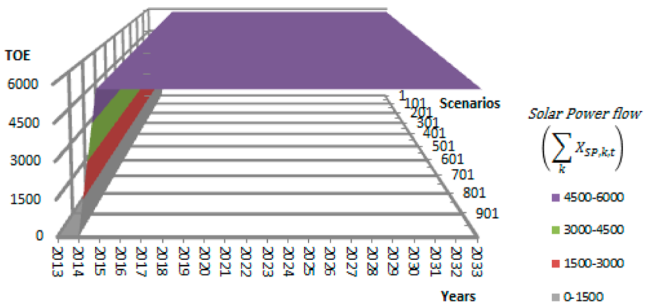

Figure 32. Temporal evolution of solar power for each scenario.

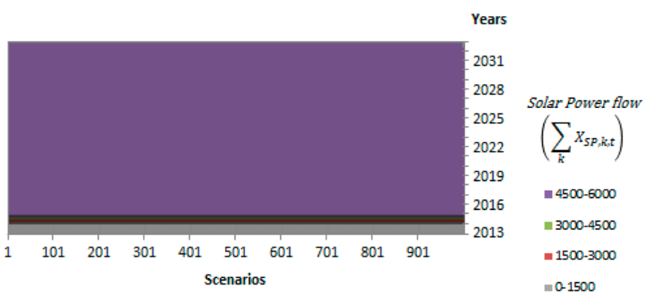

Figure 33. Solar power flow per scenario and period; level curve of Figure 32.

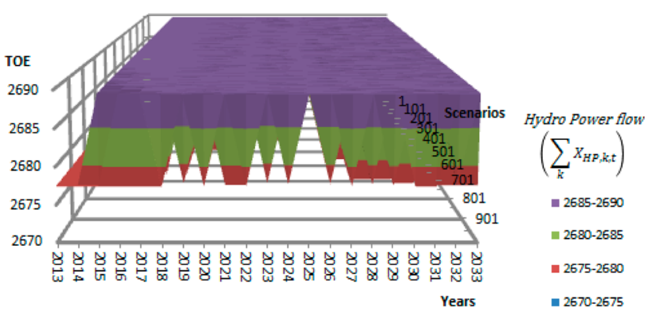

Figure 34. Temporal evolution of hydropower flow for each scenario.

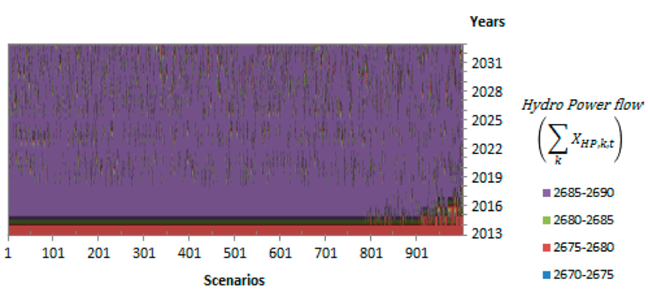

Figure 35. Hydropower flow per scenario and period; level curve of Figure 34.

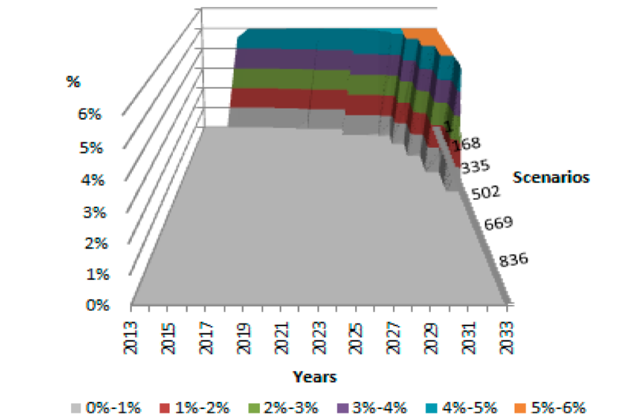

Figure 36. Gasoline unsatisfied demand per period and for each scenario.

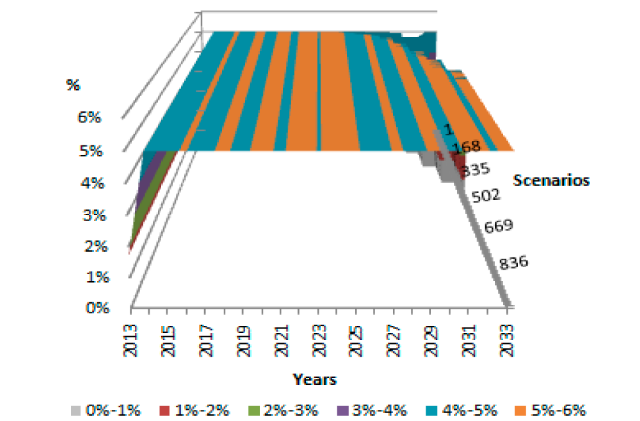

Figure 37. Diesel unsatisfied demand per period and for each scenario.

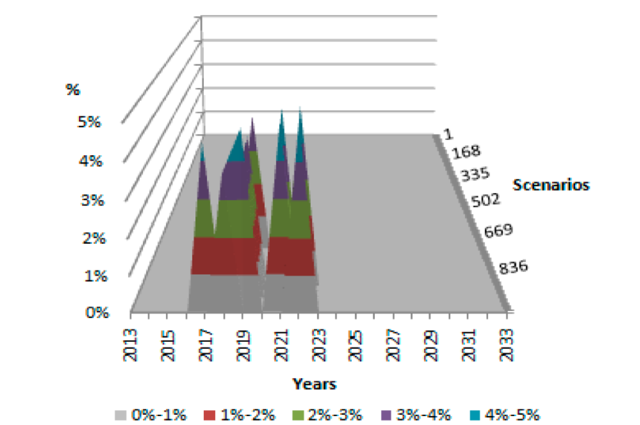

Figure 38. Electrical power unsatisfied demand per period and for each scenario.

In this case, the recourse means that demand might be not completely satisfied for some scenarios, where capacity or availability of energy sources are not enough to meet the required levels of energy. From Figure 36 to Figure 39 the unsatisfied demands for the different markets are presented.

Figure 36 presents the unsatisfied demand for gasoline in the light transportation market. The unfulfilled demand reaches values around its upper bound, 5% of total demand, when the availability of oil and gas reserves is worse (scenarios with lower values). The same upper bound is used for all markets. A similar behavior can be seen in Figure 37, in the diesel market for heavy transportation, where unsatisfied demands also have values of 5%.

Figure 38 shows the unsatisfied demand for the electrical market which presents some particular peaks raising to 4% in short periods. This short energy supply occurs at the beginning of the horizon time where the new capacity installed is not enough to meet the demand.

Figure 39 shows the commercial and residential heating market which is supplied by natural gas and solar power. This graph shows that for lesser values of gas reserves availability, the lack of supply reaches values around 5%. As it was explained

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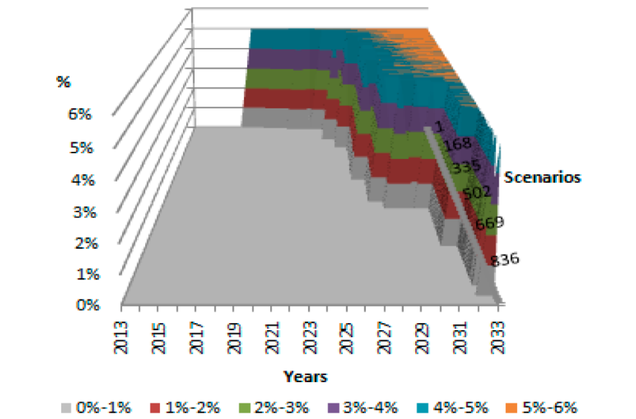

Figure 39. Residential unsatisfied demand per period and for each scenario.

in the previous section, the solar power is employed in the whole horizon time at full capacity.

5. CONCLUSIONS

Optimization models for future investments in energy sources to meet Argentinás power demands considering uncertainty in the fossil fuel reserves has been proposed. An integrated strategy has been developed in order to define an alternative energy infrastructure for the next years. A set of possible energy sources, from renewable to fossil based resources, and several consuming markets are included in the model. To consider the uncertainty in the fossil source availability we first generate a set of scenarios applying fuzzy sets methodology, and then a two-stage stochastic approach is applied. The same variation range has been considered for both models, the fuzzy model includes the lowest and greatest values of the uncertain parameters of the 2-stage model. The random behavior of resource availability in the fuzzy model causes that different investment and energy production decisions are made. There are some sources that are less sensitive to the scenario fluctuation, such as solar, hydrokinetic turbines, and in some grade wind power. But in general, strategic decisions are affected by the scenario considered. The two-stage stochastic model integrates the different decision levels involved in the problem. Only one investment solution is obtained that takes into account a set of 1000 scenarios generated assuming a normal distribution of the fossil reserves parameters, and the unsatisfied demand is never greater that 5% for all energy sources and scenarios considered. Those models can be used to plan incentives and subsidies for future energy investment. They give different perspectives of the same problem that can be used together in the definition of energy policies.

The analysis of the results reveals that the Argentinean energy infrastructure is highly sensitive to the availability of natural gas mainly because of its versatility and low cost. And as long as this resource grows, the need of oil diminishes. Given the scarcity of natural gas reserves, it would be convenient in the future to explore the technical and economic impacts of exploiting shale gas sources.

Future work includes the consideration of new sources of uncertainty that are certainly present in the decision process. The multistage stochastic approach will also be analyzed to address the uncertainty of these parameters considering that some decisions can be updated in each period, and the results will be compared with the present approach. Some of the new technologies are still under development. Therefore, it might be necessary to take into account that some performance and production rate parameters can be also random. The aim of the research group is to improve the present approach by including these new uncertain features into the model, making it more realistic but also more difficult to solve.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE:

Sets

i = sources of energy
P = crude oil
Nf = naphtha
GO = diesel oil
FO = fuel oil
GN = natural gas
BD = biodiesel
BE = bioethanol from sugar cane
EC = bioethanol from corn
WP = wind power
SP = solar power
HP = hydropower
k: = customer types
TN = transport: gasoline engines
TD = transport: diesel engines
EE = electric energy
CR = residential demand
In = industrial demand
t = time periods
r = capacity intervals
s = scenarios in the two-stage model
$\text{markets}_{i,k}$ = set that indicates what source i can satisfy customer type k
distillates_i = subset with secondary fossil sources i obtained from the processing of oil (Nf,GO,FO)
NR = subset of set i for nonrenewable sources
NFO = subset of set i for nonfossil oil (BD, BE)

Parameters

NT = tax rate
TI = interest rate
hr = annual operating hours
$P_{i,k,t}$ = selling price of energy source i for the customer type k in the period t
$PD_{i,k}$ = amount produced from each source i to each customer type k for the initial energy matrix
AC_i = cost of each additional unit of renewable source i
Bv_t = penalty cost for greenhouse gases emission in period t
$CO_{i,k,t}$ = operating cost of energy source i for the customer type k in the period t
$T_{i,k}$ = time from the moment the investment is decided until the plant is in operation for source i and customer type k
α_{dep} = percentage of invested amount that can be considered for depreciation cost

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$TVU_{i,k}$ = useful lifetime of assets for source i and customer type k
$fGEI_{i,k}$ = emission factor for each source i for each customer type k
$D_{k,t}$ = estimated demand for customer type k in period t
$Cm_{r,i,k}$ = minimum investment cost to increase capacity of source i for customer type k in the capacity interval r
$Imax_{r,i,k}$ = maximum capacity increment for source i to supply customer type k in the capacity interval r
$CSm_{r,i,k}$ = start-up cost to begin operation of source i for customer type k in the capacity interval r
$Cap0_{i,k}$ = initial installed capacity for source i and customer type k
$f_{i,k}$ = factor that relates the power source i to customer type k taking into account the performance of source i and unit conversion factor between source i and customer type k
CD_i = availability of resources i
$NewR_i$ = availability of new reserves of nonrenewable resources i
$BioNF$ = maximum percentage of bioethanol with respect to gasoline in the blend of oil
$BioD$ = maximum percentage of biodiesel with respect to gasoline diesel in the blend of oil
$Fraction_i$ = proportion of fuel i obtained when the crude oil is processed
$GGEI_{k,t}$ = greenhouse gases emitted to satisfy customer type k in period t by the initial energy matrix (in tones of CO_2)
$CD_{i,s}$ = availability of resources i in scenario s
$NewR_{i,s}$ = availability of new reserves of nonrenewable resources i in scenario s

Variables

NPV = net present value (objective function)

Positive Variables

AA_i = additional units required of the source i (NFO: biodiesel and bioethanol) expanding the initial harvested area to produce biodiesel or bioethanol
$CA_{i,k,t,t'}$ = depreciation cost corresponding to period t, of the investment made in period t' for source i, customer type k
$x_{i,k,t}$ = flow of energy from source i to customer type k in period t
$CI_{i,k,t}$ = investment cost for source i and customer type k in period t
$CS_{i,k,t}$ = start-up cost for source i and customer type k in period t
$XGEI_{k,t}$ = greenhouse gases emitted to satisfy customer type k in period t by the energy matrix proposed (in tones of CO_2)
$Cap_{i,k,t}$ = capacity decided for source i to supply customer type k in period t
$w_{i,k,t}$ = binary variable that decides to invest in source i for customer type k in period t
$y_{r,i,k,t}$ = binary variable that decides to increase capacity level r in source i for customer type k in period t
$ICap_{i,k,t}$ = increased capacity for new investments in source i for customer type k in period t
$RD_{i,t}$ = available reserves for source i in period t
$UD_{k,t}$ = demand not satisfied of customer type k in period t and scenario s
$x_{i,k,t,s}$ = flow of energy from source i to customer type k in period t and scenario s
$XGEI_{k,t,s}$ = greenhouse gases emitted to satisfy customer type k in period t and scenario s
$RD_{i,t,s}$ = available reserves for that source i in period t and scenario s
$GGEI_{k,t,s}$ = greenhouse gases emitted to satisfy customer type k in period t and scenario s by the initial energy matrix (in tones of CO_2)

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